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Research papers

Comparison of isotopic mass balance and instrumental techniques as estimates of basin hydrology in seven connected lakes over 12 years

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ABSTRACT

Mass-balance models using stable isotopes of hydrogen and oxygen provide useful estimates of the water balance of lakes, particularly in the absence of instrumental data. However, isotopic mass balances are rarely compared directly to measured water fluxes. Here we compared instrumental and isotope-based determinations of water fluxes in seven connected lakes over 12 years to quantify how agreement between the two approaches is affected by lake type and its position in the landscape. Overall, lake-specific ratios of evaporation to inflow (E/I) from instrumental measurements (median, $\tilde{x} = 0.06$, median absolute deviation, MAD = 0.06) agreed well with isotopic estimates using headwater models ($\tilde{x} = 0.14$, MAD = 0.08), with the exception of one lake with limited channelized inflow of surface waters ($\tilde{x}_{instrumental} = 0.51$ vs. $\tilde{x}_{headwater} = 0.24$). Isotope-instrument agreement improved ($\tilde{x} = 0.09$ vs. $\tilde{x} = 0.03$) when basin-specific ('best-fit') isotope models also considered local connectivity to upstream water bodies. Comparison among years revealed that mean isotopic E/I values were lowest in 2011 (mean, $\mu = 0.06$, standard deviation, $\sigma = 0.09$) during a 1-in-140 year spring flood, and highest during a relatively arid year, 2003 ($\mu = 0.22$, $\sigma = 0.19$), while interannual variability in E/I generally increased with distance downstream along the mainstem of the watershed. Similar patterns of agreement between methods were recorded for water-residence time. Isotope models also documented the expected low water yield from lake catchments ($\mu = 36.2$ mm yr^{-1}, $\sigma = 62.3$) suggesting that isotope models based on late-summer samples integrate annual inputs from various sources that are difficult to measure with conventional methods. Overall, the strong positive agreement between methods confirms that water isotopes can provide substantial insights into landscape patterns of lake hydrology, even in ungauged systems.

1. Introduction

Quantification of hydrological processes that regulate the water balance of lakes is essential to both evaluate ecosystem vulnerability to climate change and sustain the health of surface water in the face anthropogenic development (Barnett et al., 2005). Estimates of inflow (I) and evaporative losses (E) from surface waters are especially important in dry regions, such as the Canadian Prairies, where water availability is already challenged by industrial extraction and global warming during the past century (Sauchyn et al., 2016; Schindler and Donahue, 2006). In addition, as un-gauged basins predominate in the global landscape, other tools are needed to estimate how basin hydrology may respond to climatic and human pressures, and to develop effective strategies for freshwater management (Kirchner, 2006; Wood et al., 2011). For example, only 12% of the Canadian landscape is monitored by a hydrometric network with sufficient instrumentation to evaluate climate vulnerability (Coulibaly et al., 2013), yet much of the nation's landmass (high latitudes, Prairies) is sensitive to future changes in regional water balance (Pachauri et al., 2014; Sauchyn et al., 2016).

Analysis of stable isotopes of hydrogen (δ^2H) and oxygen ($\delta^{18}O$) has been employed as a reliable means to quantify general hydrological properties of diverse water bodies using limited field data, often with only a single water sample (Ala-aho et al., 2018; Brooks et al., 2014; MacKinnon et al., 2016; Mayr et al., 2007; Pham et al., 2009; Wolfe et al., 2007; Wu et al., 2017; Yu et al., 2002). This isotopic approach has been used to estimate fluxes regulating the water balance of lakes,

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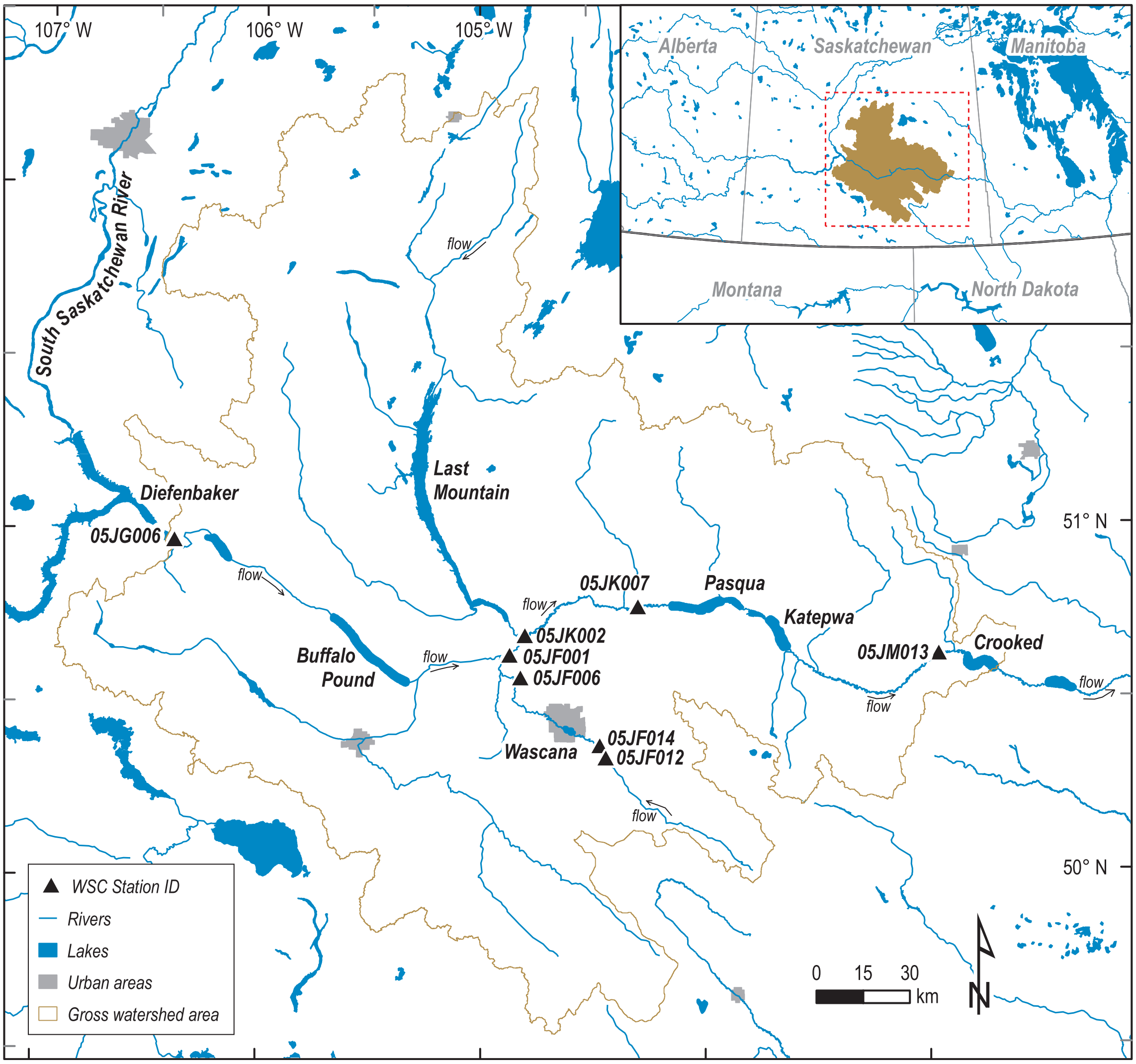

Fig. 1. Map showing locations of seven study lakes relative to gauging stations (triangles) and major hydrologic boundaries. Dominant flow direction is noted by arrows along streams. A bifurcation control structure is located at the south end of Last Mountain Lake (LML) with flow direction into or out of LML determined by lake and river levels, as well as downstream water management needs. Shading in the inset indicates the Qu'Appelle Valley gross drainage area within the broader context of central Canada.

including evaporation (E) to inflow (I) ratios (E/I) (MacDonald et al., 2017; Narancic et al., 2017; Turner et al., 2014), water residence time (Gibson et al., 2002; Petermann et al., 2018), and water yield (Bennett et al., 2008; Gibson et al., 2010, 2017). In particular, analysis of δ^2H and δ^{18}O has been used to compare hydrology among lakes at spatial scales ranging from individual watersheds (Cui et al., 2017; Kang et al., 2017; MacKinnon et al., 2016) to regional (MacDonald et al., 2017; Narancic et al., 2017a; Turner et al., 2014) and continental scales (Brooks et al., 2014). Despite increasing use, relatively little is known of how the performance of isotope-based approaches may vary on multi-annual timescales in comparison to other methods (Gibson et al., 1996; Gibson and Reid, 2014; Longinelli et al., 2008; Tyler et al., 2007).

In principle, isotope-derived estimates of water balance (E/I) and associated parameters can also be used to better understand how catchment characteristics regulate the movement of water and solutes into lakes. For example, total runoff volume and catchment water-yield (depth equivalent runoff) estimated from water isotopes have been used to quantify the influx of nutrients (Elmarami et al., 2016; Gibson et al., 2016) and acids (Bennett et al., 2008; Gibson et al., 2010). Similarly, the relationship between isotopic E/I and landscape cover has been used to assess the relative sensitivity of aquatic ecosystems to salinization (MacKinnon et al., 2016; Pham et al., 2009) and desiccation (Turner et al., 2014, 2010) due to summer evaporation. However, in most cases, relationships between catchment and surface water bodies have been studied in ungauged systems with no measure of surface inflow to constrain isotopic estimates of water balance.

Those studies that incorporate dual measurements largely focus on short-term or survey-based analyses. In the most comprehensive comparison, Gibson et al. (1998) observed a general agreement between isotopic and instrumental methods of calculating evaporation over 6 years of monitoring. Bennett et al. (2008) found that isotope and instrumental analyses collected in the fall provided similar estimates of annual catchment water yield for 49 lakes in moderate-sized drainage basins, although isotopic values were lower and more variable than instrumental estimates of the Water Survey of Canada (WSC). Similarly, comparison of groundwater flow derived from water isotopes with that based on measured flow (Sacks et al., 2014), ^{222}Rn content (Arnoux et al., 2017a,b) or solute mass balances (Krabbenhoft et al., 1990) confirms that isotope analyses can be used to quantify discrete water sources, but also suggests that isotope models perform better when constrained with instrumental data. In general, theoretical uncertainty in E/I derived from isotopic mass-balance determinations has been estimated at ± 20%, with errors mainly arising from uncertainty in isotope values of surface inflow waters, humidity, and atmospheric moisture (Cui et al., 2017; Jones et al., 2016; Wolfe et al., 2007). To our knowledge, there have been no comparisons of isotope-derived hydrological parameters with instrumental data exceeding a decade in length.

In this study, we analyzed water isotope compositions collected over 12 years from seven inter-connected lakes to quantify the degree of agreement between isotopic and instrumental measures of lake hydrology, including E/I, water residence time, and catchment water-yield. Our initial models were based on late-summer samples alone and treated all lakes as headwater systems (i.e., an unknown degree of connection), as is commonly done in regional surveys (e.g., Brooks et al., 2014; Pham et al., 2009; Turner et al., 2014). Parameter estimates from headwater models were also compared with those derived from basin-specific 'best-fit' models that were informed by an understanding of upstream basin hydrology. By comparing instrumental and isotope-based models over a series of lakes that span a range in morphological and hydrological properties, we sought to identify the conditions under which isotope mass-balance models and continuous monitoring of water fluxes provided comparable estimates of lentic hydrology. In addition, this study provides an additional method for assessing the effects of climate change on freshwaters in the Canadian Prairies.

2. Study area and data collection

2.1. Site description

The Qu'Appelle River drainage basin covers ~52,000 km^2 of sub-humid agricultural cropland and grasslands situated in southern Saskatchewan, Canada (50°00′ N-51°30′N, 101°30′W-107°10′W). This study examined seven lakes associated with the river; five of the sites (Diefenbaker, Buffalo Pound, Pasqua, Katepwa, Crooked) form a central chain along the river course, while two lakes (Last Mountain and Wascana) drain into the Qu'Appelle river mid-reach via tributaries (Fig. 1, Table 1). Study lakes vary by up to 100-fold in most morphometric parameters including surface area (2–371 × 10^6 m^2), volume (3–7487 × 10^6 m^3), and max depth (5.5–62.0 m). Land cover in the Qu'Appelle catchment is composed mainly of agricultural cropland (75%), with the remainder covered by grasslands (12%), surface waters (5%) and the urban centers of Moose Jaw and Regina (Vogt et al., 2011).

2.2. Meteorological data

Regional climate within the Qu'Appelle River basin is characterized

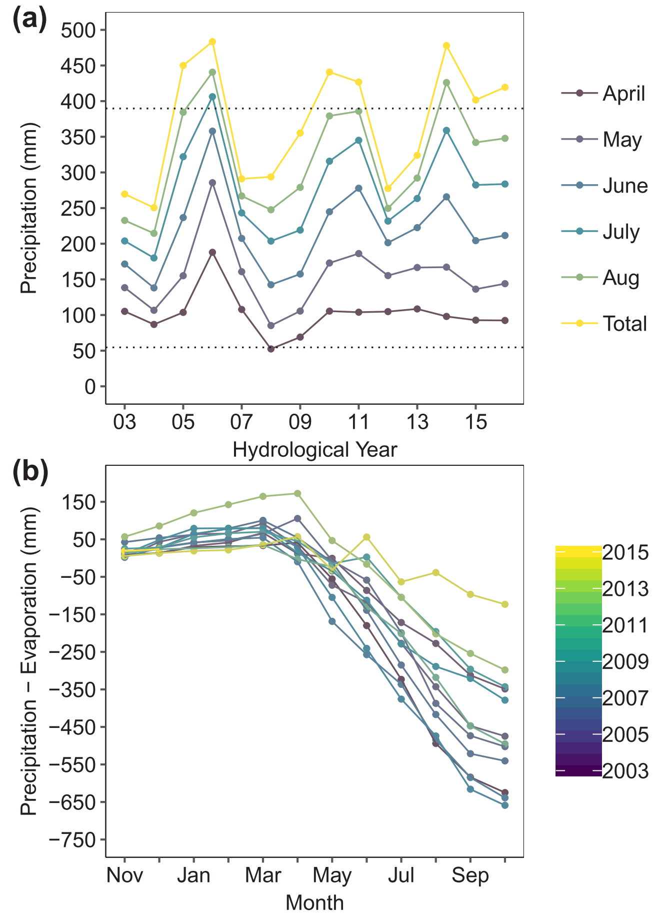

Fig. 2. General meteorological conditions for the study region from Regina, Saskatchewan, Canada, situated in the center of the Qu'Appelle River Valley (data source: Environment and Climate Change Canada, http://climate.weather.gc.ca). (a) Individual lines represent the cumulative precipitation from summer months (April – Aug.), and total annual precipitation. The dashed lines indicate the long-term (1981–2010) average winter (bottom, October 31st – April 1st), and total accumulation (top). (b) Water deficit through the study period is calculated by subtracting the cumulative potential evaporation from the cumulative precipitation. Each line represents an individual hydrological year beginning November 1st and continuing to October 31st. Seasonal dynamics in water deficit can be observed with moisture retention during winter and losses occurring in summer months.

Table 1

Study site locations and hydrological characteristics from 2003 to 2015. Mean (± SD) values of volume and surface area estimates were made using area capacity curves from Saskatchewan Water Security Agency and lakes levels from the Water Survey of Canada at each site (http://wateroffice.ec.gc.ca/). All variable values are represented by mean (± SD). Drainage basin estimates and water yield values are separated by Sink Free Drainage Area (SFDA) and Gross Drainage Area (GDA).

	Diefenbaker	Buffalo Pound	Last Mountain	Wascana	Pasqua	Katepwa	Crooked
Latitude	51.02	50.60	50.99	50.44	50.78	50.70	50.60
Longitude	−106.50	−105.41	−105.18	−104.61	−103.95	−103.64	−102.68
Surface Area m^2 x10^6	371 (14)	30 (0.2)	186 (9)	2 (0.2)	19 (1)	16 (0.2)	14 (2)
Volume m^3 x10^6	7487 (350)	93 (4)	1863 (83)	3 (0.5)	117 (8)	232 (3)	114 (9)
SFDA (m^2 × 10^6)	8.2 × 10^4	1.7 × 10^2	1.2 × 10^3	27	1.6 × 10^2	2.5 × 10^2	1.6 × 10^2
GDA (m^2 × 10^9)	1.5 × 10^2	32	15	2	37	39	44
Instrumental Inflow (m^3 × 10^6)	7402 (3202)	136 (38)	229 (157)	34 (45)	401 (325)	422 (363)	476 (405)
δ^{18}O range (‰)	1.9	2.2	2.7	4.2	4.7	4.0	4.4
δ^{2}H range (‰)	10.6	15.4	15.0	32.1	30.3	25.2	26.1
E/I (instrumental)	0.04 (0.02)	0.16 (0.03)	0.56 (0.23)	0.13 (0.20)	0.07 (0.05)	0.05 (0.03)	0.04 (0.03)
E/I (headwater)	0.03 (0.02)	0.12 (0.02)	0.23 (0.05)	0.15 (0.08)	0.18 (0.06)	0.18 (0.06)	0.18 (0.06)
E/I (best fit)	0.03 (0.02)	0.12 (0.02)	0.44 (0.10)	0.15 (0.08)	0.07 (0.06)	0.08 (0.05)	0.08 (0.04)
τ (yrs) instrumental	1.0 (0.3)	0.6 (0.1)	6.8 (2.6)	0.2 (0.3)	0.5 (0.3)	0.9 (0.5)	0.4 (0.3)
τ (yrs) headwater	0.7 (0.4)	0.5 (0.09)	2.8 (0.6)	0.3 (0.09)	1.4 (0.5)	3.2 (1.0)	1.9 (0.6)
τ (yrs) best-fit	0.7 (0.4)	0.5 (0.09)	5.5 (1.2)	0.3 (0.09)	0.5 (0.4)	1.4 (0.8)	0.7 (0.4)
Water yield (best-fit, SFDA)	204 (211)	1106 (245)	245 (93)	450 (323)	2384 (1808)	4278 (10951)	4662 (11106)
Water yield (best-fit, GDA)	110 (114)	60 (13)	20 (8)	6 (4)	10 (8)	28 (71)	18 (42)

as cool-summer humid continental (Köppen D*fb* classification), with short summers (mean temperature 19 °C in July), cold winters (mean −16 °C in January), and low mean annual temperatures (~1 °C). Mean annual precipitation is ~380 mm, with most rain falling between May and July, and most runoff during the short snowmelt period of spring (Akinremi et al., 1999; Coles et al., 2017; Fang et al., 2007). This region experiences high hydrologic variability, including centennial-scale flooding (2010–2011) and summer droughts (2008–2009), such that river inflow to lakes varies by an order-of-magnitude between years and across the catchment (Supplementary Fig. 1).

Meteorological conditions during our study period (2003–2014) were similar to long-term average conditions with annual mean temperature of 3 °C, means of ~18 °C in July and ~-14 °C in January (Fig. 2, Environment and Climate Change Canada, http://climate.weather.gc.ca). Median relative humidity was 74 % during the study period. Below-average moisture deficits were recorded during the summers of 2008 and 2009, leading to an annual precipitation deficit of ~63 cm (Fig. 2). In contrast, high precipitation during fall of 2010 and spring of 2011, combined with moist and frozen soils, caused a 1-in-140-year spring flood with regional damages exceeding $800 million CAD (Brimelow et al., 2014; Wheater and Gober, 2013). Between 2010 and 2014, regional conditions have been more humid with elevated summer rains reducing annual precipitation deficits to −32.8 cm from mean values recorded during the study period (−46.1 cm; 2000–2014) and the longer 30-year record for the climate station in Regina (−45.3 cm; 1981–2010).

2.3. Hydrological data

All study lakes are monitored and experience hydrological management, including control structures to maintain lake level and downstream water availability (Saskatchewan Water Security Agency, 2012). Source waters for the Qu'Appelle River originate from both local inputs (groundwater, precipitation) and, since the 1960s, transfer of meltwaters from the Canadian Rocky Mountains via the South Saskatchewan River and Lake Diefenbaker (Fig. 1). Water yield estimated at the outflow of the Qu'Appelle basin (~21 mm $year^{-1}$) is one of lowest in Canada (Bemrose et al., 2009). Monitoring includes continuous daily lake-level records for six of the seven basins by the WSC (http://wateroffice.ec.gc.ca/). Water level in Pasqua Lake was inferred from that of Echo Lake, a small basin located ~500 m downstream of Pasqua Lake. Area capacity curves were obtained for all lakes from the Saskatchewan Water Security Agency (SWSA). Lake evaporation was supplied by the SWSA and was calculated using the Meyers method (Martin, 2002). River inflow to each lake was estimated from two sources: gauge-measured flows of WSC and projections from the SWSA Water Resources Management Model (WRMM). The WRMM model output of naturalized flow was completed at a monthly time step resulting in outputs that are comparable to monthly mean values. When compared to gauges, WRMM underestimates river discharge during periods of low flow, and overestimates during periods of high flow (Bender, 2012). Application of this model allows estimation of inflow to lakes where direct hydrological measurements are poorly constrained (i.e., Last Mountain, Katepwa, and Crooked). Using these inflow and evaporation data, an instrumental estimate of E/I at an annual time step was calculated for each hydrological year. Additional details concerning the WRMM and gauge data are provided in Supplementary Table 1.

3. Methods

3.1. Isotope analysis

Depth-integrated water samples were collected biweekly May-August from seven study lakes during 2003–2014. Surface water samples were also collected from 2006 to 2014. For this study, isotope mass balance models used only the final depth-integrated sample taken in late August, as late-summer samples are thought to most closely represent isotopic steady state, result in more accurate estimations of annual water balance (Cui et al., 2018; Yi et al., 2008), and are commonly used in lake surveys (Bennett et al., 2008; Gibson and Edwards, 2002; Pham et al., 2009). Following collection, samples were filtered through a cellulose filter (nominal pore size 0.45 μm) and stored in tightly-sealed amber borosilicate jars at 4 °C to prevent evaporation. Samples were analyzed for δ^2H and δ^{18}O using a Picarro L2120-I cavity ring-down spectrometer (CRDS), at the Institute of Environmental Change and Society (IECS), University of Regina, Saskatchewan, Canada (http://www.iecs-uregina.ca/). All isotope results are reported in δ notation in per mil units (‰) with analytical uncertainty of 0.1‰ for δ^{18}O and 0.5‰ for δ^2H. To reduce carryover between samples, eight aliquots were analyzed from each sample, but only the last four were used for isotopic determinations. Isotope values were standardized to local and international standards, including Vienna Standard Mean Ocean Water 2 (VSMOW2) and Standard Light Antarctic Precipitation 2 (SLAP2). Data processing was completed using a Microsoft Access relational database called Laboratory Information Management System (LIMS) for Lasers 2015 (Coplen and Wassenaar, 2015). Processing with LIMS helps correct for sample carryover, instrumental drift, and isotopic nonlinearity (Coplen and Wassenaar, 2015).

3.2. Drainage basin area

Drainage areas were estimated for each lake, with the exception of Lake Diefenbaker, to allow for calculation of water yield. For Lake Diefenbaker, a drainage area was not calculated and, instead, we used the gross and effective drainage basin areas of North et al. (2015). For the remaining sites, a standard operating procedure was developed to identify gross and sink-free drainage basin areas (SFDA) using ArcHydro (ESRI, v2.1) and the Canadian Digital Elevation Model (CDEM, v1.1). We used SFDA in place of the less easily defined 'effective drainage area' (Martin et al., 1983). Base resolution of the CDEM tiles is 0.75 arc seconds, and each tile was converted to a plane coordinate projection (~20 m resolution) at the time of extraction. We modified the ESRI Terrain Pre-processing Workflow UC4 (ESRI, 2013) to identify SFDA by (a) filling any sink with an area < 3700 m^2 (i.e. 32 DEM tiles), (b) burning lakes into the DEM, (c) fencing lakes that had no topographic lip at the outlet and (d) omitting stream segmentation. Sinks ≥ 32 DEM cells, and associated basins, were thus excluded from the delineation of the SFDA. Gross drainage basin area (GDA) was delineated using the same workflow, but after having filled all upstream sinks except the lake itself. Both SFDA and GDA were crosschecked with watercourses in the CanVec (2016) reference product for blatant mismatches between adjacent watersheds at a scale of 1:50 000.

3.3. Statistical analysis

An ANCOVA-like generalized additive model (GAM) was used to compare measures of water balance (E/I) from instrumental and isotopic methods. In this GAM, lake and measured water balance were the main effects, and the model included terms for their interaction, as well as a random effect to control for between year differences. Use of the GAM accounted for the non-constant variance and the non-normal (Gamma) underlying data distribution. By accounting for the underlying pattern in time-series we were better able to assess the agreement between models. Similar GAMs were also used to assess the relationship between meteorological parameters and isotopic measures of water balance, as well as the relationship between isotope-inferred and instrumentally-measured inflow. All calculations were completed in (R Core Team, 2018) using the *mgcv* package (Wood, 2011; Wood et al., 2016).

4. Theory

4.1. Isotope mass balance

To put lake water isotope samples into a regional perspective, we compared values to a local meteoric water line (LMWL) derived from data collected in Saskatoon, Saskatchewan (1990–2010), (IAEA/WMO, 2019) and calculated using the precipitation-amount-weighted least squares regression technique (Hughes and Crawford, 2012). In addition, LMWL data were compared to three years of precipitation samples collected directly at Wascana Lake by the University of Regina (2013–2016). Despite a ~250 km separation, no practical difference was found in isotopic values of local precipitation at Saskatoon and Regina, so the decadal-scale Saskatoon data were used for all subsequent calculations. A local theoretical evaporative line (LEL) was established to visualize the projected evolution of lake water isotopes in this region, moving from the weighted mean isotopic value for local precipitation to a state of evaporative enrichment. Here the theoretical LEL was estimated by linear regression of isotopic values of weighted mean precipitation (weighted by precipitation amount, δ_P), the theoretical isotopic composition of lake waters in a closed-basin at steady state (δ_{SS}), and the theoretical maximum (limiting) isotopic enrichment (δ^*). δ_P was calculated using the data from Saskatoon, while δ_{SS} and δ^* were calculated annually for each study lake from local meteorological data (see full calculations in Supplementary 1, Eqs. 1–7). Although the theoretical LEL is helpful for visual purposes, previous hydrological studies in this region suggest that export of precipitation off the catchment to lakes is highly variable seasonally (Fang et al., 2007; Pomeroy et al., 2007) and therefore, would not necessarily intercept the LMWL at δ_P.

Water balance for each lake was calculated using meteorological data (precipitation, temperature, flux-weighted evaporation, and flux-weighted relative humidity), basin characteristics (lake area, watershed area, lake volume), and isotopic values of water sources, including lake water, inflow, and local precipitation. Calculations followed conventional isotopic methods reviewed in Gibson et al. (2016). Briefly, water balance of a lake at hydrologic steady-state can be calculated as:

$$I = Q + E \text{ and} \tag{1}$$

$$I\delta_I = Q\delta_Q + E\delta_E \tag{2}$$

where I, Q, and E are the volumes of lake inflow, outflow, and evaporation (in m^3) and their respective isotopic values, δ_I, δ_Q, and δ_E (as ‰). Here isotopic values of outflow are assumed to be the same as that of the lake water ($\delta_Q \approx \delta_L$). Although changes in lake volume occurred in all systems during the spring freshet, lake volume varies little during the remainder of the ice-free season because of the through-flow hydrological settings of the lakes. Late summer samples were used in this study to minimize departures from steady state as suggested by Yi et al., (2008) and demonstrated in other mass balance studies (Gao et al., 2018; Turner et al., 2014) (Supplementary Fig. 2). δ_E values were calculated using the Craig and Gordon (1965) model as shown in Supplementary 1 (Eq. (8)). Using this estimate, evaporation to inflow ratios (E/I) can be calculated by rearrangement of Eq. (2) as;

$$x = \frac{\mathrm{E}}{\mathrm{I}} = \frac{(\delta_\mathrm{I} - \delta_\mathrm{L})}{(\delta_\mathrm{E} - \delta_\mathrm{L})} \tag{3}$$

To solve the water balance, inflow must also be estimated from key sources including precipitation (P), runoff (R), and upstream flow (J), and solved as;

$$I = P + R + J \tag{4}$$

Similar to the basic mass balance of Eq. (3), Eq. (4) can be expanded to include the isotopic signatures of each source as;

$$\delta_I = \frac{P * \delta_P + R * \delta_R + J * \delta_J}{P + R + J} \tag{5}$$

where δ_I, δ_P, δ_R, and δ_J are the isotopic composition of inflow, amount-weighted precipitation, runoff, and upstream source waters (all ‰). We have assumed that $\delta_R \approx \delta_P$ (Gibson and Reid, 2014).

4.2. Model selection for δ_I

In many surveys of lakes, the isotopic value of inflow (δ_I) is unknown and must be approximated using one of three models, depending on data availability. First, in the absence of data on the volume and isotopic composition of inflow, investigators often model lakes as if each site were a headwater system, using the coupled isotope tracer method (CITM) (Yi et al., 2008). Second, in cases where lakes receive inflow that may have been subject to evaporation previously in upstream water bodies, δ_I is adjusted for the volume and isotopic composition of inflow ('flow-aided') to avoid over-estimation (up to 30%) of evaporative losses (Gibson and Reid, 2014). Third, in instances where the CITM produces unrealistic values, alternative headwater models can be used to account for isotopic enrichment along a lake-specific local evaporation line (LS-LEL).

This study uses the CITM of Yi et al. (2008) as the initial model for all sites because of its ability to calculate δ_I on a sample-by-sample basis. This method uses the δ_E (calculated annually by lake, Supplemental 1 Eq. (8)) and δ_L of each sample to create a sample-specific line and approximates δ_I from the intersection of the sample specific line and the LMWL. Due to the intersection with the LMWL, this method assumes that input waters are of meteoric origin and have undergone limited evaporation.

When sufficient data were available, lakes receiving input from upstream water bodies were also modeled using a flow-aided calculation that incorporates the measured isotopic value of inflow water to constrain δ_I values. This flow-aided model assumed negligible groundwater inputs and that runoff was at isotopic steady-state with δ_P, but that surface inflow was subject to some evaporation in upstream water bodies in an effort to not overestimate evaporation in the lake of interest. Here flow-aided δ_I was calculated as;

$$\delta_I = \frac{-J\delta_J\delta_L + E\delta_P\delta_E - E\delta_L\delta_P + J\delta_L\delta_P}{E\delta_E - E\delta_L - J\delta_J + J\delta_P} \tag{6}$$

Finally, when the CITM produced values that were inconsistent with the hydrological setting of the lake, δ_I was calculated using the LS-LEL method in which the intercept between the linear regression of all δ_L values for that lake and the LMWL was used to approximate δ_I (Gibson et al., 1993; Wolfe et al., 2007). This method is advantageous for lakes with many unmeasured inflow sources (including groundwater) and in situations where the isotopic values of inflow may be different from that of the amount-weighted average precipitation of the region. However, while the LS-LEL model allows for groundwater influx, the method fails to consider the effects of inter-annual variability in input waters, disregards the convention that regional lakes should converge to a common δ^*, and can return unrealistic values for δ_I in instances where evaporation is not significant (i.e., δ_L values vary parallel to the LMWL), therefore is only suggested when the CITM does not produce realistic values.

In this study, mass balances were calculated using δ_I from the CITM for all lakes. Additional models were calculated in instances where the hydrological setting indicated that upstream flow may be important. For example, the flow-aided method was used for Pasqua, Katepwa, and Crooked lakes where adequate upstream flow and isotopic values were available, but not for lakes Diefenbaker, Buffalo Pound, and Wascana where inflow data were more limited. Finally, the LS-LEL model was calculated for all lakes but used only for Last Mountain Lake because the site was known to have elevated solute levels due to evaporative concentration (Leavitt et al., 2006) and because δ_I calculated using the CITM suggested summer precipitation was the sole water source, a result which was inconsistent with regional water models and management practices (Fang et al., 2007; Pomeroy et al., 2007). In the LS-LEL

Table 2
Model selected as the best-fit model for δ_I for each sample location.

Diefenbaker	Buffalo Pound	Last Mountain	Wascana	Pasqua	Katepwa	Crooked
CITM	CITM	LS-LEL	CITM	Flow-aided	Flow-aided	Flow-aided

calculation, δ_I for Last Mountain Lake was −15.7‰ for $\delta^{18}O$, a value that is similar to that of local groundwater (-16.4‰) (Jasechko et al., 2017), higher than spring runoff (−22.3‰), but lower than that of long-term precipitation, δ_P (−14.9‰) records from Saskatoon, SK (Supplementary Fig. 3). For the remainder of this paper, will use the term 'best-fit' to describe the isotope model that was most appropriate for the study lake δ_I; including CITM (Diefenbaker, Buffalo Pound, Wascana), flow-aided (Pasqua, Katepwa, Crooked), and LS-LEL model (Last Mountain) (Table 2).

4.3. Calculation of water residence time and catchment water yield

Water residence time (years) and catchment water yield (mm yr^{-1}) were calculated for each lake at an annual time step. Specifically, water residence time (τ) was calculated from isotopic values of inflow, lakewater and evaporation, as well as lake volume (V) and the measured annual evaporation (E- Meyers Method- see Section 2.3) as;

$$\tau = \frac{(\delta_I - \delta_L)}{(\delta_E - \delta_L)} \times \frac{V}{E}. \tag{7}$$

The annual water yield (WY) was calculated by distributing the isotopically-inferred inflow across the catchment area, and not including precipitation directly into the lake, resulting in a depth-equivalent precipitation deposited into the lake from the catchment (m^3). To calculate the isotopically-inferred inflow, the annual depth-equivalent evaporation (E) off the surface of the lake (mm m^{-2}), x as water balance (E/I) calculated in Eq. (3), and P as the annual precipitation directly on the lake surface were required, as follows,

$$WY = \frac{\frac{E}{x} - P}{WA} \times 100. \tag{8}$$

5. Results

5.1. Lake-Specific variability in isotopes

The inter-annual variability in lake-water isotope (δ_L) values differed among study lakes with most points falling along a trajectory intermediate to the LMWL and the theoretical LEL (Fig. 3). Inter-annual variability was smallest in the lakes with the largest lake volumes, specifically, Lake Diefenbaker (δ^2H range = 10.6‰, $\delta^{18}O$ = 1.9‰) and peripheral subsaline Last Mountain Lake (δ^2H range = 12.8‰, $\delta^{18}O$ = 2.7‰). Both of these large lakes exhibited a narrow range in lakewater isotope values. In contrast, the smallest lake, Wascana Lake, displayed the largest variability (δ^2H range = 32.1‰, $\delta^{18}O$ = 4.2‰). Spatial variability was also apparent when comparing among lakes, as upstream sites (Diefenbaker, Buffalo Pound) consistently displaying lower δ_L values relative to downstream lakes. Although sites did not follow a sequential change completely consistent with their landscape position, in general downstream sites were positioned more closely to the theoretical LEL, suggesting that evaporation played a larger role in annual water balance of downstream lakes. At most sites, the variation in lake water isotope values lay parallel to the LMWL, suggesting that evaporation played a relatively minor role in the overall water budget, with the exception of Last Mountain Lake. In Last Mountain lake, isotopic values were positioned between the LMWL and the theoretical LEL, suggesting a system more influenced by evaporation (Fig. 3). Lake Diefenbaker clustered directly along the LMWL, a pattern that suggests minimal evaporation and which is consistent with its management as a multipurpose reservoir with fast flushing rates.

Comparison of surface and depth-integrated δ_L values revealed little difference in isotopic values and suggested that all study sites were well mixed (Fig. 3b). Consequently, integrated samples were used for subsequent analyses and could be used as an accurate representation of δ_L without underestimating evaporation. A paired *t*-test revealed no statistically significant difference between sampling methods ($p = 0.24$, $df = 62$).

5.2. Water isotope mass balance

Water mass balance (as E/I) estimated using the CITM confirmed the known hydrological setting of lakes within the Qu'Appelle catchement and suggested that lakes were flow-through ecosystems (low E/I), except for Last Mountain (E/I = 0.27–0.56) where flow was more restricted (Fig. 4). In general, mean E/I values were lowest in 2011 ($\mu = 0.06$, $\sigma = 0.09$) and 2014 ($\mu = 0.08$, $\sigma = 0.11$) and highest in 2003 ($\mu = 0.22$, $\sigma = 0.20$) (Fig. 5). Similarly, inter-annual variability in water balance was lowest for headwater Lake Diefenbaker (E/I, $\sigma = 0.02$) and was generally greater in downstream lakes (Fig. 4). These results are consistent with initial inferences based on the isotopic framework presented in Fig. 3, with lakes lying primarily along the LMWL exhibiting low importance of evaporation to their water balance.

5.3. Comparison of gauge data and CITM models

Comparison of E/I based on instrumental (blue) and CITM (yellow) showed a wide range of agreement between approaches (Fig. 4). Across years and lakes, CITM estimated a median E/I of 0.14 (MAD = 0.08), a value that was similar to the values calculated from instrumental data ($\tilde{x} = 0.06$, MAD = 0.06). Similarly, the relationship between E/I derived from isotope models and instrumental data was strong, as indicated by the GAM using lake as a random effect which explained 77% of deviance in E/I values when the year-specific trend is accounted for. Three of the seven sites (Diefenbaker, Buffalo Pound, Last Mountain) had slopes where the 95% confidence interval did not overlap with zero suggesting a positive and significant relationship between isotopic and instrumental models (Table 3). Relationships between E/I methods (Table 3) were closest to 1 in Buffalo Pound ($\beta = 1.34$ [95% confidence interval 0.02–2.7]), and weakest in Wascana ($\beta = 0.07$ [−0.95 to 1.1]). Overall, agreement between isotopic headwater and instrumental models was poorest in Last Mountain Lake, the site with the longest residence time and the greatest variability in E/I among years (Figs. 4, 5, Tables 1, 3).

A landscape gradient in E/I values was also observed, with large upstream lakes (Diefenbaker, Buffalo Pound, Last Mountain) exhibiting lower isotope-inferred measurements than did instrumental data (Fig. 5). In contrast, isotopic estimates for downstream sites (Pasqua, Katepwa, Crooked) were uniformly higher than instrumental values (Figs. 4b, 5). In general, variation in isotopically-derived E/I was similar or less than that derived from direct measurements of Qu'Appelle River inflow.

Spatial and temporal patterns for determinations of water residence time (τ) were similar to those recorded for E/I ratios (Fig. 6). Specifically, the residence time of downstream lakes (Pasqua, Katepwa, Crooked) was 1.6 years longer when calculated using the CITM in comparison to those derived from instrumental data, whereas isotope-derived residence time was ~0.2 years shorter than measured estimates in upstream Diefenbaker and Buffalo Pound lakes. CITM values agreed

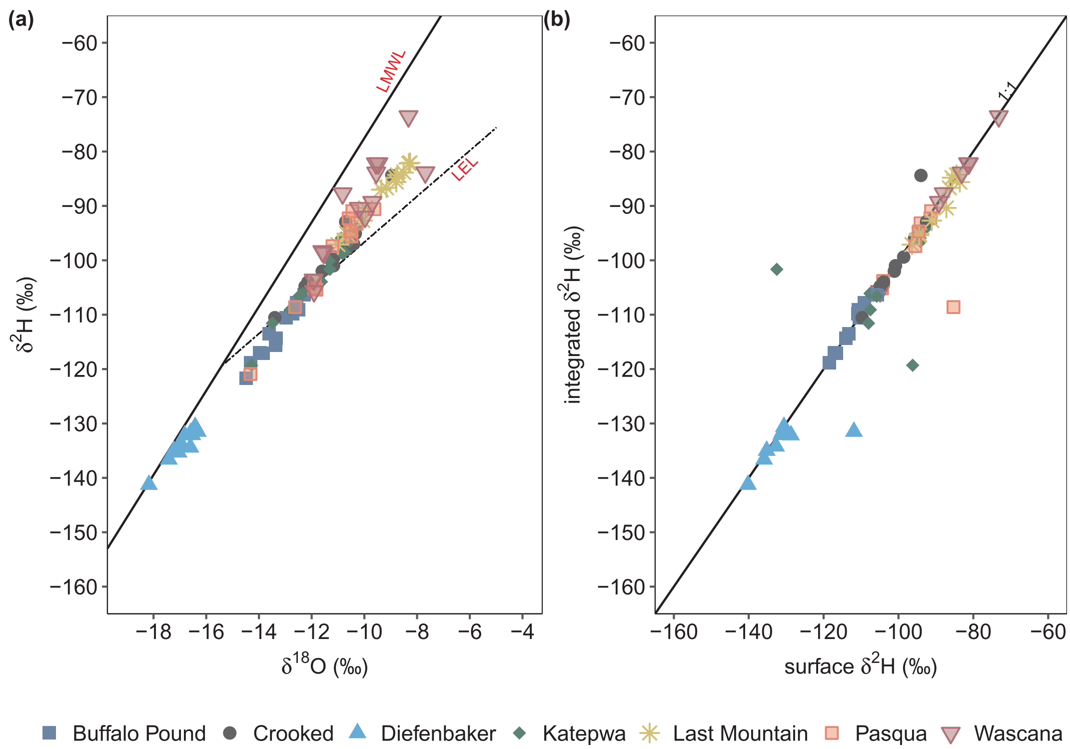

Fig. 3. (a) Raw lake water isotope data from all sites taken in August. The local meteoric water line (LMWL) is derived from data collected in Saskatoon, SK, Canada, and accessed via the Global Network of Isotopes in Precipitation (GNIP). For graphical purposes annual a theoretical LEL from all 7 sites was averaged to determine a common line throughout the study period. (b) Comparison of δ^2H values from samples taken from surface and integrated samples with a 1:1 line inserted to demonstrate to deviation from unity. In both plots colour and shape are used to differentiate lake identity.

best with instrumental data for shallow Buffalo Pound and Wascana lakes, with a median difference of < 0.15 year (Fig. 6, Supplementary Fig. 4). Isotopically-derived τ differed substantially from measured values for the two lakes with the longest residence times, although the CITM underestimated residence time relative to gauge data in Last Mountain Lake (by 4.0 yrs), and overestimated residence time for Katepwa Lake (by 2.3 yrs). Although not assessed directly here, the importance of seasonality in isotope values was unlikely a source of the disparity between methods (see Haig, 2019). Instead, seasonal variability was greatest in lakes where method agreement was lowest and residence times were less than one year (e.g. Buffalo Pound and Wascana lakes).

5.4. Comparison of water balance with instrumental data and best-fit isotopic models

Agreement between isotopic and instrumental estimates of hydrological parameters was generally improved by use of best-fit isotopic models (see Table 2 for best-fit models). For example, median instrument- and isotope-derived estimates of E/I and residence time differed by only 0.03 and 0.5 years, respectively, over all lakes and years, when LS-LEL (Last Mountain Lake) and flow-aided (Pasqua, Katepwa, Crooked) isotope models were used in place of the CITM (Figs. 4–6). The relationship between E/I derived from isotope best-fit models and instrumental data was also well modeled by a GAM using lake as a random effect (deviance explained = 83.4%). As well, a GAM of E/I values derived from best-fit isotopic models and measured precipitation balance (precipitation minus evaporation) exhibited high (74.8%) explained deviance (Table 3).

5.5. Water yield

Mean water yield was less than total annual precipitation for all lakes and most years (except 2011), suggesting that most (~90%) watershed precipitation did not enter the study lakes (Fig. 7). Mean water yield calculated using the gross drainage area for each lake ($\mu = 36.2$ mm yr^{-1}, $\sigma = 62.3$, $\tilde{x} = 15.6$, MAD = 18.8) was more than the SWSA-predicted mean value for the entire Qu'Appelle river basin (21 mm yr^{-1}), whereas calculations using the effective or SFDA resulted in higher yields ($\mu = 1899$ mm yr^{-1}, $\sigma = 6021.4$, $\tilde{x} = 490.8$, MAD = 457.1). Water yields calculated using gross drainage areas were highest for the headwater reservoir Lake Diefenbaker, whereas values were near zero for Wascana Lake and down-stream sites (Pasqua, Katepwa, Crooked). Yields were generally higher in 2011 (GDA $\mu = 143.4$ mm yr^{-1}, $\sigma = 161.3$, $\tilde{x} = 73.9$, MAD = 81.9) than in other years (Fig. 7a), except in Buffalo Pound Lake, consistent with the 1-in-140 year flood for lakes downstream of Regina during spring of that year (Brimelow et al., 2014; Wheater and Gober, 2013). Lowest water yields were observed in 2004 (GDA $\mu = 17.1$ mm yr^{-1}, $\sigma = 21.2$, $\tilde{x} = 6.7$, MAD = 7.2), a year with below-average annual precipitation (Figs. 2, 7a), and were an order of magnitude lower than those recorded during 2011.

5.6. Instrumental data and best-fit isotopic inflow comparison

GAMs examining the relationship between instrumental and isotope-inferred inflow explained most of the deviance (97.1%) with lake as a random effect (Fig. 8). When the relationship between inflow calculated using best-fit models and instrumental data was compared on the log–log scale, a linear relationship was observed (slope = 1.1) for the entire basin (Fig. 8h). This GAM demonstrated the linearity between methods for Diefenbaker (Fig. 8a), Buffalo Pound (Fig. 8b), Last Mountain (Fig. 8c) and Pasqua lakes (Fig. 8e), and non-linear relationships in Wascana (Fig. 8d), Katepwa (Fig. 8f), and Crooked lakes (Fig. 8g). All relationships between inflow methods were significant at 99% confidence interval with the exception of Last Mountain Lake

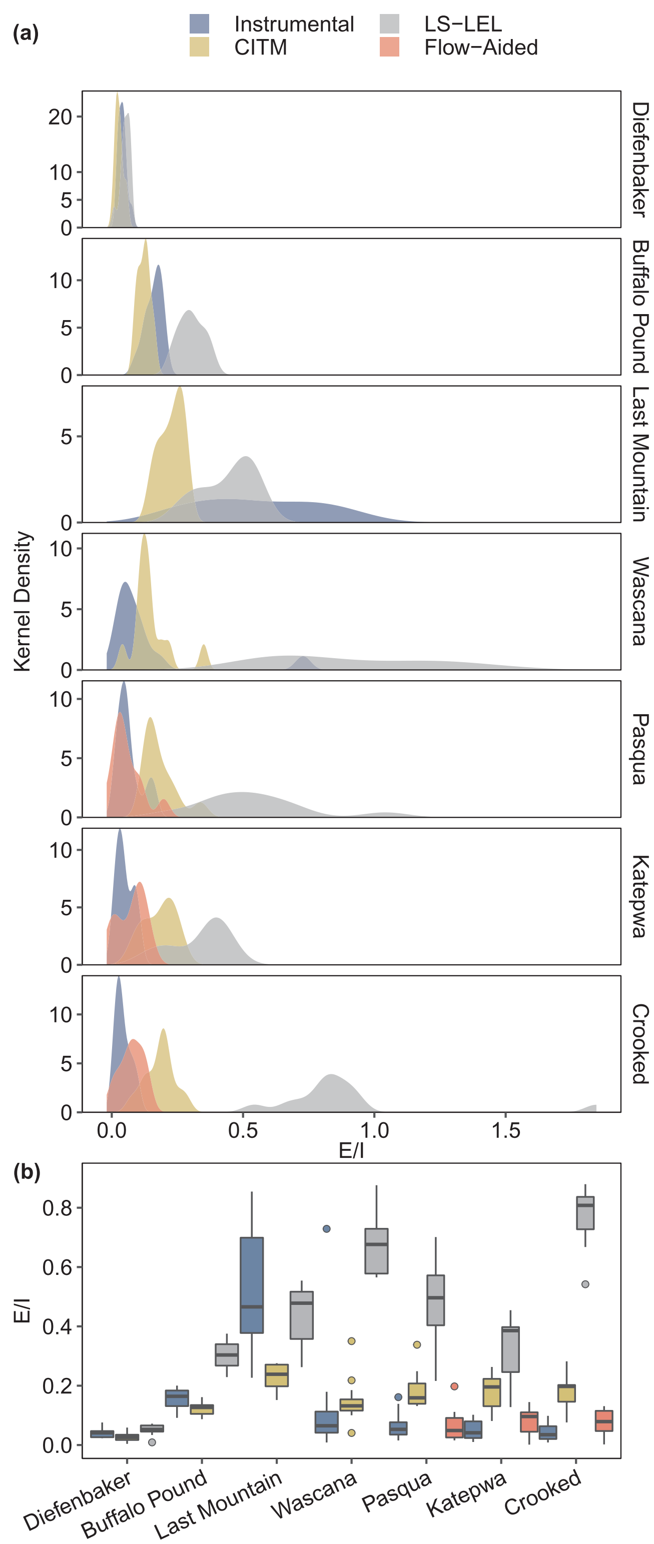

Fig. 4. Evaporation to inflow ratios (E/I) across the Qu'Appelle drainage basin calculated using instrumental (blue), Coupled- Isotope Tracer (CITM, yellow), lake specific local evaporative line (LS-LEL, grey), and flow-aided (red). (a) Kernel density plots showing the distribution of E/I values and the extent of overlap between all methods. (b) Boxplots of the E/I values for each lake showing median, upper (75%) and lower (25%) quantile, 1.5 times inter-quartile range, and outliers.

(Fig. 8c).

6. Discussion

Comparison of isotopic mass-balances and instrumental data suggests that δ^2H and $\delta^{18}O$ of late-summer water samples can characterize basic hydrology of lakes. Specifically, median values of isotopically- and instrumentally-derived determinations of E/I and water residence time differed by only 0.09 (MAD = 0.06) and 0.9 years (MAD = 1.0), respectively, across a 100-fold range in lake morphologies (Figs. 4–6, Table 1). Such agreement suggests that standard protocols (headwater models, one late summer sample) have the potential to provide robust and important insights into lake hydrology in unmonitored surface waters (Gao et al., 2018; Gibson et al., 2016; Pham et al., 2009). As well, these agreements can be improved to within 0.03 (median) for E/I through the use of best-fit models that incorporate only a modest amount of information on upstream ecosystems or in-lake evaporation. Instrumental and isotope-inferred inflow also have a strong positive relationships (Fig. 8) confirming that isotopes are a valid method for estimating flow in ungauged systems. Finally, consistent with regional models and monitoring (Coles et al., 2017; Coles and McDonnell, 2018; Fang et al., 2007; Shook and Pomeroy, 2012), isotope-based estimates of water-yield indicate that very little overland (non-channelized) flow occurs in non-flood years, and that years of high yield may be critical in sustaining lake ecosystems in this large sub-humid continental region.

6.1. Comparison of isotopic and instruments estimates of water balance

The capability of δ^2H and $\delta^{18}O$ analyses to quantify the water balance of managed lakes was demonstrated by the strong agreement between isotopic and instrumental estimates of E/I, particularly based on best-fit models. Elsewhere, the uncertainty associated with isotopic water balance in lakes exhibiting higher evaporation has been estimated (Wolfe et al., 2007), although this variation can increase when a headwater isotope method is applied to lakes (Fig. 4) where inflow may have undergone prior evaporation in upstream water bodies (Gibson and Reid, 2014). Here we find that E/I using the CITM ($\tilde{x}$ = 0.14, MAD = 0.08) agreed with instrumental values ($\tilde{x}$ = 0.06, MAD = 0.06) at the scale of the entire Qu'Appelle River catchment, as seen elsewhere (Gibson et al., 2017; Wolfe et al., 2007; Yi et al., 2008). However, we also found that this agreement could be increased substantially by using isotope models which incorporate only a modest amount of data on either upstream isotopic values or the importance of in-lake evaporation (Gibson and Reid, 2014) (median difference between individual instrumental and best-fit models 0.03 vs instrumental and headwater 0.09). In general, this additional information can be obtained by simple analysis of surface flow patterns and differences in concentrations of chemically-conservative solutes (e.g., Cl^-) among adjacent basins.

Estimates of water residence time based on best-fit isotope models were similar to those derived from continuous annual monitoring programs across the Qu'Appelle River drainage basin (Table 1). Residence time strongly affects chemical content, biological properties, and ecosystem function of lakes (Romo et al., 2013; Schindler, 2006; Tranvik et al., 2009) and is one of the most commonly estimated outputs of isotopic mass-balance calculations (Balasubramaniam et al., 2015; Brooks et al., 2014; Gibson et al., 2016, 2015; Narancic et al., 2017a). Here we show that water residence time can be approximated for a variety of open-drainage lakes using isotopic methods based solely on a single late-summer sample, a critical observation for application of the method to ungauged ecosystems. As lake vulnerability to short-term meteorological variability declines with increasing residence time (Adrian et al., 2009), the broad application of isotopic models in lake surveys will allow investigators to develop regional maps of surface water sensitivity to future climate change (MacDonald et al., 2017; Turner et al., 2010).

Agreement between isotopic and instrumental estimates of E/I and

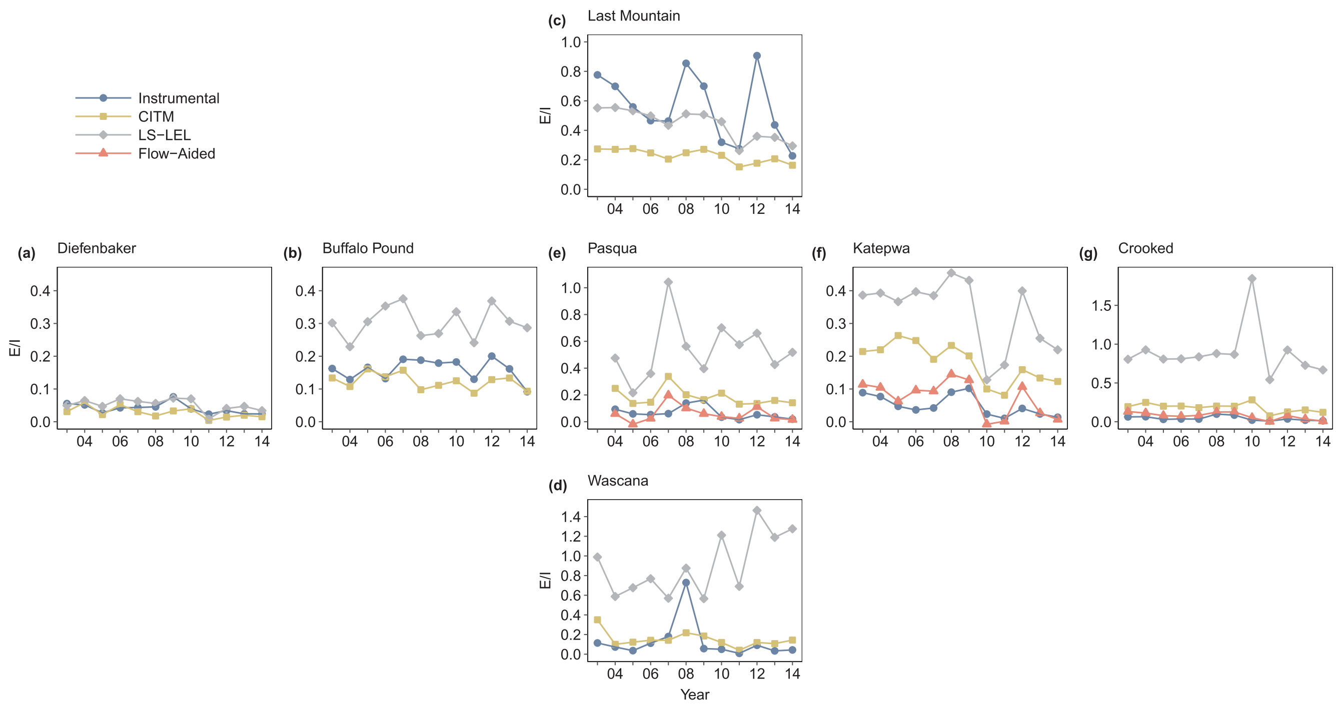

Fig. 5. Time series of water balance (E/I) calculated based on instrumental (blue), Coupled-Isotope Tracer (CITM, yellow), lake specific local evaporative line (LS-LEL, grey), and flow-aided (pink) across all sites. Positioning of panels represents the flow path within the catchment, with lakes along the center line representing basins within the central chain and off-axes lakes positioned mid-reach at their point of outflow confluence with the Qu'Appelle River.

residence time was influenced by lake position in the hydrological landscape (Figs. 4, 5). Specifically, higher E/I values and longer residence times were calculated for downstream Katepwa and Crooked lakes with CITM, LS-LEL, and 'best fit'(flow-aided) isotope methods relative to instrumental monitoring. Research elsewhere shows that such patterns can arise if isotope models do not account for enrichment of ^{2}H and ^{18}O via evaporation from inflowing waters (Gibson and Reid, 2014). In downstream sites (Pasqua, Katepwa, Crooked), evaporatively-enriched waters from Last Mountain have a variable impact on the isotopic values of inflow. Although our 'best-fit' models should account for such upstream isotopic enrichment, the persistent elevation of E/I and residence time in downstream lakes suggests that additional factors affect the agreement between instrumental and isotopic determinations. Although speculative, we suggest that monitoring programs may have overestimated the importance of channelized inflow to downstream Qu'Appelle lakes, consistent with the tendency for WRMM models to overestimate river flow during periods of high precipitation (Bender, 2012). In support of our hypothesis, we note that E/I and residence time of upstream lakes (Diefenbaker, Buffalo Pound) would be expected to exhibit few effects of upstream evaporation and that all sites had isotopically-derived values lower than those from monitoring data.

Variation in agreement between isotope- and instrumental-derived estimates of E/I and residence time may also reflect the high degree of hydrological management in the Qu'Appelle River drainage basin (Saskatchewan Water Security Agency, 2012). For example, the overall relationship between E/I values and precipitation amount (mm), evaporation (mm), and precipitation balance was weak, possibly reflecting the use of control structures on the outlet of most lakes (Table 3). Management in the basin includes urban, agricultural and industrial extractions that are elevated in Lake Diefenbaker and Buffalo Pound both of which are operated as multipurpose reservoirs (North et al., 2015). Pasqua Lake directly receives wastewater from both Moose Jaw (pop. 45,000) and Regina (pop. 220,000), which sustains river flow independent of runoff and therefore is unlikely to react to changes in local meteorological variability. In addition, the lack of basin-wide response to reduced precipitation in 2007–09 indicates that augmenting flows from upstream reservoirs may be capable to preventing hydrologic stress in downstream systems. Further research is needed to determine whether the inconsistencies between methods of assessing

Table 3
GAM slopes (β) between E/I derived from isotopes (best-fit and/or headwater models), and measured meteorology data or instrumental E/I. Each slope represents a mean value with the range as a 95% confidence interval.

Lake	Isotope Model	Precipitation (P, mm)	Evaporation (E, mm)	P-E (mm)	Instrumental E/I
Diefenbaker	CITM	−0.09 [−0.23 to 0.06]	0.23 [0.10 to 0.36]	−0.12 [−0.20 to −0.04]	0.69 [0.35 to 1.0]
Buffalo Pound	CITM	−0.10 [−0.52 to 0.32]	0.47 [0.12– 0.83]	−0.23 [−0.46 to 0.00]	1.34 [0.02 to 2.7]
Last Mountain	CITM	0.06 [−0.30 to 0.42]	0.12 [−0.18 to 0.42]	−0.04 [−0.24 to 0.15]	1.47 [0.37– 2.6]
	LS LEL	−0.09 [−0.42 to 0.24]	0.04 [−0.27 to 0.34]	−0.03 [−0.19 to 0.13]	2.45 [1.71 to 3.2]
Wascana	CITM	−0.12 [−0.57 to 0.32]	0.23 [−0.16 to 0.61]	−0.13 [−0.38 to 0.12]	0.07 [−0.95 to 1.1]
Pasqua	CITM	0.05 [−0.33 to 0.42]	0.30 [−0.02 to 0.63]	−0.11 [−0.31 to 0.10]	0.13 [−0.79 to 1.0]
	Flow-aided	−0.25 [−0.73 to 0.23]	0.39 [−0.04 to 0.82]	−0.21 [−0.44 to 0.02]	0.56 [−0.18 to 1.3]
Katepwa	CITM	0.25 [−0.22 to 0.72]	0.14 [−0.25– 0.52]	−0.03 [−0.28 to 0.23]	0.24 [−0.71 to 1.2]
	Flow-aided	−0.07 [−0.72 to 0.57]	−0.01 [−0.58 to 0.56]	0.01 [−0.30 to 0.31]	0.84 [0.0 to 1.7]
Crooked	CITM	0.14 [−0.36 to 0.64]	0.20 [−0.22 to 0.62]	−0.10 [−0.37 to 0.17]	0.42 [−0.28 to 1.1]
	Flow-aided	−0.41 [−1.37 to 0.55]	0.52 [−0.32 to 1.36]	−0.33 [−0.78 to 0.13]	1.27 [0.65 to 1.9]

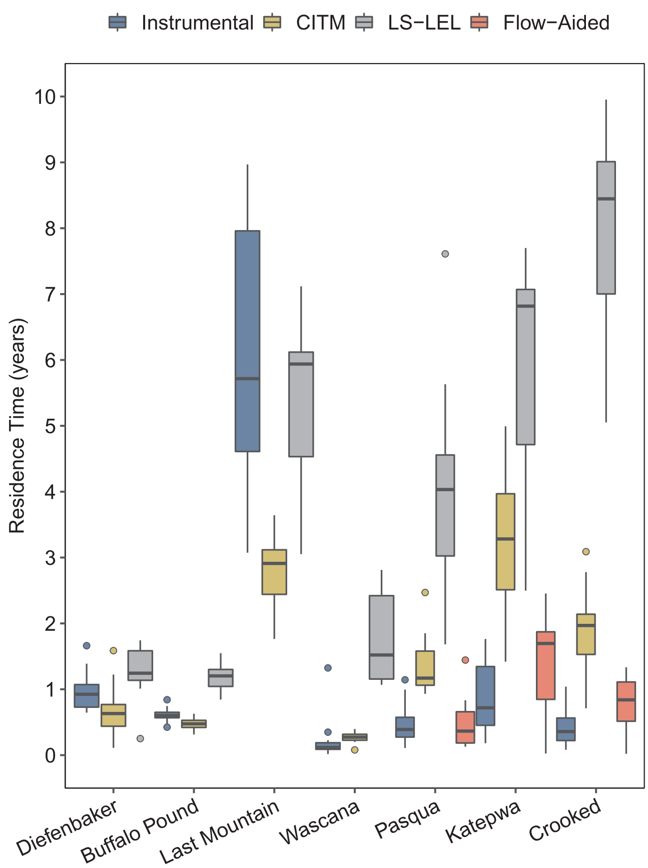

Fig. 6. Boxplots of the residence time in years showing median, upper (75%) and lower (25%) quantile, 1.5 times interquartile range, and outliers. Colours of boxes as in Fig. 4, for using instrumental (blue), Coupled-Isotope Tracer (CITM, yellow), lake specific local evaporative line (LS-LEL, grey), and flow-aided (pink).

basin-specific hydrology metrics reflects management or monitoring issues, or is part of a larger pattern related to lake position in the landscape (Gibson and Reid 2014 and above). In this regard, a survey of regional lakes not subject to manipulation or hydrologically-closed basins may be helpful (e.g., Pham et al., 2009).

6.2. Isotopic estimates of water yield & inflow in open-basin lakes

Analysis of water isotopes can be used to estimate water yield for individual lake catchments, as isotope mass balances integrate factors known to control runoff at the hillslope and catchment scale (Bennett et al., 2008; Gibson et al., 2017, 2015, 2010). Field research shows that runoff is greatest in years when snow accumulation is large and melt occurs quickly over frozen, water-saturated soils (Coles et al., 2017; Coles and McDonnell, 2018; Pomeroy et al., 2007). In this study, isotope mass-balance approaches accurately captured the low water yield of all lakes, as well as the effects of a 1-in-140 spring flood (Fig. 7, Supplementary Fig. 1), particularly in lakes Diefenbaker, Last Mountain, Wascana, Katepwa, and Crooked. This pattern suggests that these later lakes are more likely to receive elevated inputs from their local catchment during flood periods. Peak water yield was not detected in Buffalo Pound, and Pasqua Lake during the period of flooding, although water yields were above average at both sites in 2011. The ability of water isotopes to detect temporal and spatial differences in water yield during a large-scale flood emphasizes the capability of these techniques to integrate catchment scale features that control the contribution of local precipitation within a single region.

In general, isotope-based estimates of catchment water yields were

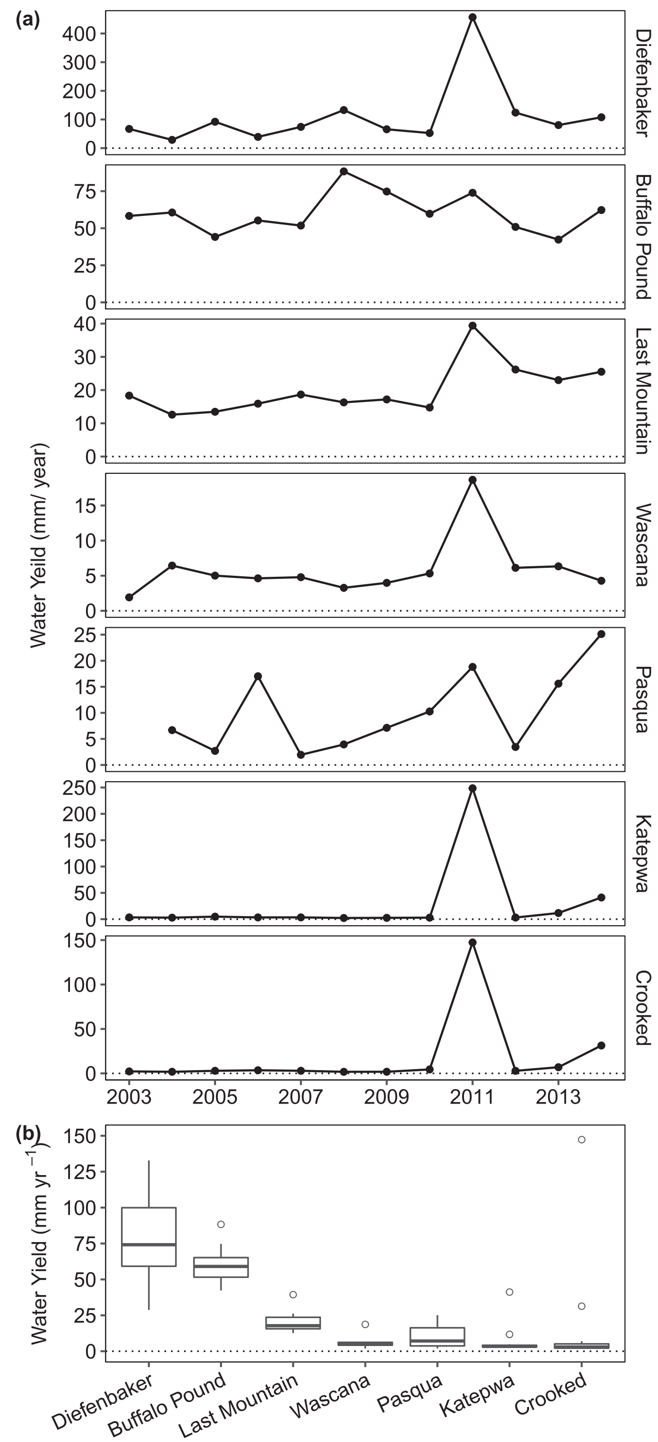

Fig. 7. (a) Boxplots of water yield showing median, upper (75%) and lower (25%) quantile, 1.5 times interquartile range, and outliers over the 12-year study period. (b) Time series of water yield (mm yr^{-1}) ordered by landscape position moving from west (top) to east (bottom). All calculations were made using the gross drainage area (see Table 2-1).

consistent with the knowledge that reservoirs exhibit higher yields than natural lakes in a given catchment (Hayes et al., 2017). Consistent with this expectation, the two headwater reservoirs, Diefenbaker and Buffalo Pound, routinely experienced elevated and variable water yields when calculated with either GDA (μ = 85.2 mm yr^{-1}, σ = 83.2, $\tilde{x}$ = 64.0, MAD = 18.8) or SFDA (μ = 655.0 mm yr^{-1}, σ = 511.8, $\tilde{x}$ = 794.0, MAD = 836.0) (Fig. 7). In contrast, water yields from other lake basins were similar to the 21 mm yr^{-1} estimated from instrumental data at the

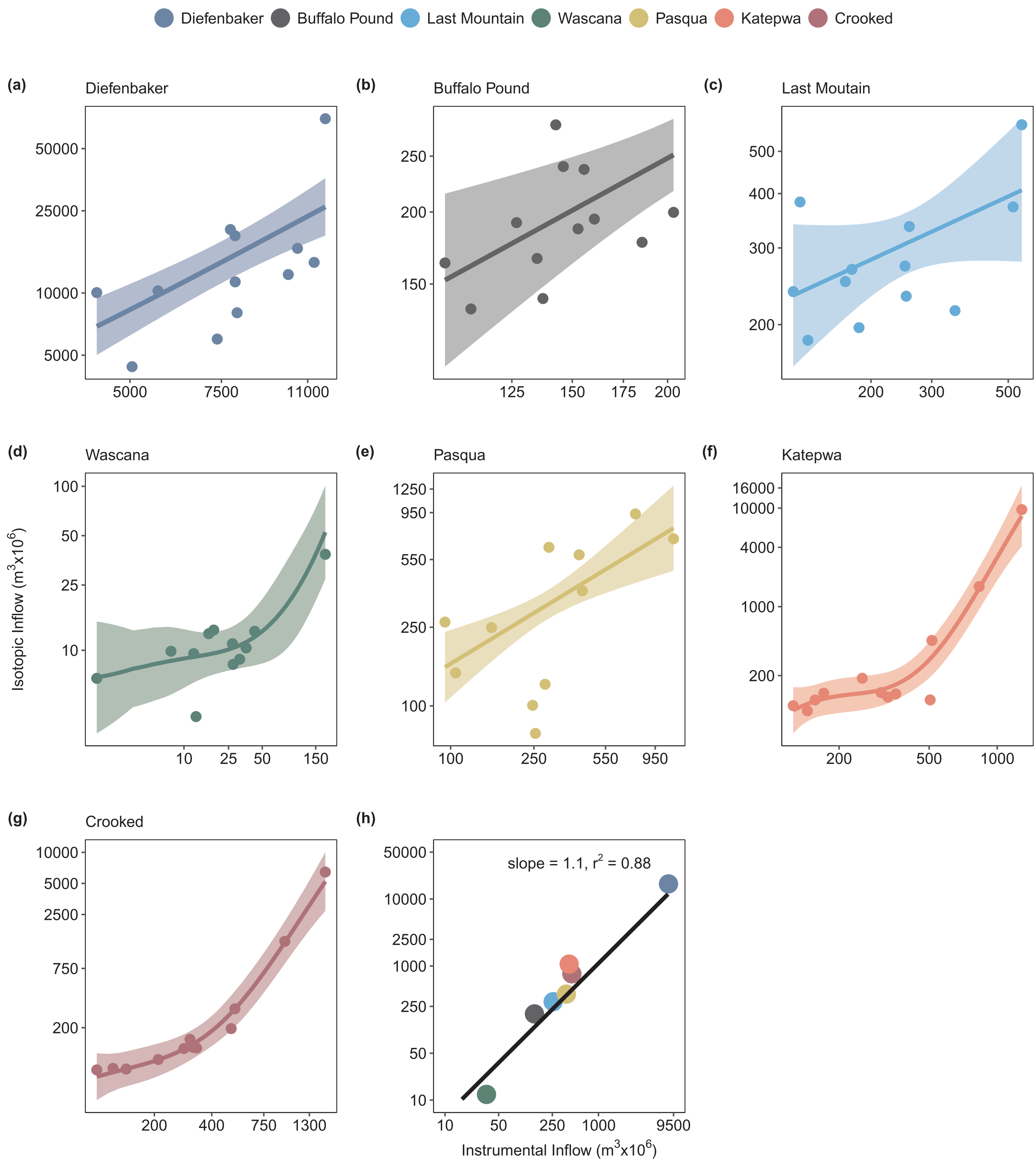

Fig. 8. Generalized Additive Model (GAM) and linear regression comparisons of instrumental and isotopically-derived lake inflow. Coloured solid lines represent the model outputs while coloured dots are the raw data. Panels (a)–(g) represent the 7 study systems. In panel (h) the mean value for each lake was used to summarize the basin wide relationship between inflow methods. All relationships between inflow methods were significant at 99% level with the exception of Last Mountain Lake ($p = 0.11$; panel (c)).

outflow of the Qu'Appelle valley during 1977–1997 (Bender, 2012), and spatial analysis of expected water yield from 1971 to 2000 (Bemrose et al., 2009). The low water yield was also consistent with studies in other agrcultural catchments (Cerdan et al., 2004). The finding of low water yield is consistent with the paradigm for the sub-humid Prairies that most runoff is collected by channelized tributaries except during the spring freshet (Coles et al., 2017; Fang et al., 2007; Pomeroy et al., 2007). However, at present, it is unclear whether the higher water yield in the sites to the west reflects decadal scale variation in contributions from the catchment, or merely the presence of reservoirs in the headwater region.

The strong positive relationship between instrumental and isotope estimates of inflow (Fig. 8) provides critical evidence needed to demonstrate that water isotopes can be used to quantitatively estimate inflow to ungauged surface waterbodies. This result is consistent with the conclusions of Gibson and Reid (2014) who compared isotopic and instrumental estimates of inflow over a five-year period. However, unlike that study, we found evidence that the relationship between instrumental and isotope values can differ among sites, and may be non-linear in some instances. Non-linear relations between precipitation and runoff have been observed earlier for the Canadian Prairies (Coles et al., 2017) and may reflect variation in soil infiltration of precipitation depending on landuse and antecedent climate conditions (precipitation, freezing, etc.). The lack of statistically-significant relationship at Last Mountain Lake (Fig. 8c) likely reflects the comparatively low degree of instrumentation in this large lake basin, or perhaps a high relative importance of unchannelized inflow. Nonetheless, the strong overall relation between observed and isotope-inferred inflow suggests that the isotopic approach is capable of capturing the main variation in inflow (channelized, overland, groundwater) to lakes that are poorly instrumented. Further research in other well studied basins with larger ranges in water balance, as well as surveys of lakes on a subcontinental landscape scale, will help further refine this powerful hydrological technique.

7. Conclusions and future implications

Lakes in this study spanned a wide range of morphology, hydrological settings and human influence, and can be used as a model drainage system to evaluate the use of isotope mass balances to estimate the hydrology of open lakes. With only isotopic values of a single late-summer water sample and minimal upstream flow data, lake-specific estimates of E/I and residence time agreed with values derived from continuous monitoring to within 0.03 and 0.3 years, respectively. Broad application of stable isotope mass budgets to ungauged ecosystems may allow scientists and managers to better identify systems vulnerable to global warming and future changes in regional hydrology. In the future, the prairie region is expected to experience reduction in stream flow and surface water availability (Gan and Tanzeeba, 2012; Sauchyn et al., 2016). Although we noted that the low flow interval of 2007–2009 could be augmented by water from reservoirs (Fig. 5, Supplementary Fig. 1), we also note that this recent period of low moisture is comparatively mild when placed in both historic and future context (Cohen et al., 2015; Gan and Tanzeeba, 2012). Consequently, additional research will be required to evaluate the role of increased conveyance in sustaining regional lakes against severe droughts (Michels et al., 2007). In contrast, we found that analysis of water isotopes was an excellent means of capturing the effects of large runoff events, such as the 1-in-140 year flood during 2011 (Blais et al., 2015), when E/I decreased synchronously in lakes subject to enhanced surface flow. Taken together, these findings suggest that water isotope mass balances can be used as a metric of climate sensitivity in managed systems and are capable of assessing management capacity without operational biases (e.g. gauge position, non-ideal operation of control structures).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author Contribution Statement

HAH and PRL designed the study, HAH, NMH, YY and PRL designed the analysis, HAH conducted all isotope analyses, HAH and GLS conducted the statistical analysis, HAH and YY calculated all isotope mass balances, KH and HAH developed and undertook the drainage area analysis, HAH led the writing of the manuscript, all authors edited/commented on all revised versions, all authors approved final versions, and PRL coordinated and funded long-term data collection.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.hydroa.2019.100046.

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