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Mapping water yield distribution across the South Athabasca Oil Sands (SAOS) area: Baseline surveys applying isotope mass balance of lakes

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A R T I C L E I N F O

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A B S T R A C T

Study region: Surveys of stable isotopes of water in 121 lakes were conducted between 2007 and 2009 to assist in characterizing baseline hydrology of the South Athabasca Oil Sands area, Alberta, a 35,000 km^2 boreal forest region with subdued relief, about 70% wetland cover, and a mosaic of lakes, rivers and buried channel networks. The region, currently under rapid development for in-situ oil sands, was close to baseline conditions at the time of survey.
Study focus: Using an isotope mass balance approach, isotope data were applied to estimate water yield to lakes across the region. High-resolution maps were created to illustrate the spatial distribution of water yield and to compare observed patterns to geologic and physiographic features.
New hydrological insights for the region: Site-specific differences in water yield were found in relation to geologic and physiographic features. Notably, high water yields were found in lakes underlain by Colorado shale, lower runoff was found in proximity to incised and buried channels. Consistent patterns from year-to-year reveal zones of low runoff which may be more susceptible to development-related impacts including changes in surface/groundwater interaction and pressurization or depressurization of aquifers or formations. The approach may be helpful for informing design of new monitoring programs to ensure runoff variability is considered. Periodic reassessments are recommended to capture potential development and/or climatic change impacts on the water cycle.

1. Introduction

In-situ oil sands production in Canada currently accounts for over 1.37 million barrels per day with extractable reserves currently estimated at 165 billion barrels (CAPP, 2018). About 57% of this production capacity is situated within the South Athabasca Oil Sands area (SAOS) (Alberta, 2016), a 35,000 km^2 lake- and wetland-rich boreal forest region situated south of Fort McMurray, Alberta (Fig. 1).

Land cover in the SAOS region is dominated by wetlands, including bogs, fens, and open water. Numerous lakes and less frequent uplands are also characteristic of the region (Gibson et al., 2015a). Permanent streams rarely occur upstream of lakes but rather tend to form as drainage channels from lake outlets. On the Stony Mountains, shallow recharge and runoff is strongly influenced by the limited infiltration capacity of the Cretaceous Colorado Shale where present. Both runoff and shallow groundwater flow through overlying Quaternary drift tend to be radially or semi-radially outwards from the Stony Mountains topographic high towards incised

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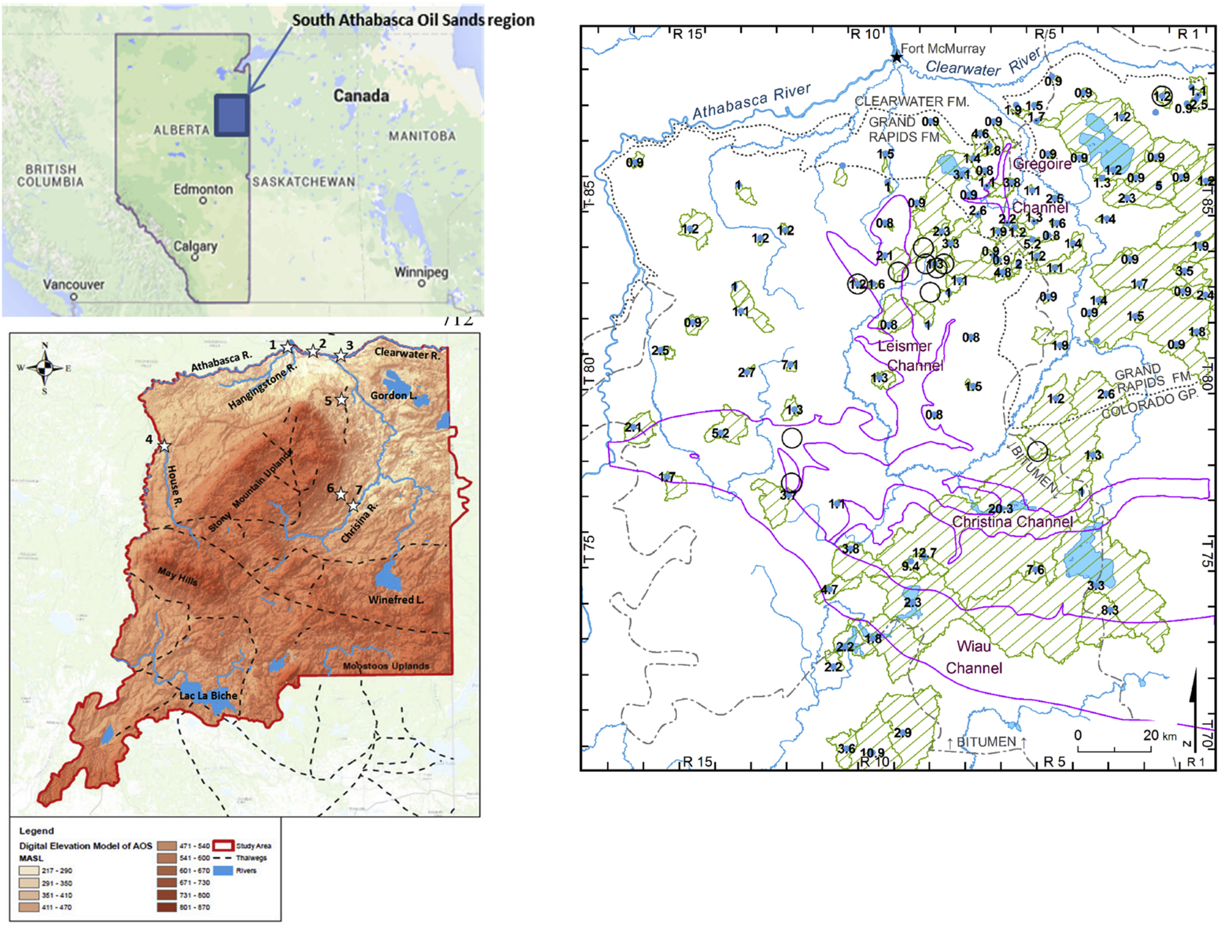

Fig. 1. (a)(top left panel) Location of South Athabasca Oil Sands region, (b) (bottom left panel) elevations and geographical features including gauging stations refereed to in the text, (c) (right panel) Location of study lakes within SAOS showing delineated watershed areas and water depth measured during the 2009 sampling campaign. The location of detailed study lakes are indicated with open circles.

river channels (Barson et al., 2001). Similar patterns are noted for deeper Cretaceous formations, including the Lower Grand Rapids Formation, Clearwater Formation and McMurray Formations, with deeper regional flows of saline formation water moving upgradient from southwest to northeast in underlying Devonian units (Barson et al. 2001). Along incised river valleys, including the Christina River, Hangingstone River, and House River, Colorado Shale units are absent such that thicker Quaternary deposits directly overlie more permeable Cretaceous and Devonian age sandstones, siltstones, shales and carbonates, allowing for deeper surface/groundwater interactions (Birks et al., 2018a, in press). The occurrence of saline springs and saline groundwater seepage areas in and near the rivers provides evidence of this discharge (Gibson et al., 2013; Gue et al., 2015; Birks et al., 2018b). Bitumen occurs predominantly within the McMurray Formation, a poorly-cemented sandstone unit which occurs typically at depths exceeding 80 m below surface, and that may also serve as an aquitard where it is present. A secondary influence on regional groundwater flow patterns is the presence of large buried channels beneath the study area; the main ones being the north-south trending Leismer Channel located in the north, and the west-east trending Wiau and Christina channels in the central and western portion (Birks et al., 2018a, in press). These channels have a significant influence on lateral groundwater flow patterns, given their comparatively higher hydraulic conductivity and overall draining characteristics, but also may affect vertical flow conditions by providing permeable conduits for downward flow into the bedrock formations.

Due to subdued topography, and complex hydrological conditions in the region, Devito et al. (2005) suggested that catchment delineation using surface topography may not be entirely representative in some systems, particularly for smaller catchments in flat areas dominated by wetlands. As principle runoff-generating units, peatlands can respond variably depending on antecedent moisture condition (i.e. depression storage and vadose zone storage capacities), and can behave differently and independently of adjacent hillslopes (Devito et al., 2005). Due to difficulties with using conventional hydrometric approaches, one important objective of this study was to develop and test new approaches for regional characterization and mapping of important water balance characteristics such as runoff in complex, poorly monitored areas.

Because oil sands deposits in the region occur at depths greater than 80 m below surface, oil sands production is carried out by in-situ methods rather than surface mining, mainly using steam-assisted gravity drainage (SAGD) techniques. This method involves

Table 1
Location and land cover distribution for detailed study lakes.

	Lat.	Long.	%Bog	%Fen	%Upland	% Lake	%Open Water	%perma-frost
NE9	56.77	−110.91	0.09	0.74	0.04	0.11	0.01	0.08
NE10	56.64	−110.20	0.04	0.54	0.32	0.10	0.00	0.01
SM1	55.76	−110.76	0.00	0.50	0.21	0.23	0.04	0.00
SM2	55.79	−111.83	0.00	0.79	0.06	0.08	0.03	0.00
SM3	56.20	−111.37	0.05	0.58	0.19	0.12	0.03	0.00
SM4	56.15	−111.23	0.01	0.69	0.17	0.05	0.02	0.00
SM5	56.17	−111.55	0.01	0.64	0.19	0.09	0.07	0.00
SM6	56.22	−111.17	0.02	0.64	0.17	0.12	0.03	0.00
SM7	55.68	−111.83	0.00	0.24	0.54	0.16	0.00	0.00
SM8	56.21	−111.20	0.08	0.79	0.00	0.11	0.03	0.00
SM9	56.22	−111.25	0.13	0.72	0.00	0.08	0.05	0.00
SM10	56.26	−111.26	0.06	0.64	0.12	0.14	0.01	0.00
Max	***56.77***	***−110.20***	***0.13***	***0.79***	***0.54***	***0.23***	***0.07***	***0.08***
Min	***55.68***	***−111.83***	***0.00***	***0.24***	***0.00***	***0.05***	***0.00***	***0.00***
Average	***56.17***	***−111.21***	***0.04***	***0.63***	***0.17***	***0.12***	***0.03***	***0.01***

drilling of horizontal well pairs through overburden and confining bedrock layers into the bitumen zone, followed by injection of high temperature steam to liquefy viscous bitumen for extraction to the surface (Alberta, 2014). While in-situ oil sands development is generally associated with reduced land-surface disturbance compared to mining, in-situ activities may directly affect water levels due to extraction and use of groundwater, or may have indirect impacts by pressurization or depressurization of aquifers or formations, creation or modification of flow pathways to groundwater, or by altering connections between aquifers (Alberta, 2014). Water quality may also be affected due to mobilization of metals and organics due to heating, or from unlikely release of production fluids or operational upsets (Alberta, 2014). The impact of in-situ development on surface water balance and runoff has not been widely discussed, but may potentially occur in response to changes in surface/groundwater interaction. Another main objective of this study was to understand potential impacts of in-situ oil sands development by establishing conditions prior to widespread implementation, and to conduct surveys that would enable future tracking of potential regional impacts over the next few decades.

A recent isotope mass balance (IMB) assessment of fifty lakes in northeastern Alberta by Gibson et al. (2015a) demonstrated that the approach can be an effective at characterizing the long-term water balance of lakes, including water yield, especially useful for site-to-site comparisons in ungauged basins. Of these detailed study sites, 12 are situated within the SAOS, and have been sampled annually in late summer/early fall by the Regional Aquatics Monitoring Program since 2002. Surface/groundwater interactions have also been characterized for one detailed study lake in the area using radon-222 (SM8; Schmidt et al., 2010). Notably, detailed air photo assessments of land cover were also carried out on these watersheds to rigorously establish wetland classes including permafrost conditions (Table 1). Similar air photo classifications of wetland types are not currently available for the entire SAOS area.

For assessment of SAOS-wide water balance conditions, similar isotopic surveys were conducted for lakes, wetlands, and various input water during late summer 2007, 2008, and 2009 (Fig. 1). These surveys formed part of a larger water sampling program aimed at characterizing isotopic and geochemical conditions across the SAOS (Birks et al., 2018a). At the time of the surveys, the SAOS region was at an early stage of development for in-situ oil sands production (~1% of proposed capacity compared to 32% today, Alberta, 2008; 2017), but growth was (and is) is expected to continue to accelerate over the next three decades. Benchmark surveys included water quality parameters and stable isotopes of water, the latter of which provide information on the sources of water in streamflow, wetland and lakes, and allow for assessment of water balance status in surface water bodies. This paper focuses only on describing isotope mass balance for 121 lakes. Given the large number of lakes sampled across the region, it was also possible to determine spatial patterns in runoff that provide additional information on the role of Colorado shale and incised and buried channels on runoff across the region. Establishing conditions at an early stage of development is expected to allow for better assessment of the possible impacts of development on runoff across the region.

IMB has been previously applied to study evaporation/inflow, water residence times, and runoff in the area (Bennett et al., 2008; Gibson et al., 2010a, 2010b). A recent review describes application of the IMB method (Gibson et al., 2015b).

While the present study builds upon the methods developed in previous studies it is unique in that it demonstrates high-resolution application of the method for mapping of runoff across a 35,000 km^2 area, which has never before been conducted. By sampling in three consecutive years, our hypothesis was that change due to development would be minor, and that differences between years would be a reflection of interannual runoff variability. This is discussed further later on. Understanding interannual variability in runoff was also considered to be a necessary control if results were eventually to be compared with repeat surveys over a period of several decades in future.

2. Study sites

The SAOS area is bounded to the west and north by the Athabasca and Clearwater Rivers, to the east by the Saskatchewan border, and to the south by the Cold Lake Beaver River Basin (Fig. 1). Wide area surveys were selected to establish pre-SAGD development conditions for lake water balance and runoff, but also to ensure geochemical characterization across a representative range of

Table 2
Morphometry, climate and derived water balance parameters for detailed study lakes based on a 9-year study (Gibson et al., 2015a).

	Elev	LA	DBA	Precip.	Evap.	WY	Runoff ratio	Res. Time
NE9	477	3.2	8.1	567	537	285	0.50	2.04
NE10	478	4.2	12.9	566	535	245	0.43	1.28
SM1	568	2.4	7.2	588	570	233	0.40	1.60
SM2	671	2.0	13.4	570	544	80	0.14	2.56
SM3	719	1.9	5.5	580	553	309	0.53	1.86
SM4	722	0.5	11.2	576	553	70	0.12	0.58
SM5	717	1.1	2.6	585	549	357	0.61	1.65
SM6	721	0.7	12.4	576	553	67	0.12	0.85
SM7	666	1.5	5.5	571	549	188	0.33	2.79
SM8	721	1.9	7.7	580	553	239	0.41	1.27
SM9	720	1.1	7.2	576	553	253	0.44	0.37
SM10	724	1.4	16.8	576	553	142	0.25	0.45
Max	***724***	***4.2***	***16.8***	***588***	***570***	***357***	***0.61***	***2.79***
Min	***477***	***0.5***	***2.6***	***566***	***535***	***67***	***0.12***	***0.37***
Average	***659***	***1.8***	***9.2***	***576***	***550***	***206***	***0.36***	***1.44***

conditions. Lake areas were used to determine lake classes following an approach similar to Henriksen et al. (1996), and a representative number of lakes from each size class were selected. Overall, 76 lakes larger than 0.5 km^2 were selected with the remainder of lakes ranging from 0.01 to 0.5 km^2. Drainage basin areas were delineated from a 30-m resolution digital elevation model using ArcGIS and ArcHydro (ESRI, 2008). The lakes are situated predominantly in headwater catchments and range in size from small, shallow lakes (1 m-depth, < 0.5km^2) to large lakes such as Christina Lake (17.3 m-depth; 21.3 km^2; Mitchell and Prepas, 1990) and Gregoire Lake (7.2 m-depth; 25.8 km^2; Mitchell and Prepas, 1990). Lakes are underlain by Quaternary tills, sandstone, siltstone, shale and carbonates of Cretaceous to Devonian age. Many of the lakes are situated in the Stony Mountains, a plateau where the Cretaceous Colorado Shale has weathered dominantly and forms a shallow, relatively impervious barrier to vertical groundwater movement. Land cover in a network of detailed study lakes (Table 1; Fig. 1) is considered to be fairly typical of the SAOS, dominated by bog, fen, open water and upland. Wetlands occupy 70% of the land area, with bogs accounting for about 6% of this total. In general, bogs occur as slightly elevated platforms with sporadic permafrost, often contributing runoff to fens which tend to occupy flatter areas. Uplands occupy sloping areas bordering streams, particularly in the lower elevational ranges. A summary of morphometry, climate and derived water balance parameters for the detailed study lakes is also included, based on a 9-year study presented by Gibson et al. (2015a) (Table 2). As a similar IMB was used, this provides important control for the spatial analysis presented here. Mean annual precipitation across the region ranges from about 560 to 590 mm, lake evaporation ranges from 530 to 570 mm, and water yield ranges from 70 to 360 mm. Water residence times for lakes are estimated to range from 4 months to 3 years (Gibson et al., 2015a). Note that some lakes were found to have water yields in excess of annual precipitation which has been a finding previously attributed to the influence of permafrost melt, which has been partially confirmed by results from tritium surveys (Gibson et al., 2016a).

3. Method

3.1. Water sampling and laboratory analysis

Water samples were collected from float plane or helicopter in 30-mL high-density polyethylene bottles with minimal headspace and tightly-sealed polypropylene lids to minimize evaporation prior to analysis. Procedures used for water sampling have been described previously (Gibson et al., 2015a, 2010a,b). For larger lakes, accessed by float plane, water samples were collected at 0.5-m depth using a Kemmerer sampler from near the centre of the lake. For lakes sampled by helicopter, grab samples were collected at similar depth near the centre of the lake. Sampling was conducted during early September to early October when larger, deeper lakes in the region (usually dimictic lakes, Taranu et al., 2010) are expected to be isothermal and therefore well-mixed (see Mitchell and Prepas, 1990). Shallow, polymictic lakes, also abundant in the area, are expected to be continuously well-mixed (Taranu et al., 2010). Note that use of grab samples to represent the whole water body presumes that the lakes were well-mixed and unstratified. In any case, stratification has been shown to have a limited influence on IMB in typical northern Alberta lakes (Gibson et al., 2002).

In addition to lakes, various types of water such as soil water, groundwater, wetland water and snow were collected and analyzed to provide baseline information for the area. Wetlands (mainly fens) were sampled by helicopter along transects from selected lakes; water being gathered from open areas by standing on the surface and creating a depression (bootwell) from which water was collected. Groundwater was collected by industrial operators from cased wells installed for water supply and/or water monitoring of specific aquifers and formations. Due to significant depth of most industrial wells, seasonal variations are expected to be minor. Soil water from forested soil was collected in summer by digging soil pits to a maximum of 1 m-depth. Moist soil was placed in sealed plastic bags and returned to the laboratory for extraction of soil water by azeotropic distillation using toluene. Snowpack samples were collected by digging pits and taking a depth-integrated sample from a vertical snow face.

All isotope data were analyzed at the InnoTech Alberta lab in Victoria, Canada within 2 months of collection using a Thermo Scientific Delta V Advantage Dual Inlet system. The water sampling containers used have been shown to have hold times of up to one year or more for oxygen-18 and deuterium without refrigeration (Spangenberg, 2012). Water samples were analyzed using a Gas-bench peripheral for oxygen-18 (see Paul and Skrzypek, 2006) and an HDevice for deuterium (see Brand et al., 1996), and are reported in δ notation in permil (‰) relative to Vienna Standard Mean Ocean Water (V-SMOW). Results are normalized on the VSMOW/SLAP scale (Standard Light Arctic Precipitation) (see Nelson, 2000). Routine analytical uncertainty is better than ± 0.1‰ for $\delta^{18}O$ and ± 1‰ for $\delta^{2}H$. All data area reported in Gibson et al. 2018a, in press.

3.2. Theory

Isotope mass balance methodology has been described in detail by Gibson et al. (2015b), and has been previously applied in a number of water resources assessments in the region (Schmidt et al., 2010; Gibson et al., 2010a, 2010b; Gibson et al., 2015a), across Canada and the US (Arnoux et al., 2017; Gibson and Reid, 2014; Gibson et al., 2016b, 2017, Gibson et al., 2018b; Brooks et al., 2014; Jasechko et al., 2014) and in Europe (e.g. Petermann et al., 2018; Vystavna et al., 2018). A brief overview of the technique is presented here.

Annual water loss by evaporation (x) can be estimated for well-mixed lakes in isotopic and hydrologic steady state using:

$$x = E/I = (\delta_I - \delta_L)/(\delta_E - \delta_L) \quad \text{(dimensionless)} \tag{1}$$

where I and E are annual lake inflow and evaporation (m^3), and δ_I, δ_L and δ_E are the isotopic compositions of inflow, lake water and evaporation fluxes (‰), respectively. While inflows and lake water can be characterized by sampling of precipitation and lake water (respectively) the isotopic composition of evaporate δ_E is estimated indirectly based on the Craig and Gordon (1965) model:

$$\delta_E = ((\delta_L - \varepsilon^+)/\alpha^+ - h\delta_A - \varepsilon_K)/(1 - h + 10^{-3}\cdot\varepsilon_K)(‰) \tag{2}$$

where δ_A is the isotopic composition of ambient atmospheric vapour, h is the relative humidity (decimal fraction), $\varepsilon^+ = (\alpha^+ - 1)\cdot 1000$ is the equilibrium isotopic separation, α^+ is the equilibrium isotopic fractionation, and ε_K is the kinetic isotopic separation. More details are provided by Gibson et al. (2015a,b). Substitution of (2) into Eq. (1) yields:

$$x = E/I = (\delta_L - \delta_I)/(m(\delta^* - \delta_L)) \quad \text{(dimensionless)} \tag{3}$$

where

$$m = (h - 10^{-3}\cdot(\varepsilon_K + \varepsilon^+/\alpha^+))/(1 - h + 10^{-3}\cdot\varepsilon_K) \quad \text{(dimensionless)} \tag{4}$$

and the limiting isotopic enrichment is given by

$$\delta^* = (h\delta_A + \varepsilon_K + \varepsilon^+/\alpha^+)/(h - 10^{-3}\cdot(\varepsilon_K + \varepsilon^+/\alpha^+)) \quad (‰) \tag{5}$$

The annual volumetric runoff R to headwater lakes can also be estimated as:

$$R = E/x - P \quad (m^3\cdot\text{year}) \tag{6}$$

where $E = e\cdot LA$; $P = p\cdot LA$; e and p representing the annual depth-equivalent of evaporation and precipitation ($m \cdot year$) and LA is the lake area (m^2). Annual depth of runoff (a.k.a. water yield) can then calculated as:

$$WY = R/DBA\cdot 1000 \quad (mm\cdot\text{year}) \tag{7}$$

where DBA is drainage basin area.

3.3. Model parameterization and assumptions

Several parameterization approaches have been used in the past within the basic theoretical framework presented above, to resolve the isotope mass balance for regional assessments. For the current application, and to be consistent with the method applied for the detailed study lakes (Table 2; Gibson et al., 2015a), we estimate the isotopic composition of input to the lakes based on the intercept of the Edmonton Meteoric Water Line (MWL) and the Local Evaporation Lines (from regression of measured lake data). While Edmonton is located 350 km south of the SAOS, a recently study at the nearby Mildred Lake, located 43 km north of Fort McMurray, proposed a slightly revised local MWL for the area (Baer et al., 2016). Use of the Mildred amount-weighted MWL, which has a slightly lower slope and increased intercept with the LEL, would have resulted in a reduction in water yield by 2–4% for all lakes, which is considered to be minor compared to overall uncertainty in the method (estimated at ± 10-15%, Gibson et al., 2005). For consistency with the detailed study lakes approach, we elect to present the results based on the Edmonton MWL. Note that the isotopic composition of atmospheric moisture is estimated from a partial equilibrium model (k = 0.4) based on a best-fit to the local evaporation line (see Gibson et al., 2015a,b; Petermann et al., 2018). A similar atmospheric moisture composition is obtained by assuming equilibrium with average soil water ($\delta^{18}O = -15.41$; $\delta^{2}H = -123.9$). Both approaches converge on representative values for isotopic composition of precipitation and atmospheric moisture during the warm months when evaporative enrichment is occurring. Such seasonally-weighted values have been shown to be more appropriate for isotope balance in cold regions than models assuming isotopic equilibrium with annual precipitation (Gibson et al., 2008).

Interpolation of monthly climate data from the North American Regional Reanalysis (NARR) (Mesinger et al., 2006) is used to assemble required estimates of climatological data for each lake site. The NARR dataset is a long-term, dynamically consistent, high-resolution, high-frequency, atmospheric and land surface hydrology dataset for the North American domain. This model dataset has a horizontal resolution of 32 km and 45 vertical layers providing a much higher resolution than the global reanalysis datasets. Firstly, monthly and annual open-water precipitation and evaporation were estimated for each site, and then the latter was used as the basis for calculating evaporation-flux-weighted values of annual temperature and relative humidity (both at 2-m height), as described previously by Gibson et al. (2015a).

Evaporation/inflow (x) was then estimated from Eq. (3) and water yield was estimated from Eq. (7). For plotting, values for δ^* which is the limiting isotopic enrichment that a water approaches as volume, $V \rightarrow 0$, were based on Eq. (5). It is important to note that water yield derived using this approach provides a combined estimate of surface water and groundwater input to the lakes rather than a method for differentiating these quantities.

Finally, lake areas (LA) and watershed areas (WA) were estimated for each sampling site in the ArcGIS program using the ArcHydro tools, where each watershed was delineated upstream of a lake outlet. Planimetric areas were calculated using equal area projections. Drainage basin areas (see Fig. 1) were calculated as a residual (i.e. $DBA = WA - LA$). Note that due to low relief in some areas, delineation of watersheds may be subject to variable errors. While high degree of spatial autocorrelation observed initially suggested that site-to-site delineation errors are likely not a substantial limitation, the water yield data are provided in Gibson et al. (2018b) to permit further geospatial assessment.

4. Results and discussion

4.1. Isotope characteristics

Isotope data for groundwater, soil water, snow, lakes and wetlands are summarized in Fig. 2a & b. Data are also provided in Gibson et al., (2018a). Soil water and groundwaters are shown to plot along a line with a slope close to 8 but slightly below the Global Meteoric Water Line (GMWL; $\delta^2H = 8 \cdot \delta^{18}O + 10$) of Craig (1961) and close to the MWL for Edmonton ($\delta^2H = 7.71 \cdot \delta^{18}O - 0.03$), and

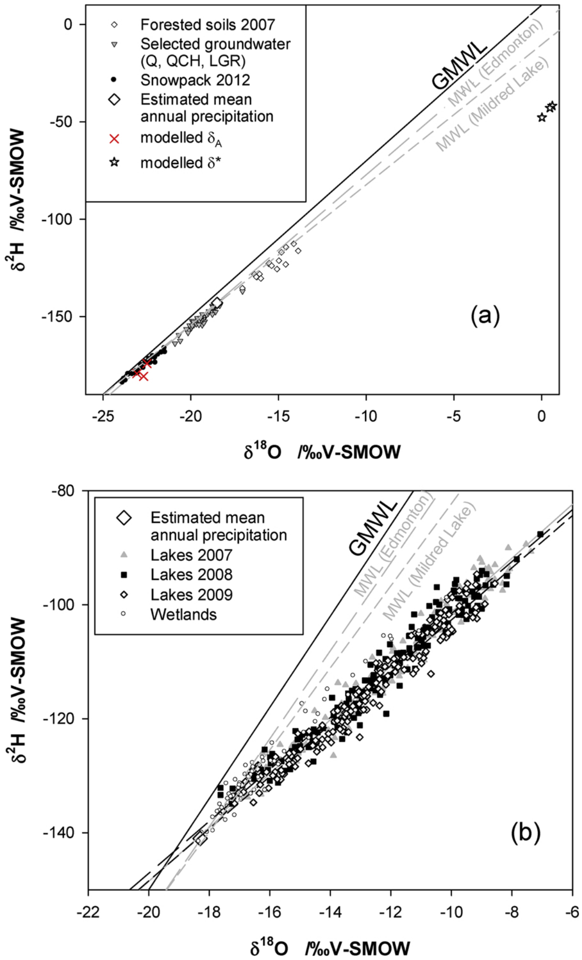

Fig. 2. $\delta^{18}O$-δ^2H signatures in (a) measured and modelled parameters, and (b) lakes and fens. Estimated isotopic composition of precipitation is also shown. Global Meteoric Water Line (GMWL) is after Craig (1961); Local Meteoric Water Lines (MWL) for Edmonton and Mildred Lake are after Baer et al. (2016). Q is Quaternary aquifers, QCH is Quaternary channels, LGR is Lower Grand Rapids Fm.

the amount-weighted Mildred Lake MWL ($\delta^2H = 7.2\delta^{18}O$-10.3‰), which are included for comparison (Fig. 2a). Lake waters plot along distinct local evaporation lines (LEL) with fairly consistent slopes of between 4.56 and 4.72 from year to year (Fig. 2b), which appears to be representative of the SAOS area. Wetlands plot close to the LEL for lakes but with less overall enrichment, presumably due to open-water evaporation being less important for wetlands than lakes. Soil waters are found to be enriched relative to groundwaters and mean annual precipitation (Fig. 2a), the latter, estimated as the intercept of the Edmonton MWL and LEL, being a useful approximation of long-term input to the lakes. Soil water enrichment in the first metre below surface is likely reflective of summer precipitation sources at the time of sampling but may also reflect some evaporation from soil or depression storage prior to recharge. Limited sampling from precipitation collectors has been carried out at selected sites in the SAOS (see Bennett, 2006; Tattrie, 2011) although samples were evidently affected by evaporation from the sampler and so are not used. Snowpack samples (Vallarino, 2014) are found to be depleted relative to groundwaters and mean annual precipitation. Quaternary aquifer, Quaternary channel and regional formation waters (Grand Rapids Formation) tend to be more depleted than mean annual precipitation as much of the groundwater system has been significantly recharged by glacial meltwater sources (see Grasby and Chen, 2008). Under colder climate conditions isotopic signatures were likely significantly depleted relative to mean annual precipitation today.

For lakes, isotopic offset along the LEL from the MWL intercept (Fig. 2b), has been shown to occur in response to evaporation losses whereby offset is generally proportionate to the fraction of water loss by evaporation from each lake (Gibson et al., 2015a,b). From maps of isotopic composition in lakes across the SAOS area, fairly consistent enrichment patterns are seen, suggesting similar water balance from year-to-year in most lakes (Fig. 3). MWL intercepts are also fairly similar for year-to-year LELs. Calculated evaporation/inflow and water yield distributions, and areal mapping of water yield are presented in the following sections.

4.2. Evaporation/inflow and water yield distributions

An overall impression of the distributions of the isotopic data, evaporation/inflow estimates, and water yield are provided in Fig. 4. Similar distributions in isotopic composition and evaporation/inflow were found for 2008 and 2009 (not shown). Positively skewed distributions are noted for water yield, as found in several previous assessments (Gibson et al., 2010a,2010b, 2015a), which reflects the tendency for most watersheds to have lower runoff, with fewer watersheds being more dynamic. We attribute this to poorly organized drainage in vast low-relief, wetland dominated areas, although more dynamic zones may occur along incised streams due to greater relief, or presumably in some cases, due to buried channels.

4.3. Water yield

Water yields (Fig. 5) were found to be distinct from evaporation/inflow patterns, the latter which closely mimic variation in isotopic composition of lakes across the region (Fig. 3). Similar spatial trends in water yield were also noted from year-to-year. In general, high water yields are predicted in the Stony Mountains, in the vicinity north and south of Gordon Lake, along the southeasterrn boundary of the SAOS and to the west of Winefred Lake (Fig. 1). High water yields also occur in zones between buried channels, i.e. between Christina and Wiau channel, and in the vicinity of Leismer channel. The high water-yield zone mapped for the Stony Mountains also appears to terminate abruptly at the Leismer channel to the east and south, which is particularly evident in 2007 and 2009. Areas of lower runoff include the Christina River and Hangingstone River corridors, areas characterized by incised river channels. Extensive tracts of the largest buried channels, namely the Christina and Wiau channels, appear to be overlain by lakes with moderate rather than high or low water yield. The main conclusion that we reach based on observing the spatial distribution of runoff is that both buried and incised channels appear to play a significant role in determining runoff or water yield and may influence its variability. Channels likely serve as regional drains that promote vertical seepage rather than lateral flow, which can lead to water being directed downward away from lakes. In contrast, plateaus or uplands, especially those underlain by relatively impervious shale, tend to promote lateral flow to lakes. We find a weak positive relationship between elevation and water yield which varies inter-annually (Fig. 6). This pattern does not support simple use of elevation to interpolate runoff to lakes as suggested by some previous studies in the region (WRS, 2004).

Water yield to lakes was evidently lower in 2007 compared with 2008 and 2009. As noted by Gibson et al. (2010a) and revealed by the data shown in Gibson et al. (2015a; Table 2), 2007 is found to be a low runoff year to lakes in the Stony Mountains as well as most lake sub-regions near Fort McMurray.

4.4. Comparison with gauge data

River discharge is routinely monitored at hydrometric gauging stations by Water Survey of Canada, and is the standard method for estimating annual water yield. While water yield data exist for 7 stations located within or near the SAOS (Table 3), only 5 stations record runoff conditions in the SAOS itself, and 3 of these stations have since been discontinued. However, three stations were operational at the time of the lake surveys, including Christina River at Chard, Pony River near Chard, and Hangingstone River near the mouth. While these are important monitoring stations for both seasonal and long-term studies, they do not provide a perspective of spatial variations in water yield across the SAOS. Water yield values based on the hydrometric gauges in the area ranged from 90 to 170 mm /year with a mean of 137 mm/year (n = 3) during 2007 to 2009. In comparison, basin average estimates based on IMB ranged between 105 and 154 mm/year, with a similar overall average of 130 mm/year. Bennett et al. (2008) also reported good agreement between water yield determined from Water Survey gauging stations and IMB in the Fort McMurray area. Inter-annual variability is also an important characteristic with standard deviation ranging between about 20 and 80 mm/year for long-term hydrometric gauging, which brackets the range observed for IMB. Slightly higher variability may be expected for lakes in the long-

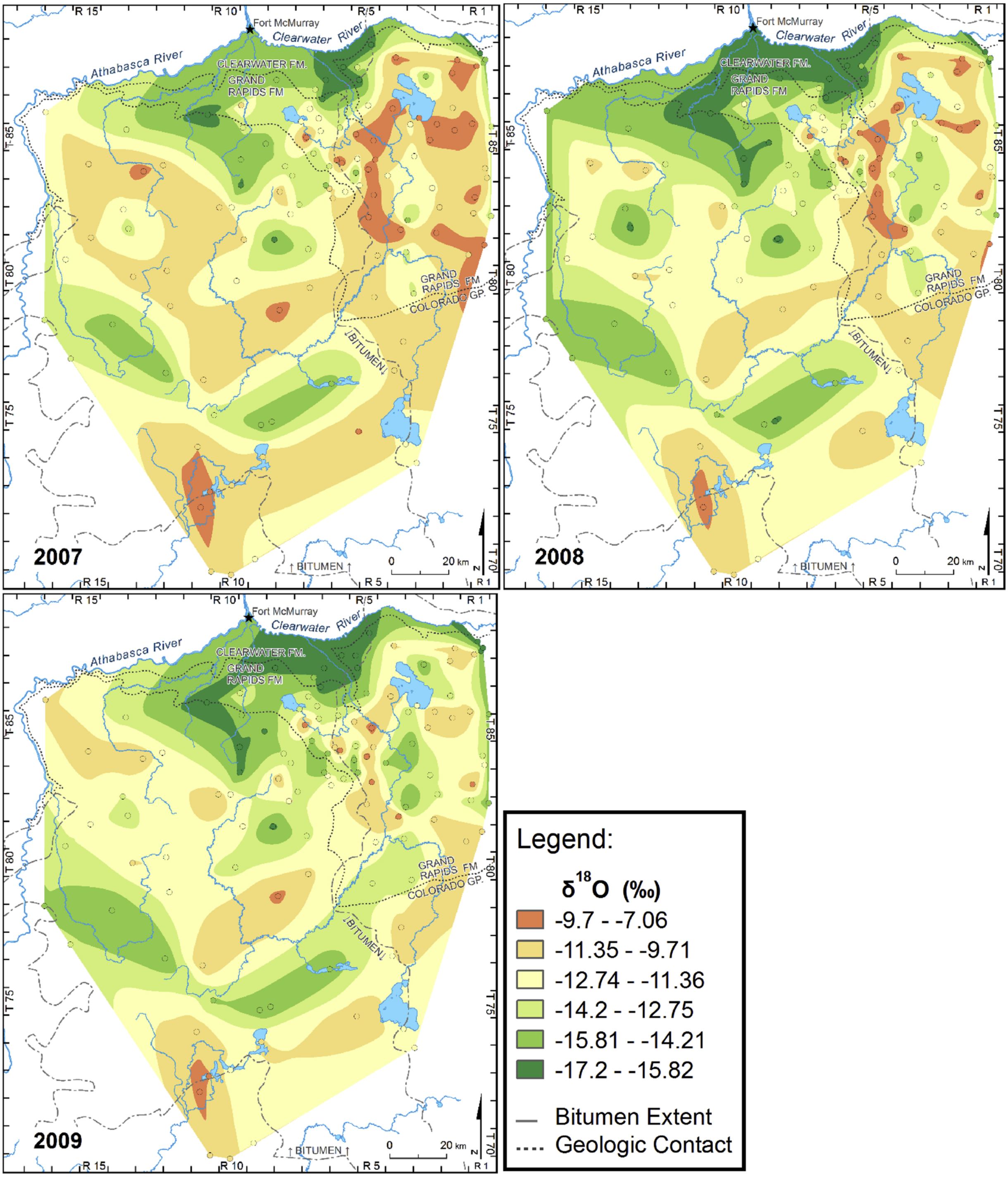

Fig. 3. Spatial distribution of isotopic composition ($\delta^{18}O$, ‰VSMOW) in lakes across the SAOS.2007–2009.

term due to the typically smaller area of the lake watersheds; the median watershed area for the IMB assessments being 12 km^2 as compared to 54 to 31,000 km^2 for hydrometric gauging. Overall, while there is agreement between hydrometric gauging and IMB in terms of general magnitude of runoff (see 2007–2009 averages, Table 4), the agreement between the two methods is not as good for the Christina River basin as it is for the Hangingstone River basin, with IMB seemingly underestimating Christina River basin runoff by roughly 20%. Given that the Christina River basin has a more extensive buried channel network than the Hangingstone River basin, this underestimation may simply reflect runoff bypass of lakes due to increased infiltration and deeper pathways of water flow via buried channels that connect to the incised channels.

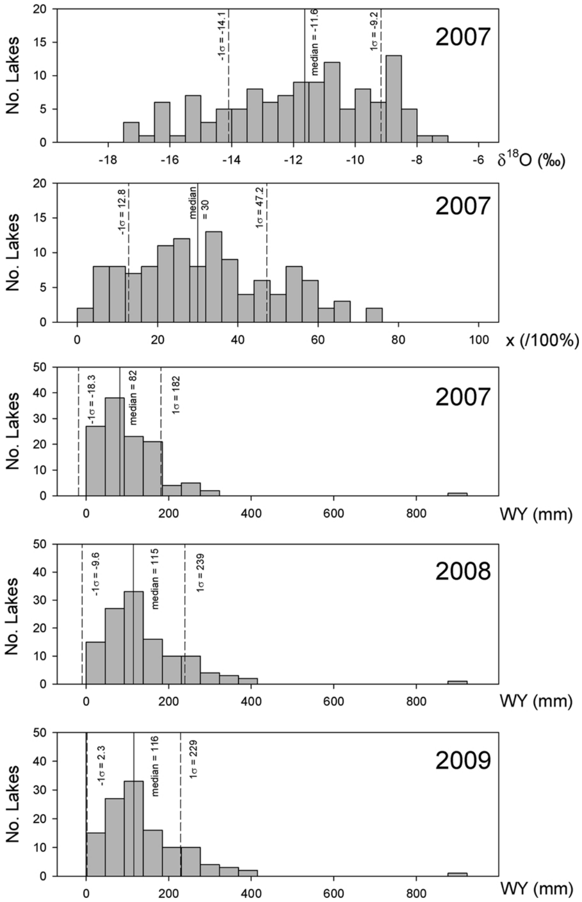

Fig. 4. Histograms of isotope data and selected isotope mass balance outputs, 2007–2009.

An important finding is that IMB offers a method for high spatial-resolution mapping of long-term water yield and potentially for monitoring temporal changes over time (Fig. 5). One important consideration is that the temporal signal of IMB is expected to be controlled by the residence time of lake water, and so is inherently variable from lake-to-lake across the region. Note that residence time is estimated to range from ~4 month to 3 years in the detailed study lakes where volume was measured. Taking a closer look at water yield during the study years, we note that gauged discharge data measured for the Hangingstone and Christina Rivers does not necessarily follow trends indicated by IMB during 2007 to 2009 (see Table 4). This may suggest that residence time plays a significant role in temporal weighting of the runoff estimates, and may potentially invoke a lag effect as well. Our assessment also reveals that shallower lateral drainage may be prevalent for lakes, whereas rivers are expected to include greater input from deep groundwater sources, especially where channels are incised. Previous lake assessments using radon-222 have also shown dominance of shallow, peatland drainage to lakes as compared to waters in contact with mineral soils (Schmidt et al., 2010). Unpublished river surveys have also revealed significantly higher radon-222 in some river reaches such as the Gregoire and Christina Rivers (Schmidt, pers. Comm.), which confirms deeper groundwater contributions. Conceptually, we emphasize that runoff to lakes is measured at different nodes in the hydrological network than water yield to rivers, and therefore needs to be regarded as a distinct hydrological flux, one that is more meaningful to lake water budgets than river budgets.

While residence time effects may be a complicating factor in spatial analysis, several benefits of the IMB perspective on regional runoff are clear: (i) information is site-specific, (ii) it can be applied at high-resolution, (ii) it offers capability to quantitatively link isotope-based monitoring with an underlying hydrologic response, and (iv) it provides a method for observing both climatic and development-related changes in hydrological regimes. While hydrometric gauging targets response in rivers, IMB in this application is shown to target lakes, although similar models could be applied to rivers provided detailed temporal sampling is carried out to establish the flux-weighted isotopic composition of river discharge. This has already been partially demonstrated, that is for estimating evaporation losses from watersheds and gross primary productivity in previous studies (Ferguson et al., 2007) but the same principles could be applied to estimate water yield.

4.5. Regional hydrology and implications

As demonstrated, IMB can be used within regional surveys to gain a higher resolution perspective of water yield to lakes than hydrometric gauging alone. As well, it can help to constrain other hydrological processes such as evaporation loss. Our results show,

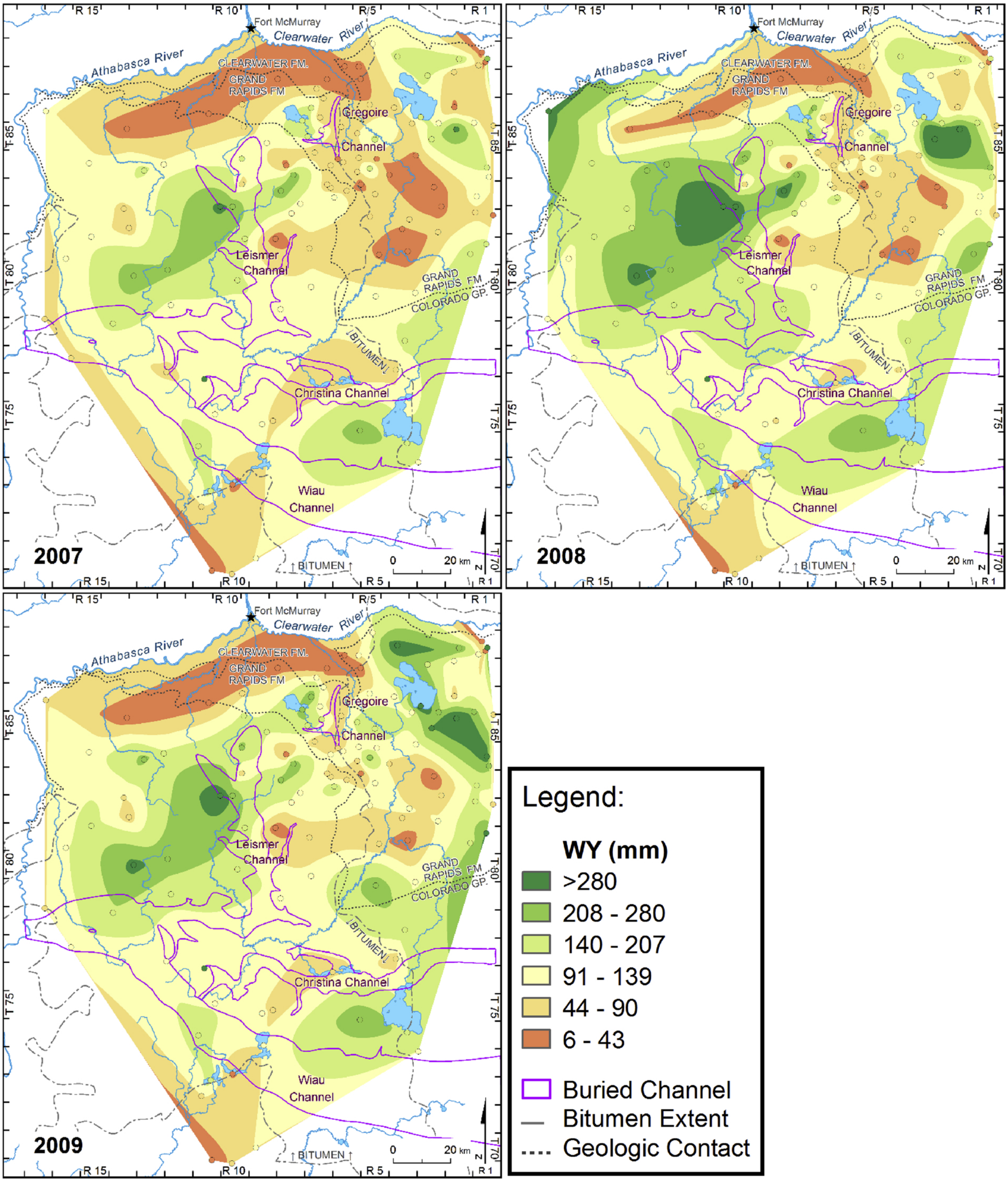

Fig. 5. Spatial distribution of water yield (mm) derived from isotope mass balance of lakes, 2007 to 2009.

for example, that spatial patterns in water yield are consistent from year to year, with the Stony Mountains plateau, an area with relatively thin (< 50 m thick) Quaternary tills overlying relatively impermeable Colorado group shales, being a high water yield zone. Typical interannual shifts in water yield were lower on the shale substrate plateaus, with standard deviation most commonly less than 40 mm/year, as compared to lower elevation areas including incised valleys, ranging upwards to 90 mm/year. Relative stability in runoff on the plateaus is attributed mainly to abundance of bogs and fens in those areas, which have a high storage capacity within peat, and effectively produce higher runoff and reduce variability.

One important implication of this study is that areas currently under SAGD development along the Christina R. valley are in an

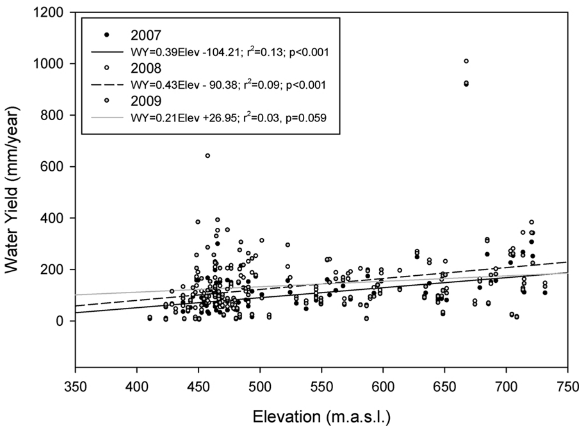

Fig. 6. Weak relationship between water yield and elevation in SAOS.

Table 3
Annual water yield based on hydrometric gauging of flow in vicinity of SAOS.

Years	Station Name	Map No. (Fig. 1)	Station ID	Lat.	Long.	DBA (km^2)	WY (mm)	1σ (mm)
1982-2012	Christina R. near Chard	7	07CE002	55°50'13"	110°52'8"	4863	132	64
1966-2012	Clearwater R. above Christina R.	3	07CD005	56°39'48"	110°55'43"	17,017	148	23
1930-2012	Clearwater R. at Draper	2	07CD001	56°41'7"	111°15'19"	30,792	121	32
1965-2012	Hangingstone R. at Ft. McMurray	1	07CD004	56°42'32"	111°21'22"	962	144	43
1930-1979	Horse R. at Abasands Park	4	07CC001	56°42"29"	111°23'40"	2130	128	17
1982-2011	Pony Creek near Chard	6	07CE003	55°52'11"	110°55'2"	279	134	77
1982-1995	Robert Creek near Anzac	5	07CE004	56°23'1"	111°1'42"	54	142	55
					Average		***136***	***44***

Table 4
Annual water yield (mm) based on IMB and hydrometric gauging, SAOS area.

Year	IMB				Gauged		
	IMB Average	Horse River basin (n = 5)	Christina River basin (n = 73)	Hangingstone River basin (n = 8)	Christina River near Chard (n = 1)	Pony River near Chard (n = 1)	Hangingstone River at Fort McMurray (n = 1)
2005	n.d.	n.d.	n.d.	n.d.	249	258	214
2006	n.d.	n.d.	n.d.	n.d.	157	88	87
2007	105	74	109	126	179	91	135
2008	138	140	137	177	162	96	137
2009	141	101	145	158	168	82	184
Average	***128***	***105***	***130***	***154***	***170***	***123***	***151***

area that is characterized by naturally lower runoff, and may therefore be more sensitive to climatic changes or development-related changes that might arise from alteration of surface/groundwater interaction or pressurization of bedrock formations. However, these areas are also characterized by higher interannual variability in water yield, so confirming the underlying causes of subtle future changes may remain a challenge.

Spatial sampling of stable isotopes of water in lakes and rivers as part of a regional monitoring network may be one way to track potential changes over time, and may provide more information on the underlying cause of water cycle variability than hydrometric gauging alone. The approach may also provide useful information for selection of detailed monitoring or study sites to ensure representativeness of the range of hydrologic conditions expected across the region. In principle, similar lake surveys could be practically applied to characterize and monitor runoff variability in other areas of rapid development such as the North Athabasca Oil Sands area, Cold Lake Beaver River watershed, and Peace River region. Regional surveys of this type have already been applied to the contiguous United States for ecological monitoring (Brooks et al., 2014) and across Canada for critical loads assessment (see Gibson et al., 2010a, 2010b, 2017, Gibson et al., 2018a).

Sensitivity of the method to uncertainty in watershed delineation in low relief catchments is a problematic issue raised by Devito et al. (2005) for conducting hydrologic investigations in the Boreal Plains region, which affects IMB as well as conventional hydrometric gauging. We suggest that this issue may be partially resolved using the IMB approach as a greater number of watersheds can be investigated, providing a more powerful statistical basis for spatial comparisons. For example, in Table 4 we compare available data for the Christina and Hangingstone River basins, which includes only 3 gauged watersheds as compared to 86 sub-catchments using IMB estimates, which clearly suggests that the latter will have a greater chance to identify anomalies and provide more robust average values.

5. Conclusions

The main finding of this study is that isotope mass balance offers a practical method for characterizing water yield variability to lakes on the Boreal Plain, as demonstrated for the Southern Athabasca Oil Sands area, a 35,000 km^2 region characterized by a mosaic of lakes, rivers, wetlands and buried channels. The current analysis also contributes to better understanding of the regional hydrology, demonstrating systematically higher runoff in areas underlain by impermeable shales, in contrast to better vertical drainage and hence lower lateral runoff associated with buried and incised channels. Development of groundwater resources is not likely to directly affect surface/groundwater interaction characteristics of lakes in areas such as the Stony Mountains that are underlain by Colorado Shale, but may be more of an issue for lakes situated along buried or incised channels that communicate more directly with aquifers and deeper groundwater formations. Indirect impacts such as depressurization (or pressurization) of confined aquifers may still be influential both on the Stony Mountains, along the Christina River valley and adjacent areas. Waste disposal, thermal heating of aquifer material, and potential escape of steam and/or contaminated water to surface and/or buried channels remain important development risks, particularly in corridors of rapid development.

The main limitation of the IMB technique is that both spatial and temporal water yield footprints are inherently different for each lake, as determined mainly by the lake residence time, and cannot be easily adjusted to obtain higher frequency outputs. While differences in spatial footprint of watersheds is a familiar concept for hydrologists, the consequences of using a long-term residence-time weighted signal is perhaps less intuitive. Nevertheless, a long-term perspective of water yield variations across the region is expected to be of particular value for design of monitoring networks to ensure that both high and low runoff areas are characterized.

Ongoing work includes a complete geochemical assessment of lakes, wetlands, and rivers across the region. Recommended future activities include repeat surveys of isotopic and geochemical tracers that may be helpful for determining the extent of SAGD impacts due to development.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2018.11.001.

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