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Review papers

Wildfire impacts on hydrologic ecosystem services in North American high-latitude forests: A scoping review

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ABSTRACT

High-latitude forests of North America are characterized by their natural dependence on large and severe wildfires. However, these wildfires also pose a range of social, economic, and environmental risks, with growing concern regarding persistent effects on stream flow volume, seasonal timing of flow, water quality, aquatic ecosystem health, and downstream community drinking water treatment. Here, we present the outcomes of a comprehensive scoping review of post-fire hydrologic studies in high-latitude forests of North America (Canada and Alaska). Our objectives were to (1) create an inventory of studies on post-fire hydrologic effects on surface water; (2) analyze those studies in terms of watershed characteristics and the type and duration of hydrologic effects; (3) identify and evaluate the link between upstream hydrologic effects with hydrologic ecosystem services; and (4) propose a research agenda addressing the link between wildfire science and hydrologic ecosystem services. We screened 2935 peer-reviewed articles and selected 82 studies to include based on their relevance according to a systematic, multi-step selection process. Next, we classified the papers into five themes: (a) runoff volume and flow regimes, (b) erosion and sediment transport, (c) water chemistry, (d) hydromorphology, and (e) aquatic food webs. For each study, we documented location, fire regime, watershed characteristics, and ecosystem services. The annual number of published studies on post-fire hydrology in high-latitude forests and, in particular, those addressing hydrologic ecosystem services, has increased steadily in recent years. Descriptions of wildfire characteristics, watershed characteristics, and effects on hydrologic ecosystem services were highly variable across studies, hindering cross-study comparisons. Moreover, there were limited efforts to extend study results to implications for forest or water management decisions regarding ecosystem services from source watersheds. Most studies focused on fire impacts on aquatic habitats and water chemistry while services of direct concern to communities, such as drinking water, were rarely addressed. We contend that study standardization, further use of geospatial technologies, and more studies directly addressing ecosystem services will help mitigate the increasing risks to water resources in northern forests.

1. Introduction

An ongoing planetary water crisis (Abbott et al., 2019) is increasingly threatening the current and future ability of forested watersheds to supply water to downstream communities and to maintain healthy aquatic ecosystems (Caldwell et al., 2016; Vörösmarty et al., 2018; Yang et al., 2017). From drinking water to fisheries, from flood mitigation to hydropower generation, "the benefits to people produced by terrestrial ecosystem effects on freshwater", referred to as hydrologic ecosystem services (*HES*, Brauman et al., 2007, p.6), are an essential component of the water security paradigm (i.e., the guarantee of safe access to sustainable quantities of quality water to fulfill daily personal needs and promote socio-economic development). The *HES* concept acknowledges the fundamental connection between forests and water, such that upstream disturbances may affect watershed processes and functions and their ability to sustain the wellbeing of downstream users

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by providing multiple services and benefits (Brauman, 2015; Brauman et al., 2007; Carvalho-Santos et al., 2014).

Among the many concerns for long-term water security, climate change and the associated upsurge of both biotic (e.g., insects, pathogens) and abiotic (e.g., droughts, wildfires) disturbances have increasingly impacted water supplies and decreased the resilience of temperate and boreal forests (Gauthier et al., 2015; Seidl et al., 2017; Stephens et al., 2014). In particular, changing wildfire activity in many regions of the planet, including high latitude forests of North America, has increased the risks to water supplies (Bladon, 2018; Coogan et al., 2019; Doerr and Santín, 2016; Robinne et al., 2019). Wildfires are a common natural disturbance in northern latitudes; however, many recent studies suggest that ongoing climate change is already changing burning conditions, with longer fire seasons, hotter and drier weather, and greater lightning activity leading to more frequent and severe wildfires (Flannigan et al., 2009; Wang et al., 2017; Young et al., 2017). Furthermore, the growing number of people attracted to northern regions for employment and recreation has influenced ignition patterns and increased the exposure of communities and watersheds to risks from fire activity (Johnston and Flannigan, 2018; Parisien et al., 2016; Robinne et al., 2016).

Fire, either natural or human-caused, has a dual effect on the capacity of ecosystems to benefit humans. While frequent, low severity, natural wildfires can help maintain forest ecosystem health and related services such as wood production, biodiversity, and recreational activities, increasingly large and severe fires can generate more toxic smoke and contaminate water (Sil et al., 2019). As a result, high severity wildfires have the potential to disrupt a broad range of ecohydrologic processes and functions in forested watersheds, such as interception, infiltration, evapotranspiration, and storage (Ebel and Moody, 2017; Poon and Kinoshita, 2018). In turn, these effects can result in rapid runoff responses, increased surface runoff, elevated erosion and sediment delivery to streams, and greater potential for mass movements (Kinoshita and Hogue, 2011; Rengers et al., 2016; Robichaud et al., 2016). These impacts may lead to deteriorated physical and chemical water quality, with potentially substantial and long-lasting effects on *HES,* such as the provision of community drinking water supply or recreational water uses (Hohner et al., 2019; Kinoshita et al., 2016; Vukomanovic and Steelman, 2019). As human population and industrial development keep growing, the reliance on *HES* from forested watersheds in many regions, including high latitude forests in Canada and Alaska, will also continue to increase (Erdozain et al., 2018; Lamothe et al., 2019; Webster et al., 2015). These growing pressures will add to existing acute water security issues in northern communities (Bradford et al., 2016; Penn et al., 2017).

In northern forested regions, water is a defining ecological, social, and economic element. For example, in Alaska, there are more than 12,000 rivers and streams draining into more than 3-million lakes larger than 2.5 ha (Alaska Department of Fish and Game, 2006). Canada has the third largest renewable freshwater supply in the world with nearly 10% of global renewable water resources (Bakker, 2007; Statistics Canada, 2017). These surface water resources provide 75% of domestic, agricultural, and industrial water use in Alaska, while providing 88% of the drinking water and 68% of the hydropower generation in Canada. Anielski and Wilson (2005) estimated the annual value of hydrologic services from the boreal forest at nearly $72-billion CAD (2002 dollars). Water also is culturally important, especially in northern latitudes, where it is often related to spiritual tradition, peoples' identity, and aesthetic and recreational values of the landscape (Brauman et al., 2007). In Canada, the Heritage River System protects 12,000 km of rivers of historical and recreational importance (Canadian Heritage Rivers System, 2010), while the Watermark Project, an online archive of personal stories and local knowledge about people's relationships with water, gives access to hundreds of testimonies from a diversity of water users (Swim Drink Fish Canada, 2016). These efforts highlight the strong dependence of Indigenous communities on healthy aquatic ecosystems for subsistence and spirituality, which remains a defining feature of northern identity (Wilson et al., 2019; Wilson and Inkster, 2018).

In light of the ongoing changes in wildfire regimes in North American high latitude forests, maintaining healthy forested watersheds that will continue to provide a wide range of *HES* is critical. This necessitates specific wildfire management practices in at-risk watersheds (e.g., fire regime restoration, fuel treatment, suppression, or post-fire restoration), informed by established scientific knowledge (Creed et al., 2017; Steenberg et al., 2019; Yeung et al., 2018). At present, there is no unified vision regarding the range of post-fire effects on *HES* as existing work is either outdated (Carignan and Steedman, 2000; Prepas et al., 2003b), narrowly focused on a subset of post-fire impacts to surface hydrology (e.g., river geomorphology; Owens et al., 2013), or has only considered a single natural region (e.g., Western Cordillera; Silins et al., 2014). Moreover, although several recent studies have echoed the growing concern of wildfire risks to water security (Bladon et al., 2014; Martin, 2019; Robinne et al., 2018), there is no formal assessment of the current state of knowledge in post-fire hydrology and the related risks to *HES* in northern latitude forests that would benefit viable watershed protection strategies. Notwithstanding the importance of this earlier work, the need to assemble the current state of knowledge on this topic is paramount to facilitate development of sustainable land management decisions and to inspire future research efforts. Specifically, if we are to address present and future compound wildfire-water risks (Hallema et al., 2018a), we need to answer the following question: What are the consequences of wildfires in high-latitude forested watersheds on surface hydrology and the provision of downstream hydrologic ecosystem services?

To begin to answer this question, we present a scoping review to document scientific knowledge on wildfire effects on watershed functioning and how these effects might impact the provision of *HES* to downstream communities. Our review covers forested watersheds of Canada and Alaska dominated by nival (i.e., streamflow regime dominated by snowmelt) to pluvial-nival (i.e., streamflow regime dominated by mixed rain and snowmelt) hydro-climatic regimes and mostly located in boreal mixedwood and Pacific conifer forests (Fig. 1). The objectives of this review were to: (1) collect, using a systematic design, studies focused on post-fire hydrologic effects on surface hydrology; (2) collect and analyze the characteristics of those studies regarding fire regime description and the nature and duration of post-fire effects on a range of surface hydrologic features; (3) assess the extent to which those studies translated potential post-fire hydrologic effects into consequences—positive or negative—on the provision of *HES*; and (4) propose a research agenda that addresses key knowledge gaps in post-fire surface hydrology in Canada and Alaska, and promotes the integration of the ecosystem services approach into wildfire risk assessment. The resulting synthesis reflects the current understanding of wildfire risk to *HES* and water security in this part of the world.

2. Materials and methods

2.1. Review type

A scoping review is a rapid and systematic approach to complete a comprehensive survey of the available, yet often scattered, knowledge pertaining to a research area whose complexity and/or novelty hinders a more traditional, in-depth type of review. The scoping review framework has gained popularity during the past two decades, particularly in the medical field (Pham et al., 2014), and several recent references illustrate that this framework may be used to address pressing environmental questions such as wildfire, water security, and ecosystem services (Bradford et al., 2016; Hanna et al., 2018; Marshall et al., 2018; Vukomanovic and Steelman, 2019).

A scoping review provides a "descriptive account of available research" (Arksey and O'Malley, 2005, p.30) that depicts and

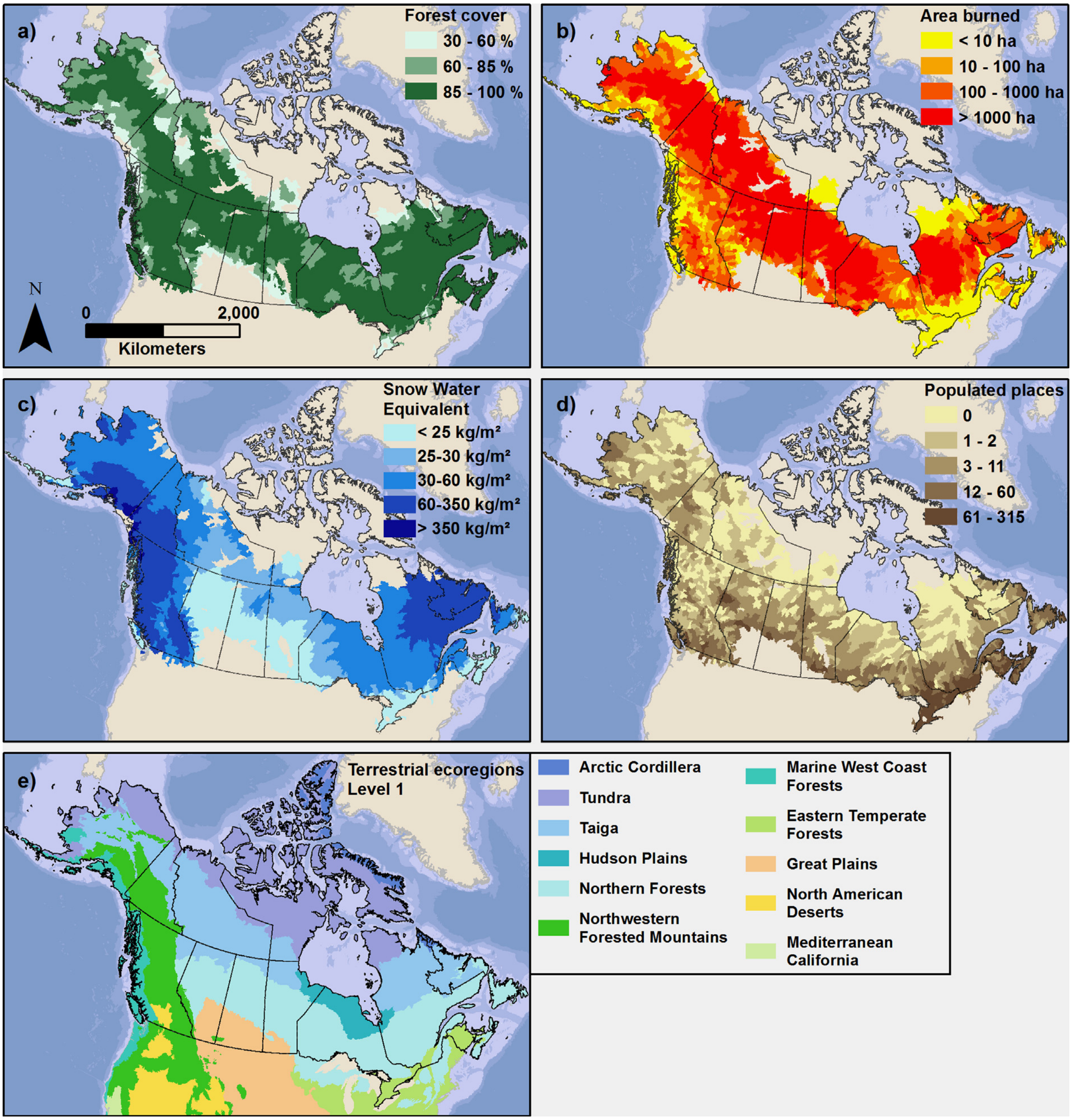

Fig. 1. Sub-sub-drainages (equivalent to Hydrologic Unit Code level 8, or HUC-8, used in USA) covering northern latitude forests of North America, displaying environmental indicators relevant to the study of wildfire-water risks to freshwater ecosystem services, with: (a) percent forest cover, (b) total area burned (1980–2017) normalized by the forest cover, (c) snow water equivalent (i.e., the theoretical amount of liquid water obtained if the snow were to be melted), (d) number of communities (Robinne, 2019), and (e) the terrestrial ecoregions of North America (Commission for Environmental Cooperation, 2009a).

disseminates the current state of scientific knowledge on a given topic. Analysis of the collected material remains superficial in nature and its quality is not assessed in depth, if at all. In other words, a scoping review is a preliminary study identifying research gaps for which further meta-analysis or state-of-the-art reviews will be necessary. It is, therefore, more accessible and of greater value for introducing emerging scientific topics to managers and policy-makers compared to more complex reviews.

We followed a systematic approach based on recommendations from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement and protocol for systematic reviews (Moher et al., 2015, 2009). However, we prioritized the published research and evaluated its quality only as needed to address the objectives of this study (Arksey and O'Malley, 2005). Thus, the scoping review process facilitated evaluation of a large body of literature, which allowed us to summarize the current state of knowledge and to identify important research gaps (Grant and Booth, 2009; Marshall et al., 2018; Pham et al., 2014).

2.2. Study search

Our review focused on surface water bodies, including lakes, reservoirs, ponds, ephemeral and permanent streams, and rivers. We constrained our review to surface water sources in northern regions because: (1) Canadian and Alaskan communities and economies rely heavily on surface water resources for diverse purposes, including domestic use, industrial uses, and ecotourism (Alessa et al., 2011; Lemelin et al., 2015; Statistics Canada, 2017); (2) Canadian and Alaskan forests are naturally fire-prone, a characteristic that is likely to strengthen with global change (Stocks et al., 2002; Wotton et al., 2017); and (3) there is

Table 1
Hydrologic ecosystem services and associated examples as defined by Brauman et al. (2007).

Extractive water supply	Irrigation, industrial water withdrawal, drinking-water
Improvement of in-stream water supply	Recreation, transportation, fish supply
Water damage mitigation	Flood and/or drought damage, reservoir sedimentation
Provision of cultural services	Religious, recreational, educational, and tourism uses
Supporting services	Habitat conservation from adequate water and nutrient inputs

scientific evidence of water security impairment due to wildfires (Emelko et al., 2011; Hohner et al., 2019; Smith et al., 2011).

We searched Scopus and Web of Science databases by topic, looking for specific terms in the title, the abstract, and the keywords only. The queries and keywords extensively targeted the association of aquatic or hydrologic vocabulary to vegetation fire and the consequences of burning (Supporting Information S1). We also applied forward-backward author searching, also called citation chaining, to collect references linked to authors either frequently identified by search engines or often cited in topical papers, until no new study could be retrieved. We listed 25 authors whose publications were individually searched for on both Scopus and Web of Science (Supporting Information S1). Finally, nine studies known to the authors, and considered relevant to this work, were added to the pool of studies to be screened (Supporting Information S1).

The search was limited to research published in English language peer-reviewed scientific journals or in French language journals, which had been translated to English. We did not constrain our search to specific years; thus, we included any 'pioneer' papers completed up to July 2018, the time of the search.

2.3. Study screening

After the original database search, we imported the list of studies to the reference manager Mendeley Desktop version 1.19.3 (Mendeley Ltd, 2019). We then screened and selected relevant studies in three steps. Reading the titles provided a first filter that helped eliminate entries unrelated to the topic of the review. Second, abstracts of remaining entries were read to check for their *a priori* relevance. We discarded, for instance, several studies whose abstracts described post-fire changes in forest-stand water budget (e.g., evapotranspiration), as well as studies whose abstracts mentioned fire and water in a different context (e.g., structural firefighting). We also removed paleo-ecological studies, unless they presented a link between fire and surface water that extended to modern days (i.e., 1980 onwards). Finally, we removed reviews, reports, and conference proceedings.

2.4. Study eligibility

Studies that remained after our initial screening were read by two of the co-authors. Initially, we read a subset of five studies to identify the relevant information we needed to gather and the appropriate level of detail to include. We used this information to develop a data-charting form, which was cross-verified for quality-control and adjusted, leading to modification of the form structure (Supporting Information S2). For each study, relevant details were collected and stored in a standardized format using the descriptive-analytical method of Arksey and O'Malley (2005) and implemented in the PRISMA protocol. In total, we included 34 study attributes in the data charting form. Irrelevant studies were "flagged" so they would not be included in the final data analysis.

Specifically, the information we collected included metadata (e.g., author, year of publication), study location, watershed physiography, fire characteristics, post-fire weather, type of water body, type of hydrologic process and/or function affected, direction of the effect (i.e., positive, neutral, negative), data analysis method, and whether or not a potential effect on *HES* was reported (i.e., yes or no) and/or evaluated (i.e., positive, neutral, negative). Fire characteristics were based on fire history, fire severity, and fraction of watershed burned. Comparatively, watershed physiography was based on basin dominant slope while precipitation characteristics were based on reported timing and intensity, which are generally the dominant controls over post-fire changes in hydrologic processes and functions (Hallema et al., 2018b; Miller et al., 2011; Moody et al., 2008; Shakesby and Doerr, 2006).

Where possible, we also extracted details regarding hydrologic ecosystem services (*HES*) from each study (Brauman et al., 2007; Carvalho-Santos et al., 2014; Ojea et al., 2012). Specifically, we noted (a) whether or not a *HES* was mentioned, (b) what type of *HES* was considered (Table 1), and (c) the direction of the effect due to wildfire.

2.5. Data analysis

Study locations were used to create a point vector layer in ArcGIS 10.5 (Environmental Systems Research Institute, 2017), allowing us to assess the spatial distribution of research. However, location information was provided in various ways in the reviewed studies, including: name of the watershed, a map, or coordinates of a point with or without specification regarding the reference point(s) (e.g., hydrometric station, watershed centroid, bounding box). We used ancillary spatial datasets to add information pertaining to ecoregions (Commission for Environmental Cooperation, 2009b), to country and state/province/territory, and to the sub-sub-drainage basin (equivalent Hydrologic Unit Code level 8 in Alaska) (Natural Resources of Canada, 2012). This facilitated assessment of the degree to which the reviewed studies were representative of northern forests. Further visualization and analysis of non-spatial attributes was accomplished using Tableau Software 2019.1.0 (Tableau Development Team, 2019).

3. Results

3.1. General observations

We performed all database searches on July 19, 2018, chaining on July 23, 2018, with seven additional studies added based on co-author knowledge on August 21, 2018. We identified 2935 potentially eligible studies after removing duplicates. The screening stage yielded 95 studies, and 82 were included in the data analysis after charting (Fig. 2, Supporting information S3).

Of the 82 studies, six were in Alaska and 76 in Canada. There were several "clusters" where experimental watersheds were located in Québec, north-western Ontario, central and northern Alberta, and in the southern Rocky Mountains and Caribou Mountains in Alberta and British Columbia. For instance, seven studies came from the Forest Watershed and Riparian Disturbance (FORWARD) project in central Alberta (McEachern, 2016), illustrating the importance of long-term monitoring (Fig. 3, Supporting information S4). However, there were no studies conducted in seven out of the 13 Canadian provinces and territories, most of which display geographic factors (e.g., historical area burned, existence of populated places) conducive to post-fire risks to community water supplies (Fig. 1).

Of the 22 ecoregions (Level II, Commission for Environmental Cooperation, 2009) intersecting northern forest watersheds (forest cover > 30%), 11 were represented in the data based on study location. *HES* were mentioned in 41 studies (50%), yet only 24 (29%) indicated the direction of the impacts (Supporting information S5). The studies

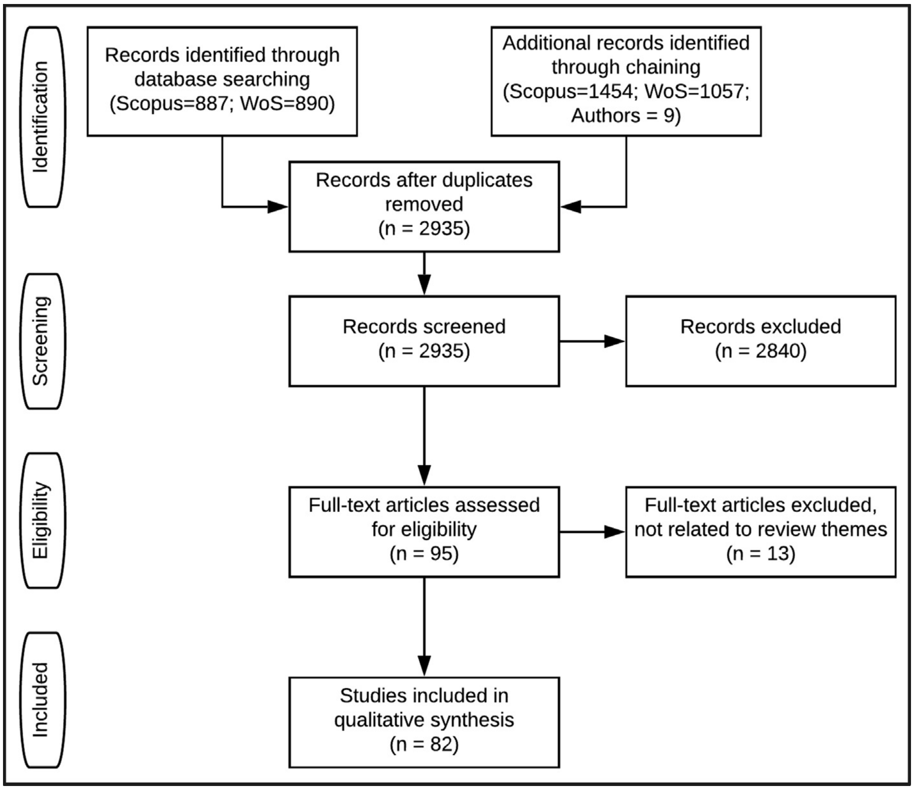

Fig. 2. Details of the review process according to the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) protocol. Eligibility criteria providing reasons for the exclusion of a study are provided in the Methods.

included in our review covered 39 years, from 1980 to 2018, with a clear increasing trend both in the number of studies on wildfire effects on hydrology and the consideration of the effects on *HES* (Table 2, Fig. 4). Post-fire changes in water quality and aquatic ecosystem function were the main focus, with 32 dedicated studies each (Fig. 5). Reviewed articles also focused primarily on supporting ecosystem services, linking changes in watershed function to habitat conservation issues and nutrient cycling (Fig. 6).

The vast majority of studies did not provide the full range of details on the wildfire characteristics, watershed physiography, or post-fire

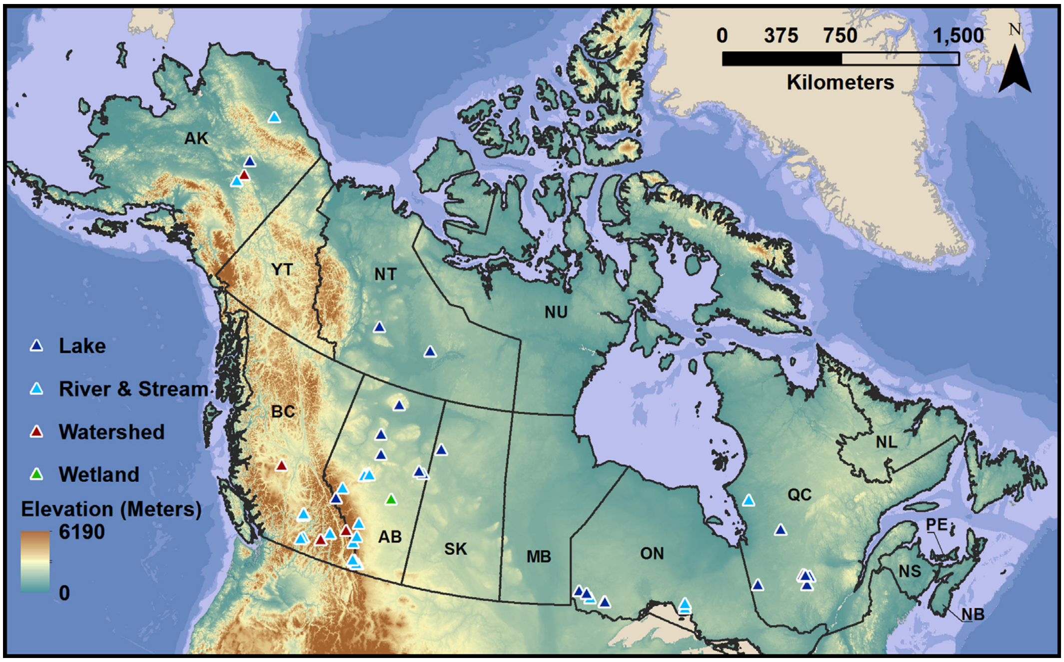

Fig. 3. Spatial distribution of the 82 scientific studies included in the analysis as a result of the scoping review process. Note the clusters of studies near the Gouin reservoir in Québec, the Experimental Lake Area in Ontario, and in the southern part of the Western Cordillera. **Labels:** AK: Alaska; YT: Yukon; NT: Northwest Territory; NU: Nunavut; BC: British Columbia; AB: Alberta; SK: Saskatchewan; MB: Manitoba; ON: Ontario; QC: Québec; NL: Newfoundland-Labrador; NS: Nova Scotia; NB: New Brunswick; PE: Prince Edouard Island.

Table 2
General characteristics of reviewed studies (n = 82) looking at post-fire changes in hydrologic processes and functions and potential effects on the provision of hydrologic ecosystem services.

Characteristic	Number (n = 82)	Percentage (%)
Publication decade		
1980–1990	1	1
1990–2000	7	9
2000–2010	43	52
2010–2020	31	38
Country - Province[1]		
USA – Alaska	6	7
Canada – Alberta	32	39
Canada - British Columbia	15	18
Canada - Northwest Territories	2	3
Canada – Ontario	10	12
Canada – Québec	16	20
Canada – Saskatchewan	1	1
Ecoregion[2]		
Alaska Boreal Interior	1	1
Alaska Tundra	1	1
Boreal Cordillera	4	5
Boreal Plains	14	17
Cold deserts	9	11
Mixed Wood Shield	21	26
Softwood Shield	4	5
Taiga Plains	5	6
Taiga Shield	2	3
Temperate Prairies	1	1
Western Cordillera	20	24
Hydrologic ecosystem service		
Extractive water supply	4	5
Improvement of in-stream water supply	6	7
Water damage mitigation	2	2
Supporting services	41	50
Multiple	16	20
Not mentioned	13	16

[1] Province is used here as a general term merging provinces, territories, and states.

[2] Level II, as defined by the Commission for Environmental Cooperation.

weather. In 84% of the studies (69 of 82) at least one detail regarding these elements was not mentioned (Table 3), (Fig. 6).

3.2. Runoff and flow regime

Post-fire changes in runoff or flow regime were quantified in 19 studies (23% of total studies). Authors reported effects of wildfire on various aspects of the hydrologic regime, including: mean annual or seasonal water yield, mean annual or daily peakflow timing and duration, hydrograph accession-recession curves (“flashiness”), total annual or daily runoff, and snow-water equivalent and snowmelt timing. Most studies emphasized the importance of precipitation variability in controlling the magnitude and longevity of the post-fire hydrologic response. However, hydrologic response was highly variable both across and within studies.

3.3. Erosion and sediment transport

Our review found 15 studies (18%) quantifying the effects of wildfire on erosion or sediment transport. Most indicated a distinct post-fire increase in either bedload transport or suspended sediment in streams. In-stream total suspended sediment varied significantly throughout the duration of any given storm event, but was generally highest on the rising limb of the first major storm event following a fire. Bedload flux did not follow this trend but gradually increased during the weeks after fire, only to decline again after several years following vegetation re-establishment. No evidence was found for wildfire effects on erosion and sedimentation in lakes and rivers in eastern Canada. In some cases authors noted that fires were not hot enough to burn the humus layer entirely, and argued that flat topography promoted the accumulation of thick organic soils protecting the underlying mineral soil.

3.4. Water chemistry

Our review found 32 studies (39%) that quantified wildfire effects on aquatic chemistry. Stream chemistry and water quality response to wildfire varied greatly depending on wildfire severity and environmental characteristics of the watershed. For example, high severity wildfire in the Canadian Rocky Mountains led to higher concentration of nitrogen (e.g., nitrate, dissolved organic nitrogen, total nitrogen), as well as phosphorus (P). Further north, increased N in boreal forest streams after a high severity fire was likely associated with recovering vegetation, because boreal forest soils are naturally N-limited. Conversely, N response in lacustrine systems seemed ephemeral, even after severe wildfire.

Changes in dissolved organic carbon (DOC) concentrations in tundra streams were limited, possibly due to decreased hydrologic connectivity between slopes and streams as a result of permafrost collapse (i.e., thermokarst). In Alaska, post-fire DOC inputs into streams were higher, but no such link was found for lakes on the Boreal Plains where the lack of change in post-fire DOC concentrations in lakes indicated they might be primarily groundwater-fed.

3.5. Hydromorphological processes

Hydromorphological processes influencing physical attributes of water bodies over time were addressed in 11 studies (13% of total studies). Studies showed that large and severe fires led to a sharp increase in in-stream loading of large wood, followed by a long-term decrease of woody inputs from the surrounding land as the forest recovered. Self-thinning of dead snags after a fire was yet another source of wood reaching streams for several decades after fire. In many cases, the increased input of large wood in the years following fire favored enhanced sediment storage behind large wood jams. Increased sediment input from bank erosion due to root decay also coincided with changes in channel morphology, with the appearance of bars and a more complex morphology (i.e., riffle-pool type). Damaging mass movements in severely burned watersheds, which were reported in southern British Columbia, were likely triggered by accelerated post-fire snowmelt or long-duration precipitation events.

3.6. Aquatic food webs

Aquatic ecosystem response to wildfire was addressed in 32 studies (39% of total studies). Lower trophic levels (i.e., plankton) in lakes showed contrasting response to fire; indeed, many studies reported no change or a marginal difference in overall species diversity compared to unburned or pre-fire conditions whereas biomass, particularly at lower trophic levels, tended to increase. A few studies observed post-fire decreases in biological activity, altered community composition, species richness and/or densities, whereas many studies indicated beneficial effects of fire with higher species population density and biological activity. The duration of post-fire effects was highly variable; some studies observed legacy effects lasting ~15–20 years, while others have observed short-lived effects (1–2 years). Post-fire effects on higher trophic levels (i.e., fish assemblage and populations) seemed limited, or even positive, at least in the short term.

Studies focusing on streams were mostly conducted in small headwaters. Post-fire environments favored biological activity, stream productivity and overall species diversity. This was due to the influence of nutrient and organic matter enrichment of the complete trophic chain over several years post-fire—from phytoplankton and microbial communities to fish. For larger aquatic animals (i.e., beavers and

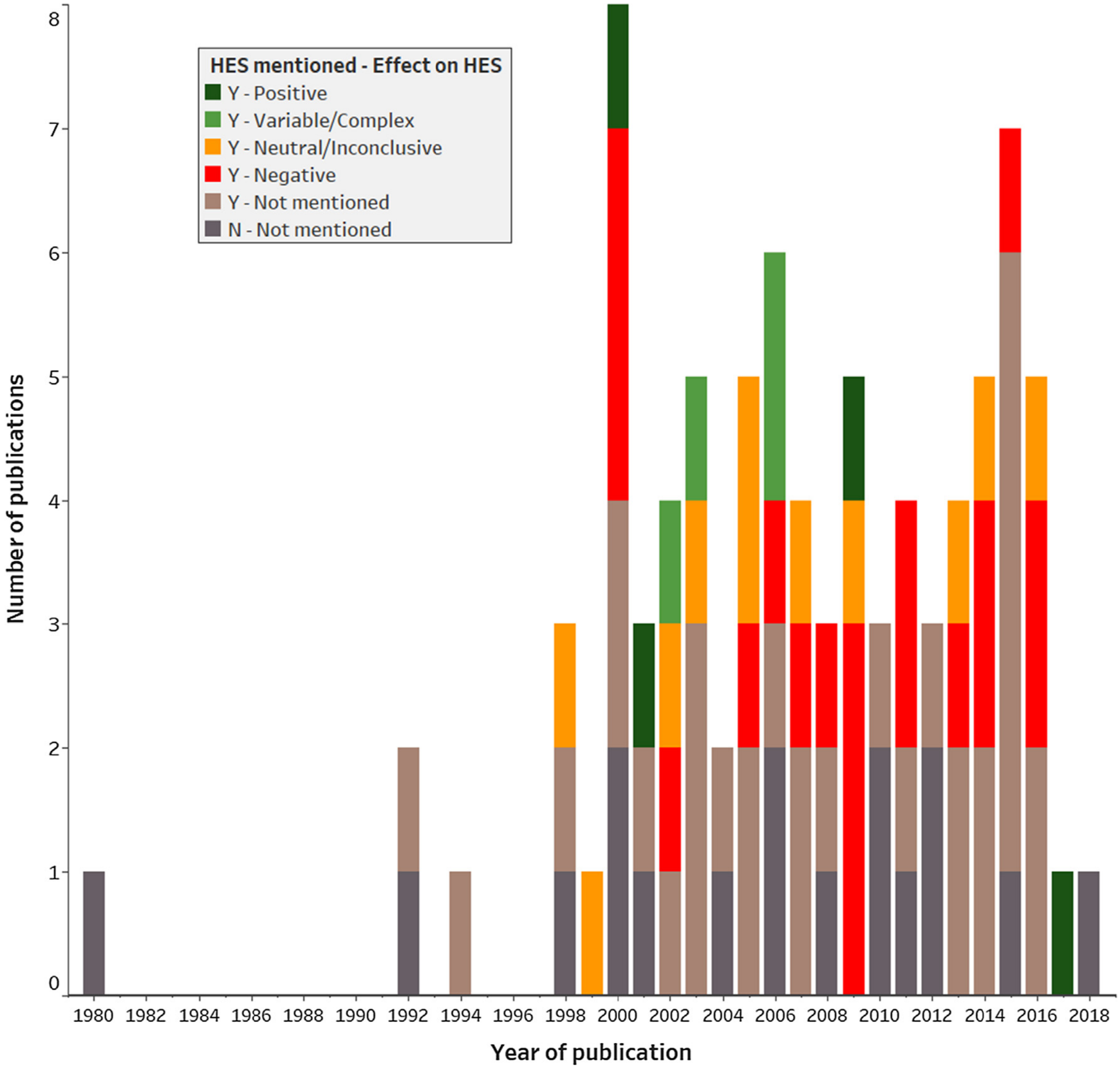

Fig. 4. Number of peer-reviewed studies looking at the consequences of wildfire activity for hydrologic processes and functions in Alaska and Canada, per year. The color code refers to the combination of potential effects on hydrologic ecosystem services (N for No, Y for Yes) and the direction of these effects according to the study results (Variable/Complex, Positive, Neutral/Inconclusive, Negative, Not mentioned). For instance, Y-Negative means that the study detected negative effect(s) of fire on HES.

waterfowls), three relevant studies provided totally different outcomes, with beavers negatively affected by even low intensity fires, whereas boreal waterfowls were resilient to fire activity and frequent prescribed burns.

Bioaccumulation of mercury (Hg) and methyl mercury (MeHg) has been a major research theme since the late 1990s, particularly in lake ecosystems. Available studies show contrasting results: a strong increase in bioaccumulated MeHg in a mountain lake, a decrease in MeHg concentration in a boreal plain lake, and no difference in MeHg or Hg concentrations in water or along the trophic chain in another boreal plain lake.

4. Discussion

4.1. State of knowledge

Our scoping review of 82 studies conducted in Canada and Alaska, revealed a positive trend in the number of studies addressing post-fire changes in hydrology and impacts to ecosystem services—a trend that we expect to continue (Musetta-Lambert et al., 2019; Robinne et al., 2019; Tank et al., 2019). While this increase in published research is likely due to increasing concern about the issues associated with wildfire on water supplies (Coogan et al., 2019; Hanes et al., 2019), some of this trend may be due to an overall increase in the number of studies published in environmental sciences over the past four decades (Aznar-Sánchez et al., 2019). Although the majority of historical studies across northern latitudes in Canada and Alaska quantified the effects of wildfire on aquatic ecosystem health or water chemistry, there was a notable increase in the emphasis on the threats of wildfire to community water supply (Emelko et al., 2016; Mahat et al., 2016; Winkler et al., 2015).

Geographically, the studies were concentrated in small clusters dispersed across the vast Canadian territory and Alaska. Consequently, some ecological regions with different wildfire regimes, hydrology, and socio-economic activity, have been overlooked. Yet further comparison with available data (Fig. 1) coupled to projected changes in wildfire regimes and hydrologic functioning indicates the ubiquity of post-fire challenges to water supplies, albeit with different local challenges (Al Ibrahim and Patrick, 2017; Price and Heberling, 2018; Robinne et al., 2019). For instance, Al Ibrahim and Patrick (2017) mentioned wildfire threats to the water supply of Halifax, Nova Scotia (population ~ 400,000); however, no wildfire-water risks study appears to

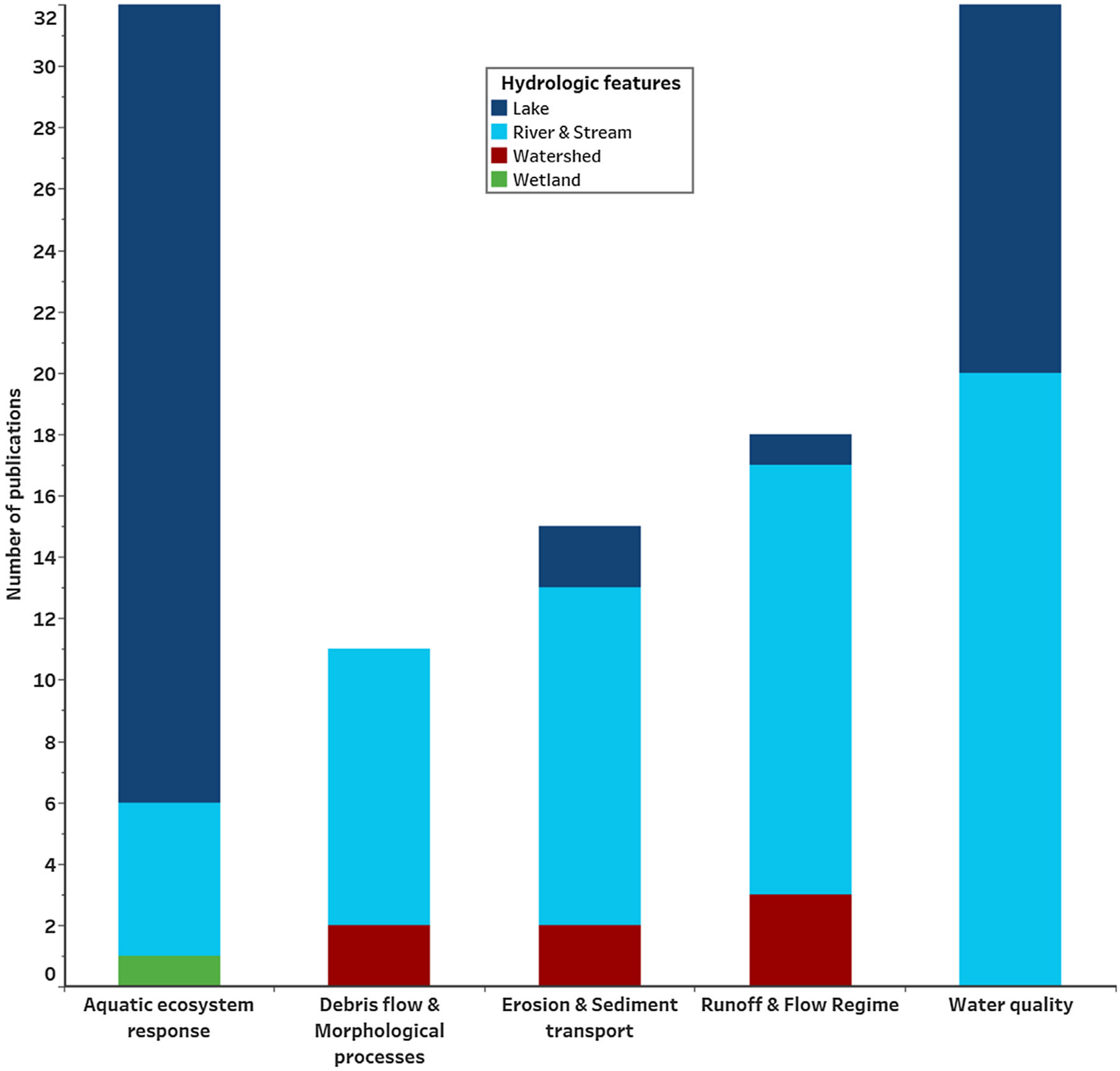

Fig. 5. Number of peer-reviewed studies as a function of the hydrologic theme(s). Eighteen studies were counted twice and four studies were counted three times as they addressed more than one theme. The color scheme refers to the type of hydrologic feature and matches that used on the map in Fig. 3.

have been conducted in Nova Scotia to date. Even in well-studied ecological regions the causes of differences in watershed response to fire remain difficult to decipher (Owens et al., 2013; Pomeroy et al., 2012; Silins et al., 2009; Springer et al., 2015). Indeed, the inherently opportunistic nature of wildfire-hydrology field research often means that pre-fire data are not available. This underscores the importance of long-term monitoring and field campaigns for data collection (Blöschl et al., 2019; Burt and McDonnell, 2015; McDonnell et al., 2018).

Our review found that the previous research across the study region has included a diversity of foci, data, and methods, which illustrates strong heterogeneity in approaches to wildfire and water problems in Canada and Alaska. Most importantly, there has been a high degree of variability in the descriptions of the fire characteristics, watershed topography, and precipitation, which hinders cross-site comparisons (Neary et al., 1999; Shakesby and Doerr, 2006). Some of this variability is due to: (a) a lack of pre-fire data, which does not allow the researcher to accurately quantify fire severity or pre-fire hydrology; (b) the short-term funding cycle that does not facilitate longer-term research on these topics; and (c) the comparatively few number of studies on post-fire fire hydrology to permit detection of trends, if present, within and across regions (Bladon et al., 2014; Blöschl et al., 2019; Moody et al., 2013). In addition, the diversity of study designs makes comparisons difficult. Notably, the sample size varied considerably (i.e., between one and 50 lakes), while in some cases the sample size changed over the course of the study whereas others mixed a set of streams and lakes.

The contrasting post-fire response of lacustrine ecosystems indicated that the environmental settings of lakes (e.g., size, depth, trophic status, peatland cover, drainage ratio, input precipitation) remained the main controls of post-fire response (> 80% variance explained in some cases) (e.g., Lewis et al., 2014; Patoine, 2002; Pinel-Alloul et al., 1998; Planas et al., 2000). For instance Charette and Prepas (2003) showed that phytoplankton response to fire—including toxic cyanobacteria—was likely controlled by depth in Boreal Plains headwater lakes. McEachern et al. (2002) and Jalal et al. (2005) suggested that wildfires in peat dominated watersheds likely would not result in increased primary productivity, which is counter to most stream studies that have illustrated that fire results in increased nutrients, increased algal productivity, and the associated public health implications. They attributed this lack of algal response in peat dominated watersheds to amplification of N limitation and light extinction due to higher DOC exports.

Shield, Plains, and Cordillera ecoregions also showed clear differences in lakes post-fire response, with a generally greater response in mountain and shield zones (Garcia et al., 2007; Garcia and Carignan, 2000) compared to the plains (Lewis et al., 2014). For instance, Kelly et al. (2006) showed a 5-fold increase in mercury (Hg) accumulation in

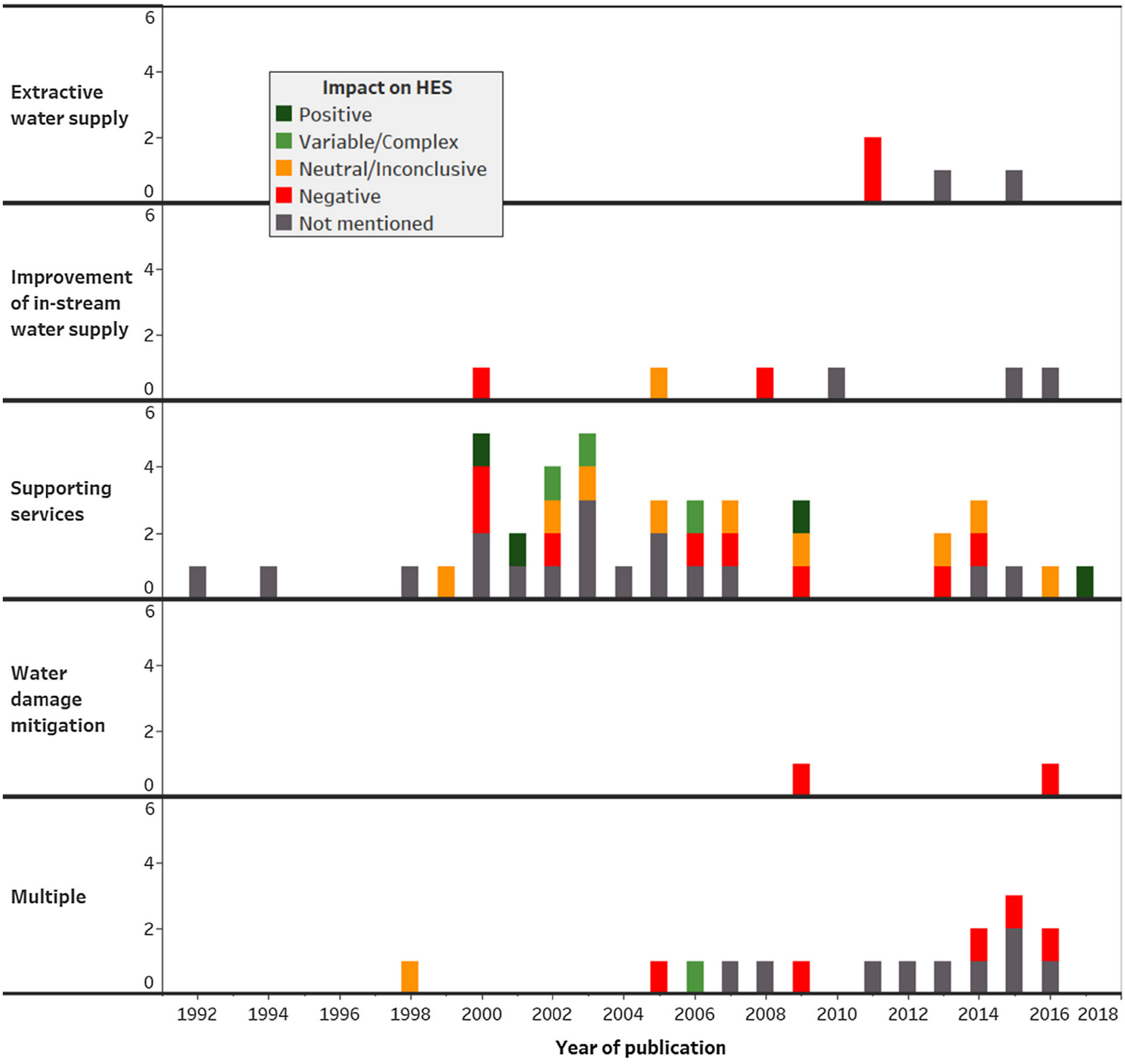

Fig. 6. Direction of the impact of wildfire on hydrologic ecosystem services, per type of service, for the studies that mentioned a potential impact.

rainbow trout in a mountain lake, reaching concentration levels potentially harmful to human health. Alternatively, Allen et al. (2005) showed a decrease in MeHg concentration in a boreal plain lake, which has previously been related to post-fire increases in DOC and productivity of lower trophic levels (Garcia and Carignan, 2005, 1999). In contrast to observations of increases and decreases in Hg after wildfires, Garcia and Carignan (2000, 1999) showed no difference in MeHg or Hg concentrations in water or along the trophic chain in the boreal plains. These contrasting observations highlight the many uncertainties that remain regarding the differential effects of wildfires on water quality across ecoregions.

Our review also showed that the hydrologic response of northern riverine ecosystems to fire is highly variable. In some studies, both annual streamflow and peakflows increased post-fire (e.g., Pomeroy et al., 2012; Springer et al., 2015), while in other studies only annual water yields increased (e.g., Eaton et al., 2010a; Mahat et al., 2015). For example, Schindler et al. (1980) reported a two-year increase in annual yield after fire, even under drier conditions on the Canadian Shield, including higher baseflows. Comparatively, Pelster et al. (2008) reported higher water yield six years after fire in the Boreal Plains.

Conversely, our review indicated that observed wildfire impacts on erosion mechanisms and water quality in northern watersheds might have important implications for watershed health and downstream water supplies. Several studies in headwaters showed post-fire stream contamination by excess nutrients, DOC, chemicals (e.g., mercury), and sediments that could create various challenges for the production of drinking-water (Emelko et al., 2016, 2011; Silins et al., 2014) or the consumption of aquatic food (Kelly et al., 2006). For example, Beaty (1994) reported a 20-fold increase in bedload transport the first year following an initial fire in northwestern Ontario that resulted in a 20-fold increase in bedload transport during the first post-fire year. Similarly, P concentrations were elevated up to 7 years after wildfire and over 10 km downstream of the burned area in a study in the Rocky Mountains (Emelko et al., 2016). Wagner et al. (2014) reported a change in stream thermal regime, with 1.0–3.0 °C increases in mean daily maximum temperature in burned watersheds of the Rocky Mountain, which can negatively impact cold-adapted aquatic organisms. Despite a majority of studies focusing on water chemistry, we note a lack of quantitative information on certain chemicals released during and after wildfire. For example, studies in North Carolina and New Mexico point to increased post-fire levels of free cyanide from ash, and sodium ferrohexacyanide from fire retardant, respectively, in surface runoff (Barber et al., 2003; Gallaher et al., 2002). Depending on the timing and concentration of release this can have episodic toxic effects

Table 3
Details pertaining to fire characteristics, watershed topography, and post-fire precipitation, as described in the reviewed material (n = 82).

Characteristic	Number (n = 82)	Percentage (%)
Description of fire history		
Yes	34	41
Not mentioned	46	56
Simulated	2	3
Fire date		
Before 1980	3	4
1980–2000	35	43
After 2000	30	36
Multiple	10	12
Not mentioned	4	5
Time since fire		
Less than a year	11	13
1–3 years	35	43
3–10 years	14	17
> 10 years	7	9
Multiple	9	11
Not mentioned	6	7
Fire severity		
Moderate	3	4
High	48	59
Not mentioned	31	37
Percent watershed burned		
< 20%	1	1
20–30%	2	2
30–80%	31	38
> 80%	21	26
Not mentioned	27	33
Watershed topography[1]		
Little or none (< = 3%)	3	4
Gentle (4–9%)	23	28
Moderate (10–15%)	4	5
Steep (16–30%)	14	17
Complex/variable	3	4
Not mentioned	35	42
Post-fire precipitation		
Below average	13	16
Average	4	5
Above average	1	1
Complex/variable	17	21
Stormy	4	5
Not mentioned	43	52

[1] Average watershed slope expressed as %.

on aquatic life, however studies on post-fire cyanide are few in number and we found none for high-latitude forests.

Northern watersheds are highly influenced by permafrost and snow. Permafrost adds another dimension to post-fire water chemistry, because it acts as a barrier to infiltration and transportation of nutrients to deeper soil layers, and restricts water to the active layer (Petrone et al., 2007). Discontinuous permafrost may regulate stream solute concentrations by forcing hydrologic flowpaths through the organic surface layer, resulting in strong variations in dissolved organic matter (DOM) inputs after a fire (Betts and Jones, 2009; Petrone et al., 2007).

Many studies also provided strong evidence for increased snow-water equivalent in burned areas (e.g., Burles and Boon, 2011; Pomeroy et al., 2012; Winkler et al., 2015), an earlier and shorter snowmelt freshet (e.g., Burles and Boon, 2011; Winkler et al., 2015), and a greater contribution of snowmelt to annual streamflow (e.g., Eaton et al., 2010a; Owens et al., 2013). Although Mahat et al. (2015) showed an increase in peakflows due to snowmelt runoff, several studies noted the opposite response, which was likely due to a decoupling of snowmelt between burned and unburned areas (e.g., Burke et al., 2005; Eaton et al., 2010b; Owens et al., 2013). Climate change may also be expected to influence the post-fire snow cover dynamics (Ireson et al., 2015), again creating uncertainty in projecting post-fire responses based on the spatially and temporally limited research in this region.

Interestingly, the current knowledge of fire effects on aquatic ecosystems generally points towards ecosystem resistance and/or resiliency in both streams and lakes. This suggests the adaptation of aquatic ecosystems to natural fire activity (Jalal et al., 2005; Kreutzweiser et al., 2012; Lewis et al., 2014), as is commonly accepted for northern forests as a whole (Burton et al., 2008; Stewart et al., 2012). For instance, Naylor et al. (2012) reported that boreal riparian forests can burn extensively, meaning that over-protecting riparian buffers from disturbances can be detrimental to aquatic habitat diversity. The observed rejuvenation effect on aquatic habitats seems to favor long-term ecosystem productivity, which suggests that safeguarding and restoring fire regimes may benefit aquatic ecosystems through enhanced watershed health (Cott et al., 2010; Tonn et al., 2004). This ecological need may be difficult to reconcile with demand for provisioning services (i.e., angling) due to potential short-term depreciation of aquatic ecosystem health and further implications for human health (e.g., mercury bioaccumulation). In fire-dependent watersheds experiencing a high demand for *HES*, risk mitigation will have to include fire as part of the solution to stabilize changing watershed functioning (Creed et al., 2014; Hanes et al., 2019; Rocca et al., 2014). Davidson and Eaton (2015) and Charron and Johnson (2006) also strongly suggested stream aquatic habitat dependency on post-fire hydrologic pulses of water, sediment, and debris influencing stream morphology and riparian vegetation. Implications of these findings are important for habitat conservation as they suggest that fire disturbances—within their natural range of variability—and the associated post-fire pulses are necessary processes supporting long-term aquatic ecosystem health in northern forests (Jentsch and White, 2019; Rocca et al., 2014).

Global environmental change, especially climate change, was rarely addressed specifically and only in simulation studies (Mahat and Anderson, 2013). In northern latitudes, the balance between annual precipitation and annual potential evapotranspiration provides a rough index of water availability for streamflow, as well as soil and groundwater recharge. However, post-fire changes in snow cover, expected decreases in snowmelt and glacier contributions to streamflow, and increases in PET (Hember et al., 2017; Marshall et al., 2011; Vincent et al., 2015) suggest a stronger possibility of scenarios where wildfire leads to the contamination of limited water supplies from forests in these regions (Bladon et al., 2014). Similar concerns have been expressed in other parts of the world, such as Australia (Lane et al., 2010) and Portugal (Santos et al., 2015), where wildfire activity is already demonstrably affected by climate change and other anthropogenic stressors. Although summer storms in the central boreal forest and wet years in the western mountains seem to be primary triggers for post-fire response (e.g., Burke et al., 2005; Prepas et al., 2003a), shifts in seasonality and magnitude of precipitation will increasingly complicate our ability to project post-fire responses.

4.2. Limitations

Our scoping review enabled us to rapidly and systematically summarize the literature associated with the pressing environmental questions associated with wildfire, water security, and ecosystem services in northern latitudes. However, the scoping approach is limited due to a focus on the quantity of available information rather than on an in-depth analysis of its quality, as would be completed in more typical reviews. Thus, while this approach enabled us to address the main topics in the selected studies and note the general results, our findings are not meant to provide conclusive evidence nor any guideline regarding the best approach to study wildfire risks to water security in northern watersheds.

Our review was also limited in scope, and did not include studies in peatlands. We acknowledge the importance of peatlands, which cover no less than 13% of the Canadian landmass, and 64% in the boreal forest (Tarnocai et al., 2011). However, peatlands uniquely play a critical role in wildfire spread and affect water distribution horizontally and vertically within the landscape (Thompson et al., 2019; Waddington et al., 2015). As such, they also buffer the impacts of wildfires on water quantity and quality (Pelster et al., 2008; Prepas et al., 2006). Despite their critical importance, they were beyond our focus on surface water bodies and we strongly encourage continued research in these unique environments.

Finally, our review focused on the effects of wildfire on a subset of hydrologic functions in northern latitude studies. Again, we acknowledge that wildfires are known to have direct effects on many other hydrologic processes (e.g., interception, evapotranspiration) (National Research Council, 2008). We also acknowledge that local post-fire changes in the forest water balance can ultimately affect the broader water cycle and *HES* in high latitude watersheds (Bond-Lamberty et al., 2009; Waddington et al., 2015). However, in constraining the objectives of our review, we felt that most impacted hydrologic processes would at least be indirectly addressed in other aspects of our review.

5. Research agenda

In this first systematic review of post-fire hydrology in the high-latitude forests of North America, we have covered 40 years of research on hydrology, geomorphology, water quality, and aquatic ecosystem quality in lakes, open wetlands, and rivers. Despite an increasing number of studies on wildfire impacts on water chemistry and aquatic ecosystem responses to wildfires, other hydrologic services like drinking water source supply, recreation, and fish health have received comparatively less attention. Based on our results and recent publications addressing the forest-fire-water nexus elsewhere (Bladon, 2018; Hallema et al., 2019a; Martin, 2016), we propose a list of priorities for post-fire hydrologic research in this region (Carignan and Steedman, 2000; Mahat et al., 2015).

Our results show marked differences in study design, description of the hydrologic setting, fire characteristics, and general reporting of results. This hinders cross-site comparisons and detection of general patterns in post-fire watershed response. As such, this precludes the ability to design appropriate fire and post-fire management strategies (e.g., prescribed burn programs, mechanical fuel reduction, fire suppression, post-fire forest restoration) to effectively mitigate effects on freshwater resources. We argue for the need for the wildfire-water research community to develop a more standardized protocol for the description of watershed settings and the post-fire environment. This will help ensure that the same information is captured across studies and that their results are comparable, thereby enabling researchers to undertake meta-analyses and develop watershed health indicators adapted to northern fire conditions (Dunn and Bakker, 2011; Flotemersch et al., 2016; Smith et al., 2016).

Studies on post-fire changes in ecohydrological processes and freshwater services have mainly focused on aquatic habitats and water chemistry, despite evidence that *HES* are connected (Creed et al., 2016; Sun et al., 2017). The lack of studies analyzing cultural services is a problem that can be extended to the ecosystem services literature as a whole (Satz et al., 2013), whereas the lack of studies focusing on other *HES* is related to the relative novelty of the topic. Post-fire hydrologic studies should strive to describe results within the context of hydrologic services, especially when they involve water supply issues to downstream communities, so that appropriate indicators of risks to water resources can be developed (Creed et al., 2016; Grizzetti et al., 2016; Vollmer et al., 2018).

Future research must also prioritize studies with a focus on fire impacts on other *HES*, particularly drinking-water provision, flash flood mitigation, and recreational uses, as exemplified by Jordan (2016) and Emelko et al. (2011). The combined effect of wildfires and climate trends on water supplies also necessitates regional assessments of water issues (Hallema et al., 2019b), which should be integrated with transparent cost-benefit analyses of *HES* degradation due to wildfire (Price and Heberling, 2018). We acknowledge that conducting such studies is challenging due to the absence of baseline information (e.g., spatial, economic) on the majority of hydrologic services provided by high-latitude forests, the large spatial extent of fire activity across the region, the strong variability in vulnerability of communities relying on fire-affected watersheds, and the uncertain costs and benefits of enhancing hydrologic resilience of fire-prone watersheds (e.g., with fuel treatments). We therefore argue for an initial focus on quantifying and mapping *HES* provided by northern forest watersheds, which future efforts could build on. However, the mapping approach must be adaptive and part of an ongoing effort as illustrated, for instance, by the high-resolution mapping of river characteristics in Canada (Ouellet Dallaire et al., 2019), and by the assessment of drinking-water production costs that can be related to upstream forest health and disturbances (Price et al., 2017; Robinne et al., 2019).

Temporal and spatial scales affect our understanding of ecohydrologic processes and hydro-sociological interactions that cannot be captured by studies at a single watershed-scale conducted over a few years (Bakker, 2012; Sivapalan et al., 2014). Recent work on forest-cover and water yield interactions revealed that the effect of cumulative disturbances at large scales is not monotonic or unidirectional, and could have long-lasting and extensive effects (Li et al., 2018, 2017; Zhang and Wei, 2014). Therefore, there is a need to study longer-term interactions between hydrologic and fire regimes in northern watersheds. To date, most studies are short term and focus on the aftermath of a single wildfire—a common pitfall of post-fire environmental assessments, in general (Neary et al., 1999; Vieira et al., 2015). However, high-latitude forests are generally fire-prone and fire-dependent, which suggests a likely dynamic equilibrium between landscape fire occurrence, its resulting pattern on the forest mosaic, and the movement of water across the landscape (Chanasyk et al., 2003; Devito et al., 2012). Understanding this equilibrium might be key to designing future strategies to adapt to global environmental change, where wildfires have a place in ensuring water security. In this respect, the need for the creation and maintenance of long-term ecological research sites combined with a thorough analysis of existing data could provide invaluable insights to learning how to cope with more unpredictable hydroclimatic extremes (Huntington, 2006; Milly et al., 2008). As such, increasing data availability combined with a multi-scale approach to studying compound fire-hydrologic processes and services may be key to enabling effective decisions to preserve water security in Canada and Alaska (Bakker, 2012; Bakker and Cook, 2011).

Finally, the limited number of studies that have used computational modeling, data mining, and remote-sensing technologies indicates that cutting-edge advances in the general hydrologic sciences have yet to be mainstreamed in the sub-field of post-fire hydrology, at least in Canada and Alaska. For example, remote-sensing methods to monitor inland waters and the ecosystem services they provide have made significant progress (de Araujo Barbosa et al., 2015; Palmer et al., 2015). Specifically, recent studies have relied on remote sensing to identify potential harmful algal blooms in lakes and reservoirs (Keith et al., 2018; Kudela et al., 2015). Given that algal blooms have been noted as a major post-fire challenge to drinking-water supplies, this would seem like an opportunity for the post-fire hydrology research community to address. Hydrologic modeling of northern regions has also made significant advances with the development of dedicated modeling frameworks such as the Cold Region Hydrologic Model (Pomeroy et al., 2007) and Raven (Chernos et al., 2017) that remain to be fully tested in a post-fire environment. Addressing emerging questions associated with global environmental change requires the use of such advanced technologies (Carignan and Steedman, 2000; Thompson et al., 2013). Adapting current hydrologic models to enable scenario testing for post-wildfire conditions can provide testable hypotheses regarding the magnitude of hydrologic effects associated with high severity fires, the temporal and spatial duration of effects, and the interact with other pressures such as climate change and human demand for water. Moreover, the combination of simulation modeling with remote-sensing data could also be used to improve understanding of the effects of wildfires on key water quality parameters (e.g., sediment, limiting nutrients, carbon) in both upstream and downstream environments, as well as the potential impacts on aquatic ecosystem health (e.g., primary productivity, fish habitat modeling). Such modeling efforts could provide important information for the implementation and the revision of source water supply and protection strategies. Post-fire simulation modeling could also further help decipher the future effect of global change, particularly climate variations and increasing water demand of expanding urban areas (Rodrigues et al., 2019).

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2019.124360.

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