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Isotope-based water balance assessment of open water wetlands across Alberta: Regional trends with emphasis on the oil sands region

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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: Water sampling for stable isotopes (^{18}O and ^{2}H) was carried out during 2009–2019 across Alberta, Canada, as part of a survey targeting 1022 open water wetlands. The study presents the first site-specific wetland water balance assessment spanning Grassland, Parkland, Foothills, Mountains, and Boreal regions, including the oil sands region, a corridor of rapid development.
Study focus: Climate reanalysis, watershed data, and isotopic data for wetlands were incorporated into a steady-state isotope mass balance model, and applied to estimate site-specific evaporation losses from the wetlands, as well as runoff, groundwater inflow, total outflow, and seasonal drawdown. Regional-scale water balance fluxes, water balance indicators and site-specific classifications were mapped and described.
New hydrological insights for the region: Systematic variations in evaporation losses, watershed runoff to wetlands, wetland discharge, and net groundwater inflow are revealed across the major subregions of Alberta including the oil sands region. Isotope balance calculations suggest that 13% of wetlands are predominantly evaporative, 87% have surface and/or groundwater outflow, 90% have positive water yields, 47% likely have groundwater inflow, and 2% are apparently fed by allochthonous water sources (either snow or glacial melt). For the 3 oil sands regions, a scoping survey suggests that between 20% and 40% of wetlands within the bitumen zones are detectably groundwater reliant compared to 35–50% in the wider vicinity of the deposits.

1. Introduction

Wetlands are vital elements of water and biogeochemical cycles in natural watersheds of western Canada, supporting habitat for microbes, plants, insects, amphibians, reptiles, birds, fish, mammals, and an array of valuable ecosystem services to society including recreation, improvement of water quality, carbon sequestration, erosion, drought and flood control, regulation of seasonal low flows, and mitigation of interannual and long-term climate changes. Intensive and extensive anthropogenic activities including urbanization,

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agriculture, mining, and oil and gas development have led to degradation and loss of natural wetlands worldwide including within Alberta (Roy et al., 2018). Approximately 20,000 km^2 or 14.4% of the rapidly developing Alberta Oil Sands Region (AOSR) has some evidence of human footprint (Eaton and Charette, 2017). In addition, up to 70% of wetlands have been lost due to various land use activities in the Grassland/Parkland regions of Alberta (Roy et al., 2018). Despite the recognized ecological value of wetlands, relatively few quantitative studies have been conducted to characterize the role of wetlands in the regional water balance. The degree to which wetlands are under the direct influence of groundwater, the magnitude of groundwater recharge or discharge from wetlands, and the relative importance of wetland storage among the many sources feeding river discharge, remain to be widely studied in detail at the local and regional scale. Such factors are particularly important for predicting broader impacts on the water cycle from land use impacts and climatic change, especially in regions under rapid development such as the AOSR. Oil sands development, including mining and in situ extraction of bitumen has accelerated over the past 30 years in wetland-rich regions of the province, including the Athabasca, Cold Lake and Peace River regions (Fig. 1). Characterizing and mitigating anthropogenic impacts to wetlands in these areas is of primary concern to joint federal/provincial monitoring and research organizations as well as policy makers. This study focuses on characterization of water balance in a representative 20-km x 20-km gridded network of open-water wetland sites across Alberta operated by the Alberta Biodiversity Monitoring Institute (ABMI), a not-for-profit publicly funded multi-sector research alliance organization. While the network was created and is largely maintained for the purpose of monitoring biodiversity and habitat changes, water samples have been collected for stable isotope analysis of ^2H and ^{18}O as part of a joint program with InnoTech Alberta for the specific purpose of investigating water balance processes and the relationships between hydrology, vegetation and ecosystems. To date, water samples have been obtained from 1022 out of 1656 sites, or roughly 2/3 of sites spanning the province's 662,583 km^2. Open water wetlands were selected among the common wetland types in Alberta (bog, fen, marsh, open-water, swamp; AEP, 2020) as they occurred in all ecoregions across the province including Grassland, Parkland, Foothills, Rocky Mountains, and Boreal Forest.

Groundwater reliance is an important unknown for open water wetlands. Both shallow and deep groundwaters are potential inflow

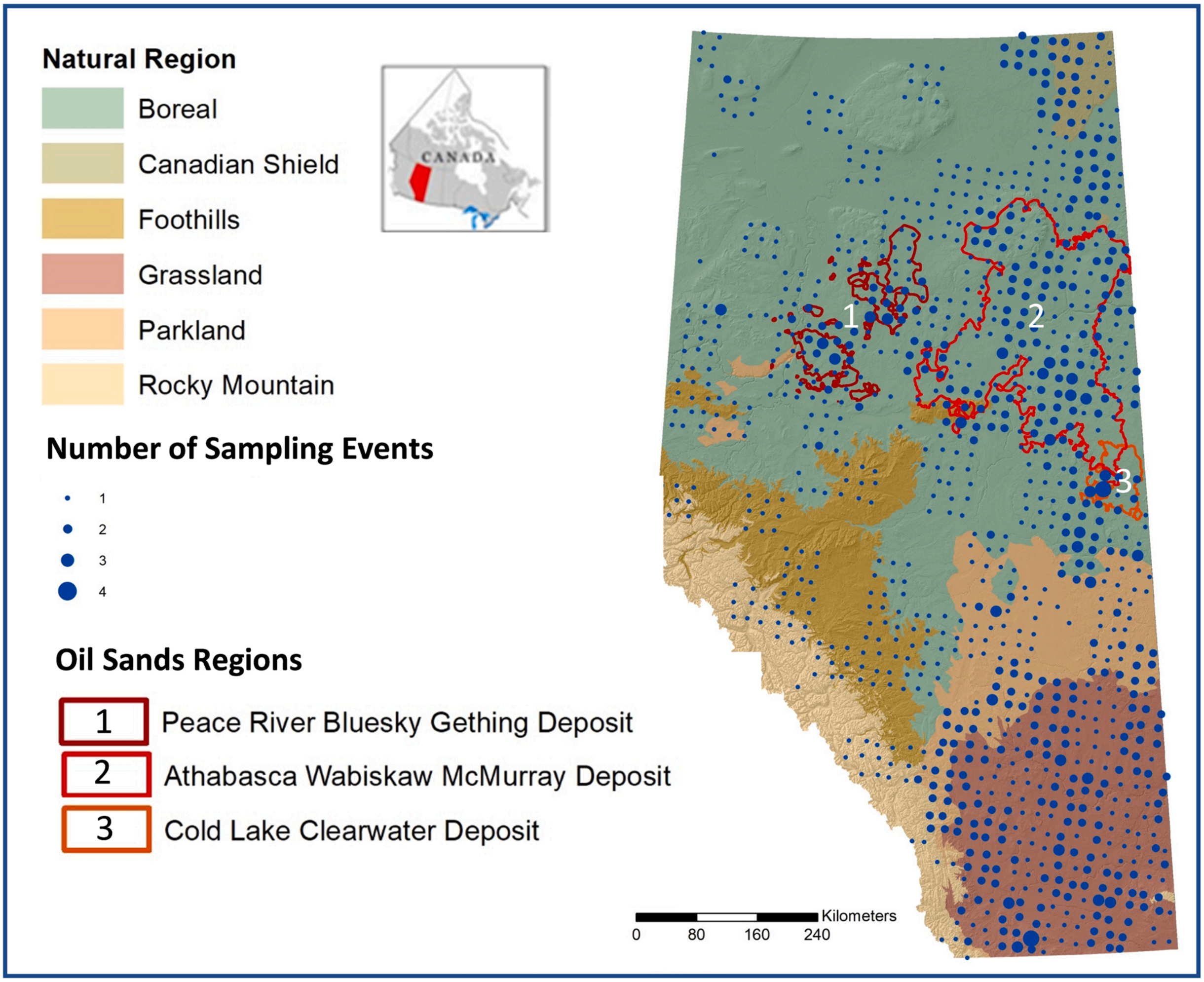


Fig. 1. Map of Alberta, Canada showing location of ABMI open water wetlands sampled between 1 and 4 times during the field program. Natural regions and the three main oil sands regions of Alberta are also shown.

sources and outflow sinks for these ecosystems based on previous hydrologic investigations. Deep groundwater sources may include discharge from saline formations which manifest as localized springs or broader seepage zones, especially within the hyporheic zone or along incised river valleys of the lower Athabasca region (Jasechko et al., 2012; Gue et al., 2015; Birks et al., 2018). Deep groundwater may also flow along structural or geological contacts such as the Devonian Prairie evaporite salt-dissolution-collapse breccia zone (Broughton, 2013), which serve as preferred pathways for deep groundwater to enter surface water bodies. In northeastern Alberta, including along the Clearwater River and lower Athabasca Rivers, seeps and springs are typically found to be glaciogenic, which has been inferred from geochemical and isotopic fingerprints (Grasby and Chen, 2005; Birks et al., 2019). These waters are distinct from deep-basin brines typical of southerly and westerly strata of the Alberta Basin, which are thought to be associated with buried seawater (Connolly et al., 1990b). Overall, shallow aquifer sources within unconsolidated sediments and/or till, which often closely resemble the isotopic composition of modern precipitation, are expected to be more important and more ubiquitous sources to wetlands. Buried channels, which are abundant in many areas of Alberta, may also be influential in controlling groundwater exchange with lakes and rivers (Andriashek and Atkinson, 2007; Alberta Geological Survey, 2021). In the Boreal Forest region, shallow bedrock is dominated by Cretaceous sandstone and shales, including the bituminous McMurray Formation in the Athabasca Region, the Gething and Bluesky Formations in the Peace Region, and the Clearwater Formation in the Cold Lake region, which overlie more permeable Devonian strata comprised largely of carbonates and evaporites. Surface mining of bitumen is confined to 20% of the Athabasca deposit where the bitumen zone occurs at less than 60 m below surface, whereas bitumen extraction in all other deep-seated zones within the deposit utilizes various in-situ technologies (Mahaffey and Dubé, 2016). Several regional plateaus within the Boreal Plains region, including the Stony, Muskeg, Birch and Caribou Mountains are underlain by impermeable shales and are dominated by thin tills with extensive bog formation. Topographically driven flows from these plateaus to adjacent lowlands are prevalent (Barson et al., 2001).

The Parkland region tends to have moderately thick overburden, with relatively impermeable bedrock. Grasslands are similar to Parklands but semi-arid, with depression-focused recharge occurring only during spring melt.

Rocky Mountain areas, especially sediment-filled river valleys, are important recharge zones whereas thin overburden in the Foothills region tends to limit the scale of aquifers, although gravel deposits or interconnected tills may form important local water sources for some wetlands.

The stable isotope surveys by ABMI were conducted over a decade, from 2009 to 2019, during field visits to the sites, and analyses were performed by InnoTech Alberta within two months of the date of water collection. Although this inventory also facilitates regional comparisons between hydrologic indicators and physical, chemical, and biological properties of wetlands in the province, this paper focuses on hydrology and water balance. Thus far, there has been considerable interest in this dataset from the ABMI, Alberta Environment & Parks (AEP), the Oil Sands Monitoring program (OSM), and Environment & Climate Change Canada (ECCC), with potential applications of the dataset or isotope mass balance synthesis products for: (a) evaluating site-specific wetland water balance; (b) examining wetland dependence on groundwater; (c) assessing streamflow dependence on wetlands; (d) understanding relationships between plant community characteristics and associations with wetland water balance, (e) and for investigating the regional impacts and sustainability of bitumen extraction and related activities in the Peace, Athabasca, and Cold Lake Oil Sands regions. The potential to use isotopic indicators to examine and monitor the underlying causes of change in water quality and quantity, such as changes in water sources and/or water balance associated with land cover and climate change, is of paramount interest to these organizations.

Isotope tracers have been widely utilized in hydrological studies in Canada including studies of lakes, rivers and watershed hydrology (Gibson et al., 2005, 2020; Birks and Gibson, 2009, 2021). The evaporation process is traceable owing to enrichment of the heavy isotopologues ($^1H^1H^{18}O$, $^1H^2H^{16}O$) compared to the common isotopologue ($^1H^1H^{16}O$) in the residual liquid due to fractionation by diffusion through the atmospheric boundary layer (Horita et al., 2008). A number of recent studies have demonstrated the value of isotopes for quantifying water balance of natural lakes in a wide variety of settings including boreal, arctic, prairie, and coastal areas (Pham et al., 2012; Arnoux et al., 2017; Wan et al., 2020; Gibson et al., 2016a, 2017, 2018, 2019a, 2019b). These studies were also successful in capturing altered water balances associated with operation of artificial recharge galleries (Masse-Dufresne et al., 2020) and mine tailings ponds (Baer et al., 2016; Chad et al., in press). While several studies have used isotopes to determine contribution of wetland runoff to river discharge, including St. Amour et al. (2005) and Gibson et al. (2016c), relatively few studies have directly assessed water budgets of wetlands (Bam and Ireson, 2019). A subset of the ^{18}O data reported here was previously used to explore statistical relationships between hydrologic setting and plant communities in Grassland/Parkland areas (Roy et al., 2018), although the dataset has not otherwise been used for water balance assessment. We recognized a unique opportunity to leverage the wetland isotope dataset to inform several provincial monitoring/scientific objectives which help to fill gaps in understanding of the role of wetlands in regional runoff, relationships between water balance and vegetation communities, and the impact of disturbances of different kinds and magnitude on water balance and vegetation communities. Quantitative interpretation of the isotopic dataset allows for assessment and mapping of hydrological indicators and site-by-site water balance classifications, which are expected to serve as a first demonstration of the regional-scale impact attribution capabilities of the method.

Once systematic isotopic enrichment signals were confirmed from ABMI open water wetlands across the province, our initial hypothesis was that water balance was mainly responding to regional climatic drivers including precipitation, evaporation, evapotranspiration, humidity and temperature, but with secondary influences arising from local factors such as land cover and landscape position. Overall, differences between ecoregions were anticipated, which we demonstrate in the results and discussion, but the analysis offers a novel perspective, including some unanticipated results, of water balance variations in wetlands on the regional and provincial scale.

2. Method

2.1. Study sites

Study sites across the Province of Alberta are shown in Fig. 1. While the precise geographic location of ABMI monitoring sites is maintained as confidential to protect the integrity of the sites and its landowners, the sites were originally selected by ABMI based on nearest neighbor to a pre-defined 20-km grid, which is publicly available. Public coordinates can be used to identify the site locations to within a radius of 10 km from the precise geographic coordinate, so that resolution remains only slightly reduced but still is quite useful for capturing regional-scale patterns. Wetlands are defined by ABMI as water bodies with an open surface area of between 1 and 100 ha, with a maximum depth between 0.5 and 2 m, and a low probability of complete water evaporation within or between years, i.e., they are permanent wetlands. To be selected for study a wetland also had to support a well-developed zone of wetland vegetation so that plants could be sampled effectively. The ABMI's wetland selection criteria did not preclude human created or modified wetlands.

2.2. Climate data

Climate parameters were obtained from the North American Regional Reanalysis (NARR) dataset (Mesinger et al., 2006). Gridded (32-km) monthly climate data (2009–2019) were extracted for the grid cells corresponding to the location of each of the ABMI sampling sites. The parameters extracted included: (i) total precipitation at surface (mm yr^{-1}), (ii) total evaporation at surface (mm yr^{-1}), (iii) 2-m relative humidity (%), and (iv) 2-m temperature (K). Raw data were averaged and evaporation-flux weighted so that water balance calculations were representative of the open water (evaporation) season (see Gibson et al., 2019a).

2.3. Watershed and open water delineations

Application of the isotope mass balance (IMB) model required delineation of watershed areas, wetland areas, and wetland elevations for each of the ABMI sampling locations; this information was derived from digital elevation model data. Individual watersheds were delineated in the ArcGIS program using the ArcHydro tools, and hydrographic and elevation datasets then were used to depict wetland outlet locations. The planimetric areas of both the wetland and watershed polygons were calculated in ArcGIS. Land cover classification was based on Alberta Biodiversity Monitoring Institute (2013).

Water balance indicator rasters were created using the Spatial Analyst Kriging tool in ESRI ArcGIS (version 10.7.1). Cell size was set to 5000 m and all other tool defaults were retained. The kriging method was ordinary and used the spherical semi-variogram model. Each raster cell was interpolated using 12 variable points.

2.4. Water sampling and isotopic analysis

Water samples were collected in 30 mL high density polyethylene bottles by ABMI field staff during 2009–2019, typically in mid-summer (June or July), using field protocols developed by InnoTech Alberta and widely used in previous isotope-based assessments in the region (see Gibson et al., 2019a). Repeat sampling, where conducted, was carried out in subsequent years within 2 weeks of prior year visits to each site. Samples were returned to the laboratory, refrigerated, and analyzed within 3 months of collection using a Thermo Scientific Delta V Advantage isotope ratio mass spectrometer. Oxygen and hydrogen isotopes were analyzed on separate subsamples, with oxygen determined by equilibration with carbon dioxide using a GasBench II (Paul and Skrzypek, 2006) and hydrogen determined by injection of water on hot chromium using an H-Device reactor (Brand et al., 1996). Results are reported in "δ" notation in permil (‰) relative to Vienna Standard Mean Ocean Water (V-SMOW) and normalized to the SMOW-SLAP scale where SLAP is Standard Light Arctic Precipitation (Nelson, 2000). Analytical uncertainty predicted based on 2-σ of repeats is ± 0.0.09 for $\delta^{18}O$ (n = 159) and ± 0.52 for $\delta^{2}H$ (n = 160).

2.5. Isotopic characterization of precipitation and atmospheric vapour

Isotopic composition of precipitation was estimated from time-series ensembles (2009–2019) using a modified version of the model of Delavau et al. (2015) that included $\delta^{2}H$ for all NARR coordinates falling within the Canadian landmass, from which climate data for Alberta sites were extracted. The regression-based model relied mainly on monthly data collected by the Canadian Network for Isotopes in Precipitation (CNIP) (Birks and Gibson, 2009), the United States Network for Isotopes in Precipitation (USNIP) (Welker, 2012) and Global Network for Isotopes in Precipitation (GNIP) (IAEA/WMO, 2014). Amount-weighted annual values for $\delta^{18}O$ in precipitation were calculated as the dot product of the sequence of monthly isotopic values and precipitation amounts, divided by the total precipitation.

Isotopic composition of atmospheric moisture was estimated using the precipitation-equilibrium assumption (Gibson et al., 2008):

$$\delta_A = (\delta_P - \varepsilon^+)/\alpha^+ \ (‰) \tag{1}$$

where ε^+ (‰) is the equilibrium water-vapour isotope separation (Horita and Wesolowski, 1994), and α^+ (decimal notation) is the equilibrium isotopic fractionation, where these quantities are related by $\varepsilon^+ \cdot 10^{-3} = \alpha^+ - 1$. To account for seasonally variable conditions under which evaporation takes place, the exchange terms in Eq. (1) were evaluated on a monthly time step and evaporation-flux-weighted for each grid point. Evaporation flux weighting was achieved by computing the dot product of the sequence of monthly δ_A outputs from Eq. (1) and monthly evaporation, divided by the total evaporation. Similar calculations were made to estimate evaporation-flux-weighted temperature and relative humidity at 2-m atmospheric height.

2.6. Water and Isotope Mass Balance

The site-specific water balance of each open-water wetland was evaluated based on the balance between water inputs (*I*), water outputs (*Q*), and evaporation (*E*), which regulate long-term wetland volumetric changes (dV/dt) according to

$$dV/dt = \sum I - \sum Q - E \ (m^3) \tag{2}$$

Considering that inputs included precipitation on the lake (*P*), surface runoff to the wetland from the watershed (*RO*), and groundwater input to the wetland (GW_{in}), and outputs included surface outflow (SW_{out}), and groundwater discharge (GW_{out}), the wetland water balance, as illustrated in Fig. 2, can be expressed as

$$dV/dt = P + RO + GW_{in} - SW_{out} - GW_{out} - E(m^3) \tag{3}$$

which, for the case of hydrologic steady state, simplifies to

$$P + RO + GW_{in} - SW_{out} - GW_{out} - E = 0(m^3) \tag{3a}$$

A first approximation of surface runoff to the wetland was estimated from the precipitation minus evapotranspiration deficit

$$RO = P_W - ET_W \ (m^3) \tag{4}$$

where P_W is precipitation on the watershed and $ET_W$is evapotranspiration from the watershed. While this relationship is approximate, as RO may also include shallow subsurface flow from the surrounding watershed, it was tested and found to be a useful indicator of surface reliant wetlands, as compared to groundwater reliant wetlands, the latter likely receiving excess input from recharge outside the immediate catchment area or from deep-seated groundwater sources. Note that in the case of vertical fluxes derived from climate data, volumes are calculated based on the annual equivalent depths, whereby

$$P = p \cdot LA(m^3) \tag{5}$$

$$E = e \cdot LA(m^3) \tag{6}$$

$$P_W = p \cdot WA(m^3) \tag{7}$$

$$ET_W = et \cdot WA(m^3) \tag{8}$$

where *LA* is lake area (m^2), *WA* is watershed area (not including the wetland itself) (m^2), *p* is precipitation depth (m), *e* is open-water evaporation depth (m), and *et* is evapotranspiration depth (m). Similarly, we denote other depth-equivalent variables including: (i) runoff; $ro = RO \cdot WA^{-1}$, (ii) groundwater inflow; $gw_{in} = GW_{IN} \cdot DBA^{-1}$, and (iii) total discharge; $q = (SW_{OUT} + GW_{OUT}) \cdot DBA^{-1}$, where drainage basin area, $DBA = LA + WA$.

Isotope mass balance (IMB) was applied to the open-water wetlands based on the methodology of Gibson et al. (2016b). Similar

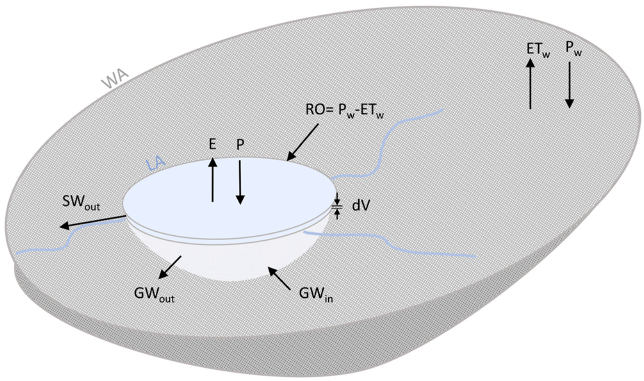


Fig. 2. Schematic of wetland-watershed system showing water balance fluxes. Note that P is precipitation on the lake, E is open water evaporation, RO is surface runoff, GW_{in} is groundwater inflow, GW_{out} is groundwater outflow, SW_{out} is surface outflow, and *dV* is change in volume. Note that P_w is precipitation on the watershed and ET_w is evapotranspiration from the watershed, where *RO* is approximated as P_w-ET_w. Wetland open water area (*LA*) and watershed area (*WA*) are determined based on areal delineations.

approaches have been applied for lake water balance assessments in Alberta (Wolfe et al., 2007; Gibson et al., 2019a, 2019b) and elsewhere in western Canada (Gibson et al., 2017, 2018; Wan et al., 2020).

Isotope-based evaporation/inflow (x) for the wetlands was calculated as follows:

$$x = E/I = (\delta_I - \delta_L)/(\delta_E - \delta_L)\ (unitless) \tag{9}$$

where δ_I is the mean weighted isotopic value (‰) of input (I), i.e a weighted mixture of isotope values in precipitation (δ_P), runoff (δ_{RO}), and groundwater inflow (δ_{GWin}) and. δ_L is the mean isotopic value of the wetland water body, assumed to be well mixed such that it is also representative of liquid outflows, δ_{out}, including potential surface water and groundwater outflows. (Q_{out}, GW_{out}). δ_E is the mean weighted isotope value for evaporation from the wetland water body which we evaluate using a simplified Craig and Gordon (1965) model approach given by (Gibson et al. 2016b) as

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

where δ_L and δ_A are isotopic compositions of the wetland water body and ambient atmospheric moisture (‰), respectively, h is ambient relative humidity (decimal fraction), and ε_K is the kinetic contribution to the liquid-vapour isotopic separation (in ‰) (Horita et al., 2008). These terms were also evaporation-flux-weighted.

Due to lack of site-specific isotopic data on watershed runoff and groundwater sources at each site, we assumed that the isotopic composition of inflow was well-characterized by that of precipitation, i.e., $\delta_I \approx \delta_P$. This approach has been applied successfully in other assessments within Alberta (e.g., Gibson et al., 2016a, 2020), and is most applicable for headwater catchments wherein runoff and groundwater are non-evaporated and derived from local precipitation sources. The simplification of $\delta_{out} \approx \delta_L$ is supported by our observations in previous studies that small, shallow open water wetlands are typically well mixed in summer. Substitution of δ_E into Eq. (9) then yields:

$$x = (\delta_L - \delta_I)/(m(\delta^* - \delta_L))\ \ (unitless) \tag{11}$$

where

$$m = \left(h - 10^{-3}\cdot(\varepsilon_K + \varepsilon^+/\alpha^+)\right)/\left(1 - h + 10^{-3}\cdot\varepsilon_K\right)(unitless) \tag{12}$$

and

$$\delta * = (h\delta_A + \varepsilon_K + \varepsilon^+/\alpha^+)/\left(h - 10^{-3}\cdot(\varepsilon_K + \varepsilon^+/\alpha^+)\right)(‰) \tag{13}$$

Isotope-based evaporation loss (x) evaluated from Eq. (11) can then substituted into the steady-state wetland water balance given in Eq. (3a).

$$x\ =\ E/(P + RO + GW_{IN})(unitless) \tag{14}$$

For this assessment we make use of climatological data via Eq. (4) to estimate watershed runoff (RO) as a metric to evaluate whether a wetland is sustained largely by runoff from its local watershed, i.e., fed by local precipitation recharge (here termed surface water reliant) or whether a water balance deficit exists requiring additional water input to account for RO deficits. This additional water is GW_{in} estimated by rearranging Eq. (14) to obtain

$$GW_{in} = \frac{E - x(P - RO)}{x}\left(m^3\right) \tag{15}$$

which represents groundwater inflow that may derive from deep sources or from outside of the topographically defined catchment, as would be the case for regional groundwater flows. Several scenarios are observed for sustainable wetlands, including:

(i) surface water reliant wetlands, where $RO\ >\ 0$; $GW_{IN} \simeq 0$,

(ii) groundwater reliant wetlands, where $GW_{in} > 0$,

(iii) wetlands within disconnected watersheds, where $RO\ <\ 0$ and $GW_{in} > 0$.

Note that wetlands may be both groundwater reliant and situated within disconnected watersheds, as is the case for many wetlands across much of the Grassland region. There are also ~ 30 sites (2.9%) in our analysis that yielded unrealistically large GW_{in} estimates that appear to exceed potential groundwater input volumes. These sites are found to be mainly located along glacial meltwater channel deposits or flood prone areas near river channels, as for the Peace Athabasca Delta region. For context, it is important to note that in previous applications of the isotope balance method for lakes in Alberta, RO and GW_{in} were left undifferentiated and referred to as water yield (*see* Gibson et al., 2019a). The current approach was introduced here as a first-approximation method for differentiating surface versus groundwater dependency of wetlands.

Because liquid outflows occuring from the wetland by either surface or groundwater pathways are isotopically indiscernible, these fluxes cannot be separately resolved by the isotope balance. As a result, water outputs including SW_{out} and GW_{out} remain grouped as Q in our analysis, where

$$Q\ =\ (1 - x)\cdot I\left(m^3\right) \tag{16}$$

While it is possible to identify occurrence of surface outflow based on air photo or satellite imagery interpretation, and thereby eliminate SW_{out} from the balance when not present, such an analysis has not yet been conducted.

We note another potentially useful isotope-based water balance indicator, discharge/inflow, a.k.a., throughput, defined as

$$Q/I = 1 - x(unitless) \quad (16a)$$

which we apply along with evaporation/inflow (x), to illustrate broad trends in water balance across the province.

Due to the shallowness of some open-water wetlands included in the survey, a simple correction for the isotopic effect of volumetric reduction was applied which describes water bodies where drawdown is controlled by evaporation ($dV/dt = -E$). The initial isotopic composition δ_0 was estimated by

$$\delta_0 = (\delta_L - (\delta* - 1)f^m)/(f^m)(‰) \quad (17)$$

where seasonal volumetric drawdown was characterized by

$$f = \overline{D}/(\overline{D} + E)(unitless) \quad (18)$$

and $\overline{D}$ is the mean water depth measured in each open water wetland at the time of sampling. Implementation of this correction required that δ_0 from Eq. (17) be used in place of δ_L in Eq. (10) and Eq. (11). A similar approximation was recently applied for estimating water balance of tundra lakes with measurable seasonal drawdown (Wan et al., 2020). Note that the volume of water required to refill the wetland to account for seasonal drawdown was also added to the estimate of GW_{in} calculated from Eq. (15), although groundwater reliant wetlands tended to have reduced seasonal drawdown as compared to many surface-water reliant wetlands.

3. Results and discussion

3.1. Isotope characteristics of precipitation and open-water wetlands

Wetland surface waters were found to be differentially enriched in ^{18}O and ^{2}H consistent with the effect of isotopic fractionation of water during evaporation under variable wetland water balance conditions, as noted in numerous previous studies of Canadian surface waters (see Gibson et al., 2016b). In dual isotope space ($\delta^{18}O$ vs. $\delta^{2}H$; Fig. 3) the isotopic composition of precipitation at ABMI sites is shown to plot close to the Canadian Meteoric Water Line (CMWL; see Gibson et al., 2020), with precipitation values for individual sites ranging from $-$ 23.25‰ to $-$ 15.74‰ in $\delta^{18}O$ ($-$177.26‰ to $-$117.90‰ for $\delta^{2}H$) as influenced by climate, including mean annual temperature and continentality of each site. In contrast, open-water wetlands are found to plot below the CMWL along an evaporation line with a slope close to 5, and individual wetlands are found to be enriched to varying degrees (Fig. 3). Isotope values for open-water wetlands ranged from -22.53 to -2.25‰ for $\delta^{18}O$ and -173.54 to -60.0‰ for $\delta^{2}H$, with offset between wetland water and precipitation at some sites reaching as high as 16.64‰ for $\delta^{18}O$ and 78.15‰ for $\delta^{2}H$. Similar isotopic enrichment ranges have been reported in regional lake surveys in central and northern Alberta (Wolfe et al., 2007; Gibson et al., 2016a, 2019a).

Note that water balance was not calculated for open water wetlands sites that were found to have depleted isotopic values relative to precipitation by up to 3.5% in $\delta^{18}O$ and 27‰ for $\delta^{2}H$, indicating that the current water balance model framework was not valid for these sites. Potentially, this may have been due to systematic error in precipitation model estimates or may alternately reflect the presence of water derived from allochthonous sources, i.e., sources other than modern precipitation recharged within the delineated watershed of the wetland. The sites in question are classified, mapped and discussed later on.

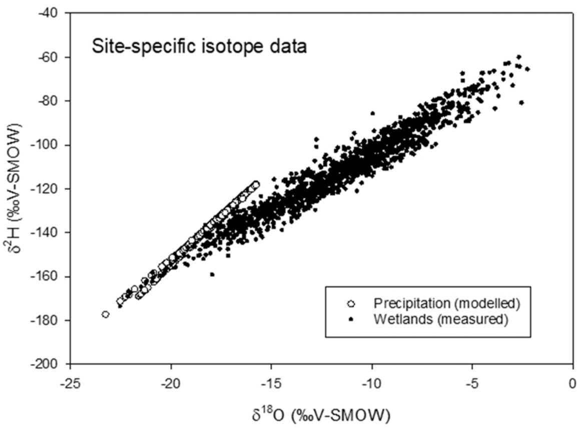


Fig. 3. Dual isotope plot showing measured isotopic composition of wetlands for Alberta, 2009–2018 (solid circles) compared to mean annual precipitation (open circles). Note that modelled mean annual precipitation is based on Delavau et al. (2015) and closely resembles the CMWL.

3.2. Climate data, landscape runoff and individual water fluxes

Histograms showing distributions of depth-equivalent values of precipitation, evaporation, and evapotranspiration used in the analysis are shown in Fig. 4, as well as watershed runoff calculated by Eq. (4), isotope-based estimates of groundwater inflow based on Eq. (15), and total outflow based on Eq. (16). Precipitation (i.e., long-term annual values) ranged from 360 to 890 mm (average = 550 mm) and evaporation ranged from 280 to 400 mm (average = 206 mm), both with relatively symmetrical distributions (Fig. 4). Evapotranspiration ranged from 54 to 590 mm (averaging 400 mm), and runoff ranged up to 594 mm, averaging 147 mm, with less regular distributions. We note that wetlands in the Grassland Region tend to have higher evapotranspiration than precipitation, and therefore yield negative runoff according to Eq. (4), which is a strong indication of non-contributing areas or watershed disconnection. Calculated groundwater inflow, which together with runoff forms the total water yield to the wetlands, is shown to be positively skewed, as is the total estimated outflow. Similar skewed distributions have been found in previous water yield surveys using isotopes across western Canada (see Gibson et al., 2018). The current IMB approach improves upon previous approaches as use of Eq. (4) to estimate surface runoff allows for a first-order partitioning of surface and groundwater inputs. As for outflows, we point out again that partitioning of surface and groundwater discharges are not possible as the isotopic response in the wetland is equivalent and indistinguishable for both flow pathways.

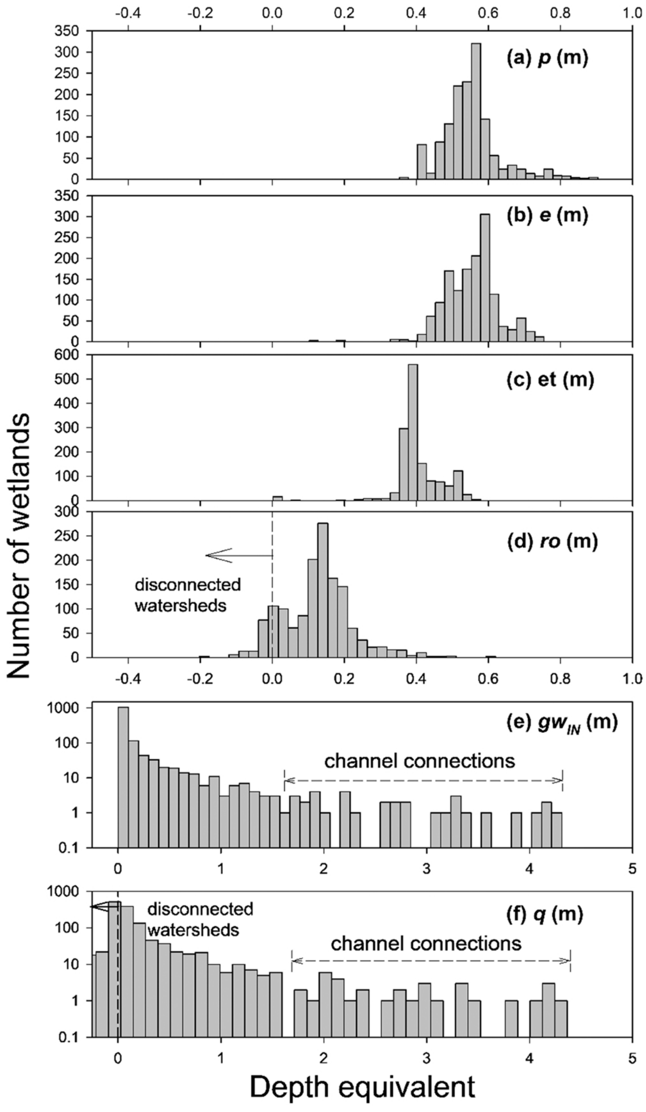


Fig. 4. Histograms showing depth-equivalent water balance fluxes for open water wetlands across the province, including (a) precipitation, (b) evaporation from open water, (c) evaptranspiration, (d) watershed runoff, (e) groundwater inflow to wetlands (normalized to watershed area), and (f) total outflows (normalized to watershed area). Negative runoff and negative total outflows are identified for disconnected watersheds. Unrealistic inflows/outflows (and exaggerated positive skews) shown in (e) and (f) at ~30 sites are attributed to connection/interaction with stream channels.

3.3. Latitudinal variations

Latitudinal variations in water balance fluxes illustrate the extent of climate driven variability across Alberta (Fig. 5). Mid-latitude peaks in runoff, are driven by gradients in precipitation, combined with more subdued gradients in evaporation and evapotranspiration. Note that the resulting groundwater inflows and outflow show no obvious latitudinal patterns, but rather appear in some high throughput cases to be directly coupled. This would be expected, for example, in floodplain wetlands along river channels, which are dominated by flushing. Combination of these individual water fluxes to assess systematic variations in site-to-site water balance is discussed below, and then is applied to classify wetlands according to dominant water balance features.

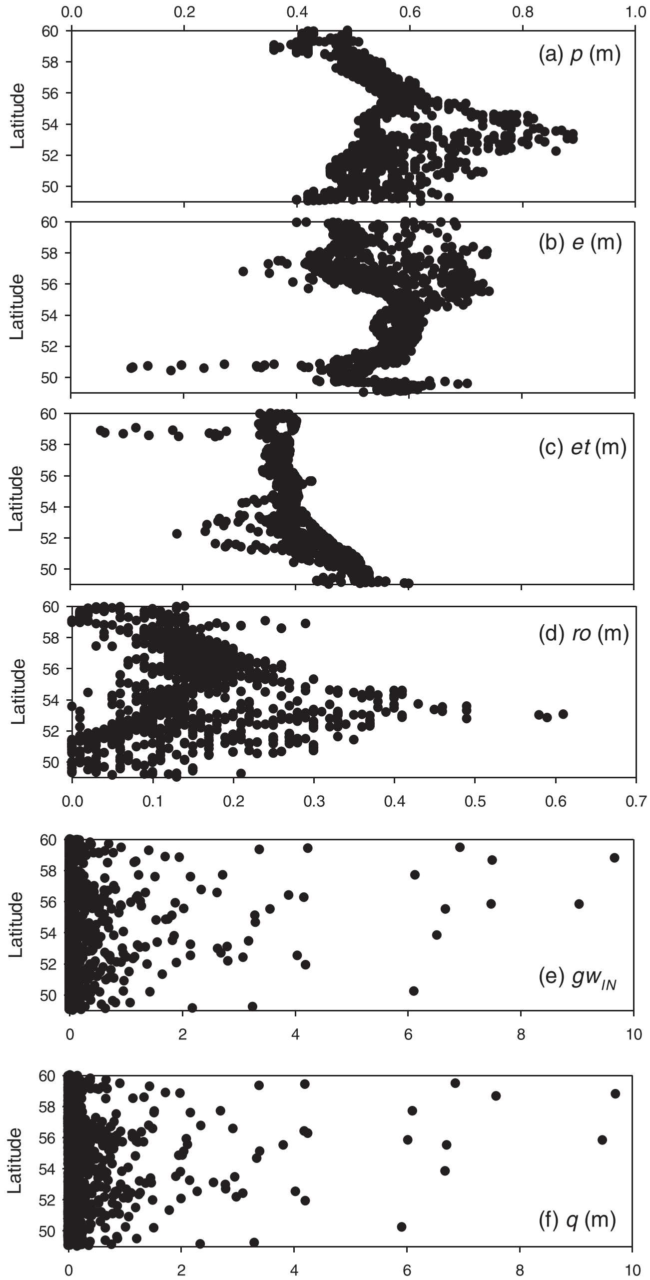


Fig. 5. Latitudinal variations in water balance fluxes, inlcuidng (a) precipitation, (b) evaporation from open water, (c) evapotranspiration, (d) watershed runoff, estimated as P-ET using Eq. (4), (e) calculated groundwater inflow, and (f) total outflows including surface and groundwater outflows.

3.4. Water balance indicators

Evaporation loss and throughput were calculated for the ABMI open water wetlands based on Eqs. (11) and (16a), respectively, allowing for characterization of province-wide variations in water balance. The ratio of precipitation-derived inputs was also calculated based on the approach developed by Wan et al. (2019) but did not significantly improve upon the other indicators at the provincial or regional scale. Basic maps showing variations in the indicators (Fig. 6) revealed significant site-to-site differences, depicting a patchwork of complex water balance sub-regions across the province. Notably, evaporative zones (Fig. 6a) are well-delineated based on evaporation/inflow whereas high throughflow, high runoff areas are most visible based on the discharge/inflow indicator (Fig. 6b). The latter type are found in association with topographic highs, in particular the Mountains and Foothills regions, as well as regional upland plateaus in the oil sands region including the Caribou Mountains and Birch Mountains, both situated northwest of Fort McMurray, the Muskeg Mountains situated northeast of Fort McMurray, and the Thickwood/Pelican/MartenHills, situated west and southwest of Fort McMurray (Fig. 6b). Regional plateaus within the Grasslands region, including Cypress Hills, Rolling Sand Hills and Waterton Lakes area, are also visible as higher throughflow, higher runoff zones (Fig. 6b). Wetlands in these areas appear to be robustly connected to the regional drainage networks. Low runoff areas, visible as light-green coloured areas on the discharge/inflow map (Fig. 6b) demark areas where open- water wetlands have lower throughputs and so appear to be more tenuously connected to the regional runoff. These areas include low-lying areas along the Peace River, Athabasca River valley, Beaver River, North Saskatchewan River, and the Battle River. Internally within these areas are situated many endorheic areas, mostly individual sites, where very evaporative, low discharge conditions are evident (mainly visible as dark blue areas on the evaporation/inflow map (Fig. 6a) or as tan-coloured specks on the discharge/inflow map (Fig. 6b). While regional patterns are clear, we also presume that characteristics such as landscape position may exert important influences on water balance of open water bodies at individual sites, as observed in previous field studies (e.g. Devito et al., 2005, 2017). One of the most evaporative areas appears to be along the Prairie Grassland fringe, where evaporation/inflow is found to approach or exceed 100% (dark colours, Fig. 6a). Surficial and bedrock geology, presence of peatlands, permafrost, river floodplain settings, and proximity to incised and buried channels are also expected to be influential (Andriashek and Atkinson, 2007; Gibson et al., 2019b).

Further classification of the water balance is explored in the following section based on site-specific characteristics such as

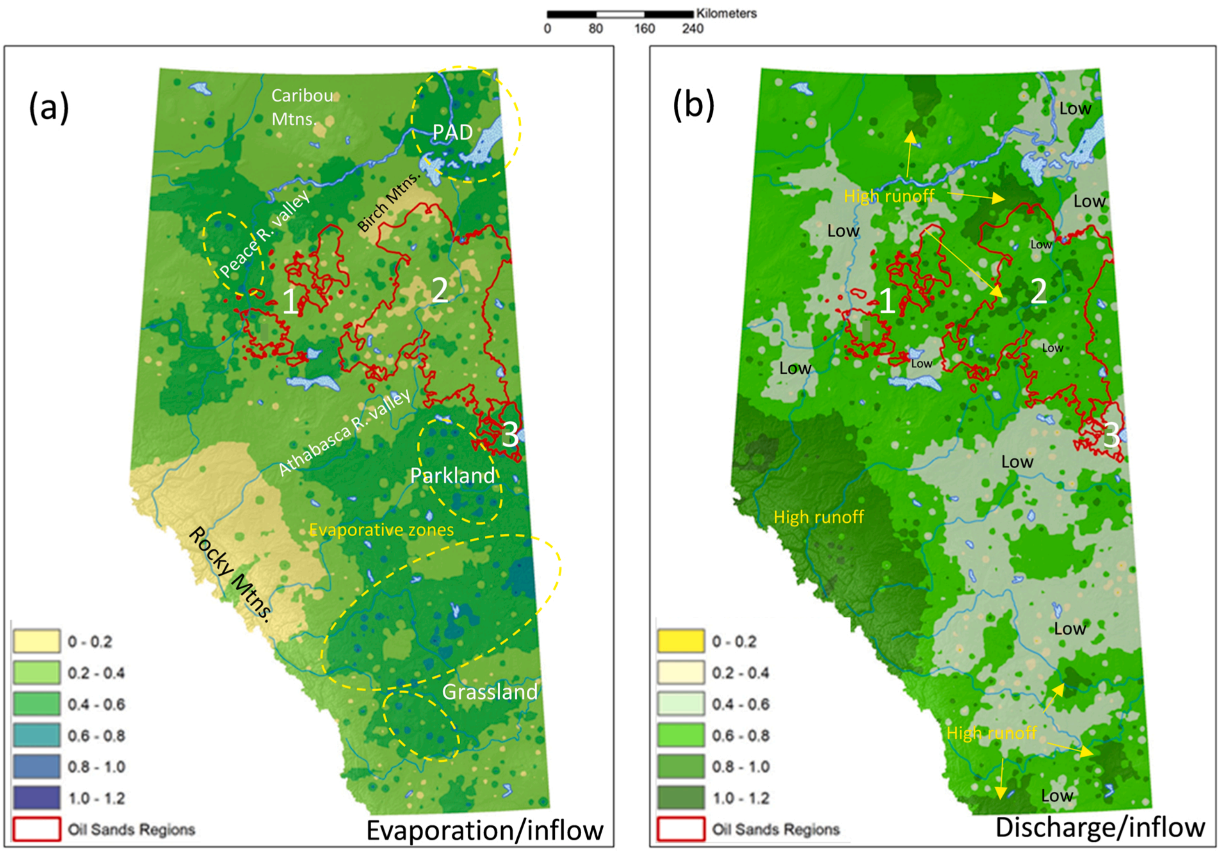
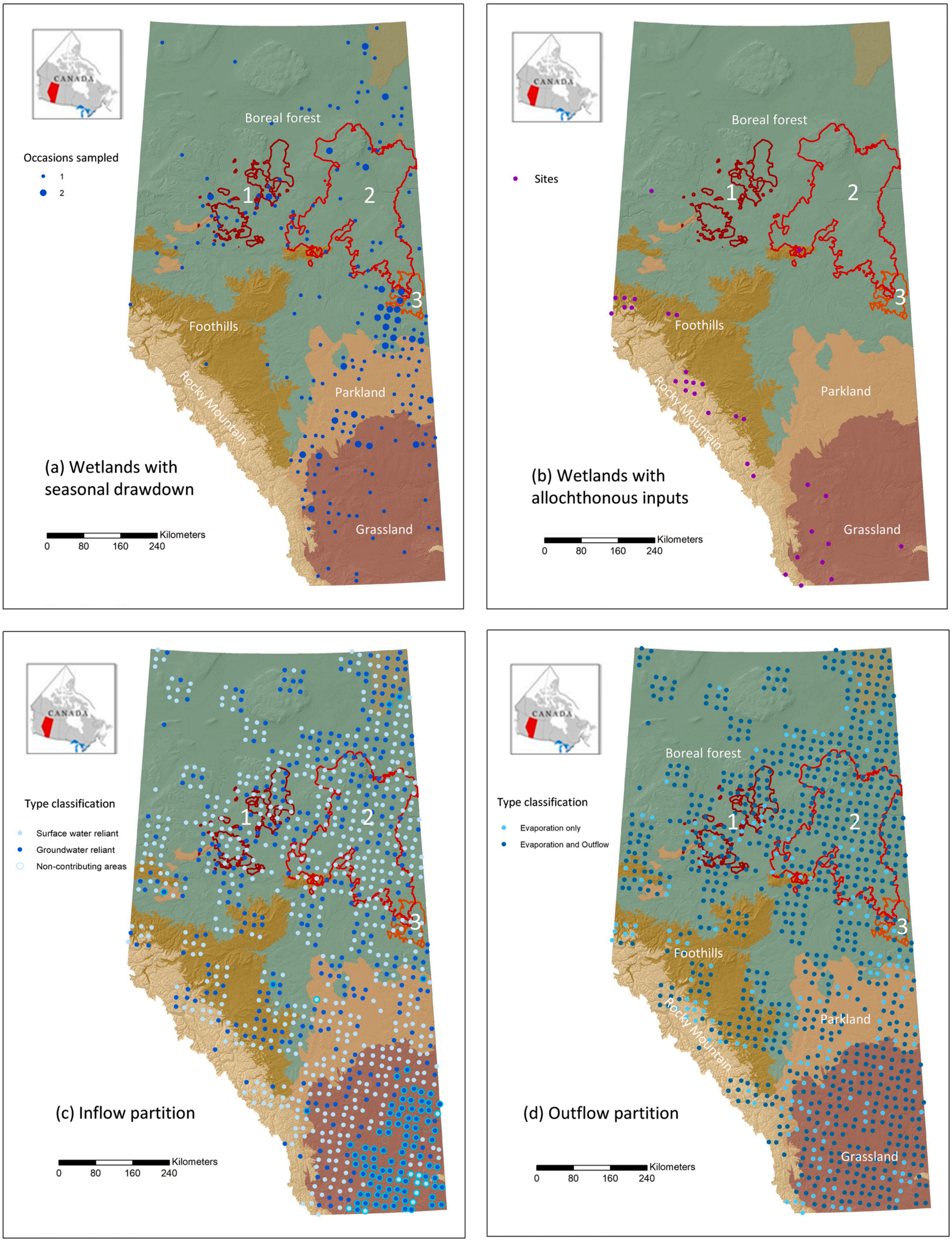


Fig. 6. Provincial maps showing distribution of complimentary water balance indicators based on isotope mass balance, (a) evaporation/inflow (x); (b) throughput i.e., total outflow/inflow (ΣQ/I). The three main oil sands regions are shown, including (1) Peace, (2) Athabasca, (3) Cold Lake. Evaporative zones are identified in Fig. 6a with yellow dashed ellipses; zones of high and low runoff ratios are labelled in Fig. 6b.



(caption on next page)

Fig. 7. Province of Alberta maps (with inset showing position in Canada) illustrating isotope-based site classifications: (a) wetlands with seasonal drawdown; and (b) wetlands with allochthonous inputs, i.e. $\delta_L > \delta_P$. Note 1, 2, and 3 outline bitumen extent for Peace, Athabasca, and Cold Lake Oil Sands regions, respectively. Fig. 7 (con't). Province of Alberta maps illustrating isotope-based site classifications: (c) Wetland inflow partition, differentiating surface and groundwater reliant sites and disconnected or non-contributing areas, (d) Wetland outflow partition, differentiating evaporation only versus evaporation and outflow (discharge) sites. Note that 1, 2, and 3 delineate the extent of the Peace, Athabasca, and Cold Lake Oil Sands regions. See text for discussion.

distribution of wetlands with volumetric drawdown, and through closer examination of inflow and outflow partitioning.

3.5. Water balance classification

3.5.1. Sites with volumetric reduction

Wetlands with significant volumetric drawdown were distinguished initially based on evaporation/inflow (*x*) greater than 100% in the pre-calibrated model. These wetlands are shown generally to cluster in the Parkland region, northern Grassland region, near the southern Boreal/Parkland transition, and in the Peace Lowland (Fig. 7a). Such conditions appear to be generally less common moving northward along diminishing evaporation gradients. While it was initially surprising to find that volume reduction appeared less frequently in the semi-arid Grassland region, we attribute this result to better groundwater connectivity in these areas, which appears to be prerequisite to wetland permanence, an important site selection factor which likely was influential in this climate zone. We note a high degree of similarity between spatial distribution of wetlands with apparent volumetric reduction based on isotopes (Fig. 7a) and spatial distributions of volume, surface area, and number of geographically isolated wetlands across Alberta, as identified by Cui et al. (2021).

3.5.2. Sites with Allochthonous Sources

Our IMB model is applied to quantify the site-specific water balance scaled primarily using the degree of evaporative isotopic enrichment attained by open-water wetlands compared to local precipitation. Across the ABMI sampling network, a total of 30 open-water wetlands (2% of sites) were found to be model outliers, having wetland isotope values that were depleted relative to predicted precipitation isotope values at the site. Systematic distribution of these sites within the province, mainly along the Rocky Mountain Foothills region (Fig. 7b), may suggest that the Delavau et al. (2015) model underestimated the commonly observed altitude effect of isotopes in precipitation (Dansgaard, 1964), or more likely, that wetlands were receiving water from higher altitude areas outside the topographically delineated catchment. Such occurrences have been noted previously in alpine regions where bedrock layers may extend beyond topographic boundaries (Cochand et al., 2019). Wetland landscapes often originate as discharge from springs at the base of talus slopes which can store large amounts of groundwater (Christensen et al., 2020), in some cases accounting for more than 75% of annual streamflow (Clow et al., 2003). Evaporation in such systems is often minor and “suspended” groundwater storage, i.e., storage and seasonal redistribution of snow and glacial melt, may cause extended freshet recessions dominating the hydrograph throughout the summer period (Cochand et al., 2019). It is important to note that meltwater, which may contain glacial melt and permafrost thaw derived from precipitation falling under colder climate conditions, as during the last glaciation, may also be influential in some watersheds. While we can reasonably presume that these sites have distinct water balance properties reflecting alpine or sub-alpine conditions, the IMB model would require input sources to be better defined, which would require additional sampling and site-specific ground-truthing to be quantitatively applied at these sites.

3.5.3. Inflow partitioning

Runoff to wetlands, approximated from Eq. (4), was found to be positive for 90% of sites, with 10% of sites having a long-term runoff deficit. The latter sites are generally clustered in the Grassland region, which is known to frequently have watersheds with partial area contributions, where large areas of the watershed may become disconnected from regional drainage networks and where wetlands typically occupy low-lying areas or depressions. Such wetlands are typically connected to large areas of the watershed only during the snowmelt period (Costa et al., 2020). Groundwater inflow was found to be important for 47% of wetland sites (Fig. 7c), and based on the IMB results, we conclude is essential for maintaining wetlands in the Grassland region (cyan highlighted area; Fig. 7c). Examples of such wetlands, which may in some cases be temporary or semi-permanent, have been described in previous studies as groundwater-wetland ecosystems or Prairie potholes (van der Kamp and Hayashi, 2009; Sloan, 1972).

While all open-water wetlands in the southeastern Grasslands region appear to be reliant upon groundwater, mainly driven by climatic factors, i.e., high evaporative demand, there are some wetlands in the Parkland region, Boreal region, and Peace Lowland areas that also appear to be reliant upon groundwater, and some that are not. Differentiation of these wetland types provides clear targets for further map analysis as well as for site-specific investigations into water balance controls and related mechanisms. Among important local controls are relief, surficial and bedrock geology, permafrost thaw, presence of peatlands, landscape position, and proximity to incised and buried channels, as noted previously.

For the Boreal forest region, the role of groundwater appears to vary significantly from site to site, even among nearby wetlands. It is important to note that classification of wetlands according to inflow mechanisms should be regarded as a first approximation and does not preclude that groundwater exchange may be occurring at certain times of year, though to a much lesser degree, even for surface water reliant sites. The classification should be viewed as a water balance constraint on whether surface or groundwater sources are the most significant determinant of the long-term water balance.

3.5.4. Outflow partitioning

Wetlands were also differentiated based on dominant water loss mechanisms (Fig. 7d), the main mechanisms being evaporation and liquid outflow, the latter comprised of surface and/or groundwater discharge. Lakes that are predominantly evaporative are highlighted in light blue (Fig. 7d). Based on IMB, these wetlands do not appear to have significant liquid outflows. Such wetlands, analogous to evaporation pans that lose water principally by evaporation, generally occur in local clusters or as individual sites scattered widely across the province. Evaporative lakes, which account for 13% of total sites, appear to be more common in the western part of the Grassland region, and in the southern Boreal/Parkland transition, overlapping with areas where volumetric reduction is also detected. This consistency supports the conclusion that these sites are evaporation driven. The majority of wetlands scattered across the province (87%) lose water by both evaporation and some form of liquid outflow. Unfortunately, from IMB evidence alone, we cannot differentiate the liquid outflow mechanism, as both surface outflow and subsurface outflow are isotopically non-fractionating. As noted previously, identification of surface outflows may be possible from further air photo or satellite-based analysis, which remains a planned future activity.

4. Discussion

4.1. Regional water balance trends

Broad trends in wetland water balance discernable from the IMB on the provincial and regional scale appear consistent with many features of wetlands, lakes and watersheds observed previously based on hydrologic field studies and modelling. The disconnection of wetlands detected in endorheic zones within the Grassland region, and generally weaker connection between wetlands and large southern rivers, are broadly consistent with the description of these areas as non-effective drainages by Wolfe et al. (2019). 'Non-effective' drainage area, defined as the difference between the gross and effective watershed area, has been found to be a reliable index of the hydrological dynamics across the region (Shook and Pomeroy, 2012). Studies of Prairie potholes by van der Kamp and Hayashi (2009), Shook and Pomeroy (2011) and others, have also shown that potholes located in smaller depressions are largely dependent on snowmelt or shallow groundwater, and may completely dry up seasonally or during times of drought. However, a class of larger, semi-permanent wetlands has also been described (Wolfe et al., 2019), which we suggest are similar to many of the ABMI wetlands in this region, which were screened to remove non-permanent sites. Based on our analysis, these sites appear to have sustained groundwater inputs on which they rely. Clusters of surface water reliant wetlands are also found in the Grassland region, although these appear to be associated with regional uplands such as the Cypress Hills, which were found to support higher watershed runoffs (see Fig. 6b). A transition to more surface water reliant sites is evident along northern and western fringes of the Grassland region where *RO* deficits subside, although groundwater reliant sites are still predicted to be numerous.

The Parkland region has previously been described as a lake-rich region with high potential for evaporative isotopic enrichment and low runoff, including some areas with negative water yields, i.e., non-effective drainages (Wolfe et al., 2019). Based on an IMB assessment and statistical analysis of 50 lake-watershed systems spanning the region, higher runoff to lakes was found to be linked in general to higher percentage of wetlands (Gibson et al., 2016a). In some cases higher inflow may also reflect buried channel interaction (Baker et al., 2017). In that study, groundwater was estimated to account for approximately 40% of inflow to Sylvan Lake (52.35°N, 114.2°W), which is among the deepest lakes in the region (mean depth of 9.6 m), described as having an anomalously high degree of groundwater connectivity compared to other lakes. Based on results from these previous studies, we posit that water depth is an important control on groundwater interaction for open water bodies, such that wetlands ($<$ 2 m depth) are likely to have weaker connections to groundwater than most lakes. The water balance results for ABMI wetlands in the region reveal that sites are approximately divided between surface water and groundwater reliant sites, and roughly divided between evaporation-dominated and discharge dominated sites. Many wetlands have isotopic enrichment levels suggesting evaporative seasonal drawdown, which is consistent with recent findings for shallow lakes in the region based on IMB (Gibson et al., 2016a). Water yield to wetlands in both Grassland and Parkland sites is significantly lower than for Mountains, Foothills and Boreal regions, consistent with estimates by Kienzle and Mueller (2013).

The Rocky Mountains and Foothills regions, characterized by alpine and sub-alpine conditions, respectively, have been described as the hydrologic apex of North America and source regions for many of Alberta's large rivers (Rood et al., 2008). Our finding of the occurrence of a significant number of wetlands potentially receiving allochthonous inputs, and the dominance of wetlands with high throughflow and lower evaporation, are expected considering the topographic gradients and other factors mentioned previously (Cochand et al., 2019).

The Boreal Forest region is dominated by low-lying wetland-rich terrain interspersed with regional uplands that drive topographically driven groundwater flows (Barson et al., 2001). Regional groundwater flows, often saline, flow eastward from the Rocky Mountains and enter the incised river valleys of the lower Peace and Athabasca Rivers. Incised river channels and buried valleys, as well as occurrence of impermeable bedrock, salt dissolution features, sinkholes and complex fault networks create complex conditions for surface/groundwater interaction (Birks et al., 2018, 2019). Our IMB assessment suggests that wetlands in the region are commonly losing water by evaporation and both surface and/or subsurface discharge, they are less prone to seasonal drawdown than wetlands in the Parkland or Grasslands region, and they are divided almost equally between surface water and groundwater reliant types. Considerable site-to-site variations are consistent with previous field studies that have shown hydrogeological setting, landscape position and watershed morphometry to be influential in determining the water balance of lakes and wetlands (Devito et al., 2017; Gibson et al., 2019a). Lake hydrology has been reported to be strongly influenced by wetland cover type and extent (Prepas et al., 2001). In some typical examples, lakes have also been found to be moderately reliant on groundwater in regional uplands (Schmidt et al., 2008), although deeply incised rivers are known to be the focal points of regional groundwater inflow (Birks et al., 2018). Further discussion of wetland conditions the oil sands region is provided below.

4.2. Alberta oil sands region

Wetlands evidently play key roles in the Alberta oil sands region, including water storage, filtration, flood control, carbon and nutrient sequestration, as well as sustaining unique vegetation communities and wildlife habitat (Volik et al., 2020). Understanding the water balance of wetlands, including distribution and degree of surface/groundwater interaction and groundwater reliance, and relationship to geomorphic and geologic controls, is an important prerequisite to understanding and predicting how wetland ecosystems may be affected by cumulative development activities.

From the ABMI dataset, comparisons of the inflow partitioning status of open-water wetlands in the Peace River, Athabasca, and Cold Lake oil sands districts reveals significant regional differences in the numbers and proportions of surface versus groundwater reliant types (Fig. 8). This initial scoping assessment suggests that groundwater reliant wetlands account for between 20% and 40% of ABMI sites within the various bitumen zones, whereas such sites appear to be more common in the larger vicinity of each deposit (36–51%). Reduced frequency of groundwater reliant wetlands in the bitumen zone itself compared to the larger reference areas is consistent with unique geological features of the bitumen zone including occurrence of widespread impermeable Cretaceous shales (having formed cap rocks for bitumen in many areas) and bitumen impregnated rock itself, which both form effective aquitards to reduce vertical water movement (Barson et al., 2001; Birks et al., 2019). Enhanced potential for groundwater exchange in the vicinity

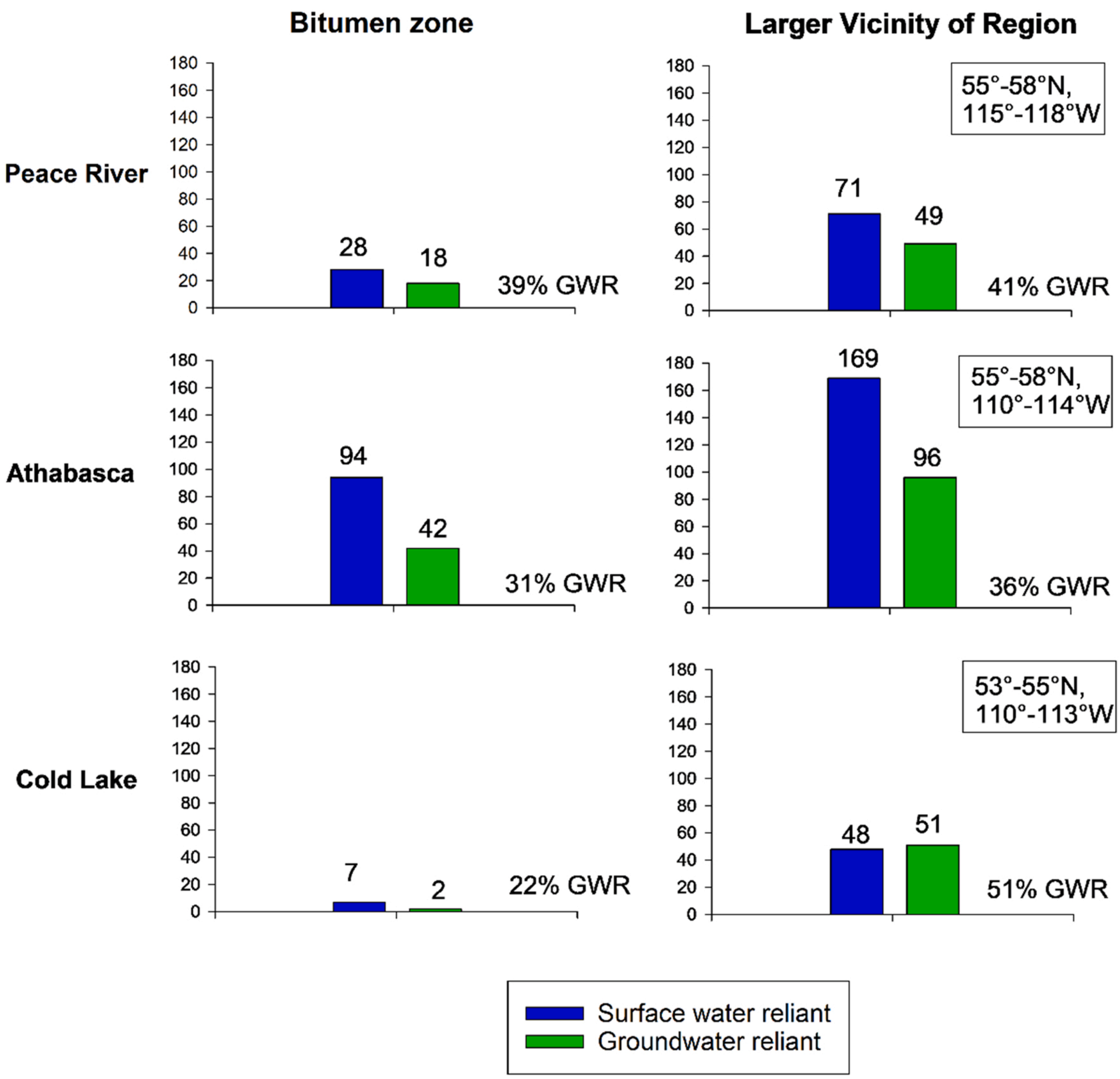


Fig. 8. Counts of surface water reliant and groundwater reliant wetlands in the three oil sands regions based on isotope mass balance. Oil sands bitumen extent for each region is shown in Fig. 1; latitude-longitude ranges are provided.

of the Athabasca deposit may be associated with upward movement of formation waters beyond the bitumen edge and beyond the erosional limit of the Colorado Shale. In contrast, groundwater reliance in the Cold Lake region appears to be somewhat more common owing to presence of thicker unconsolidated sediment layers over relatively impermeable bedrock. The Peace River region appears to have a higher proportion of groundwater reliant sites within the bitumen zone, which may be due to the less continuous nature of the bitumen deposits there.

It is important to note that the ABMI sites only include open-water wetland types, whereas fens and bogs are significantly more abundant in the oil sands region. While this may limit the potential value of the current dataset, it also recognizes the potential value of broader water sampling programs that include a diversity of wetland types, including fens, bogs, and marshes, in addition to open-water wetlands. Significant potential also exists for the use of similar isotopic techniques to monitor reclaimed or constructed treatment wetlands, which has proven challenging (Ketcheson et al., 2017).

Further analysis of the quantitative IMB results in combination with physical setting, substrates, vegetation, geochemistry, and ground-truthing of individual wetland sites and their characteristics will be required to explore a mechanistic understanding of specific controls on groundwater/surface water interaction and their relative importance for wetlands. While further refinement of IMB model parameters is ongoing, the current version of the IMB outputs demonstrates considerable potential for a first-approximation quantitative assessment.

4.3. *Potential applications*

4.3.1. *Network design and monitoring*

One interesting application of the IMB approach is for regional network design, to target specific wetland types such as groundwater reliant systems or to stratify monitoring based on water balance conditions to ensure that the full range of variability is captured within a regional monitoring framework. Water sampling, augmented by sampling of isotopic archives in aquatic sediment from open water bodies or shallow cores from peat-forming wetlands (bogs and fens), may be useful for establishing a temporal record of baseline conditions prior to development (see Gibson et al., 2022). Archives may also provide a means for establishing baseline conditions in areas lacking traditional baseline monitoring, or as an approach to build longer environmental baselines, thereby providing extended time-series records for constraining the natural range of variability of hydrologic or hydrogeologic conditions. This would presumably assist in strengthening of adaptive management strategies and risk assessment frameworks for both surface water and groundwater reliant systems (see Rohde et al., 2017).

4.3.2. *Connectivity to streams and groundwater*

IMB results from this study may be informative for study of wetland sources to receiving waters such as streams and rivers, possibly as quantitative indicators of wetland connectivity. Analysis of spatial distribution of volumetric estimates of wetland discharge within the framework of a reach-wise streamflow assessment may provide an approach to establish the importance of wetland sources of streamflow generation for better understanding of the role of wetlands in flooding, drought, low flows, and sustainability of ecosystems. Resources of potential value for this type of assessment include isotopic monitoring data from streamflow gauging stations across Canada (Gibson et al., 2021) as well as multi-decadal streamflow isotope records from stations in key development regions (Gibson et al., 2016c).

Similarly, we suggest there may be potential value in comparing isotopes in precipitation and shallow groundwater from surficial aquifers, bedrock subcrop, or springs and seeps to identify recharge versus discharge settings, to validate or challenge the preliminary assumption that groundwater isotope values are similar to locally recharged precipitation, or to map groundwater development risk. Isotopic datasets compiled for the Groundwater Observation Well Network (GOWN) (e.g., Humez et al., 2016) and by industry consortia such as Canadian Oil Sands Innovation Alliance (COSIA) (e.g., Birks et al., 2019) may be particularly important resources for such an analysis. Given the isotopic differences in ^{18}O and ^{2}H values between modern precipitation, glaciogenic brines and deep-basin brines, it would be prudent to test the sensitivity of the isotope balance results to variations in relative contributions from these sources.

4.3.3. *Water quality-water quantity relationships*

ABMI wetland monitoring also included sampling of physico-chemical properties such as water depth, temperature, pH, dissolved oxygen, conductivity, total nitrogen, total phosphorous, dissolved organic carbon, land use (%) according to agriculture, urban-industrial, soft linear, hard linear, human water use, and non-agricultural uses (Roy et al., 2018). A preliminary province-wide correlation analysis was carried out to illustrate similar inter-relationships between hydrology of the wetlands and their physico-chemical properties, which may be useful for scoping future studies. Province-wide, we found positive correlations between evaporation/inflow and the following variables: temperature ($r^2 = 0.167$), electrical conductivity ($r^2 = 0.178$), total nitrogen ($r^2 = 0.229$) and total phosphorous ($r^2 = 0.130$). Such correlations are broadly suggestive of evaporation and flushing rates being influential in controlling thermal conditions and nutrient budgets in open-water wetlands. A more detailed assessment, including regional stratification may be useful for investigating systematic influence of agriculture, urban impacts, and industrial development on the wetland water cycle.

4.3.4. *Wetland plant communities and biodiversity*

A recent ABMI-sponsored study spanning the Grassland/Parkland regions used functional trait-habitat relationships at 322 sites to measure influence of environmental factors on ecological communities. (Roy et al., 2018). They showed that annual plants are often associated with high disturbance habitats (e.g., at the edge of wetlands), whereas perennial plants tend to dominate in low disturbance habitats (e.g., at the core of wetlands). Groundwater-fed sites were found to be associated with plant functional groups that prefer hydrologic stability, including perennial and upland species. This contrasted with evaporative wetlands which tended to be shallower, had higher nutrient levels, and were positively associated with species tolerating higher levels of disturbances, such as annuals. A similar analysis incorporating sites across the province or for other regions would potentially be useful for identifying similar patterns in a wider range of ecosystems.

5. Summary and conclusions

A province-wide IMB assessment based on ^{18}O and ^{2}H was presented for the Province of Alberta, Canada (662,583 km^2), based on water sampling of 1022 ABMI wetland sites evenly distributed across Alberta on a 20-km grid, and visited during 2009–2019. The sites were representative of most ecoregions in the province, including Grassland, Parkland, Rocky Mountains, Foothills, and Boreal Forest. An IMB model was developed incorporating regional reanalysis climate data, areal watershed delineation information, and isotopic data for wetlands and precipitation, and was used to quantify and map water balance indicators and to classify sites by inflow and outflow partitioning characteristics. The approach utilized a steady state model, but incorporated a simple algorithm based on mean water depth and evaporation loss at each site to account for seasonal volumetric drawdown.

The assessment has revealed systematic variations in evaporation losses, watershed runoff to wetlands, wetland discharge, and net groundwater exchanges across the major subregions of Alberta including the AOSR. IMB calculations indicated that ~90% of the wetlands received runoff (water yield) from their watersheds, ~47% of sites including apparent groundwater inflow. Outflow was found to be most commonly by a combination of evaporation and liquid discharge (~87% of sites), however, 13% appeared to be evaporation only. A small number of mainly foothills and mountain sites (2%) showed evidence of being fed by allochthonous water sources (either snow or glacial melt). An additional 3% of sites appeared to have unreasonable throughflows, suggestive of glacial meltwater channel or stream channel connections. Combined with geospatial analysis, the isotope method is capable of identifying open water wetlands that may be reliant on, or under the direct influence of, groundwater, although these findings remain to be ground-truthed, and require further map and satellite analysis to confirm explanatory geomorphic or geological controls. While some refinements may be required for operational use, the IMB is potentially a practical approach for wetland water balance assessment that is complementary to ongoing monitoring strategies, especially in rapid development areas such as the Alberta Oil Sands region.

CRediT authorship contribution statement

John Gibson: Conceptualization, Methodology, Funding acquisition, Project management, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Paul Eby:** Formal analysis, Data curation. **Jean Birks**: Formal analysis, Resources, Writing – review & editing. **Colin Twitchell:** Conceptualization, Resources, Funding acquisition. **Christine Gray:** Formal analysis, Data curation, Writing – review & editing. **Jahan Kariyeva:** Writing – review & editing.

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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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101036.

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