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RESEARCH ARTICLE

Bridging Indigenous and Western sciences in freshwater research, monitoring, and management in Canada

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Abstract

1. Mutually respectful and reciprocal relationships between people and their environment is a central tenet of many Indigenous worldviews. Across the Americas, this relational connection is particularly evident when it comes to freshwater ecosystems. However, there are numerous threats to these central relationships between Indigenous peoples and their environment. Using all available ways of knowing to conserve, prioritize, and restore relationships between Indigenous peoples and the environment they live in, and are a part of, is critical. Despite legislative requirements and policy commitments, developing and implementing inclusive approaches that bridge multiple ways of knowing remains a challenge.
2. This systematic map examines the extent, range, and nature of published case studies that seek to bridge Indigenous and Western sciences in ecological research, monitoring, or natural resource management across Canada's freshwater aquatic ecosystems. A total of 74 Canadian case studies from 72 articles were included in the systematic map. There were 30 distinct species of focus across the collection of case studies.
3. This systematic map highlights the diversity of ways knowledge systems can be woven, but that the application of these approaches is limited to some key regions (the Pacific and northern regions) and species (whitefish and salmon). The extent and nature of information provided with regards to demographics (e.g., gender, age) of Indigenous knowledge holders contributing to the studies varied widely and in general was poorly reported. Across all of the case studies included in the systematic map there were 78 distinct Indigenous knowledge systems represented.
4. Fifteen different methodological approaches were identified with community-based participatory research being the most prevalent approach. The presence and diversity of Indigenous methodologies employed was also notable and was greater as compared to a previous study of Canada's coastal marine regions.

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5. Collectively, these findings point to a potential emerging transformation in research focused on freshwater ecosystems, habitats, and species to a practice that elevates the role of Indigenous communities, centres Indigenous science and knowledge, and is informed by Indigenous ways of being and doing.

KEYWORDS
Aquatic management, co-production, ecological research, freshwater management, Indigenous knowledge systems, Indigenous science, systematic map, traditional ecological knowledge

1 | INTRODUCTION

Mutually respectful and reciprocal relationships between people and their environment is a central tenet of many Indigenous worldviews (Berkes, 2012; Diver et al., 2019; Kimmerer, 2013; Larsen & Johnson, 2017; McGregor, 2018; Virtanen et al., 2020). This long-standing relational connection to the more-than-human-world (i.e., nonhuman beings such as plants, animals, water, and rocks) can be found among Indigenous peoples globally (Berkes, 2012; Cajete, 1994; McGregor, 2018; Virtanen et al., 2020). Across the Americas, this relational connection is particularly evident when it comes to freshwater ecosystems. For example, water is essential to life in Anishinaabek Creation stories (McGregor, 2014). This is also reflected in the important role of Indigenous women as keepers of the water across what is known to many Indigenous peoples as Turtle Island (i.e., the North American continent; Anderson, 2010, Anderson et al., 2013; McGregor, 2008a; Privott, 2019). In addition to the relational connection to water, there are many instances where a similar relationship can be found with fish across the northern part of Turtle Island and Inuit Nunangat[1] (Todd, 2014; Latulippe, 2017). For the Paq'tnkek Mi'kmaq it is the *Ka't* (American eel; Davis et al., 2004). For the Teetł'it Gwich'in it is *łuk dagaii* (broad whitefish; Hodgson et al., 2020). And for First Nations spanning the Pacific Northwest it is salmon (Colombi & Brooks, 2012; Armstrong & William, 2015) and herring (*linang* to the Haida and *wáṅái* to the Haíłzaqv/*Heiltsuk*; Gauvreau et al., 2017; Jones et al., 2017).

These relational connections draw attention to the importance of moving beyond intrinsic and instrumental values related to the environment to also considering the central role of relational values (Chan et al., 2016; Pascual et al., 2017; Sheremata, 2018). Instrumental values pertain to human needs (e.g., species contributing to food security and material well-being) and intrinsic values pertain to nature's inherent value (i.e., those beyond any direct or indirect benefit to humans; Chan et al., 2016; Pascual et al., 2017; Sheremata, 2018). Relational values are those values directly tied to desirable relationships (e.g., respectful and reciprocal relationships between people and their environment; Pascual et al., 2017). So, while the species noted above contribute to food security and material well-being (i.e., instrumental values) there are important relational values that have often been overlooked by Western institutions and value systems.

Furthermore, there are numerous threats to these central relationships among Indigenous peoples and their environment (Lyver et al., 2019; Tang & Gavin, 2016). For example, relocation (i.e., enforced or voluntary) and migration of Indigenous peoples has resulted in changes to traditional livelihood practices and/or a loss of traditional rights (Ballard, 2012; Tang & Gavin, 2016). In other instances, the general degradation or alteration of waterways, species, and habitats have negatively impacted the ability of Indigenous peoples to maintain their relational connections and practice their rights (Fox et al., 2017; Tang & Gavin, 2016). These threats are further compounded by the intensifying impacts of climate change (Lyver et al., 2019). For example, Watt–Clouter (2005, 2015), in asserting an Inuit 'right to be cold' highlights the impacts of climate change on Inuit culture, traditional lands, and relational connections with animal relatives (see also Jodoin et al., 2020). The impacts and consequences associated with the loss of relationships and continued engagement with the environment are significant, including the loss of knowledge, language, and cultural institutions (Lyver et al., 2019). Accordingly, conserving and restoring the myriad relationships between Indigenous peoples and the environment can help to support both reconciliation and self-determination. As Anishinabe scholar Deborah McGregor notes, it is critical to recognize these relationships as relational responsibilities founded with environmental justice for all (McGregor, 2009).

Using all available ways of knowing (see Table 1) to conserve, prioritize, and restore relationships among Indigenous peoples and the environment they live in, and are a part of, including their traditional territories, is critical (Fox et al., 2017). Indeed, drawing upon multiple ways of knowing, such as Indigenous science and Western science (see Table 1), is an important undertaking, which can strengthen the evidence base for policy advice and decision making (Alexander, Provencher, Henri, Taylor, et al., 2019; Ban et al., 2018; Henri, Martinez-Levasseur et al., 2020; Johnson et al., 2016; Mistry & Berardi, 2016; Tengo et al., 2014). Accordingly, environmental research, monitoring, natural resource management, and conservation practices that are inclusive of Indigenous science and knowledge are essential.

Indigenous peoples around the globe comprise less than 5% of the world's population yet protect 80% of global biodiversity (Toledo, 2013). This relationship to biodiversity is particularly salient between Indigenous peoples (specifically First Nations, Inuit and Métis) and

[1] Inuit Nunangat refers to the Inuit homelands in present day Canada, including the Inuvialuit Settlement Region (Northwest Territories), Nunavut, Nunavik (northern Quebec) and Nunatsiavut (northern Labrador) (ITK, 2018).

TABLE 1 Glossary of key terms (adapted from Alexander, Provencher, Henri, Taylor, Lloren et al., 2019)

Term	Definition
Knowledge system	A knowledge system is made up of agents, practices, routines, and institutions that organize the production, validation, transfer, and use of knowledge (Cornell et al., 2013; Miller & Munoz-Erikson, 2018).
Indigenous knowledge system	An Indigenous knowledge system is a 'cumulative body of knowledge, practices, and beliefs, evolving and governed by adaptive processes and handed down and across (through) generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment' (Díaz et al. 2015). An Indigenous knowledge system may be further defined as 'a "high-context" body of knowledge built up over generations by culturally distinct people living in close contact with a "place"' (Johnson et al., 2016: p. 5) that includes Indigenous science and improves through processes of *addition* and *revision* (Nelson, 2005).
Indigenous science	Indigenous science is 'a "multi-contextual" system of thought, action and orientation applied by an Indigenous people through which they interpret how Nature works in 'their place' […] Indigenous science is derived using the same methods as modern Western science including: classifying, inferring, questioning, observing, interpreting, predicting, monitoring, problem solving, and adapting" (Johnson et al. 2016:5). Indigenous science is embedded in an Indigenous knowledge system.
Western science	With roots in Greek philosophy and the Renaissance, Western science is a fluid and evolving body of knowledge that tends to favour objectivity and reductionism (Mazzocchi, 2006). Western science includes knowledge appropriated over the ages from many cultures, and such knowledge 'was modified sufficiently to fit Eurocentric worldviews, metaphysics, epistemologies, and value systems' (Aikenhead and Ogawa, 2007:543).
Bridging knowledge systems	A process that maintains the integrity of each respective knowledge system while enabling the reciprocal exchange of understanding for mutual learning (Rathwell et al., 2015). This is akin to what Johnson et al. (2016) refer to as weaving knowledge systems.

freshwater ecosystems, habitats, and species in Canada (e.g., Anderson, 2010; Latulippe, 2017; McGregor, 2008,2014; Schuster et al., 2019; Todd, 2014), which has ~20% of the world's freshwater supply in the Great Lakes alone, shared with the United States (Statistics Canada, 2020). The relationship with water is further evident when one looks at a map of Canada, where almost all Indigenous communities are located next to water. While Canada has a history of evidence informed decision making and environmental management (Cooke et al., 2016), the effective consideration and inclusion of Indigenous knowledge in environmental governance continues to pose a perennial challenge (Eckert et al., 2020; Henri, 2012; Menzies & Butler, 2006; Nadasdy, 2003; Sandlos, 2007).

Through the Government of Canada's commitment to achieving reconciliation with Indigenous peoples (First Nations, Inuit, and Métis) and evidence informed decision making, there has been a renewed emphasis on the inclusion and consideration of Indigenous knowledge in regulatory decisions, project reviews, environmental research, and governance. Evidence of this commitment is most apparent in the amended 2019 *Fisheries Act* (i.e., Bill C-68), the 2019 *Impact Assessment Act*, *Canadian Energy Regulator Act* and *Canadian Navigable Waters Act* (i.e., Bill C-69), and in the 2019 Minister Mandate Letters (see Trudeau 2019 Mandate Letters). A common thread found across these legislative requirements and ministerial mandates is an explicit emphasis on the consideration and inclusion of Indigenous knowledge to guide decision making.

Despite the legislative requirements and policy commitments, developing and implementing inclusive approaches that bridge multiple ways of knowing remains a challenge (McGregor, 2008; Walsey & Brewer, 2018). In response, there has been an emerging consensus on the need for easily accessible examples and strategies (i.e., how to do so) for bridging Indigenous science and Western science that are accessible to Indigenous communities, researchers, regulatory programs, and decision-makers seeking to build on this knowledge base and implement new legislative requirements. There are a plethora of place-based case studies from across the globe that have provided key insights on this front (e.g., Bélisle et al., 2018; Stefanelli et al., 2017; Thompson et al., 2020; Thornton & Scheer, 2012). Canada is no exception. For example, a recent systematic map identified over 70 published case studies across Canada where Indigenous and other science-based knowledge were brought together in coastal and marine research and management (Alexander, Provencher, Henri, Taylor, Lloren et al., 2019). Similarly, Castleden et al. (2017) examined integrative approaches in the context of water research, management, and governance across Canada. In this paper we seek to build upon and extend the ecological/environmental context of such reviews to freshwater ecosystems more broadly, including for example empirical case studies where the focus may be on freshwater species (e.g., trout, walleye, beaver) and habitats (e.g., rivers, ponds, wetlands; see Section 2.4.2).

This systematic map examines the extent, range, and nature of published case studies (i.e., peer-reviewed academic literature, grey literature, and theses/dissertations) that seek to bridge Indigenous and Western sciences in ecological research, monitoring, or natural resource management across Canada's freshwater aquatic ecosystems. Systematic mapping is an evidence synthesis method that 'collates, describes and catalogues available evidence (e.g., primary, secondary, quantitative or qualitative) relating to a topic of interest' using rigorous, objective, and transparent processes (Haddaway et al., 2016; James et al., 2016). By cataloguing and describing the evidence and its associated meta-data via a searchable database, report (e.g., narrative synthesis), and in some instances a geographical information system, systematic maps help to identify key research gaps that may benefit from additional primary research and highlight knowledge clusters that would permit more in-depth analysis (Haddaway et al., 2016; James et al., 2016). Accordingly, compiling such a collection is a crucial first step in support of future analysis and/or evidence synthesis.

In this manuscript, we distinguish between 'Indigenous science' and 'Western science' (Table 1). We recognize that there is a risk in simplifying or reifying knowledge systems which are diverse, complex, heterogeneous, and increasingly intertwined through negotiations across epistemological and cultural boundaries (Agrawal, 1995; Alexander, Provencher, Henri, Taylor, Lloren et al., 2019; Cajete, 2000; Ford, 2015; Johnson et al., 2016). However, when seeking to examine instances where multiple ways of knowing have been brought together, delineations help facilitate explorations at such intersections. In addition, while the case studies we are reviewing have predominantly described 'Indigenous knowledge', we prefer employing the term 'Indigenous science' to avoid reinforcing an artificial dichotomy between Indigenous knowledge systems and Western science. We think of 'science' as something all societies create within their own ontological constructs (Johnson et al., 2016; Turnbull, 2000a, 2000b). As Turnbull states: 'Science, in the general sense of systematic knowledge, was never uniquely Western, having exemplifications in a wide variety of cultures both ancient and modern, including Islam, India and China, the Americas, Africa and the Pacific' (Turnbull, 2000a: p. 6).

TABLE 2 Comparison between freshwater search terms used in this review and terms employed in the published protocol

Marine search terms used in Alexander, Provencher, Henri, Taylor, et al. (2019)	Freshwater search terms used in this review
Ecosystem	Aquatic
Habitat	Freshwater
Marine	Stream
Coast	Water
Aquatic	River
Wetland	Fluvial
Ocean	Lake
Sea	Pond
Wildlife fish	Wetland
Whale	Estuary
Marine mammal	Reservoir
Polar bear	Canal
Bird	
Seabird	
Shorebird	
Food-web	
Alga	
Seaweed	

2 | MATERIALS AND METHODS

2.1 | Question and question components

What methods, models, and approaches have been used in studies that seek to bridge Indigenous and Western sciences in freshwater research, monitoring, or management in Canada?

The primary question can be broken down into the following three components:

Population: Cases of freshwater research, monitoring, or management.

Study design: Articles that report empirical results, either qualitatively or quantitatively, and where knowledge weaving practices and/or methods are discussed or inferred that seek to bridge Indigenous and Western sciences.

Geographical scope: Case studies conducted within Canada's jurisdictional boundaries, as well as cases where traditional Indigenous territories overlapped contemporary nation-state boundaries (i.e., the Canada–US border).

2.2 | Systematic map protocol

The original protocol was published in March 2019 (Alexander, Provencher, Henri, Taylor et al., 2019). However, all relevant methodological details have been included here and in the accompanying supplementary material (see Supporting Information 1 and 2). This systematic map followed the Collaboration for Environmental Evidence Guidelines (CEE V.5; 2018) and complied with the *Reporting Standards for Systematic Evidence Synthesis in Environmental Research* (ROSES) (Haddaway et al., 2017; see Supporting Information 1). Our methods deviated from the original published protocol in the following four ways: (i) marine search terms were replaced with freshwater-specific terms (see Table 2); (ii) Google was not used as a search engine; (iii) eligibility criteria were modified; and (iv) some data extraction codes were modified. Reviewers were never responsible for making decisions about articles they have authored during any stage of this process.

2.3 | Searching for articles

This systematic map used standardized search terms across four publication databases, specialized websites, and one web-based search engine. The bibliographies of relevant reviews and systematic reviews were screened to identify any articles that may not have been found using the search strategy noted above. Searches were conducted between July 2019 and December 2019.

2.3.1 | Search terms and languages

The search string was adapted from the published protocol to replace terms related to coastal and marine environments with those specific to freshwater environments to reflect the scope of this map (see Table 2).

A scoping exercise was done to evaluate the sensitivity of the new search terms and their wildcards. Database-specific search strategies (including Boolean operators), date ranges, and number of returns for each database can be found in Supporting Information 2 (2.1, Literature searches). A collection of benchmark papers ($n = 10$; Supporting Information 2.2; Table S6) was used to ensure relevance and comprehensiveness of the search strings. All searches were conducted in English.

2.3.2 | Searches

Searches for relevant case studies were conducted through bibliographic databases, specialized websites, a web-based search engine, and calls for evidence. All search results within Canada's jurisdictional boundaries were retained regardless of publication year, as well as results where Indigenous territories overlapped contemporary nation-state boundaries (i.e., the Canada–US border).

Four bibliographic databases (i.e., ISI Web of Science Core Collections, Scopus, ProQuest Dissertations & Theses Global, and Federal Science Library [Canada]) were searched in July 2019 using Carleton University's institutional subscriptions. See Supporting Information 2 for search details. As a supplement to the bibliographic database searching, a search using Google Scholar was performed in November 2019 using two simplified search strings to search for additional published literature and grey literature (see Supporting Information 2.1). The top 250 search results for each search string were saved in small batches in 'My Library' and exported for screening in Excel. In a deviation from the published protocol, Google was not used as a search engine for this review due to its lack of consistency and limited ability to return relevant results in past reviews. Specialist websites (i.e., Library and Archives Canada, Canadian Public Documents Collection, Government of Canada Publications, Fisheries and Oceans Canada) relevant to the topic were manually searched using their built-in search facilities in August and September 2019 using six simplified English search term combinations (see Supporting Information 2.1). The top 30 search results from each website (up to 180 results per website), sorted by relevance, were screened for inclusion in the systematic map. The bibliographies of 35 articles identified as relevant reviews during screening stages (see Supporting Information 2.3, Table S7) were hand-searched for any additional relevant articles that were not captured during the above searches.

Calls for evidence were also used to complement the search strategy described above. To capture relevant articles, reports, and grey literature, these calls were circulated among the authors' professional networks and on social media platforms (i.e., Twitter, Facebook). In addition, calls for evidence were distributed via personalized emails to the Aboriginal Aquatic Resource and Ocean Management (AAROM) recipient groups/organizations ($n = 33$) and co-management boards in Canada with a mandate related to freshwater ecosystems ($n = 18$) in November 2019.

2.4 | Article screening and study eligibility criteria

2.4.1 | Screening process

The results from all four bibliographic databases were exported as .RIS files and imported into EPPI Reviewer 4 (Thomas et al., 2010) where duplicates were removed prior to screening. Results from Google Scholar screened at both the title and abstract stage and full-text stage were exported directly in Excel.

All articles were screened for inclusion in the map at two distinct stages: (i) title and abstract and (ii) full text using the criteria outlined below (see Section 2.4.2). Prior to screening articles at title and abstract, a consistency check was performed on an initial subset of 558/5576 articles (10% of articles imported into EPPI Reviewer) by three reviewers (SMA, LN, and AB). Inter-reviewer Kappa statistics ranged from 0.471 to 0.542 indicating a 'moderate' level of agreement between reviewers (Landis & Koch, 1977). Discrepancies were discussed and the inclusion criteria were clarified before the same three reviewers screened another subset of 101/5576 articles, which resulted in inter-reviewer Kappa statistics ranging 0.710–0.807 indicating a 'substantial' to 'almost perfect' level of agreement. Any discrepancies were again discussed, and a fourth reviewer (JJT) was brought in to reconcile any differences before screening was allowed to proceed. Attempts were made to find the full text of any article included at title and abstract using Carleton University subscriptions or by using inter-library loan services when needed. Prior to full-text screening, a consistency check was again performed between the three reviewers (SA, LN, and AB). A random subset of 65 articles (20% of articles included at title and abstract) were screened in two batches resulting in Kappa statistics ranging 0.082–0.909 indicating a large variation in agreement between the three reviewers. Discrepancies were discussed and inclusion criteria were further clarified with the help of a fourth reviewer (JJT). Another subset of 20 articles were screened by the three reviewers resulting in Kappa statistics ranging 0.432–0.765 indicating 'moderate' to 'substantial' agreement and screening was allowed to proceed after any discrepancies were reconciled and the inclusion criteria were reviewed and clarified a final time. During screening reviewers had the ability to request a second opinion from another member of the review team for any articles with unclear eligibility. At no point during title and abstract or full-text screening was a reviewer allowed to influence the inclusion decision for any article that they authored.

2.4.2 | Eligibility criteria

A pre-established set of eligibility criteria (Table 3) guided article screening. All four inclusion criteria needed to be met to be included in the final dataset of articles and case studies.

TABLE 3 Eligibility criteria

Population	
Case studies that concern freshwater water bodies (e.g., lakes, rivers, source water), habitat, ecosystems, or species (including Diadromous fish).	
Study design	
Articles that report empirical results – either qualitatively or quantitatively – where knowledge weaving practices and/or methods are discussed or inferred. Empirical studies included fall into one of three broad categories: (1) studies focused on environmental/ecological research and monitoring (i.e., those reporting on direct or indirect observation or experience from Indigenous science and Western science (i.e., environmental data); for example, Fraser et al. (2006); (2) studies focused on the processes and practices of bridging knowledge systems in the context of decision-making (e.g., Latulippe, 2017); and (3) studies concerned with perceptions of ecological or environmental phenomenon (e.g., perceptions of ecosystem services Levine et al., 2017).	
Geographical scope	
Case studies conducted within Canada's jurisdictional boundaries, as well as cases where traditional Indigenous territories overlapped contemporary nation-state boundaries (i.e., the Canada-US border).	
Language	
English.	

2.4.3 | Critical appraisal

Critical appraisal refers to the processes of assessing the validity of studies included in evidence synthesis (e.g., systematic reviews and systematic maps). Key aspects focus on evaluating 'internal validity' – the extent to which individual studies are free from bias – and 'external validity'– the extent of generalizability of individual study findings (CEE V.5). However, given the broad objective and scope of this systematic map, the validity of individual case studies was not appraised. Accordingly, it is important to note there has been no appraisal as to the quality or extent of knowledge bridging – only that it is present or reported to have occurred.

2.4.4 | Data coding strategy

For this study, coding and data extraction were conducted at the case study level rather than at the article level. The result of this is that in some instances a single article (e.g., Arsenault et al., 2018) could contribute two or more case studies. A standardized questionnaire (Supporting Information 2.5) was deployed through Google Forms to collate responses and ensure consistency across coders. The questionnaire (Supporting Information 2.5) was modelled on (Alexander, Provencher, Henri, Taylor, Lloren et al., 2019) with slight modifications to a few variables (e.g., changes in categorical variables) and a few additional questions. Specific changes are noted in Supporting Information 2.5. Included studies were coded by one of three team members (SA, LN, and AB). However, prior to coding and data extraction, a consistency check was conducted with the questionnaire. Three reviewers (SA, LN, and AB) extracted data from a random subset of four of 58 articles (7% of articles included at full text from publication databases; does not include specialist websites or other sources of literature) as a consistency check. All coding decisions were reviewed by the review team and any discrepancies were reconciled and clarified before allowing data extraction by the three reviewers to continue. In addition, the lead author reviewed all coding decisions for consistency upon the conclusion of meta-data coding. Resulting data compiled from the Google Form was exported and recorded in a comma separated file. Formatting of the data was standardized in R and analysed using a customized script. The R code and data files used for formatting and analysis can be accessed via OSF here.

2.4.5 | Data mapping method

Narrative synthesis was used to summarize findings and insights (Popay et al., 2006). As a textual approach, narrative synthesis was used to explore relationships within and between studies – through textual descriptions, grouping and clustering cases, and content analysis – particularly those related to understanding the variability of study design, settings, and study populations (Popay et al., 2006). To help identify trends and gaps in the evidence, narrative synthesis was complemented by the use of descriptive statistics, figures, tables, and framework-based synthesis. Specifically, framework-based synthesis (e.g., Dixon-Woods, 2011; Alexander, Provencher, Henri, Taylor, Lloren et al., 2019) guided the development of three structured matrices (Figures 5, 6 and 10). Maps depicting the centroid of case study polygons (reflecting the approximate geospatial extent for each) used ArcMap 10.6.1 (ESRI, 2019), bar graphs were made using base R, and structured matrices developed using ggplot2 (Wickham, 2016). Sankey data visualizations (Figures 7–9) were produced in R using the publicly available package networkD3 (Allaire et al., 2017).

3 | RESULTS

3.1 | Number and types of articles

Searches across four bibliographic databases and Google Scholar resulted in 5988 records once duplicates were removed (See Supporting Information 2.1 and Figure 1). Screening at title and abstract – based upon the eligibility criteria (Table 3) – resulted in 424 articles

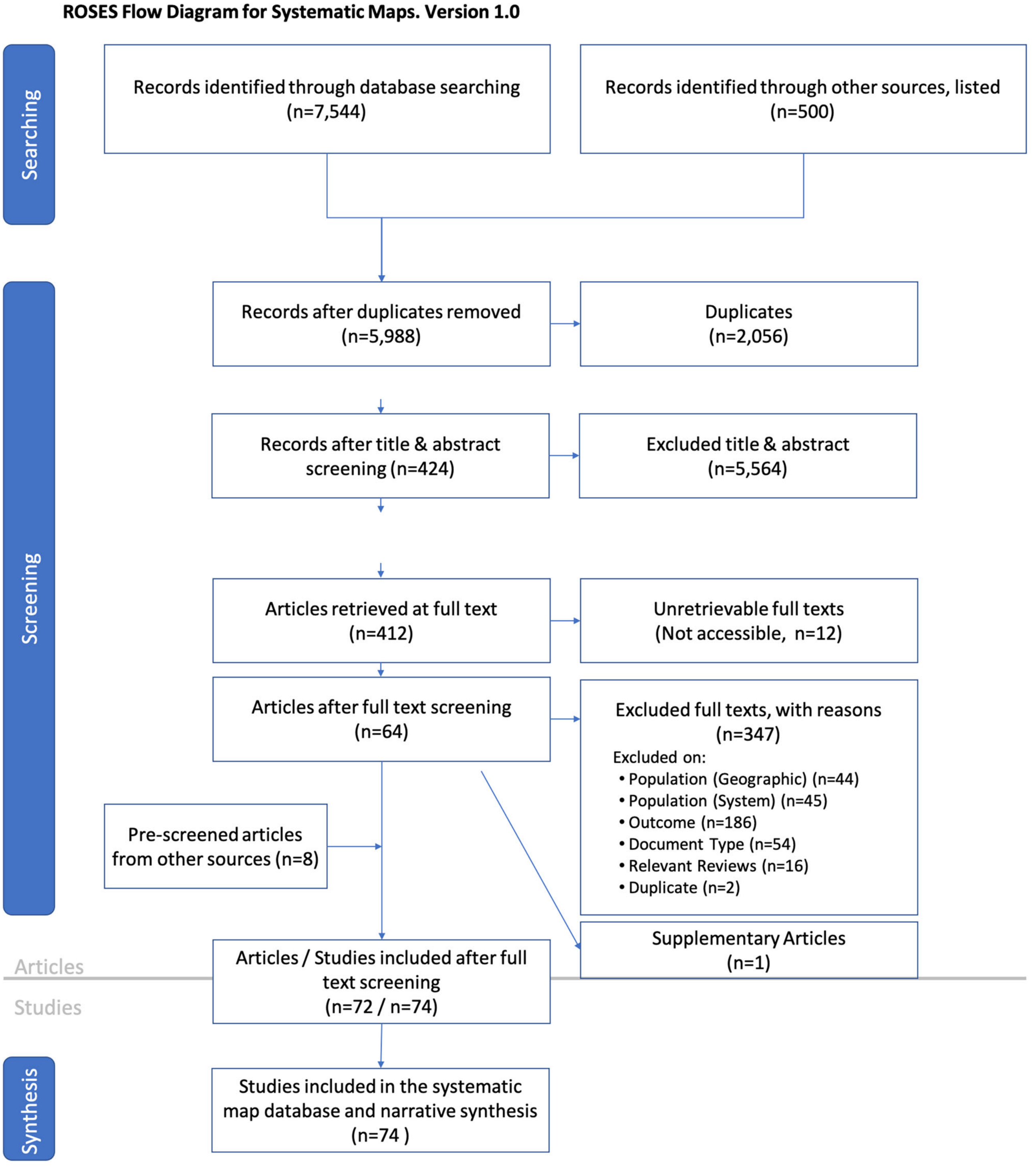

FIGURE 1 ROSES flow diagram

identified as relevant. All but 12 articles were retrieved for full text screening (via open access, Carleton University institutional subscriptions, or interlibrary loan). Screening at full text resulted in the exclusion of 347, the majority of which were excluded on outcome (i.e., the articles did not include Indigenous science and Western science [i.e., environmental data]). A complete list of excluded articles accompanied by their reason for exclusion can be found in Table S8 (Supporting Information 2.4, Excluded at full text). After the two-stage screening process, 64 articles were included in this systematic map from bibliographic databases and Google Scholar. Screening specialist and supplemental sources (e.g., contributed grey literature, organizational websites, reference lists of relevant reviews) resulted in an additional eight articles being included in the systematic map. Combined, the systematic map includes 74 individual case studies from 72 articles.

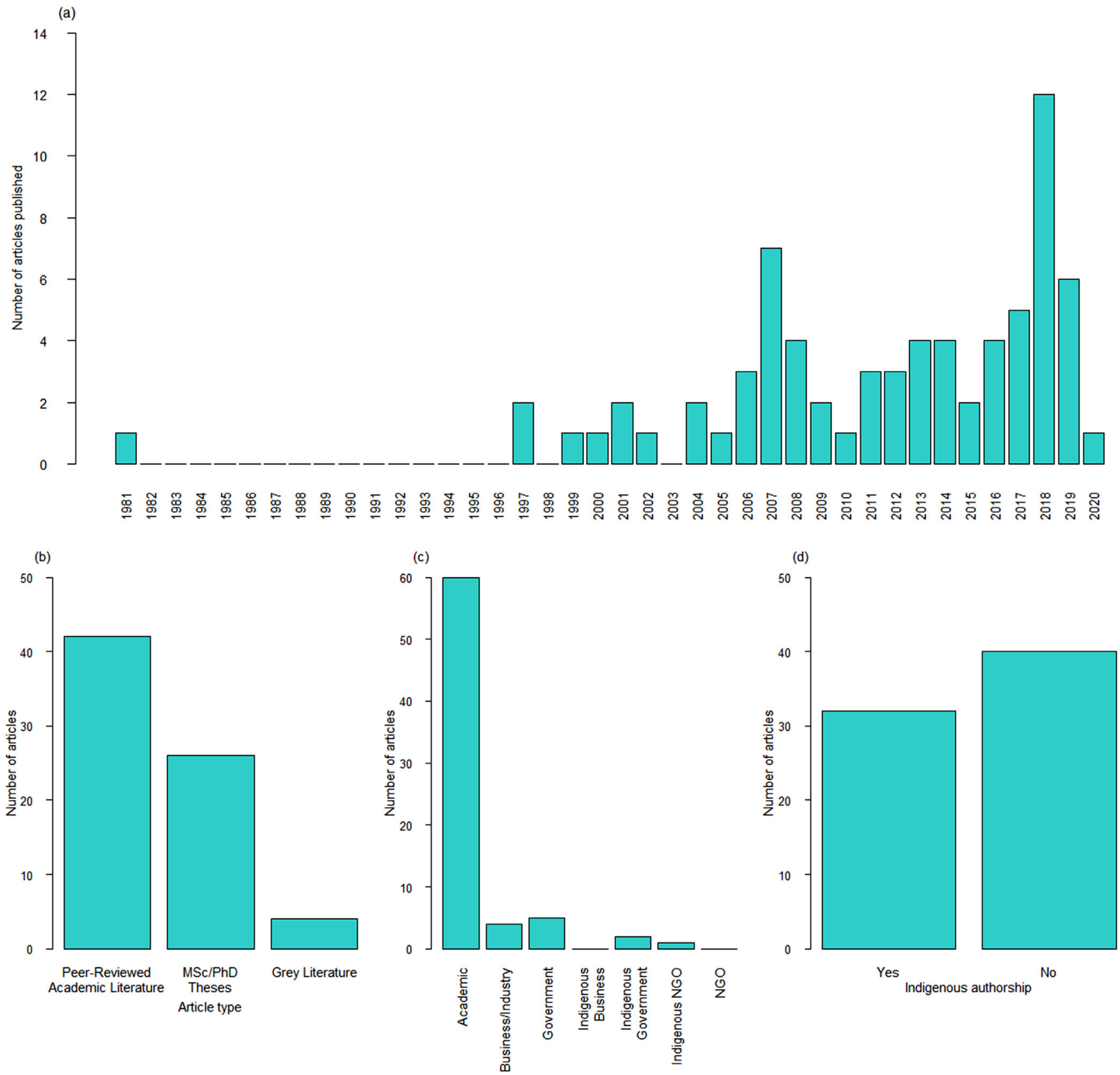

FIGURE 2 Bibliographic characteristics of articles included ($n = 72$)

The 72 articles and 74 case studies varied across a number of metrics related to the frequency of publications, article type, and with regards to authorship affiliations and Indigenous representation. Over 50% of case studies have been published in the last decade (47/72 since 2010, Figure 2a). However, over 94% of the studies included have been published since 2000 suggesting a potential turning point for the emergence of this field and related integrative practices (94%, 68/72, Figure 2a). Between 2004 and 2020 there were minor variations in annual volume of publications ranging from 1 to 7 articles in a given year, this being aside from an anomalous 2018 with 12 publications (Figure 2a). Peer-reviewed academic literature accounted for the majority of publications (44/72) while grey literature accounted for the least (four out of 72, Figure 2b). The majority of first authors were from academic institutions (60/72, Figure 2c). Among the publications included in this systematic map, approximately 44% ($n = 32$) had Indigenous authors or authors who represent Indigenous communities, organizations, and/or governments (Figure 2d).

3.2 | Systematic map

A systematic map constitutes the central output from this research. This map is composed of a database in the form of a case-based matrix that includes relevant meta-data and coded values (e.g., binary, categorical) for the case studies (Supporting Information 3), as well as the geographical distribution and location of each case study (Figure 3, Supporting Information 2.6, Figs. S1 and S2).

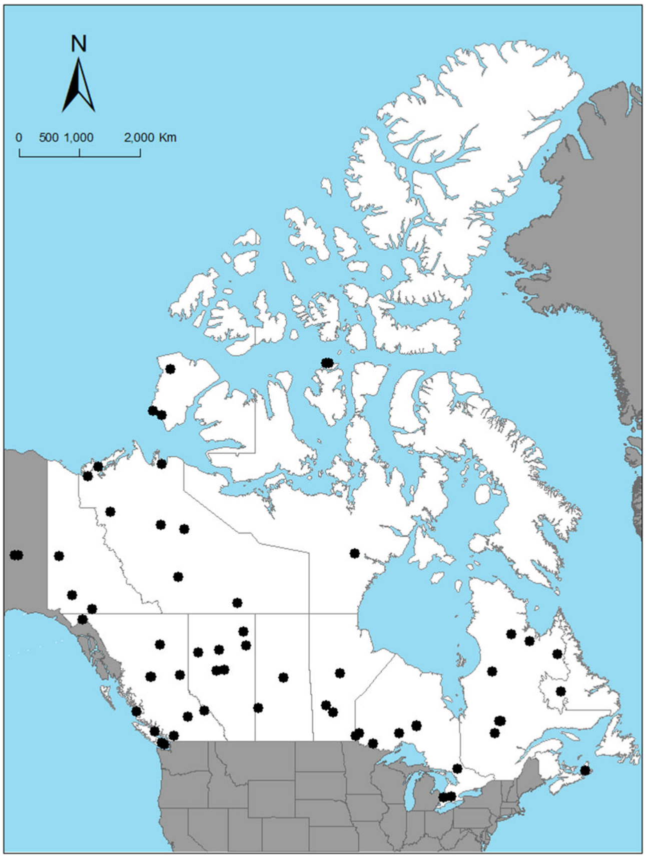

FIGURE 3 Geographic distribution of case studies included in the systematic map (*n* = 74; locations reflect the centralized point of each case study)

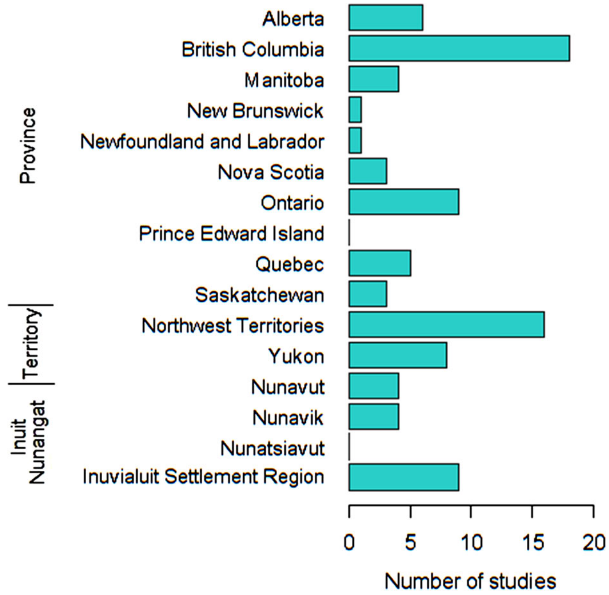

FIGURE 4 Geographic distribution of case studies by province, territory and Inuit Nunangat

3.3 | Geographic distribution of included case studies

While the 74 case studies identified and included in this systematic map span across Canada's freshwater ecosystems, they are far from being evenly distributed. At the sub-national level (i.e., province, territory, Inuit regions), the number of case studies that have been conducted in both British Columbia (24%; 18/74; Figures 3 and 4) and the Northwest Territories (22%; 16/74; Figures 3 and 4) account for close to 50% of the studies. However, when the four Inuit regions that form Inuit Nunangat are viewed collectively (i.e., Inuvialuit Settlement Region, Nunavut, Nunavik, and Nunatsiavut), the number of case studies (20%; 15/74; Figures 3 and 4) is also notable and on par with both British Columbia and the Northwest Territories.

3.4 | Empirical, ecological, and hydrological scope of included studies

The empirical focus of the case studies fell into two broad categories: (i) environmental/ecological research and monitoring; and (ii) management and decision making. Case studies that were characterized as environmental/ecological research and monitoring, which accounted for over 60% (45/74), reported on observations (direct or indirect) or experience from Indigenous and Western sciences. The remaining 40% (29/74) of case studies focused on bridging knowledge systems in the context of decision making, specifically with regards to the processes and practices of knowledge bridging.

Examining the ecological focus of the included case studies revealed insights regarding which species have been studied and where. There were 30 distinct species across the collection of case studies included in the systematic map (Figure 5). Notable clusters of case studies include *Coregonus* spp. (whitefish, *n* = 11), *Oncorhynchus* spp. (Pacific salmon, *n* = 9) and *Salvelinus* spp. (char, *n* = 9). From a geographical and jurisdictional standpoint, the Northwest Territories stands out with regards to taxonomic coverage (*n* = 12). In addition, the Northwest Territories had a cluster of case studies concerning *Coregonus* spp. (whitefish, *n* = 5). Other notable regions with regards to taxonomic coverage include Alberta (*n* = 8) and Ontario (*n* = 10).

Case studies were also characterized based upon the hydrological scale and focus (i.e., basin, watershed, water body). By far, the most prevalent hydrological scale at which case studies are focused is best classified as water body (*n* = 63; e.g., river, lake, pond; Figure 6). Notable clusters of case studies at the hydrological scale of a water body can be found in the Northwest Territories (*n* = 12), British Columbia (*n* = 9), Inuvialuit Settlement Region (*n* = 8), and Ontario (*n* = 8).

3.5 | Methods, models and approaches

A core objective for this systematic map was to identify the diversity and better understand the landscape with regards to the methods, models, and approaches employed to bridge multiple ways of knowing. To this end, we specifically focused on two key aspects: (i) methodology

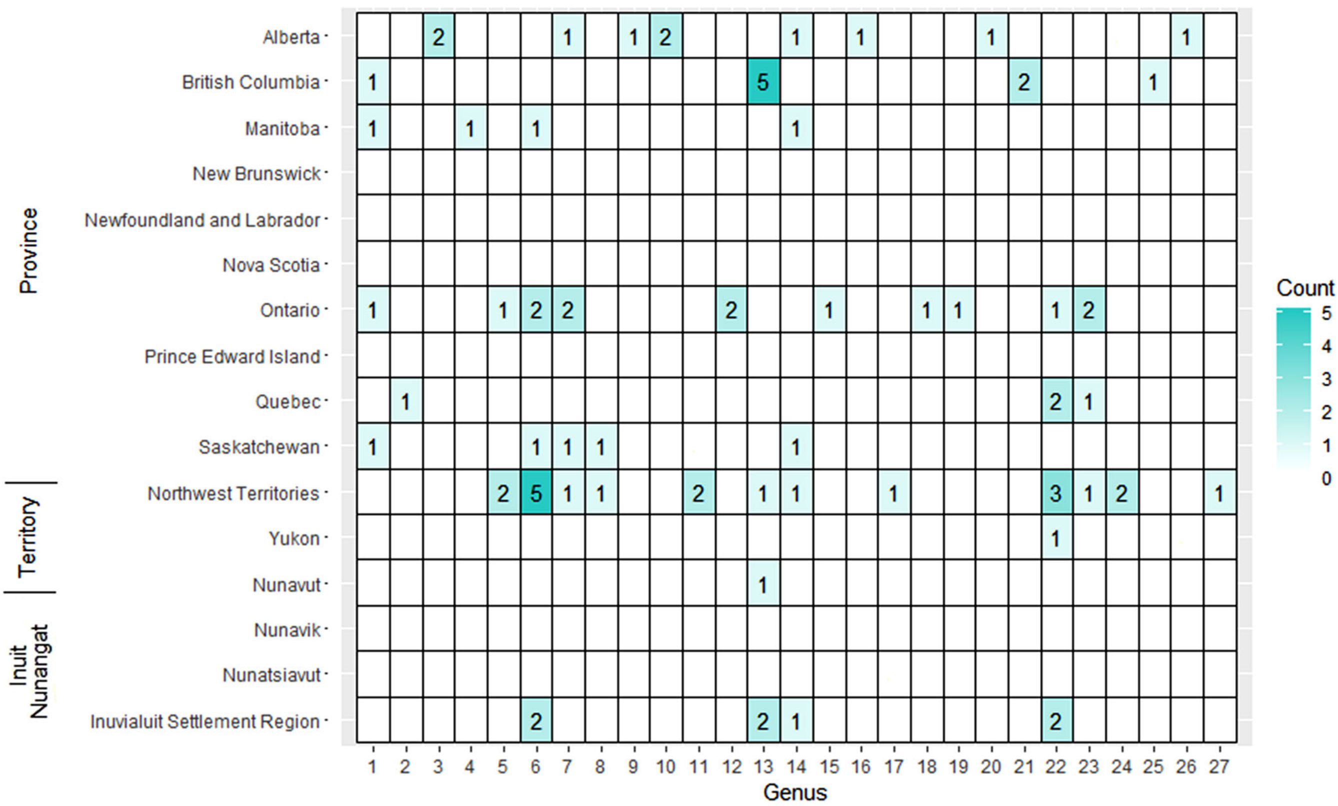

FIGURE 5 Structured matrix showing the frequency with which the location of a case study fell within each jurisdiction and focused on a species ($n = 21$). Genus are as follow: 1 = *Acipenser* spp., 2 = *Aeromonas* spp., 3 = *Anodonta* spp., 4 = *Castor* spp., 5 = *Catostomus* spp., 6 = *Coregonus* spp., 7 = *Esox* spp., 8 = *Hiodon* spp., 9 = *Lampsilis* spp., 10 = *Lasmigona* spp., 11 = *Lota* spp., 12 = *Micropterus* spp., 13 = *Oncorhynchus* spp., 14 = *Ondatra* spp., 15 = *Papilio* spp., 16 = *Perca* spp., 17 = *Platygobio* spp., 18 = *Pomoxis* spp., 19 = *Populus* spp., 20 = *Rana* spp., 21 = *Sagittaria* spp., 22 = *Salvelinus* spp., 23 = *Sander* spp., 24 = *Stenodus* spp., 25 = *Thaleichthys* spp., 26 = *Thymallus* spp., 27 = *Ursus* spp

(i.e., overarching research design); and (ii) methods. In the case of methods, we focused on identifying and distinguishing between the methods used for collecting Western scientific data and those used for acquiring, compiling, documenting, or representing Indigenous science and knowledge.

An examination of methodologies revealed a number of results with regards to research design. The first notable finding was that there were 15 different research designs used (Figures 7 and 8). The second notable finding was that community-based participatory research was the most prevalent methodology employed (Figures 7 and 8). The third notable result was both the presence and diversity of Indigenous methodologies employed (Kovach, 2010; Figures 7 and 8). While visualized in aggregate here to illustrate and highlight how their application collectively compares to other methodologies, it is important to note that there were four different Indigenous methodologies employed: (i) Indigenous Métissage (Donald, 2012); (ii) Spirit-Cantered (Debassige, 2010); (iii) Two-Eyed Seeing (Bartlett et al., 2012); and (iv) Anishinaabe Mino-Bimaadiziwin (Debassige, 2010). These four methodologies are what Drawson et al. (2017) referred to as culture-specific, given their origins are rooted in specific Indigenous cultures. In addition, there were four other research approaches applied across the case studies examined here that Drawson et al. (2017) highlighted as methodologies that have been adapted from a Western context to an Indigenous cultural context: (i) mixed methods; (ii) Emic-etic approach; (iii) community-based participatory research; and (iv) story telling.

The specific methods employed to mobilize Indigenous science and knowledge systems (hereafter Indigenous science) and collect Western scientific data were also characterized. In the context of freshwater research and monitoring there were 13 different methods employed to document, compile, and mobilize Indigenous science (Figure 8). With regards to methods used for Western scientific data there were 18 different methods employed (Figure 8). When examining the application of diverse methods across different hydrological scales we find that for those focused on water bodies (e.g., rivers, lakes) draw upon the entire suite of Indigenous science methods ($n = 13$) and all but one of the Western science methods ($n = 8$). Whereas those case studies at the watershed level ($n = 5$ and $n = 5$ for Indigenous science and Western science methods, respectively) and basin level ($n = 4$ and $n = 4$) both employed far fewer methods (Figure 9). Constructing a structured matrix to examine the pair-wise application of Indigenous and Western science methods was also revealing (Figure 10). Frequent combinations included: (i) document review (Western science) and interviews (Indigenous science); (ii) abiotic sampling (Western science) and interviews (Indigenous science); and (iii) document review (Western science) and workshops (Indigenous science).

FIGURE 6 Structured matrix showing the frequency with which the location of a case study fell within each jurisdiction and hydrological scale of the research ($n = 74$)

3.6 | Indigenous science and demographics of knowledge holders

Details concerning the demographics of Indigenous participation and contributions were examined for each case study to better understand the representation of Indigenous science and knowledge systems, and knowledge holders. The extent and nature of information provided with regards to demographics varied widely and in general was poorly reported. For example, the majority of case studies did not report the age group of knowledge holders (65%; 48/74; Figure 11a) or the gender of knowledge holders (62%; 46/74; Figure 11c). Indeed, 13 case studies did not report demographic details regarding age group, gender, or whether Elders were included. The reported contribution of youth is relatively low (19%; 14/74; Figure 11a). While there appears to be higher levels of youth involvement in the more recent reports and literature (i.e., 2018 and 2019), there is no clear pattern that youth involvement has changed over time. The participation and contribution of Indigenous science and knowledge from Elders was the most common to be drawn upon (76%; 56/74) and most commonly reported demographic (Figure 11a). The majority of case studies involved Indigenous science and knowledge systems of First Nations (77%; 57/74), with significantly fewer case studies including Inuit knowledge (16%; 12/74) and Métis traditional knowledge (8%; 6/74; Figure 11d). Across all of the case studies included in the systematic map there were 78 distinct Indigenous science and knowledge systems represented.

4 | DISCUSSION

4.1 | Evidence gaps and insights

This systematic map revealed a few notable evidence gaps and some key insights. The first notable evidence gap concerns how few studies there were from Newfoundland and Labrador and New Brunswick, and the complete absence in Nunatsiavut. The second notable evidence gap was the relatively small number of studies that included Métis traditional knowledge. While there was not a complete absence, as was found by Alexander, Provencher, Henri, Taylor, Lloren et al. (2019), the number of case studies in the freshwater context that involved

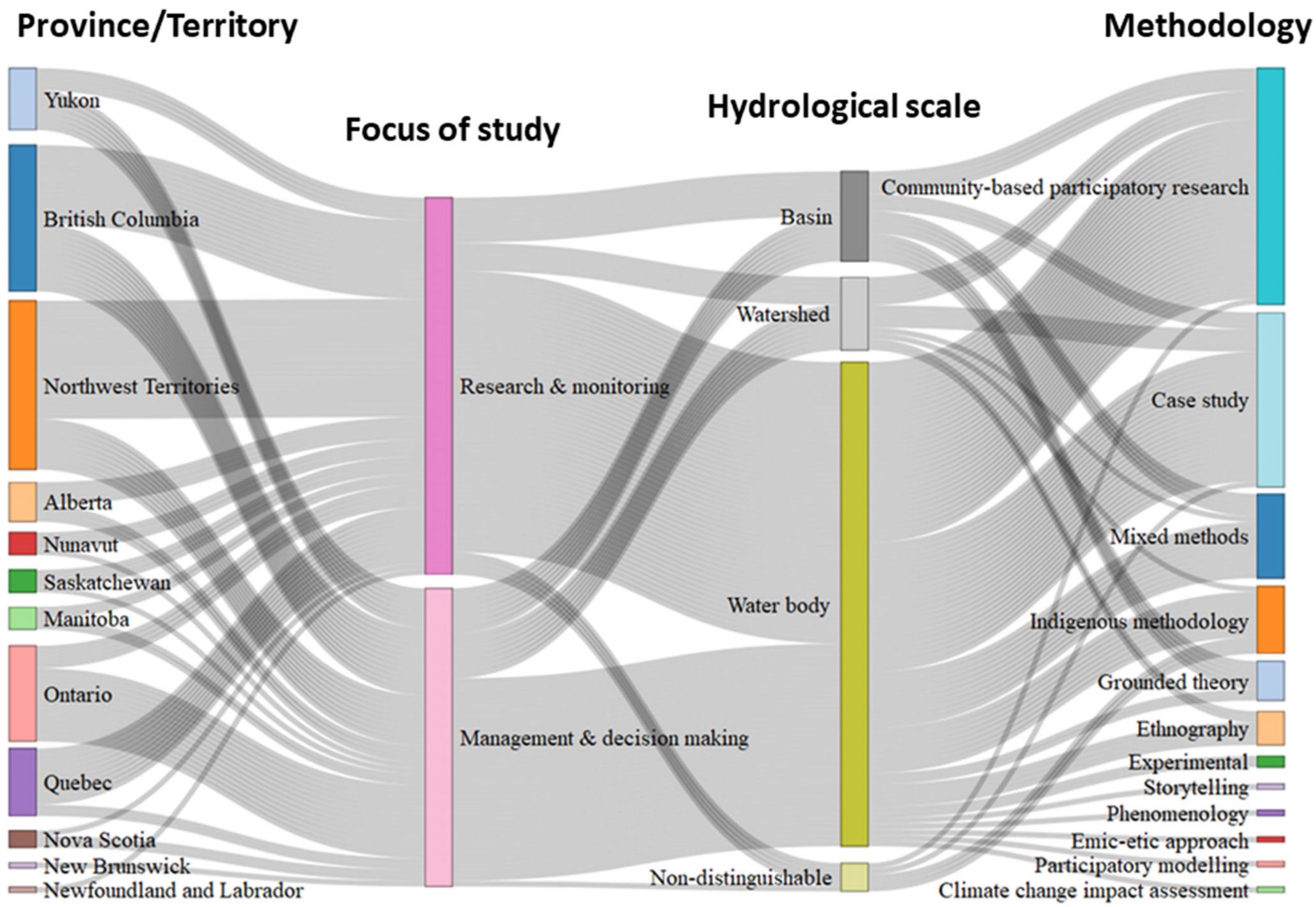

FIGURE 7 Relationship among regions, study focus, hydrological scale, and methodology for selected case studies ($n = 74$). Indigenous methodology includes: (i) Indigenous Métissage; (ii) Spirit-Centered; (iii) Two-Eyed Seeing; and (iv) Anishinaabe Mino-Bimaadiziwin. *Note that Inuit Nunangat cases are included via their respective province or territory

weaving Métis traditional knowledge and Western science was quite small, accounting for only 8% of the studies identified and included.

Reporting on the demographics of Indigenous participation and contributions continues to be a critical gap that has been similarly identified (Hitomi & Loring, 2018; Alexander, Provencher, Henri, Taylor, Lloren et al., 2019). Indeed, age and gender were not reported in over half of the case studies. However, based upon what was reported, there were some important observations. First, male and female knowledge holder participation rate in the freshwater case studies were comparable (Figure 11c) as compared to trends observed in research focused on environmental and climatic change where male bias definitely characterizes who is engaged in those studies (Hitomi & Loring, 2018). This lack of a gendered bias in freshwater studies could reflect the special relationship between Indigenous women and water (e.g., women as protectors of the sacred water in Syilx culture; Anderson, 2010; Anderson et al., 2013; McGregor, 2008a; Privott, 2019).

Second, with regards to youth participation as knowledge holders in this systematic map, we found 19% of studies (14/74) involved youth, which is higher than reported in the previous coastal/marine systematic map using the same protocol (7%; 5/71 studies reporting involving youth; Alexander, Provencher, Henri, Taylor, Lloren et al., 2019). While time trends in these small sample sizes (an artefact of the habitat and geographic scope of the systematic map) are difficult to determine, it would be informative to see whether cases of youth involvement across all the habitat types (coastal/marine, freshwater, and terrestrial) have been consistent over time since the literature started emerging 20 years ago or if youth engagement is a more recent phenomenon in the field. There have been numerous calls to diversify knowledge holders and include youth (e.g., Henri, Brunet, et al., 2020), and a future analysis of this could explore if these calls have been answered or are at least being considered more regularly in project planning. In regions where youth make up the majority of the population, programs that involve youth in Indigenous and Western science weaving are critical to engaging the next generation of environmental leaders (Provencher et al. 2013; Pedersen et al., 2020).

There were also several insights that emerged from this systematic map, specifically with regards to the methodological approaches, research methods, and the demographic of knowledge holders which we speak to further below.

One of the central objectives of this systematic map was to examine and document the 'methods, models, and approaches' employed to bridge multiple ways of knowing. To this end, there are some particularly salient findings and associated insights related specifically to the: (i) greater diversity of methodological approaches; (ii)

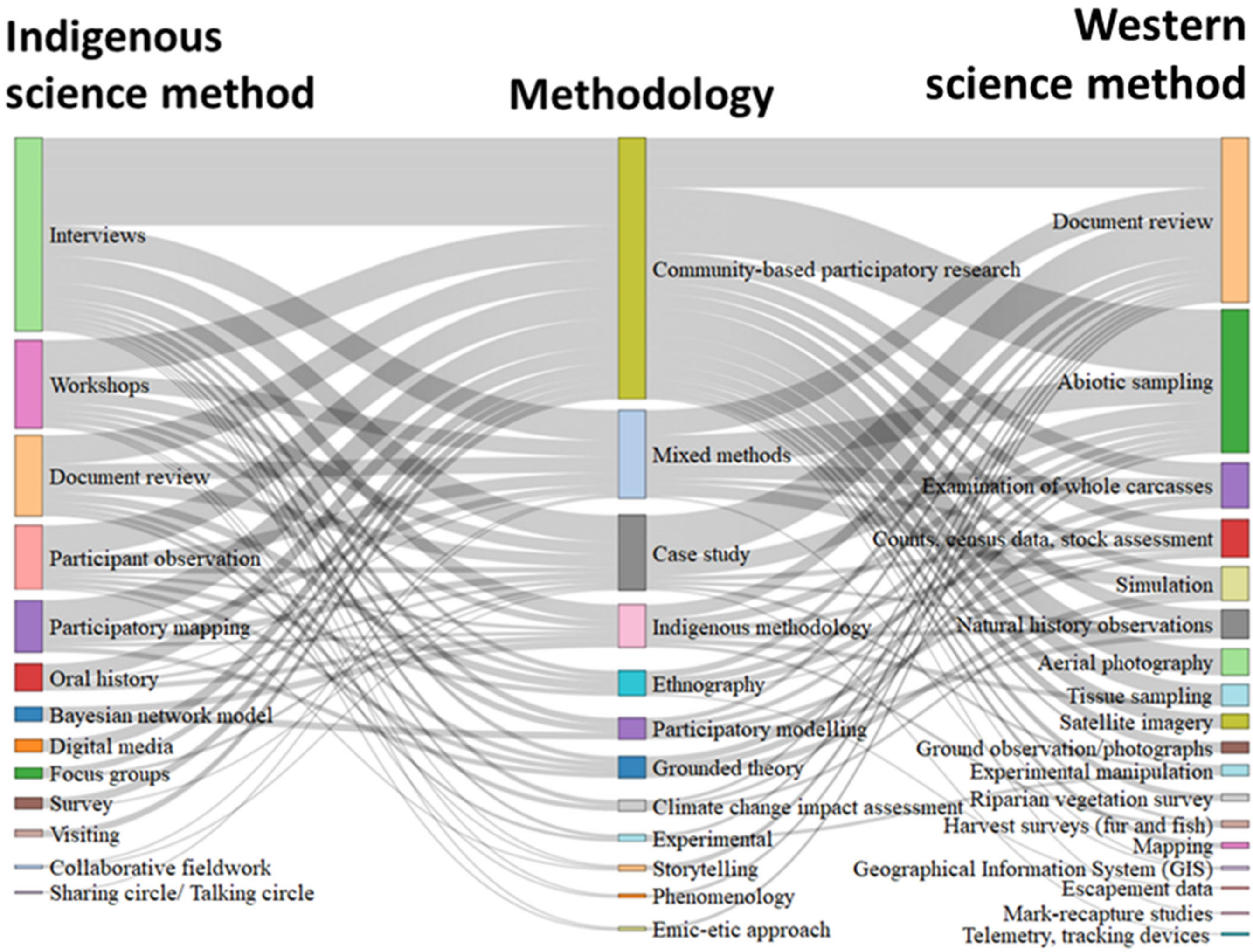

FIGURE 8 Relationship between Indigenous science methods, methodology and Western science methods for selected case studies classified as research and monitoring ($n = 45$)

prevalence of community-based participatory research; and (iii) presence and diversity of Indigenous methodologies employed. Indeed, there were three times as many methodological approaches ($N = 15$) compared to what Alexander, Provencher, Henri, Taylor, Lloren, et al. (2019) found when examining a similar set of case studies across Canada's marine and coastal ecosystems. This methodological diversity was mirrored by a greater diversity of research methods (see below). In addition to these differences in research approaches, we found that among the publications included in this systematic map, approximately 44% ($n = 32$) had Indigenous authors or authors who represent Indigenous communities, organizations, and/or governments – more than double what was found when in a similar systematic map focused on Canada's marine and coastal ecosystems (21%; Alexander, Provencher, Henri, Taylor, Lloren, et al., 2019). Collectively, these findings point to a potential emerging transformation in research focused on freshwater ecosystems, habitats, and species to a practice that elevates the role of Indigenous communities, centres Indigenous science and knowledge systems, and is informed by Indigenous ways of being and doing.

Another key finding here was the greater diversity of methods employed in the freshwater context compared to what was found in Alexander, Provencher, Henri, Taylor, Lloren et al. (2019) – which focused on the coastal-marine context – both with regards to methods employed to document, compile, and mobilize Indigenous science and knowledge systems and when it came to methods used for Western scientific data (Figure 8). Most striking is that this diversity is not spread across the case studies. We find that case studies focused on the hydrological scale of water bodies (e.g., rivers, lakes) draw upon nearly the entire suite of methods, whereas those case studies at the watershed level and basin level employed a much smaller subset of methods (Figure 9). While the structured matrix examining the pairwise application of methods was revealing, its limitations are evident as these methods are not just employed in pairs. These observations and insights together suggest a set of important questions and further inquiry focused on digging deeper into the common bundling of methods and exploring whether certain methods and/or bundles are more commonly associated with particular research questions and/or scales (i.e., ecological, hydrological). Insights from a more in-depth and

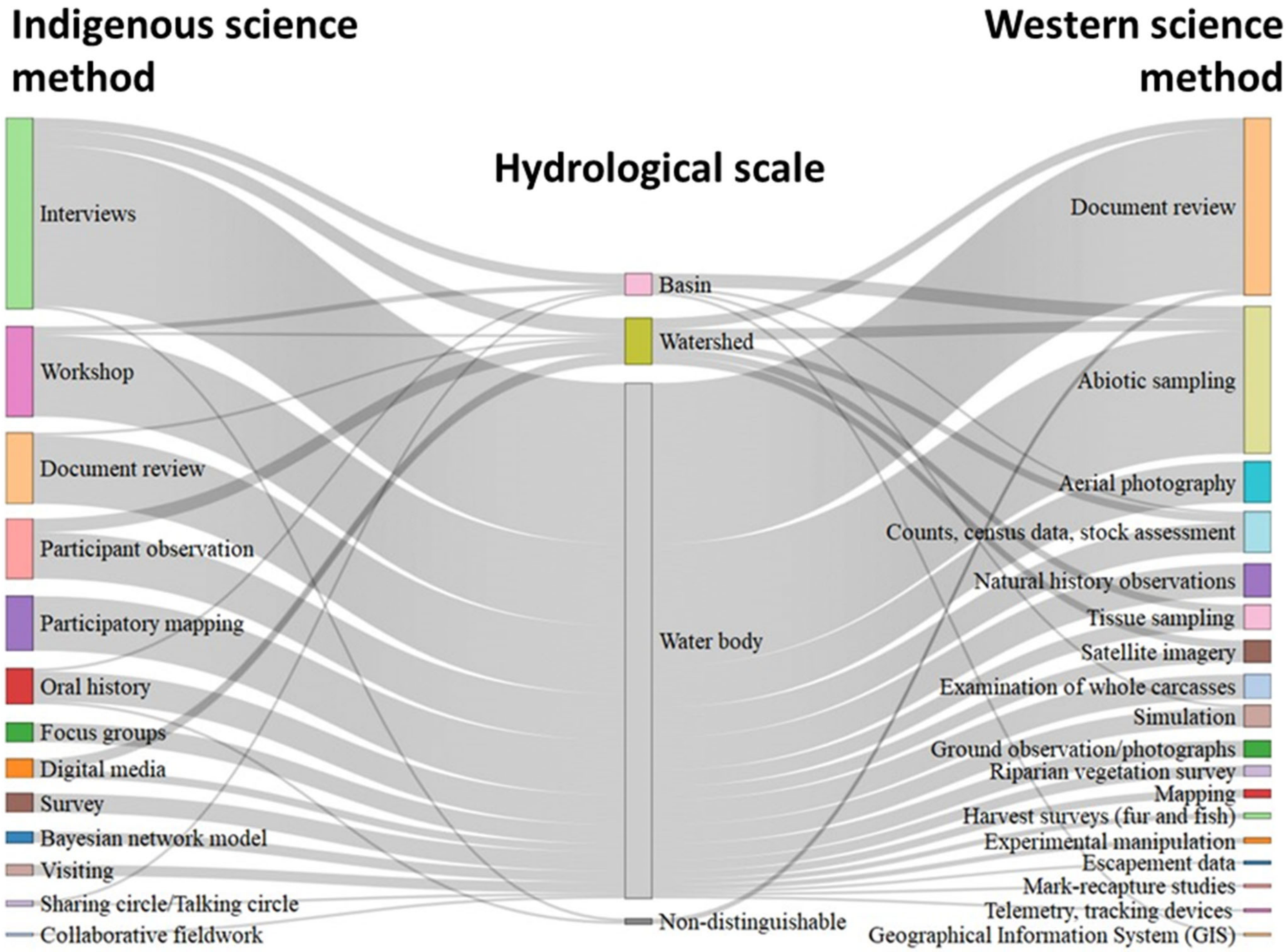

FIGURE 9 Relationship between Indigenous science methods, hydrological scale and Western science methods for selected case studies classified as research and monitoring ($n = 45$)

Western science methods \ Indigenous science methods	Bayesian network model	Collaborative fieldwork	Digital media	Document review	Focus groups	Interview	Oral history	Participant observation	Participatory mapping	Sharing circle/ Talking circle	Survey	Visting	Workshop
Abiotic sampling	1		1	4	1	16	3	5	5	1	1		7
Aerial photography			1	1	1	3	1	1	2		1	1	3
Count	1		1	1		7		1	1				3
Document review	1	1		8	3	22	4	7	4	1	2		11
Examination of whole carcasses				2		2		2	1				1
Experimental manipulation				1		1							
Field measurements									1		1		1
Geographic Information System (GIS)						1							
Ground observation/photograph									1		1		1
Hydrologic data analysis							1	1				1	
Imagery							1	1				1	
Mapping							1	1				1	
Mark-recapture study				1									
Natural history observation	1		1	1		5	1		2				1
Remote sensing			1			1		1					
Riparian vegetation survey				1	1	1							1
Satellite imagery									1		1		1
Simulation				2		4		1	1				
Survey						1	1						
Telemetry				1									
Tissue sampling			1			4		2	1				1

Freq: 0, 5, 10, 15, 20

FIGURE 10 Structured matrix showing the frequency where specific Indigenous science methods were employed alongside specific Western science methods for case studies classified as research and monitoring ($n = 45$)

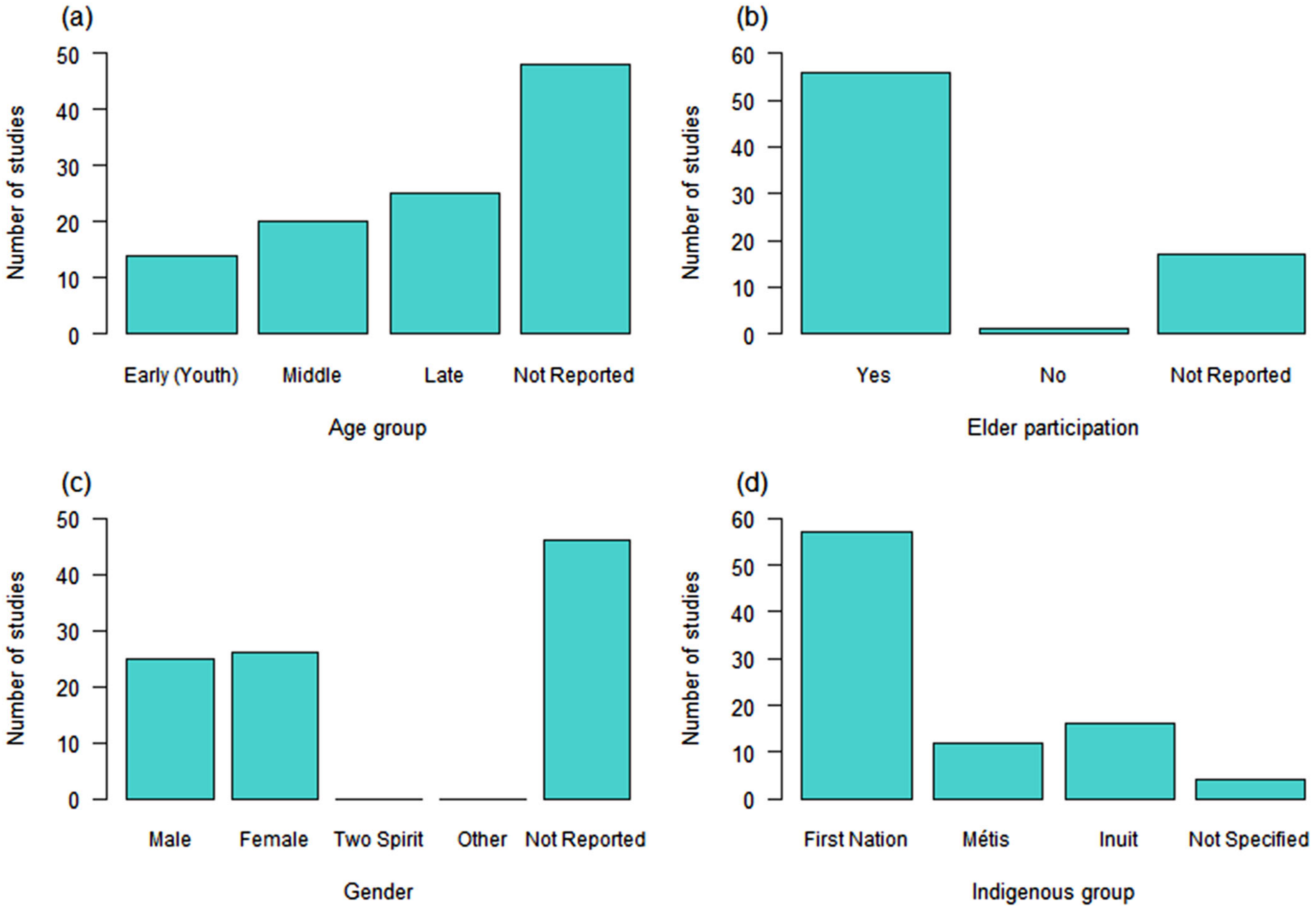

FIGURE 11 Demographics of knowledge holders

nuanced analysis could help to illustrate the diverse pathways to bridging multiple ways of knowing and provide guidance for practitioners.

4.2 | Limitations of the methods used

While the systematic map method used here as outlined above aimed to be comprehensive, we acknowledge its limitations. Specifically, there are five potential limitations associated with the search strategy employed. These limitations are related to: (i) search terms; (ii) language; (iii) citation screening; (iv) semantic challenges; and (v) eligibility criteria. Indigenous, Aboriginal, First Nation, Inuit, and Metis were included in the search strings. While these were included to be inclusive of the common distinctions, it is important to note that they are relatively contemporary 'labels' often imposed externally and do not always reflect how Indigenous peoples self-identify. This search was limited to English language terms and results. However, French is one of Canada's official languages and thus impacts the inclusion of studies published in the French language (e.g., francophone theses). Reference lists of 35 relevant reviews were screened (backwards citation screening) as a way to identify potential empirical studies not captured by the search string. We did not, however, conduct any forward citation screening (e.g., papers that cite the relevant reviews) as another means to identify potential empirical studies not captured by the search string. Fourth, as Cheng et al. (2019) highlight, there is an inherent semantic challenge for interdisciplinary fields such as this, which are characterized by a high diversity of terms used across studies. Finally, there are limitations related to the eligibility criteria – specifically *study design*. As noted in the eligibility criteria above, we articulated the study design as follows:

Articles that report empirical results – either qualitatively or quantitatively – where knowledge weaving practices and/or methods are discussed or inferred

The benefit of defining the criteria as such is that it helped facilitate the screening and identification of examples that could provide insights when it comes to *methods, models, and approaches*. However, the absences of weaving practices and/or methods being discussed or inferred does not mean that a given study did not employ such practices and methods. This in turn has implications as well for the evidence base as noted in the following section.

4.3 | Limitations of the evidence base

It is equally important to note the limitations of the evidence base. Alexander, Provencher, Henri, Taylor, Lloren et al. (2019) highlighted two key aspects related to knowledge bridging in practice, noting that changes to a search strategy would struggle to identify examples where the contributions of Indigenous knowledge are never acknowledged or are published as a separate, stand-alone study. Here, we also draw attention to the limitations of the evidence base that is borne out of the criteria used for the *study design* requiring the discussion or inferring of weaving practices and/or methods. Having placed these specific parameters on the screening – which in many cases was necessary – means that we have captured a particular constellation of case studies where multiple ways of knowing are brought together. However, there may be other pathways and approaches (e.g., Indigenous-led research and monitoring) where the weaving and bridging of knowledge is inherent and embedded within all of the work because it was conducted by and with Indigenous knowledge holders and a dichotomy between knowledge systems was never articulated.

Another limitation of the evidence base is the inherent bias towards peer-reviewed academic literature and underrepresents grey literature studies (from consultants or Indigenous organizations) or Indigenous-led initiatives that were not documented through publications or reports. The associated bias for written material versus other mediums (e.g., video documentaries) and the unnecessary emphasis on Western peer-review standards for credibility makes it difficult for non-academic community reports or Indigenous-led initiatives to bother going through the peer-review process as Western practices of peer-review do not align with Indigenous validation systems that are in place (see Loseto et al., 2020). Furthermore, some reports and studies may not be widely distributed or easily accessible. Indeed, community and Indigenous-led reports are often kept with Indigenous organizations and not shared with external researchers, organizations, and governments for varying reasons such as mistrust and fear. This last point speaks to the importance, more broadly, of strengthening and renewing relationships based upon recognition of rights – including knowledge sovereignty – and respect (see Wong et al., 2020 for a more in-depth discussion).

5 | CONCLUSION

Drawing upon all available ways of knowing to conserve and restore relationships between Indigenous peoples and the environment is critical (Fox et al., 2017). Furthermore, using Indigenous and Western sciences is an important undertaking which can strengthen the evidence-base, build trust, and enhance legitimacy for decision making (Alexander, Provencher, Henri, Taylor, Lloren et al., 2019; Ban et al., 2018; Henri, Martinez-Levasseur, et al., 2020; Johnson et al., 2016; Mistry & Berardi, 2016; Tengo et al., 2014).

5.1 | Implications for policy, management and research

Compiling a collection of case studies is a crucial first step in support of future analysis and/or evidence synthesis. For example, future in-depth analysis of such a collection of case studies could: (i) help identify better practices and approaches to guide future projects; (ii) provide critical insights for engaging with multiple knowledge systems; and (iii) highlight successful examples that offer promising pathways for moving forward (Alexander, Provencher, Henri, Taylor, Lloren et al., 2019). Indeed, this systematic map identified close to thirty published case studies that focused on the processes and practices of bridging knowledge systems in the context of decision-making. Further, in-depth analysis and evaluation of these case studies, especially when combined with the other approximately thirty case studies identified by Alexander, Provencher, Henri, Taylor, Lloren et al. (2019) could provide key insights and more nuance across different decision-making contexts (e.g., co-management of natural resources, conservation planning, regulatory decisions).

Bridging Indigenous and Western sciences, as illustrated across many of the case studies included in this systematic map: (i) highlights the many benefits that can come with applying multiple ways of knowing to devising management strategies (Reid et al., 2021) and; (ii) can further strengthen relationships with First Nation, Métis, and Inuit communities in Canada, which have often been marginalized from environmental research and decision making (Berkes, 2009). Furthermore, bridging knowledge systems offers a promising approach and pathway to help bend the curve on freshwater biodiversity (*sensu* Tickner et al., 2020) and achieve the UN Sustainable Development Goals (e.g., Goals 14 and 15). It is important to note though that not all Indigenous communities choose to engage with Western science, nor acknowledge the settler-state's forms of governance, instead choosing to maintain and practice Indigenous scientific and governance systems (Ariss & Cutfeet, 2012).

The results of this systematic map also provide key insights to inform the practices and processes associated with research and monitoring. First, there are many pathways and approaches to bridging Indigenous and Western sciences that can help to inform a wide diversity of research questions across multiple ecological and hydrological scales. However, these approaches are often contextual, place-based, and will vary depending upon the question at hand. Accordingly, further inquiry would help to parse out these different pathways. Second, it is important to remember that the methodological approaches and methods were operationalized through a wide suite of research practices. While not the focus of this review, Wong et al. (2020) highlight the importance and imperative of ethical research practices (e.g., free, prior, and informed consent). Similarly, a closer examination of the bridging and weaving process will be essential to identify examples that support the co-existence of knowledge systems and seek to 'remedy, rather than reinforce, existing power relations; respect differences, instead of suppress them; and uphold, as opposed to diminish, their unique strengths' (Reid et al., 2021, p. 4).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

The review process was coordinated by SMA and JJT. SMA, LN and AB conducted the screening of articles and data extraction. JFP and JIL contributed to data analysis. SMA led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

DATA AVAILABILITY STATEMENT

The systematic map database is archived in OSF: DOI 10.17605/OSF.IO/VM4AP (Alexander et al., 2021) and can also be found in Supporting Information (Supporting Information 3 Systematic Map Database). The R code and data files used for formatting and analysis can be access via OSF linked above.

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