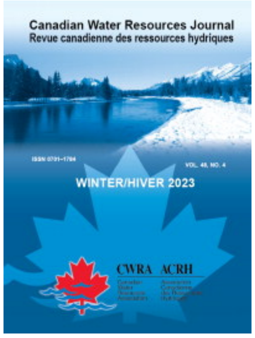

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COMMENT

The state of isotope hydrology research in Canada (2007–2022)

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ABSTRACT

In the past twenty years, there has been an exponential increase in isotope hydrology, specifically stable isotopes in water, applications in research internationally, with Canadian researchers among the top five contributors globally. The Canadian isotope hydrology community continues to actively participate in international collaborative research projects through direct partnerships and in association with the International Atomic Energy Agency (IAEA) Isotope Hydrology Section, supporting water resources research in developing nations. Among Canada's most significant contributions to the isotope hydrology community in the past two decades has been advances in analytical tools and tracer-aided modelling, and the development of new national isotopes in water monitoring networks. The objective of this paper is to highlight recent progress in Canadian isotope hydrology research based on topical prominence in the peer-reviewed literature, and to outline future strategic directions. Future endeavours in this field must continue to push open source, accessible and interoperable codes and models for isotope aided modelling along with repositories of isotope in precipitation and streamflow observations from Canada-wide networks. A coordinated effort to fund isotope data networks for early climate change detection is needed, involving academic, industry and government partnerships.

RÉSUMÉ

Au cours des vingt dernières années, il y a eu une augmentation exponentielle des travaux traitant des analyses d'isotopes en hydrologie, en particulier les isotopes stables dans l'eau. Plusieurs recherche ont été complétées au niveau international, avec des chercheurs canadiens parmi les cinq principaux contributeurs dans le monde. La communauté canadienne de l'hydrologie isotopique continue de participer activement à des projets de recherche collaboratifs internationaux par partenariats et en association avec l'Agence Internationale de l'Energie Atomique (AIEA), Section de l'hydrologie Isotopique, soutenant la recherche dans les pays en développement. Parmi les contributions les plus importantes du Canada à la communauté hydrologique isotopique au cours des deux dernières décennies, on compte la mise en œuvre d'outils d'analyse et de modélisation assistée par traceur, et le développement de nouveaux isotopes dans les réseaux de surveillance de l'eau. L'objectif de cet article est de mettre en évidence les récents progrès de la recherche canadienne en hydrologie isotopique basés sur la littérature évaluée par des pairs, et de décrire les futures stratégies et orientations. Les efforts futurs dans ce domaine doivent continuer à pousser les logiciels libres, les codes et modèles accessibles et interopérables pour la modélisation assistée par isotopes avec des référentiels d'isotopes dans les observations de précipitations et de débits pour les réseaux pancanadiens. Un effort coordonné pour financer des réseaux de données isotopiques pour une détection précoce du changement climatique est nécessaire, impliquant les universités, l'industrie et les partenaires gouvernementaux.

HIGHLIGHTS

1. Development of a new Canadian operational isotope in streamflow monitoring network
2. Open source analytical and scripting tools available to facilitate non-expert isotope informed regional water balance
3. Advances in tracer-aided modelling tools that have improved process-based model calibration
4. Isotopes in water have contributed to enhanced understanding of groundwater systems and wetland dominated regimes
5. Canada has contributed to numerous IAEA collaborative research programmes, significantly influencing best practices in the field of isotope hydrology over the past decade.

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Introduction

Recently the Chair of the Intergovernmental Panel on Climate Change, Hoesung Lee, stated '*This report is a dire warning about the consequences of inaction*' in response to the release of the IPCC sixth assessment report (AR6), further stating that urgent action is required to deal with increasing risks imposed by a rapidly warming planet and notes the interdependency of all living systems and socioeconomic strength and security (IPCC 2022). The present-day reality is that climate change is a complex and 'wicked problem' (Kosow et al. 2022), one that requires multifaceted and transdisciplinary solutions, as well as enhanced data networks to detect and respond to both process and system level change.

The International Atomic Energy Agency (IAEA) has stated that '*environmental isotopes are one of the most powerful tools to investigate climatic changes and the environmental response to those changes*' (IAEA 2001). Stable isotopes in water (^{18}O, ^{2}H) are preserved in natural archives in the environment within anything that contains or contained water, such as sediments, ice and permafrost, plants and bones, and other sources of organic matter. We can extract present day information from current water sources, or reconstruct paleohydroclimate information from natural archives, that help us to understand the past, present – and now through modelling – potentially the future water cycle under changing climates. This information is critical for water management decisions, energy production, and agriculture, underpinning socioeconomic stability and viability globally.

Isotope hydrology, specifically the study of stable isotopes in water (^{18}O, ^{2}H) involves the measurement and detection of small variations in the mass of a volume of water that result from systematic fractionation in the natural environment. Fractionation is the process of mass discrimination that results from temperature and phase changes, or molecular diffusivity. The mass differences between isotopes in water molecules alters water's boiling and freezing points, ability to evaporate or diffuse in natural systems, and use by and within ecological systems. Consequently, the distribution and fate of water in the hydrologic cycle is impacted in known, specific ways and measured against a global standard regulated by the IAEA. When combined with hydrologic knowledge such as streamflow or precipitation data, the volume of water from a given source can be ascertained. These effective tracers of the water cycle were generally recognized in hydrology in the 1970s, with some of the earliest studies being isotope hydrograph separation (IHS) studies seeking to uncover subsurface contributions to surface water, or runoff by tracing 'old' (subsurface or groundwater) and 'new' (rain, snow, runoff) water contributions to the hydrograph (Dinçer et al. 1970; Sklash and Farvolden 1979), with earlier studies underpinning the theoretical advances needed to apply tracers at watershed scales (Craig and Gordon 1965; Craig 1961). In Canada, some of the earliest studies in the 1980s similarly focused on HIS, but with the added complexity of integrating cold regions science and snowmelt contributions for isotope tracers (Klaus and McDonnell 2013).

The use of isotopes as tracers in hydrology has increased exponentially since these first published hydrologic studies, as documented in a recent review of isotope tracers and large scale modelling (T.A. Stadnyk and Holmes 2022). Canada is among the top five nations for scholarly output within the field of isotope hydrology, and Canadian researchers are well known for advancing cold region science relating to isotopes in water retrieved from Scopus$^{(R)}$. The last major review of advances in Canadian isotope hydrology was provided by Birks and Gibson (2009), which followed an earlier review by Gibson et al. (2005). The prominence of isotope tracers, or stable isotopes composition in the academic literature has increased significantly over the past decade (2012–2022) according to Scopus$^{(R)}$.

The most frequently occurring themes in the hydrology literature are stable isotopes, oxygen isotope, isotopes, soil water, groundwater, precipitation, evapotranspiration and catchment hydrology-related (Figure 1(b)). By year, these themes have continually gained traction since 2012, with Precipitation and Evaporation being the most popular studies, followed by groundwater, soil water and then rivers, as defined by topical area T.2762 (i.e. Meteoric water; Water; Isotope Composition). Based on the prominence of topical themes identified by the international literature and community, this review is organized to first present recent progress in Canadian isotope hydrology research in the following key areas: (1) precipitation monitoring and tracing, (2) streamflow monitoring and tracing, (3) hydrologic modelling, (4) lakes and wetland surveys, and (5) groundwater surveys. We then summarize additional contributions to paleohydrologic studies and urban hydrology, and further outline contributions to the Canadian industrial and practitioner community, education and outreach initiatives and international cooperation, before summarizing future trends and directions of this highly dynamic field of research. Supporting this review is an extensive literature review (2007–2022), focusing primarily on the Canadian context and

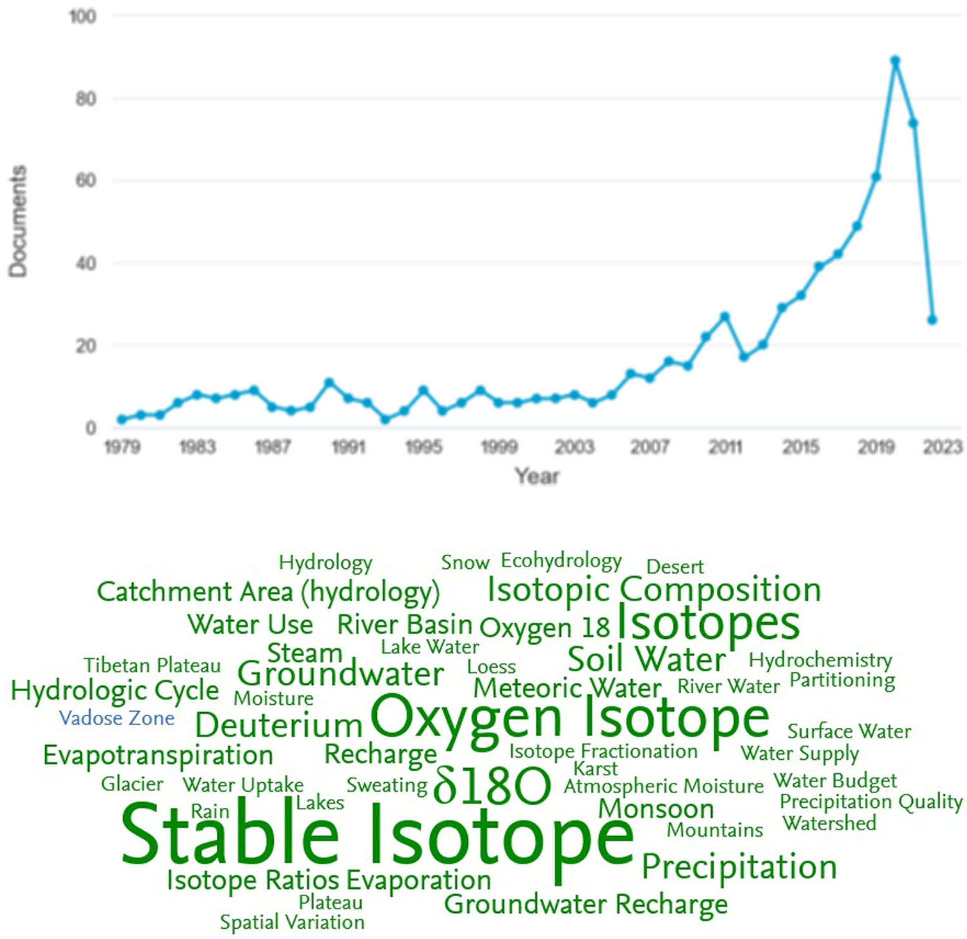

Figure 1. Isotope hydrology per-reviewed literature summarized (a) by year since the onset of tracer-aided hydrological investigations based on Scopus® data for isotope hydrology literature, 2022-07-03, and (b) significant topical themes emerging from the 2012–2022 publication period.

community of research, that has been cited throughout and summarized in Supplemental Material Table S1.

Precipitation monitoring and modelling

Canadian meteoric water sampling

Canada has been a long-standing contributor to the IAEA's Global Network for Isotopes in Precipitation (GNIP), and data from Ottawa, Ontario, Canada is one of the longest running isotope time-series available for North America. The Canadian Network for Isotopes in Precipitation (CNIP) operated between 1997 and 2008 as a joint venture between university and government researchers and supervised by a scientific sub-committee of the Canadian Geophysical Union with the objectives of providing the spatial and temporal data necessary to examine the sensitivity of isotope fields to changes in hydroclimate, particularly in northern areas where the signal to noise ratio is much lower. The network consists of 19 stations (black circles on Figure 2) distributed across Canada (spanning almost 40° of latitude and 70° of longitude) collecting weighted monthly precipitation samples for ^{18}O and ^{2}H from Canadian Air and Precipitation Monitoring Network (CAPMoN) stations.

Isotopes have been monitored in Canadian precipitation through a variety of local studies with the goal of developing Local Meteoric Water Lines (LMWL) for hydrological investigations (Baer, Barbour, and Gibson 2016; Fritz et al. 2022; Peng et al. 2004), and national (Jean Birks and Edwards 2009) and international data compilations and interpretations (Mellat et al. 2021). Regional collection of isotopes in precipitation has been undertaken typically to determine LMWL and input functions for surface water and groundwater studies. Within the framework of PACES (*Programme d'Acquisition de Connaissances sur les Eaux Souterraines*), and supported by Quebec Ministry of the Environment, nearly all regional groundwater studies in Quebec now collect isotope data to support development of LMWL and isotope

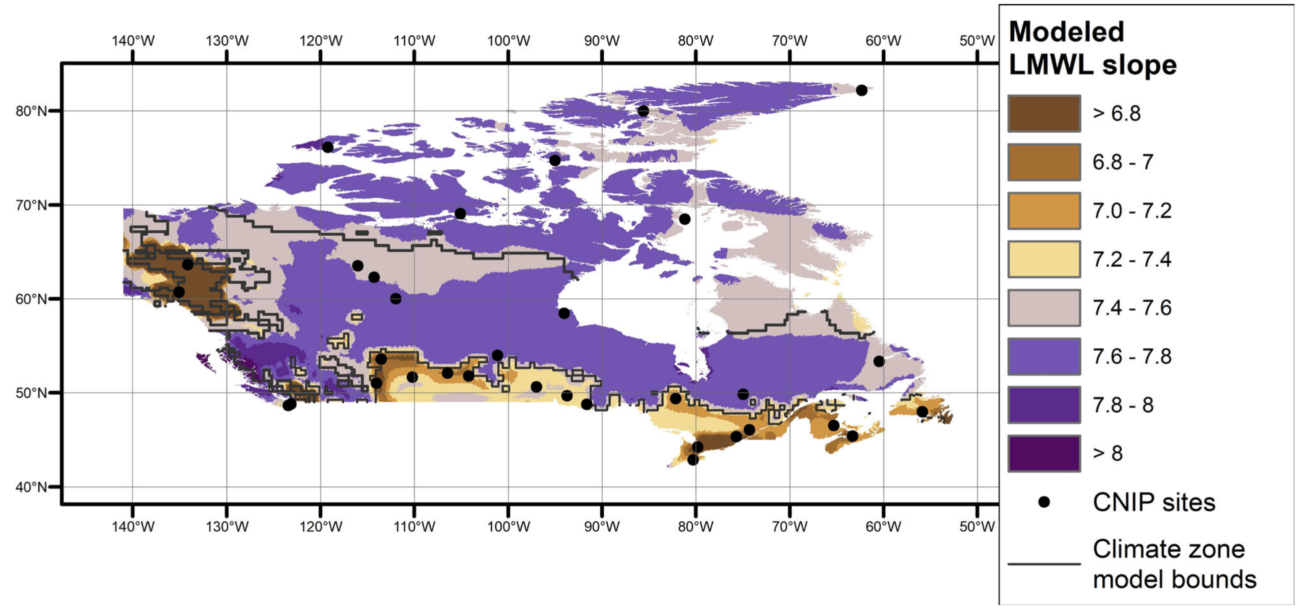

Figure 2. Modelled isoscape for Canada based on simulated d18O and d2H from the Delavau et al. (2015) model, represented as slope of the local meteoroic water line (LMWL) across Canada. Black circles represent CNIP stations.

frameworks (Rey et al. 2018). For a similar purpose, monthly composite precipitation sampling has been integrated into Oil Sands Monitoring in northern Alberta (Government of Alberta 2022), where sampling was initiated in 2019 at three locations spanning the latitudinal gradient across the major oil sands regions, and in selected watersheds. These type of data support interpretation of river, lake and groundwater datasets, as well as surface water-groundwater interactions and are all publicly available through the Quebec Ministère de l'Environnement and/or the GNIP database. Similar initiatives supported by industry (e.g., Manitoba Hydro) have contributed to the isotopes in precipitation database in northern Manitoba (Aaron Smith, Delavau, and Stadnyk 2015).

Characterizing the isotopic composition of winter precipitation and snowmelt is also a significant challenge globally (e.g. Koehler 2019). From 2010–2014, Canadian researchers participated in a coordinated effort to examine best practices for snow and snowmelt sample collection in cold regions (Penna et al. 2014). A high latitude Canadian study site was implemented at the University of Manitoba to test various sampling strategies and provide recommendations for effective sample collection techniques across the Prairies. Unlike the European sites where the passive capillary samplers were highly effective (in part due to aging of the snowpack), the flat Prairie sites have a tendency to flood during the spring freshet due to frozen soils and a lack of drainage, contaminating the capillary samplers with soil water and highly enriched melt water. Similarly, the Canadian site snow cores are found to be reasonably representative of snow pack isotopic composition due to less again and better preservation of isotopes in precipitation signals.

Atmospheric moisture

Atmospheric moisture or δ_A is important to measure or estimate accurately for isotope water balance studies as it is required for successful application of the Craig and Gordon model (Craig and Gordon 1965), the commonly used method for quantifying isotopic enrichment processes during evaporation. A recent collaborative study with Australian scientists (Crawford et al. 2019) allowed for multi-year testing of various direct and indirect methods for characterizing δ_A including use of a Fourier Transform Infrared Spectrometer (FTIR), a liquid-vapour equilibrium model utilizing isotopes in precipitation data, as well as a class-A evaporation pan method. Importantly, the study confirmed reasonable agreement between direct FTIR and class-A pan estimates on weekly time-steps and was found to be superior to the assumption of equilibrium between precipitation and atmospheric moisture. Expanded experimental work on direct measurement of isotopes in the atmospheric boundary layer is expected in the near future in Canada due to recent availability of more practical, cost-effective laser instruments fitted for field-based operation (Stadnyk 2019).

Canadian isoscapes

Due to the temporal and spatial limitations of isotope precipitation monitoring, a geostatistical model of the isotopic composition of Canadian precipitation was developed by Delavau et al. (2015). This precipitation model was developed based on the results from Delavau, Stadnyk, and Birks (2011) which recommended a statistical model using meteorological data and geographic information, including climate zones, as input data. Observation data from 36 CNIP/GNIP stations and 27 northern USNIP sites were used in model development, including data from 1979 to 2010 (Delavau et al. 2015). Input data required to run the model for a location includes latitude, longitude, elevation, Köppen-Geiger climate class, teleconnection index values (such as the North Atlantic and Artic oscillations) and climate data (such as air temperature and atmospheric precipitable water content).

Precipitation models across Canada were created using multiple stepwise regressions, with independent model equations for each season and climate region class, each retaining a sub-set of relevant predictor variables. The methodology described in Delavau et al. (2015) for modelling ^{18}O was later applied to ^{2}H as well. The end result of these modelling efforts is monthly estimates of isotopes in precipitation, expanding the observational record using widely available data (Figure 2). This Canadian model is restricted to North American land north of 41° latitude, and the sparse observational data used to create the regression equations limit confidence in the model performance in remote areas, but it has successfully filled in precipitation isotope records in many locations (Gibson, Eby, et al. 2022; Gibson, Holmes, et al. 2021; Holmes et al. 2020; Holmes et al. 2022b).

Tap water tracing

A Canada-wide survey of ^{18}O and ^{2}H in tap water was conducted between 2008 and 2011, including representative summer season water samples from 425 cities and towns (Bhuiyan 2022). Samples were classified according to independent information and differentiated as groundwater, river water or lake water sourced. The investigation resembled previous surveys carried out across the contiguous United States of America (Bowen et al. 2007) revealing spatial isotopic distributions that superficially resemble isotopic distributions in precipitation. However, as in the USA study, post-precipitation processes were also found to leave an imprint on river- and lake-fed supplies that were apparently influenced by water balance factors including high rates of evaporation in continental areas. Groundwater-fed sources were found in most cases to closely resemble the isotopic signatures of annual average precipitation. The study establishes a baseline for monitoring tap water resources across Canada and is expected to be of particular use for forensic studies across Canada.

Isotopes in rivers & hydrograph separation

Development of a Canadian isotope river monitoring network

In cooperation with InnoTech Alberta, a formal isotope national sampling program for streamflow was operated by the Water Survey of Canada between 2013 and 2019 and continues informally today. Stable isotopes, ^{18}O and ^{2}H, were measured in streamflow samples collected from 331 gauging stations across Canada, amassing a dataset of 9206 isotopic analyses made on 4603 individual water samples, and an additional 1259 analysis repeats for quality assurance/-quality control. The dataset includes flow-weighted averages and other basic statistics (Gibson, Eby, et al. 2021). Concurrent flow data used to estimate flow-weighted averages were extracted from the historical database of the Water Survey of Canada.

These data were applied in two subsequent papers including a description and systematic analysis of the spatial and temporal isotopic distributions across Canada (Gibson, Holmes, et al. 2020) and application of isotopic data to obtain a first-approximation estimate of the partitioning of evaporation losses and evapotranspiration from watersheds across the network (Gibson, Holmes, et al. 2021). The latter assessment was compared with results reported in previous studies for river and lake basins across North America and globally, including those of Jasechko et al. (2013), Schlesinger and Jasechko (2014) and Ferguson and Veizer (2007). Overall, analyses revealed examples of high latitude Canadian watersheds with both high transpiration relative to evapotranspiration ratio (T/ET; mostly western and northern Canada) and low T/ET (from the lake and wetland-rich Nelson River basin), with average values of 80.3 ± 20.7% (±std) for the Canadian network. As noted by previous investigators (e.g. Schlaepfer et al. 2014), overestimation of T/ET may be attributable to 'hydrologic decoupling' which can also correspond to a partial watershed contribution in arid regions, as might be occurring periodically in numerous lake basins that were considered (Jasechko et al. 2013). Gibson, Eby, et al. (2021) also provide a new approach for classification of watersheds by dominant water loss mechanism, which is effectively a national partitioning of runoff, evaporation and transpiration.

Overall, the national isotope survey data are expected to be a useful resource for the Canadian hydrologic community when combined with precipitation isotope datasets and analytical or numerical models. Benefits include insights for water resource management and planning, tracing streamflow sources, water balance estimation, evapotranspiration partitioning, residence time analyses, and early detection of climate and land use changes in Canada (Gibson, Eby, et al. 2021). With regards to sampling and sample collection, two contributions are noted that provide guidance. The first is an analysis of the reliability of various containers for free and dissolved natural gas sampling (Eby, Gibson, and Yi 2015) and the second is a review of appropriate times for sampling lakes in seasonal climate zones (Cui, Tian, and Gibson 2018). Though high frequency sampling is always preferred, the extrapolation to large scale studies means this is often prohibitive both in terms of cost and spatial terrain coverage. The suggested optimal sampling window for lakes in seasonal climates, such as Canada's, was October due to the likelihood of well-mixed conditions, but this may need to be adjusted to account for study-specific objectives and regional seasonality.

Hydrograph separation

Synoptic and time-series isotopic sampling of large northern rivers has been motivated by the need to label freshwater sources to the Arctic Ocean and for characterization of sub-basin hydrology and water source dynamics in the Mackenzie River (Yi et al. 2012; Yi et al. 2010). These studies also supported a concurrent study of geochemistry and ecology of tributaries, which as described in two previous reviews of isotope hydrology in Canada (Birks and Gibson 2009; Gibson et al. 2005), demonstrate the value of isotopes in the river surveys and gathered support within the scientific and technical community for the initiation of a National Isotope Monitoring Program supported by the Water Survey of Canada and the National Hydrometric Service.

Regional hydrograph separation based on increasing observations of ^{18}O and ^{2}H in rivers has also been more ubiquitously applied throughout Canada. In a first of its kind isotope hydrograph separation (IHS) study, isotopes were applied to partition streamflow sources in the Athabasca River and its tributaries to characterize systematic shifts in the surface groundwater ratios along the main stem of the Athabasca River and for several major tributaries. This has proven to be useful for management of groundwater resources in the oil sands region (Gibson, Yi, et al. 2016), providing considerable insight into runoff generation mechanisms operating in six tributaries and at four stations along the Athabasca River. Bansah and Ali (2017) contributed to a better understanding of the effects of tracer choice (^{18}O or ^{2}H) on defining end member contributions when using IHS, and highlighted the complexities of using mean transit time (MTT) convolution techniques to determine stream water age in intermittent, prairie streams (Bansah and Ali 2019).

At the same time, evidence of some limitations for traditional streamflow-based hydrograph separation using recursive digital filtering (RDF) techniques emerged. An interesting case study of basin-scale hydrograph separation was presented by Stadnyk, Gibson, and Longstaffe (2015), which directly compared IHS techniques using the Grand River isotopic monitoring network in southern Ontario and RDF techniques (i.e. BFLOW and HYSEP) for baseflow separation. The study highlighted that while RDF are commonly applied, they are designed only to detect and filter low frequency hydrograph variation – regardless of process causation – which can result in low frequency (low noise) components attributed to glacier, lake and wetland sources (i.e. surface derived sources) being attributed to groundwater. IHS, on the other hand, can detect subsurface components separately from surface components providing there is sufficient fractionation to distinguish sources from one another.

Several reviews of IHS literature, both in Canada and abroad, have demonstrated the recent application of IHS for source separation and transit time studies (Tetzlaff, Buttle, Carey et al. 2015; Klaus and McDonnell 2013). In Canada, many studies have focused on high-latitude, cold regions basins where IHS has proven useful for defining snowmelt, wetland and groundwater contributions to the hydrograph (Tetzlaff et al. 2018.

Data visualization & dissemination tools

Computational resources have become more ubiquitous and led to considerable advances ine fields of data generation and visualization in the past two decades. Supporting the field of hydrology, the move towards open-source scripts, codes, coding tools, and models (Knoben et al. 2022; Anderson et al. 2019), as well as partnerships with computer science to advance data visualization and GIS-based analyses have emerged (Xu et al. 2022). Under the guiding FAIR (i.e. findable, accessible, interoperable, reproducible) principles of scientific data management (Wilkinson et al. 2016), the goal is to increase transparency and reproducibility in the management and analyses of scientific data. The next generation of scripts, models and codes should be easily findable, freely available and accessible to the entire community, be interoperable among different studies and models, and reproducible such that proper workflows and documentation are provided to support analyses. It is also important that under these guiding principles benchmarking standards are made available, which for Canadian isotope hydrology, are analogous to the basin-scale assessments performed by Gibson, Holmes, et al. (2020) and Gibson, Eby, et al. (2021). A good example of this is the recent study by Ahmed et al. (2023) which provided a benchmarking standard for models run in the Canadian Prairie basins from a multimo intercomparison study.

In the spirit of these principles, a recent trend has been to publish the underlying isotope analytical outputs and model data as separate publications (e.g. Gibson, Birks, and Moncur 2019b; Gibson, Yi, et al. 2020), or to contribute historical datasets (e.g. Gibson and Edwards 2002) to established repositories such as WaterIsotopes.org for wider use by the scientific community. This is the intent of the simple analytical tool called 'Hydrocalculator', which was created through a collaboration of Canadian and Australian scientists (Skrzypek et al. 2015) and allows users to implement complex isotope mass balance equations describing evaporative enrichment in a simple to use interface that access a 'behind-the-scenes' data repository. The tool has been widely adopted worldwide and has been cited 160 times in the peer-reviewed literature as of the date this article was published.

The Canadian Society for Hydrological Sciences (CSHS) hydRology R package is another example of an open-source community development project that has advanced both research and operational hydrology analytics through a variety of R functions and data embedded within the Comprehensive R Archiving Network (CRAN) (Anderson et al. 2019). A future operational release of the hydRology package is planned to include an isotope hydrology analytics tool (isohydRology).to facilitate access to data from the operational Canadian isotope monitoring network to the broader hydrologic community. Embedded in the tool will be a series of functions that perform basin-scale ($>500\,km^2$) water balance assessment for water yield (runoff), hydrologic partitioning (evaporation relative to inflow: E/I and T/ET) and residence time for 323 watersheds in the National Hydrometric Network (NHN). This will expand the accessibility of global open-source data for isotopic ratios recently introduced by American researchers into the Canadian domain (Putman and Bowen 2019). The goal is to facilitate isotope-based water balance assessment without *a priori* isotope hydrology expertise, increasing the accessibility of isotope hydrology to the community-at-large, and uptake and demand for isotope data from Canada's monitoring network.

Advances in hydrological modelling

Advances in coupled modelling

Significant advances in the field of isotope-enabled hydrological modelling have been realized in recent decades owing in large part to increased accessibility and efficiency of high-performance computing platforms, particularly within the Canadian community. Modelling studies range from analytical methods to perform continuous IHS and water balance computations, to fully coupled isotope-hydrologic models. With the emergence and accessibility of high-performance computing (HPC), large domain, high resolution modelling has become more computationally affordable and facilitates integrated environmental prediction models that include coupled simulation of streamflow, runoff processes, and (for example) isotope tracers at finer scales both geographically and temporally (sub-hourly) across continental and global domains.

Some Canada-wide and continental modelling studies exist, with contributions to water balance and evapotranspiration partitioning (Gibson, Holmes, et al. 2021; Jasechko et al. 2013), groundwater (Jasechko, Wassenaar, and Mayer 2017) and streamflow age (Jasechko et al. 2016). The only Canada-wide modelling studies that currently exist are from isotopically enabled regional climate model land surface schemes, which are equivalent to buckets of runoff on a coarse resolution land surface and are not directly comparable to isotopes in streamflow (Stadnyk and Holmes 2022).

Isotopes have also been deployed to aid hydrological model calibration and validation, demonstrating advantages for long-term simulation when the calibration is 'tuned to' (using isotope information) process flux and storage (Holmes et al. 2022a; Stadnyk and Holmes 2020). A recent review by Stadnyk and Holmes (2022) examines contributions to tracer-aided model calibration, including advances made by the Canadian community to advance the utility of isotope tracers as secondary sources of information for hydrologic model calibration (T.A. Stadnyk and Holmes 2022). As this review demonstrates, however, the majority of coupled modelling studies exist on regional scales owing to the increased computational complexity of both model calibration and application. Regional studies integrate isotope tracers to elucidate process-based understanding of storages, flow paths and hydrologic fluxes, with the primary focus within Canada on understanding wetland storages and flow paths for runoff generation (Table S1). Below is a regional summary of the major studies published from 2007–2022.

Arctic and Northern systems

Isotope tracers in streamflow have been utilized to trace freshwater contributions to the Arctic marine system along the Canadian continental shelf (Newton et al. 2013), and within the PARTNERS programme for the six major Arctic draining rivers (Yi et al. 2012). Globally, isotope mass balance modelling is gaining popularity in Arctic draining watersheds to identify runoff sources and to examine subsurface contributions and changing permafrost dynamics. Water-mass balance models utilizing isotope tracer data are also being applied across several regional, inland study sites in the Northwest Territories (Connon et al. 2014; Quinton et al. 2019), Yukon (Tetzlaff et al. 2018; Tetzlaff, Buttle, Carey, et al. 2015), and Hudson Bay lowlands (Orlova and Branfireun 2014). Though isotope tracer and hydrological studies in the Arctic and high-latitude regions of Canada remain of utmost importance, there remains a lack of published, peer-reviewed literature due to the under-studied, under-gauged nature of this region. The recent sixth assessment report of the Intergovernmental Panel for Climate Change has highlighted the importance of understanding hydrology in polar regions, along with Canada's Changing Climate Report (IPCC 2022; Intergovernmental Panel on Climate Change 2021)

Boreal regions

Gibson and Edwards (2002) established a simplified water-isotope mass balance mixing model for Boreal lakes that has formed the basis for much of the research and applications to lakes and wetlands across Canada and globally, and the majority of isotope hydrologic modelling in the Boreal regions of Canada (J.J. Gibson, Birks, and Yi 2016). Complex and highly seasonal hydrology in the Boreal wetland dominated regimes has necessitated alternative techniques for water balance studies, and isotopes in water have proven particularly advantageous. In the past decade, modelling has shifted from IHS techniques to lumped and process-based continuous (in time and space) coupled models.

Smith, Welch, and Stadnyk (2016) applied a lumped, conceptual model to better understand hydrologic controls in the Boreal dominated Odei River basin (6,300 km^2), a tributary of the lower Nelson River, and to simulate evapotranspiration partitioning based on changing seasonality of lower Nelson high-latitude region (Smith, Welch, and Stadnyk 2018). A study examining wetland controls in the lower Nelson River was conducted to improve modelling of streamflow volume and timing (Welch, Smith, and Stadnyk 2018). To better characterize timeseries partitioning, a fully distributed and more physically based coupled isotope-tracer model was established for the Odei River basin (Holmes et al. 2020), and the Fort Simpson, Northwest Territories region, that facilitated IHS and snowmelt contributions to streamflow (C. J. Delavau, Stadnyk, and Holmes 2017).

Coupled isotope-hydrologic modelling methods have also been applied in the Muskoka River in north-central Ontario to identify principle hydrologic components and their time variant nature (Tafvizi et al. 2022) following from extensive regional isotope surveys (James et al. 2020). In the Ontario Precambrian shield region, modelling of regional trends in evaporation has been conducted (Gibson et al. 2017). Gibson, Birks, and Yi (2016) performed extensive surveys and analytical modelling of boreal shield lakes, and partitioning of streamflow in the Alberta oil sands region of Canada. Extensive isotope mass balance modelling studies have also been performed in the Peace-Athabasca River delta region (e.g. Wolfe, Falcone, et al. 2007)

Mountain basins

Relatively fewer isotope hydrology modelling studies (than other regions of Canada) have been conducted in the mountainous regions. In part, this is due to flow being kinetically (gravity) driven in the mountain, where process contributions and source water mixing pathways are less variable due to the well-mixed nature of turbulent streams. The input of rainfall or snowmelt into mountainous systems tends, instead, to dominate the regional runoff response. Snowmelt and glacial isotopes in water signatures can also be difficult to distinguish in some cases (due to similar isotopic compositions), adding further uncertainty for water isotope tracer applications in regions with both contributing components. IHS modelling has been used to look at wetland contributions in the Canadian Rockies (Hathaway et al. 2022) and for groundwater contributions in high elevation terrain (Carey, Boucher, and Duarte 2013; Somers and McKenzie 2020). Isotope modelling has also been used to examine surficial recharge of groundwater (Hayashi and Farrow 2014) in the Rocky Mountain ranges, and for groundwater contribution in the Okanagan basin of the British Columbian Interior (Wassenaar, Athanasopoulos, and Hendry 2011).

Prairie basins

Isotope hydrologic modelling studies are more common across the low-lying, wetland and agriculture dominated Canadian Prairies. Isotopes have proven particularly useful in these basins to elucidate process-based partitioning, time evolving runoff contributions, evaporation and water loss, and complex runoff generation processes. Isotope hydrologic modelling has been applied from individual runoff generation processes, such as contributions from snowmelt (e.g. Pavlovskii, Hayashi, and Lennon 2018), to prairie-wide water balance partitioning (Haig et al. 2021; Pham et al. 2009). Following from the earlier work by Gibson and Edwards (2002), lake isotope water balance mixing models have been adapted to specifically model time variant isotopic signatures and water balance partitioning in wetland complexes in the Prairie and Boreal regions of Canada (Glavonjic 2020; Gibson et al. 2017).

Atlantic, St. Lawrence/Great Lakes

The Great Lakes water balance, particularly water loss due to evaporation has been modelled using isotope tracers, where evaporation is an important operational loss component that is difficult to quantify hydrologically (Jasechko, Gibson, and Edwards 2014). Rivers contributing to the Great Lakes have similarly been modelled using coupled-isotope-hydrologic models, such as the Grand River in southern Ontario region (Stadnyk et al. 2013; Stadnyk-Falcone 2008). Surveys and modelling of isotope composition have been integral to understanding upstream to downstream process and tributary influences on the St. Lawrence seaway (Rosa et al. 2016). Further downstream, isotope hydrology has been applied for groundwater recharge studies and surface water and runoff generation studies along the eastern seaboard (Arnoux et al. 2017; Timsic and Patterson 2014).

Applications in hydrological studies

Lake & wetland surveys

Lake and wetland hydrology, especially regional scale processes, have proven difficult to monitor hydrology conventionally due to the sheer number of lakes and wetlands and vast areas of the country that are remote and ungauged (Gibson et al. 2017; Remmer, Neary, et al. 2020). The areal extent of lakes and wetlands in Canada have been estimated at 758,000 km^2 and 1,290,000 km^2, respectively, accounting for 7.6% and 13%, respectively of the land mass of Canada (National Wetlands Working Group 1997), representing close to a quarter of the world's total inventory.

Isotopic methods, especially ^{18}O and ^{2}H, have been widely applied in hydrologic field studies and regional surveys across Canada to provide water balance and flow path information, mainly at ungauged sites. Notably, recent lake studies have included investigations of thermokarst and permafrost thaw at high latitudes (Cochand, Molson, and Lemieux 2019; Gibson, Yi, and Birks et al. 2019; Turner et al. 2014; Wan, Gibson, and Peters 2020), assessment of acid sensitivity (Gibson et al. 2017; Gibson, Birks, and Yi 2016; Scott et al. 2010), understanding the role of water balance and climate as determinants of trophic status and lake level (J.J. Gibson, Birks, and Yi 2016), identifying carbon sources (Castrillon-Munoz, Gibson, and Birks 2022), quantifying surface/subsurface interaction (Arnoux et al. 2017; Hokanson et al. 2022; Pham et al. 2009), regional water yield assessment (Gibson, Birks, and Moncur 2019a), chain-of-lakes runoff generation (Gibson and Reid 2010, 2014), and deltaic hydrology investigations (Neary et al. 2021; Remmer, Owca, et al. 2020). A review of theoretical approaches to estimating water balance and evaporation losses from lakes using ^{18}O and ^{2}H was conducted (Gibson, Birks, and Yi 2016), and in addition to stable isotopes in water, a number of studies have applied tritium and radon-222 for tracing groundwater inputs to lakes (Arnoux et al. 2017; Graham et al. 2016; Wan, Gibson, and Peters 2020).

Studies using ^{18}O and ^{2}H for wetland hydrology have been less numerous than for lakes (Table S1); however, isotopes continue to offer advantages in low-relief terrain over conventional hydrologic approaches. In these settings, isotopes are particularly valuable for identifying connectivity patterns, flow paths and for ecohydrological assessments. Whitfield et al. (2010) and others demonstrated use of stable water isotopes for understanding geochemical variation and vegetation patterning in response to hydrologic conditions. A study by Roy et al. (2019) used ^{18}O variations as indicators of plant traits expected in open water wetlands across Alberta's grass and parklands. Based on an isotope-balance methodology similar to that used for lakes, a site-specific water balance for open-water wetlands was applied at more than 1000 sites across the Province of Alberta and demonstrated an approach for classifying the degree of groundwater reliance, tendency for seasonal water level drawdown, and detection of sites with allochthonous water sources likely from suspended subsurface storage of glacial or snowmelt originating from higher altitudes (Gibson, Eby, et al. 2022).

Particularly in ecohydrological assessments, isotopes are increasingly combined with other analytes of interest to connect water quality and ecosystem health to hydrology. A significant inventory of isotopic data, including ^{18}O, ^{2}H, ^{13}C in Dissolved inorganic carbon (DIC), ^{15}N and ^{13}C in particulate organic matter (POM) for a range of wetland types, as well as major ion and nutrient geochemistry, was reported by Gibson, Eby, et al. (2021). This inventory includes vertical profiles of pore water collected from drive-point piezometers in addition to water table wells, as it was intended to evaluate connectivity of the various surface and subsurface compartments of typical sites as a contribution to a multidisciplinary study of nitrogen critical loads.

Groundwater surveys

Groundwater studies have generally been conducted more earnestly in regions of rapid development, where water isotope data, combined with geochemistry, solute isotopes and age dating techniques can provide valuable information about aquifer connectivity. Specifically, to constrain conceptual hydrogeological models (Birks et al. 2019; Gibson, Yi, and Birks et al. 2019; Matheson, Hamilton, and Kyser 2018), evaluate sources of recharge (Chesnaux and Stumpp 2018; Jasechko, Wassenaar, and Mayer 2017), identify groundwater flow systems and sources of contaminants (Cochand, Molson, and Lemieux 2019; Humez et al. 2016; Suchy et al. 2018), and groundwater surface water interactions (Gibson, Birks, and Moncur 2019a; Gibson, Birks, and Yi 2016; Jasechko et al. 2012).

Regional groundwater isotopic surveys have been especially useful in the Alberta oil sands region where groundwater has been found to be an important source of the Athabasca River and its tributaries (Gibson, Yi, et al. 2016). These surveys include investigation of the origin of saline seeps along the Athabasca River proximity to oil sands operations in the North Athabasca Oil Sands (NAOS) region (Birks et al. 2018; Gibson et al. 2013), which were supported by parallel assessments from the Alberta Environment and Parks (AEP) Long Term River Network (LTRN) dataset (Jasechko et al. 2012). Similarly, a comprehensive regional isotopic assessment of surface waters in the South Athabasca Oil Sands (SAOS) region included multiple tracers and allowed for evaluation of regional watershed catchment yield estimates (Gibson, Birks, and Moncur 2019a) and refinement of conceptual models of groundwater flow and aquifer connectivity (Birks et al. 2019). Through a new data sharing agreement facilitated by Canada's Oil Sands Innovation Alliance (COSIA), datasets collected by individual operators throughout the SAOS (including 293 groundwater samples) was established to publish this comprehensive geochemical and isotope groundwater dataset so that data could be interpreted in a regional context and used to evaluate conceptual models of groundwater flow (Birks et al. 2019). The results from the above studies, and several others in this region, are considered important and are contributing towards a better understanding of the susceptibility of rivers in this region to climate and development-related impacts.

Paleohydroclimatic studies

Paleohydrologic reconstructions are another application of isotope data, particularly for Canada where hydrologic records are notoriously short or absent (i.e. large ungauged regions). Studies can be broadly classified as hydrological and ecohydrological. Ecohydrological studies have primarily focused on Δ^{18}O-Temperature or carbon proxies from tree ring data that are used to reconstruct climate or examine water use conditions and forest biomass (Boucher et al. 2017; Giguère-Croteau et al. 2019; Nicault et al. 2014). A similar body of research utilizes stable isotopes in water analysed from sediment cores and aquatic cellulose to reconstruct paleohydroclimatology, with particular emphasis on high-latitude northern regions of Canada (Bouchard et al. 2017; Zabel et al. 2022). A number of paleohydrologic studies have been carried out at lake and wetland sites within the Athabasca NAOS region at the McClelland Wetland Complex, where lake sediment records permit reconstruction of hydro-ecological conditions dating back 325 years (Zabel et al. 2022). This record allowed for the evolution of conditions at the site to be examined from pre-industrial development to present day under climate warming, and offered insight into the natural range of variability in water level and ecosystem response for this site. Also within the Athabasca NAOS region, a concurrent study of peat cellulose ^{18}O examined variations in vegetation succession for an adjacent wetland draining to McClelland Lake (Gibson, Birks, et al. 2022). Despite wide swings in isotopic composition of source water reflecting variations in hydrologic conditions over the past 10,000 years, vegetation communities were found to be relatively tolerant, suggesting that features such as fen patterning at the site can be preserved.

Similar strategies to extend historical hydrological records, or to understand past variations in hydrologic conditions have been employed at other anthropogenically altered or affected sites across Canada, including the Hudson Bay lowlands (Turner, Wolfe, and Edwards 2010; Wolfe et al. 2011), the Peace Athabasca Delta (Hall et al. 2012; Savage et al. 2021; Wolfe et al. 2012) and in general, to high latitude regions (Brahney et al. 2010; MacDonald et al. 2017) to disentangle climate-driven from human impacts on the water balance and ecosystem.

Urban hydrology & wastewater effluent

Urbanization can alter hydrological processes, and urban areas can become sources of potential contamination to surface and groundwater through both point and non-point sources. Isotope tracers have proven useful in identifying natural and anthropogenic changes in hydrological processes (Wassenaar, Athanasopoulos, and Hendry 2011; Zhong et al. 2021) and for tracing sources and fate of contaminants in urban areas (Tanna et al. 2020). Mean Transit Times (MTT) determined using $\delta^{18}O$ in urban watersheds have also been compared with agricultural watersheds to evaluate the effects of urbanization on transport pathways (Meriano, Howard, and Eyles 2011; Parajulee, Wania, and Mitchell 2019). A recent study reported on the use of isotopes and other constituents for tracing of wastewater effluent along a 15-km stretch of the Bow River downstream of Calgary's Bonnybrook Wastewater Treatment Plant outfall (Tanna et al. 2020). The City of Calgary is the fifth largest city in Canada and relies on the Bow River (headwaters of the Nelson River basin) for much of its water supply. Motivating this study was the many drugs and organic compounds not metabolized by the human body nor removed from treated sewage, and as such, often persist downstream and may therefore be present in downstream community water intakes. Water samples were collected and analyzed for a multi-tracer suite including various isotopic species, major anions/cations, dissolved metals, dissolved organic carbon and nutrients, H_2S, and a suite of pharmaceuticals and artificial sweeteners during several sampling events. This was an important first attempt at evaluating the efficacy of deploying a multi-tracer suite for detecting and quantifying potential impacts of wastewater constituents in river water in Canada.

Community collaboration, cooperation and outreach

Industrial and practitioner applications

Isotopic methods have been widely used in industrial and mining applications such as tracing contaminants, natural water sources, and water cycling. A recent special issue focusing on water and environmental management in oil sands regions (Gibson and Peters 2022) includes 21 peer-reviewed contributions, six of which incorporated the use of isotopic methods. These studies described use of isotopes across a wide variety of applications including tracking water circuits within an oil sands mining operation (Chad et al. 2022), evaluating the hydrology of natural and restored wetlands (Biagi and Carey 2022; Gibson, Eby, et al. 2022), tracing carbon cycling in lakes (Castrillon-Munoz, Gibson, and Birks 2022), paleolimnological assessment (Zabel et al. 2022), improving hydrologic model calibration (Holmes et al. 2022b), and as a tool for nitrogen emissions detection (Wieder et al. 2022). Successful use of ^{18}O and ^{2}H has also been demonstrated in previous studies within the oil sands region (Baer, Barbour, and Gibson 2016). A novel study of flood water impacts on an artificial recharge system also demonstrated an important engineering design application of stable water isotopes (Masse-Dufresne et al. 2021).

Isotopes have also been deployed by the Canadian hydropower industry, with both Manitoba Hydro and Hydro-Quebec investing in isotopes in water research and development activities to better understand system water balance and process partitioning, particularly water losses. Hydro-Quebec has utilized isotope water balance to support calculations of water loss and runoff contributions for their system (Carrer et al. 2016; Stevenson et al. 2018), while Manitoba Hydro invested in an operational isotope monitoring network spanning 90,000 km^2 (2009–2019) to support water balance partitioning and hydrologic modelling (calibration) improvements (Holmes et al. 2020; Smith, Delavau, and Stadnyk 2015; Smith, Welch, and Stadnyk 2018). BC Hydro has invested in paleohydrologic research using isotope tracers across the Peace-Athabasca Delta region to investigate past flooding and water level variability (Remmer, Owca, et al. 2020).

Partnerships between academia and industry are particularly important for advancing the field of isotope hydrology. For example, InnoTech Alberta proactively supports and integrates academic-led studies into their investigations, which often involve municipal or Provincial government partnerships (Tanna et al. 2020), and companies such as BC Hydro (Wolfe, Falcone, et al. 2007), Hydro-Quebec (Hélie, Hillaire-Marcel, and Rondeau 2002; Rosa et al. 2016), and Manitoba Hydro (Smith, Delavau, and Stadnyk 2015) have similarly reached out to academic partners to lead isotope hydrology investigations. Many of these data collected from industrial-academic partnerships have contributed to the Canadian isotope monitoring network. Not only do they represent significant financial investment and funding stability, but they increase the development of new tools focused on operational outcomes and applications, which facilitates the uptake and relevance for the community-at-large.

Educational resources & outreach

Integral to the success of long-term isotope monitoring networks and research development is the support from a broader hydrologic community for isotope hydrology. For this to be successful, education and training that targets professionals and a next generation of isotope hydrology trainees are a crucial element. It is important to invest in training opportunities that invite industrial and government partners to work alongside students in the university setting to foster application-based research opportunities, career development and networking, and professional certification opportunities. Internationally, there exist training and development courses coordinated through the IAEA (https://www.iaea.org/topics/isotope-hydrology-training-courses) that are available to the general public. These courses offer support for data networks and processing, isotope analytical interpretation, modelling, and measurement of isotopes. There are also guidance documents produced by the IAEA that provide background on isotope hydrology, and technical documents that provide standard methods for analysis, sampling and modelling (IAEA 2013).

Outreach initiatives with Canadian youth are equally as important for stimulating long-term interest in the isotope hydrologic sciences and discipline. Citizen science youth networks have the advantage of collecting large amounts of data over vast regions, while engaging youth in science, engineering, technology, and management (STEM) projects and concepts. Indirectly, such school-based initiatives also target the general public through technology transfer from children to parents. A good example of such an initiative is the isotope in rainfall monitoring project at Ecole King George in Calgary, Alberta through the University of Calgary Hydrologic Analysis Laboratory (UC-HAL). The Collect'O network in Montreal is another example of a participatory citizen science network established by Université du Québec à Montréal researchers (https://hydro-sciences.uqam.ca/en/collecto-en/the-project/) (Salomon 2022) to obtain precipitation isotope data at the appropriate temporal (intra- and inter-event) and spatial (multiple locations spanning urban/rural zones around Montreal). This network was initiated to provide a high-density monitoring network in an urban setting to fulfil a research need, but that is also contributing to educating the public on isotope hydrology. Isotope tracers are also increasingly being incorporated into Community Based Monitoring Programs in the North, such as in OSM (e.g. Fort McKay Métis Nation), and will help introduce isotope hydrology techniques to First Nations communities (Wilson et al. 2019). Opportunities like these are important for the education and empowerment of youth, and the self-determination of communities in the North as isotopes act as early indicators of climate change by establishing a link between changing local weather and the global climate, and then the hydrologic impact.

International cooperation & transboundary waters

Canadian researchers have continued to have significant impact within the international communities Coordinated Research Project (CRP) programme run by the International Atomic Energy Agency (IAEA). Participation in CRPs relating to precipitation, water quality, snowmelt monitoring (Penna et al. 2014), global water balance, and global river monitoring networks (Halder et al. 2015) have helped to establish international guidance and standards for the isotope hydrology community (Table 1). Canadian researchers are supporting modelling efforts in developing countries who lack access to HPC facilitates or the modelling expertise required to conduct regional coupled isotope-hydrologic simulation for long-term water balance assessment and flood

Table 1. IAEA CRPs that Canadian Researchers have contributed to since 2007, which have helped to shape international isotope hydrology standards and guidance.

CRP ID	Title	Year From	Year To	Canadian Chief Scientific Investigator
F33016	0BGeostatistical Analysis of Spatial Isotope Variability to Map the Sources of Water for Hydrology Studies	2006	2010	Birks, J.
F32006	1BUse of Environmental Isotopes in Assessing Water Resources in Snow, Glacier, and Permafrost Dominated Areas under Changing Climatic Conditions	2010	2014	Birks, J.
F33020	2BEnvironmental Isotope and Age Dating Methods to Assess Water Quality in Rivers Affected by Shallow Groundwater Discharges	2012	2016	Gibson, J/.J.
F33021	3BApplication and Development of Isotope Techniques to Evaluate Human Impacts on Water Balance and Nutrient Dynamics of Large River Basins	2014	2018	Helie, J.-F.
4BF32007	5BIsotopes to Study Nitrogen Pollution and Eutrophication of Rivers and Lakes	2016	2020	Gibson, J.J.
6BF33023	7BUse of Long-lived Radionuclides for Dating Very Old Groundwaters	2016	2022	
8BF31005	9BIsotope-enabled Models for Improved Estimates of Water Balance in Catchments	2018	2023	Stadnyk, T.A.
10BF33024	11BUse of Isotope Techniques for the Evaluation of Water Sources for Domestic Supply in Urban Areas	2018	2022	Barbecot, F.
F31006	12BIsotope variability of rain for assessing climate change impacts	2019	2023	Birks, J.
F33027	13BIsotopic Assessment of the Impacts of Climatic and Hydrological Changes on Wetland-groundwater Ecosystem Interactions	2022	2026	
F31007	Understanding the Importance of Convective Rain Events and Tracing Their Impact on the Catchment with Isotopes	2023	2028	Barbecot, F.

prediction. In the pan-Arctic region, studies of the six largest rivers contributing to the Arctic basin involved a broad collaboration led by US researchers at Woods Hole Oceanographic Institution and the USGS, alongside Russian and Canadian collaborators (Yi et al. 2012; Yi et al. 2010). Several international contributions to global lake and wetland studies involved Canadian researchers, including lake water balance investigations led by the US EPA (Brooks et al. 2014), and studies led by the Czech Republic (Vystavna et al. 2018), Germany (Petermann et al. 2018), and China (Wan et al. 2019).

Recently, the International Joint Commission, a transboundary water agency committed to promoting the sharing and protection of water basins spanning Canada and the United States of America supported an International Watershed Initiative study to deploy water isotopes in the St. Mary's-Milk River (SSR) system. After a one-year pilot study, stable isotopes in water were shown to be distinct and useful tracers of water source (originating from different headwater basins), and preserved different evaporative enrichment signals (International Joint Commission 2021). A three-year study to employ isotope-hydrologic water balance modelling has now been commissioned as one means of supporting water diversion and evaporative loss calculations for the SSR system. This project is an excellent example of international collaboration between Canadian and USA water practitioners, and of the value of joint Canada-USA isotope monitoring networks (precipitation and streamflow data), and also of collaboration between the academic and governmental sectors in water resources management. In this capacity, isotopes are proving to be useful for supporting water governance and policy-based decision-making.

Future trends & directions

The recent uptick of stable isotopes in water in the hydrologic literature has led to several emerging trends, applications and future directions forn hydrological applications.

Precipitation monitoring

A national Canadian Network has not yet been formalized, but isotope monitoring on a national scale is occurring piecemeal, with the intent to make these data publicly available for future hydrological and hydroclimatological applications. Health Canada operates a precipitation network to monitor radiogenic isotopes in precipitation, and expansion of this network to include stable isotopes has been piloted in collaboration with the IAEA and ECCC. Isotope monitoring was recently re-established isotope monitoring at select CAPMoN stations through ECCC and the new network will use event samples collected from some of these stations to update monthly weighted isotope distributions for ecological provenance studies and these data will eventually be contributed to the GNIP database (Koehler 2019). A formal mechanism and governance, including funding, for the operation of a national isotope in precipitation monitoring network is critical for early climate and hydrologic change detection in Canada.

Streamflow monitoring

Similar to the network for isotopes in precipitation, a formal governance structure and operating funds to support a national isotope in streamflow monitoring network is critical for the early detection of shifts in hydrological regimes. A partnership with Canada's Water Survey and ECCC affords reasonable sampling frequency at a national scale for cost effective program delivery. Funding for this network has not yet been formalized, however, and therefore puts it at risk of decommissioning. Such a network could easily be supplemented by Canadian researchers and industry already investing in water sampling should the Federal government commit to a national repository for isotope data to be established and maintained relative to a set standard. Following the FAIR principles of scientific data management, these data should be findable and accessible (open source), and have supporting scripts for data manipulation and (re)formatting that are interoperable and reproducible. Coordination of such monitoring networks (for precipitation and river isotopes), and data management could potentially fall under the jurisdiction of the proposed Canada Water Agency (CWA) and Freshwater Action Plan (FAP) funding announced by the Canadian Government (ECCC 2022).

Modelling

Advances in isotope hydrologic modelling for Canada are highly dependent on the availability and accessibility of observations from monitoring networks. Leveraging existing open-source and accessible isotope hydrology data (Gibson, Eby, et al. 2021) has resulted in large scale modelling applications across Canada and North America, offering insight into regional controls and differences in water balance. Perhaps, and more importantly, this has established a baseline for hydrologic change as the global climate continues to warm at an unprecedented rate. With computational advances and accessibility to HPC platforms, more detailed process and physics-based models have been developed that afford detailed representations of process hydrology and hydrograph separations. Future simulations should push to larger continental and pan-Arctic scales, linking with ecohydrologic and thermodynamic processes to facilitate cumulative effects assessments from upstream to downstream that are relevant and important to northern and Indigenous communities. Biogeochemical modelling advances are critical to the understanding of environmental impacts under changing climates, and isotopes in water are often complimentary to other physical or geochemical analytes, helping to position transport mechanisms of various constituents. Linking such simulation capabilities to perform true cumulative effects (upstream to downstream, and across ecosystems) is a critical next step for the modelling community.

Community tools

As models and data repositories continue to develop, it is important for the community to subscribe to the FAIR scientific principles and ensure findable, open-access, interoperable and reproducible methods, including analysis scripts and modelling tools. Models should have formal benchmarking standards for new users to evaluate against for quality control and assurance. Scripts and tools developed as front-end interfaces can facilitate advances in isotope hydrology even from non-experts, making isotope data more ubiquitously accessible to the community-at-large. And communities of developers need to ensure synergist advances are being made, without the risk of 'reinventing the wheel', by investing in codes and scripts that are interoperable among different models and platforms. An isotope hydrology community portal and data repository will facilitate accessibility and interoperability of such tools, but needs oversight and quality control/assurance from a national body such as the CWA.

Citizen science

Along the lines of community development, leveraging a broader pool of scientists, researchers and public stakeholders to facilitate isotope monitoring would be beneficial to the Canadian network given the expanse of the landmass, and imbalanced population-water centres (i.e. population concentrates in the south, while the majority of Canada's water resources are in the north). Community monitoring is emerging as a useful tool, with significant interest from northern communities owing to the impacts and visibility of a changing climate in the pan-Arctic regions. If implemented coincident with tools to facilitate documenting evidence and uploading real-time data on sites and sample retrievals, the quality of such data can be preserved and highly informative. Examples of similar initiatives for tracking sea ice have already been proven highly successful in Canada's North (Krupnik, Aporta, and Laidler 2010; Ljubicic et al. 2014). It is not too farfetched to consider citizen science contributions to Canada's isotope in precipitation or streamflow monitoring networks, but proper oversight and coordination would be needed to facilitate these contributions, and the longevity of such programs, which again could potentially be partially or fully managed through the proposed CWA and FAP.

Collaboration

Stable isotopes in water data and tools present considerable opportunities for transdisciplinary research applications and advances, bridging the fields of geochemistry, biology/ecology, modelling, data analytics, computer programming, and water governance and policy. The examples of existing academic and industry partnerships presented demonstrate considerable potential for advancement of operational hydrology when isotopes in water are successfully utilized. The barrier that continues to exist is education of the broader hydrologic community on the benefits and applications of isotopes in water, and the information content they provide not found in other hydrologic data. Sustained interest from both communities will in turn aid in more solid funding supports for monitoring networks, increasing the information available for isotope informed studies. Canada lags other developed nations in funding and supporting isotope monitoring networks, however, our scientific and collaborative advances in applying isotopes continue to be relevant internationally.

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