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ARTICLE COMMENTARY

Baseline geographic information on wildfire-watershed risk in Canada: needs, gaps, and opportunities

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Untapped resources in wildfire-watershed risk assessment

Awareness of wildfire risks to water security, or wildfire-watershed risks (WWR) for short, has been growing in Canada (Coogan et al. 2019; Pomeroy et al. 2019; Robinne et al. 2020). This comes from the realisation that watersheds are increasingly vulnerable to compound stressors, including more seasonal variation in water availability (Ireson et al. 2015; Bonsal et al. 2020), increased occurrence of droughts and extreme precipitation events (Bush and Lemmen 2019), and a changing nature and exacerbating impact of fire activity (Coops et al. 2018; Hanes et al. 2019). Although water resource protection is a top priority for wildfire management agencies across the country (Tymstra et al. 2020), baseline information on the vulnerability of source waters to wildfire remains limited despite the high potential for water supply disruption (Martin 2016; Hohner et al. 2019; Robinne et al. 2021). As climatic and hydrologic extremes are expected to grow in magnitude and frequency, increasing the risk of water security issues, there is an urgent need for greater access to baseline WWR information. Improved access can facilitate development of more targeted watershed management policies and strategies, especially for communities relying on water originating from upstream forests, to protect source water supply and security.

Data—spatial data, in particular—are at the core of modern risk governance (Klinke and Renn 2012; Neuvel, Scholten, and van den Brink 2012). Risk governance relies on acquiring knowledge, which itself relies on aggregated information derived from the collection and synthesis of available data sources. As such, data availability and openness of data are critical to improved knowledge and informed decision-making (Weichselgartner and Pigeon 2015; Månsson 2018; Månsson, Abrahamsson, and Tehler 2019). With the term open data, we refer to datasets that are Findable, Accessible, Interoperable, and Reusable, or FAIR (Wilkinson et al. 2016). In this context, access to open data is widely acknowledged as a prerequisite to the production of scientifically sound information to enable disaster risk reduction policies. Notably, the Emergency Management Strategy for Canada (EMS), which implements the United Nations Office for Disaster Risk Reduction (UNDRR) recommendations proposed in the Sendaï Framework for Disaster Risk Reduction (hereafter, Sendaï Framework), strongly promotes data openness to facilitate the production of innovative risk knowledge (Weichselgartner and Pigeon 2015; UNISDR 2015; Godsoe, Ladd, and Cox 2019; Public Safety Canada 2019).

In recent years, there has been substantial growth in the heterogeneity of both spatial and non-spatial open data provided by different levels of governments in Canada. However, reports of data scarcity continue

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to emerge, both in the fields of water and wildfire science (Garda, Castleden, and Conrad 2017; Mortsch, Cohen, and Koshida 2015; Tymstra et al. 2020). For decades, data scarcity and data fragmentation have been viewed as obstacles to the development of a national water strategy, contributing to the present needs to protect water resources from wildfire impacts (Bakker and Cook 2011; Sankey 2018; Godsoe, Ladd, and Cox 2019; Mamuji and Rozdilsky 2019; Johnston et al. 2020). While we acknowledge that more data are needed to increase our understanding of the variability in post-fire watershed responses and to improve Canada's national capacity to mitigate the increasing risk to water supply from wildfires, we also note that currently available data resources remain largely unused in the development of baseline information and hypotheses on WWR in Canada (e.g., Robinne 2020; Robinne et al. 2019). In a recent TED Talk, Sonaar Luthra, the CEO of Water Canary, echoed this statement by saying: "[…] when we don't use the data we have, we don't encourage investment in new technologies, we don't encourage more data collection, and we certainly don't encourage investment in securing a water future" (Luthra 2019). In other words, a better understanding of data gaps and needs will improve data collection efforts towards the development of absolute indicators of WWR that can supplant relative ones, which are commonly used for the production of risk information in data-limited settings (e.g., Thompson, Scott, Langowski, et al. 2013; Robinne et al. 2019).

In this commentary, we provide a critical assessment of Canadian capacity to produce nationally relevant WWR baseline information using existing open spatial data sources from federal, provincial, and territorial governments (see Data availability section). In line with the EMS objective to "improve understanding of disaster risk" (Public Safety Canada 2019), we review the mechanisms by which wildfire impacts water security to highlight data needs. We also provide a series of maps resulting from the integration and aggregation of the spatial datasets we found according to the FAIR principles as examples of how available data may be used to develop new approaches to risk analysis. We then discuss avenues to improve and leverage available spatial information to inform the production of WWR baseline knowledge to help identify research and governance priority areas. Finally, we provide recommendations on how the EMS can play a pivotal role in advancing WWR governance to fulfil Canada's demand for risk reduction (McNie 2007; Henstra, Minano, and Thistlethwaite 2019; Public Safety Canada 2019).

General WWR data needs

WWR studies cover a broad range of topics, from highly specific matters such as the physical interactions between wildfire and hydrology within a small mountain watershed, to general analyses of watershed vulnerability to wildfire over a whole country (Table 1) (Martin 2016; Robinne et al. 2021). Although a diversity in topics, scale, and scope calls for particular, context-specific data (sections below), there are three fundamental data requirements common to any WWR analysis: terrain, soils, and precipitation. Ideally, these basic data sources would have a national extent and a high spatial resolution in order to capture variation in wildfire-watershed processes across spatio-temporal scales (Hallema et al. 2017).

Terrain data is used to derive hydro-geomorphologic information such as river network length and density, as well as other essential watershed characteristics that influence water and sediment movement (e.g., slope and aspect, incline of the river bed) (Miller et al. 2016). In Canada, WWR analysts have access the Canadian Digital Elevation Model, which is being slowly replaced by the High Resolution Digital Elevation Model derived from both LiDAR and high-resolution satellite data. Data representing soils are equally important, given that they control watershed response to precipitation, hence runoff, erosion, streamflow, and water quality—all processes that can be heavily modified by wildfires (Shakesby and Doerr 2006; Neary, Ice, and Jackson 2009). The Government of Canada provides the Soil Landscapes of Canada and the Soil Texture by Ecodistrict, available at a coarse scale nationally (Soil Landscapes of Canada Working Group 2010; Canadian Soil Information Service 2013) and as a high resolution product limited to agricultural regions. The absence of a high-resolution soils dataset for wildland areas represents one of the main barriers to WWR research in Canada. The final essential risk factor influencing post-fire watershed response is precipitation: hardly any changes to hydrology or water quality might be detected in the absence of post-fire rain or snowfall; on the contrary, small storms might have disproportionate hydrologic and water quality effects due to the absence of soil cover (Murphy et al. 2015; Hallema et al. 2018). Environment and Climate Change Canada (ECCC) collects data from more than 1500 active weather stations, and holds an archive of more

Table 1. Idealized data sources and opportunities towards advancing WWR research and management in Canada.

Data	Relevance to WWR	National availability	Limitations/challenges	Priority	Suggested actions	Stakeholder(s)
Forest ecosystem and wildfire regime data						
Burn severity	• Post-fire changes to vegetation cover, soil structure, hydraulic behaviour • Post-fire emergency modelling of flash floods and threats to water quality	Available	• Labour intensive • Need near-immediate access to satellite imagery over the fire for emergency purposes	High	• Train and deploy teams to collect data right after fire (see BAER teams in the USA) • Use various remote-sensing products to create near real-time severity products	• Provinces • Federal • Academia
Fire perimeters	• Post-fire changes to aboveground vegetation cover and watershed functioning • Post-fire emergency modelling of flash floods and threats to water quality	Available	• Possible delays in data availability for accurate delineation • Non-comprehensive historical coverage before 1980	High	• Train and deploy teams to collect satellite/aerial data soon after fire for emergency purposes	• Provinces • Federal • Private sector
Fire probability	• Pre-fire watershed hazard exposure assessment • Location and prioritization of at-risk watersheds • Evaluation of fire hazard reduction strategies	Inexistent	• Varying terminology • Computationally and data intensive • High-skilled work	High	• Create and maintain an open high-resolution dataset • Provide pre-packaged watershed statistics	• Provinces • Federal
Forest attributes	• Pre-fire watershed functioning • Production of forest fuel grids for fire hazard models • Post-fire changes to aboveground vegetation cover and recovery	Available	• Coarse spatial and temporal resolution	Medium	• Create and maintain a high-resolution dataset • Mix multi-sources and multi-resolution datasets	• Provinces • Federal • Private sector • Academia
Soil attributes	• Pre-fire watershed functioning and baseline integrity assessment • Pre-fire risk assessment and test of risk reduction strategies • Post-fire emergency modelling of changes in streamflow and threats to water quality	Available	• Low spatial resolution that limits use in modelling • Important sources not in a GIS-ready format (scanned maps)	Top	• Digitization of existing soil/surficial geology map archives (GeoScan) • Investments in predictive soil mapping • Mix multi-sources and multi-resolution datasets	• Provinces • Federal • Private sector • Academia
Watershed and freshwater data						
Streamflow	• Pre-fire watershed functioning and baseline integrity assessment • Post-fire watershed monitoring of changes to annual, peak and low flows	Available	• Limited coverage in northern latitudes and remote watersheds	High	• Extend and densify coverage • Invest in modelling in ungauged basins	• Provinces • Federal • Academia • NGOs
Water quality	• Pre-fire watershed functioning and baseline integrity assessment • Post-fire watershed monitoring of sediment yield, nutrient loading and heavy metals	Available	• Limited spatial and temporal coverage • Monitoring emphasis often on human settlements and activities	Top	• Extend and densify coverage • Integrate non-governmental datasets	• Provinces • Federal • Academia • Citizens • NGOs
Aquatic species	• Pre-fire watershed functioning and	Limited	• Limited spatial and temporal coverage due to varying	Top	• Extend and densify coverage	• Provinces • Federal • Academia

(*continued*)

Table 1. Continued.

Data	Relevance to WWR	National availability	Limitations/challenges	Priority	Suggested actions	Stakeholder(s)
	baseline integrity assessment • Post-fire watershed monitoring of impact on aquatic biodiversity, including benthic invertebrates and fish		monitoring protocol and capacity		• Standardize and integrate non-governmental datasets	• Citizens • NGOs • First Nations
Digital Elevation Model	• Pre-fire watershed conditions through hydrographic analysis • Pre-fire erosion and water pollution risk assessment and mitigation strategy • Post-fire emergency modelling for watershed restoration guidance	Available	• No hydrologically-corrected DEM • Varying spatial resolution • Aging and incomplete dataset	Medium	• Increase spatial resolution • Propose hydrologically-corrected products • Propose high-confidence hydrographic dataset	• Provinces • Federal • Academia • NGOs
Water resource planning jurisdictions	• Pre-fire risk assessment and mitigation • Post-fire watershed monitoring and restoration responsibilities	Available	• Regional variations in water management and watershed planning	Low	• Create and maintain one reference national dataset • Harmonize watershed planning rules	• Provinces • Federal • Academia • First Nations
Climate and weather data						
Precipitation	• Pre-fire watershed functioning, baseline integrity assessment, and extreme hydrological events • Critical input for wildfire models and danger rating systems used in risk prevention and mitigation • Post-fire emergency debris flow and flood modelling through extreme event monitoring	Available	• Limited coverage by weather stations in northern latitudes • Coarse spatial resolution of derived interpolated products • Lack of WWR-specific products: rainfall erosivity, extreme event	High	• Extend and densify weather station coverage • Integrate non-governmental datasets • Design and maintain WWR-specific products	• Provinces • Federal • Academia
Temperature	• Pre-fire watershed functioning and baseline integrity assessment • Critical input for wildfire models and danger rating systems used in risk prevention and mitigation • Post-fire modelling/monitoring of watershed recovery	Available	• Limited coverage in northern latitudes • Coarse spatial resolution	High	• Extend and densify coverage • Integrate non-governmental datasets	• Provinces • Federal • Academia
Ecosystem services and benefits data						
Drinking water plants/intakes	• Pre-fire risk assessment and mitigation through source water assessment and protection • Post-fire emergency modelling of water pollution and potential water treatment failure	Partially available	• Malevolent use of the data (i.e., terrorism) • Varying data quality • Varying data availability (under province jurisdiction)	Top	• Standardize data production through jurisdictions • Push for open-access • Design and maintain aggregated datasets that don't compromise security	• Provinces • Academia • First Nations
Commercial freshwater fisheries	• Pre-fire risk assessment and mitigation through	Partially available	• Regional products available	Medium	• Harmonize regional datasets at national level	• Federal • Provinces • Private sector

(*continued*)

Table 1. Continued.

Data	Relevance to WWR	National availability	Limitations/challenges	Priority	Suggested actions	Stakeholder(s)
	habitat conservation and source protection • Post-fire fish population monitoring and assessment of economic losses		• Varying spatial and temporal resolution • Varying level of information and accessibility		• Standardize data production through jurisdictions • Extend data creation efforts and sharing for uncovered areas	
Contaminated sites	• Pre-fire risk assessment and mitigation through source water assessment and protection • Post-fire water quality monitoring and pollution surveillance	Available	• Limited spatial information • Incomplete dataset	Medium	• Increase geographic details (e.g., provide site polygon) • Integrate multiple sources of data • Maintain and share a national dataset	• Provinces • Federal • Academia • Private sector
Dams and other hydraulic structures	• Pre-fire risk assessment and mitigation through source water assessment and protection • Pre-fire evaluation of risk to hydropower generation • Post-fire modelling and monitoring of sediment and nutrients inputs and changes to water quality	Available	• High uncertainty in data quality • Varying and unstandardized sources • Not user friendly	Medium	• Integrate non-governmental datasets • Create and maintain a national reference dataset • Integrate small structures	• Provinces • Federal • Academia
Water recreation areas/sites	• Pre-fire risk assessment and mitigation through source water assessment and protection • Post-fire modelling and monitoring of sediment and nutrients inputs and changes to water quality that can endanger users (e.g., algal blooms)	Partially available	• High uncertainty in data quality • Varying and unstandardized sources • Not user friendly	High	• Create and maintain a national reference dataset • Integrate information on recreational water licences	• Provinces • Federal • Municipalities • Watershed councils
Endangered aquatic ecosystem and species	• Pre-fire risk assessment and mitigation through source water assessment and protection • Ecological functioning, baseline integrity assessment, and role of fire in habitat health • Post-fire population monitoring	Partially available	• Varying sources • Low spatial and temporal resolution • Not user friendly	High	• Integrate non-governmental datasets • Improve accessibility • Improve data collection	• Provinces • Federal • Municipalities • Watershed councils • Academia • NGOs

This list in not exhaustive. A list of actual datasets is provided in S.1. National availability refers to the availability of a FAIR dataset for the entire country. Given the fragmented nature of water governance in Canada, and thus the various sources of data that can be used by different levels of government for risk management purposes, we included non-governmental stakeholders.

than 8000 stations since 1840. ECCC, through the Canadian Centre for Climate Services, has been working with a number of partners to develop and deliver numerous high-quality climate products derived from historical observations and state-of-the-art physical models (Environment and Climate Change Canada

2021).These sources of data provide WWR analysts with a wide array of choices to design retrospective studies or future scenario-based risk analyses.

WWR analyses can essentially be divided in two categories: pre-fire (*ex-ante*) and post-fire (*ex-post*). Pre-fire studies are based on simulation models that predict fire regime metrics and the degree to which watershed functioning might be altered given a number of wildfire scenarios, the end goal being the creation of prevention measures within a risk-reduction logic (Elliot, Miller, and Enstice 2016; Gannon, Wei, and Thompson 2020). Post-fire studies, on the other hand, are driven by the collection and analysis of observational data for impact analysis and monitoring of wildfire effects (Silins et al. 2014); these observations might also be fed to simulation models for the purpose of emergency watershed restoration (Miller et al. 2016; Neris et al. 2021). Both WWR categories are, however, co-dependent: observational datasets are paramount to developing simulation models that project the expected effects and their influence on risk levels. Conversely, predictions from simulation models can indicate where uncertainties lie and where further data collection might be needed (Kennedy et al. 2017; Nunes et al. 2018; Neris et al. 2021). We thus contend that the data needs, gaps, and opportunities discussed herein can be used for either approach, depending on the end goal of the analysis and the creativity of the analyst, but in any case, access to these data sources remains critical (Fekete et al. 2015).

Data needs, gaps, and opportunities for understanding the effect of wildfires on streamflow and water quality

The impact of wildfires on water resources often manifests through changes in annual streamflow, peak flows, and low flows, which can persist for multiple decades and drive a range of water quality responses (see for e.g, Loiselle et al. 2020; Niemeyer, Bladon, and Woodsmith 2020). Therefore, a first step in the assessment of wildfire-water risk is the creation of baseline hydrologic datasets, where deviations from normal conditions may point to a fire-related disturbance. Such assessment usually look at relationships between time series of various water and wildfire metrics (Wine and Cadol 2016; Hallema et al. 2017). Besides a few rare studies (e.g., Owens et al. 2013), however, there has not been any retrospective analysis of the records from the >7000 active and historical hydrometric gauges available in Canada—contained in the HYDAT database—although analytical methods exist (Hallema et al. 2018; Wine, Cadol, and Makhnin 2018). Despite unequal coverage, HYDAT is a FAIR dataset, either accessible via the National Water Data Archive website, the Environment Canada Data Explorer software, or various Application Programming Interfaces (APIs) (e.g., tidyhydat package in the R programming environment (Albers 2017)). Furthermore, detailed burned area and burned severity products are now provided by the Government of Canada for the entire country: both derived primarily from the Landsat satellite data archive, the National Burned Area Composite (NBAC) provides a high-resolution fire perimeter database from 1986 onwards, and the Canadian Landsat Burned Severity (CanLaBS) provides a set of 30 m raster grids comparing pre- and post-fire vegetation cover from 1985 to 2015 (Guindon, Gauthier, et al. 2020; Guindon, Villemaire, et al. 2020; Hall et al. 2020). Analysis of watersheds with multiple decades of hydrometric data and fire activity could improve our understanding of watershed response magnitudes, timing, and recovery to fire.

An initial exploration of some available data indicates variable spatial overlap between gauged watersheds for which boundaries are available (Figure 1(a)) and fire activity of the past 40 years (Figure 1(b)); many of the most fire-prone watersheds in Ontario and Quebec are ungauged. Specifically, 676 of the 1675 gauged watersheds available (40.3%) have experienced a fire in the past four decades. Those fires burned an area of 3.06 km^2 on average, and a long-term watershed's percent area burned of 11.5%. These statistics suggest that wildfires in Canada might be an important driver of watershed functioning (Robinne et al. 2020), and that a wildfire signal might be detectable in certain regions through hydro-statistical analysis (Hallema et al. 2018; Spence et al. 2020). Further exploration could be done by making watershed boundaries available for the >7000 gauges available in HYDAT, which would fix, at least in part, data coverage issues in the eastern part of the country, and provide richer historical sources for these areas already covered by active gauges. Empirical analysis of watershed response drivers can help us predict what may happen in ungauged basins (Hrachowitz et al. 2013); indeed, recent advancements in computing power and analytical techniques such as machine learning and deep learning offer the potential to expand the utility of observational data (Nearing et al. 2021).

Wildfires also typically impact water quality, especially through increased sediment yield, nutrient loading, and heavy metals (Bladon et al. 2008; Pereira and

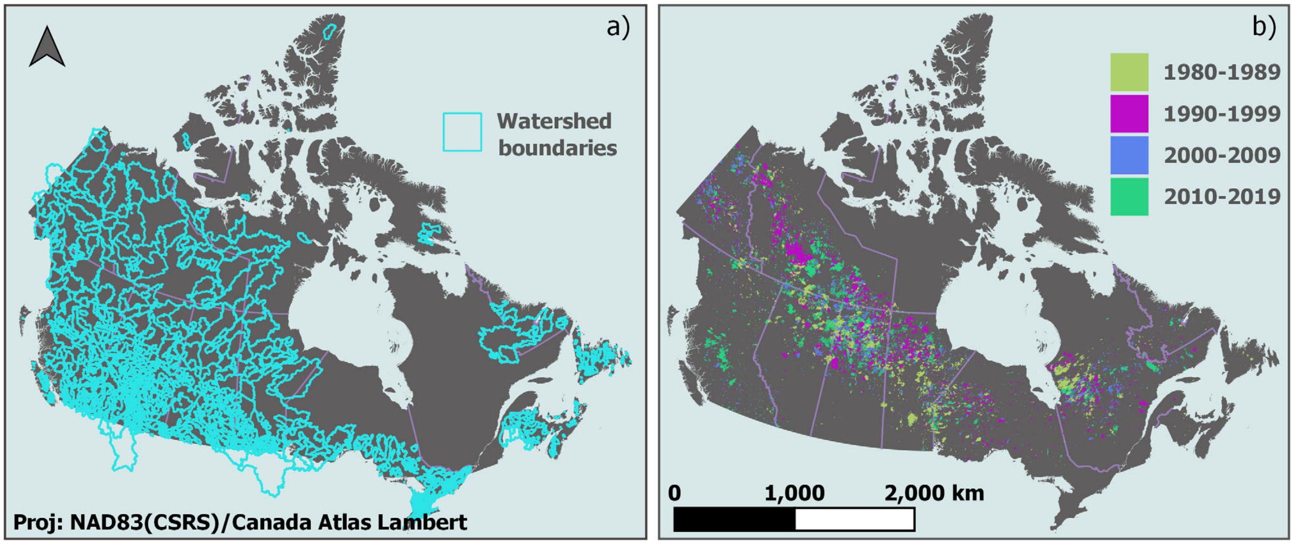

Figure 1. (a) Gauged watershed polygons available from Water Survey of Canada ($n = 1675$); (b) fire perimeters per decade since 1980 from Natural Resources of Canada ($n = 34,341$). Source: Author.

Úbeda 2010; Emelko et al. 2011). However, the limited number of federally operated water-quality gauges ($n = 339$) precludes the development of a retrospective nationwide analysis. That said, an increasing number of open datasets—municipal, provincial, governmental, and from academic research groups—containing water quality data are becoming available. For example, the regional DataStream databases and the Environmental Monitoring System in British Columbia represent valuable sources of water quality data. Accessing and merging such disparate sources is becoming increasingly important for regional water conservation authorities and watershed councils in order to fulfil their water management mandates, as exemplified by the work by Grand River Conservation Authority in Ontario (Grand River Conservation Authority 2020) and the Fraser Basin Council in British Columbia (Fraser Basin Council 2021). The recent Watershed Reports by WWF-Canada (2017, 2020) are further illustrations of what can be achieved with these various datasets at a national scale.

Data needs, gaps, and opportunities for aquatic habitat protection

Healthy aquatic habitats provide a wealth of ecosystem services (e.g., recreational opportunities, cultural values, commercial fishing). However, the health of aquatic ecosystems depends on overall watershed health, which can be adversely affected by atypical forest disturbances (Gresswell 1999; Brauman et al. 2007; Bixby et al. 2015). Many studies addressing the impact of wildfires on aquatic habitats in Canada suggest a rapid post-fire recovery (i.e., less than 10 years), and even cases of beneficial effects to aquatic habitats (Cott et al. 2010; Emelko et al. 2016). The role of fire for sustaining aquatic biodiversity thus remains a matter of debate across the various regions of Canada (Gresswell 1999; Carignan and Steedman 2000; Robinne et al. 2020). But studies have provided widespread evidence of post-fire changes in aquatic ecosystems, including short-term negative impacts on primary productivity, invertebrate communities, and fisheries, especially salmonids (Rieman et al. 2003; Silins et al. 2014). Although many salmonid species are listed under the Species At Risk Act (SARA), existing population data deficiencies hinder in-depth understanding of wildfire-fish interactions, and, thus, the development of appropriate conservation actions (Rieman and Clayton 1997; Turcotte et al. 2021). Such limitation represents a concern in a country where fishing remains critical for food security in First Nation communities (Marushka et al. 2021), and where recreational fishing represents CAD $2.5-billion (Fisheries and Ocean Canada 2020). Nevertheless, there are no recent consolidated data describing inland fisheries throughout Canada—the last geographic information was released in 1974 as part of the national atlas—and provincial and territorial fisheries datasets, when they exist, often differ in format, content, and accessibility.

Another option is to look at the aquatic biomonitoring network database of Canada, known as the Canadian Aquatic Biomonitoring Network (CABIN) (Environment and Climate Change Canada 2019). This network is an ECCC effort to standardize the collection and analysis of benthic macroinvertebrates in freshwater streams. Its standardized monitoring protocol is used by governments, First Nations, academia, industry, and NGOs across Canada. CABIN monitors freshwater ecosystem health with standardized methods, a database, and training, which is offered through the Canadian Rivers Institute at the University of New Brunswick (Canadian Rivers Institute 2021). The standardization ensures consistent and comparable data across the country. Biomonitoring is a useful aquatic monitoring tool because biological communities are often impacted by chemicals and contaminants, invasive species, habitat degradation, climate change, as well as changes in annual water yields, peak flows, low flows, and timing of availability (Friberg et al. 2011; Environment and Climate Change Canada 2018). Organisms like benthic invertebrates are useful to show environmental change (Chadd and Extence 2004), like those triggered by wildfires (Spencer, Gabel, and Hauer 2003; Silins et al. 2014), especially when monitoring occurs consistently (i.e., repeated over years to decades), allowing for a deeper understanding of the ecological community and its relationship to external pressures.

We completed a preliminary analysis of the National Fire Database (NFDB) and CABIN data at the sub-sub-watershed level to assess how many samples had been collected since 1980 within burned perimeters (Robinne 2020). The maps show that, except in the north-western part of the country, only a limited number of samples has been collected in areas of high historical area burned in the boreal conifer and mixed-wood forests (Figure 2). Part of the explanation for the low sampling rate may be that the sampling protocol was designed for streams and may be less applicable in areas with large wetland or lake coverage. That said, even in burned watersheds where CABIN samples exist, the number of samples drops off rapidly. In particular, the number of revisited sites within burned perimeters is limited. Even though the use of CABIN seems to be of limited interest at first glance, an argument can be made for using this standardized protocol—or an adapted version—to create monitoring sites within burned watersheds. There is also still the possibility to maximize the use of existing CABIN records through paired-watershed studies, a common way of comparing the impacts of varying levels of disturbance on diverse water resource metrics (Brown et al. 2005).

While traditional taxonomy is still the norm for identifying the contents of most CABIN samples, emerging DNA metabarcoding technology has the potential to provide a quicker and more cost-effective identification method (Pawlowski et al. 2018; Edge et al. 2020). The DNA metabarcoding process begins with the homogenization of bulk benthic samples. DNA is then extracted for next-generation sequencing (NGS) analysis. This compares the DNA from the sample to a reference library of known genetic sequences, often allowing for species-level identification. ECCC is collaborating with several partners, including WWF-Canada, the University of Guelph and Living Lakes Canada, through the Sequencing the Rivers for Environmental Assessment and Monitoring (STREAM) project (Environment and Climate Change Canada and University of Guelph 2019), to explore the potential for a nationally standardized protocol for the collection and analysis of bulk benthic macroinvertebrate samples and a corresponding assessment tool for aquatic ecosystem health, using eDNA metabarcoding and its outputs (Robinson et al. 2021). Such genomic approaches offer tremendous opportunities for the large-scale survey of aquatic ecosystems affected by wildfires (see e.g., Carvalho et al. 2019).

Data needs, gaps, and opportunities for community water supply protection

Wildfires in municipal watersheds can disrupt drinking water production in downstream communities, likely for several years after the burn (Hohner et al. 2019). The 2016 Horse Creek fire in Fort McMurray, Alberta, has, from the time of fire to 2019, incurred CAD $9 million of additional, unplanned water treatment expenditures (Pomeroy et al. 2019). Such extraordinary expenses can become a significant burden on small communities, whose water management is often undermined by budget limitations (Perrier et al. 2014). Many source-water supplies for municipalities across Canada may also be at risk from wildfires, particularly in a context of enhanced wildfire activity due to historical fire and forest management (Parisien et al. 2020). Yet, many of these communities lack source water protection plans specifically addressing wildfire hazards (Al-Ibrahim and Patrick 2017; Pomeroy et al. 2019).

Including post-fire hazards in such plans would typically start with a spatial and historical analysis of wildfire activity within a watershed; a national assessment of historical fire activity within municipal watersheds only requires spatial data on wildfire activity (e.g., Landsat-based NBAC and CanLaBS) and spatial boundaries of municipal watersheds, similar to the attempt shown in Figure 3. Such an approach applied to British Columbia—where municipal watershed data are available—revealed that 63% of these watersheds have experienced a burn since 1980, for a median area burned of

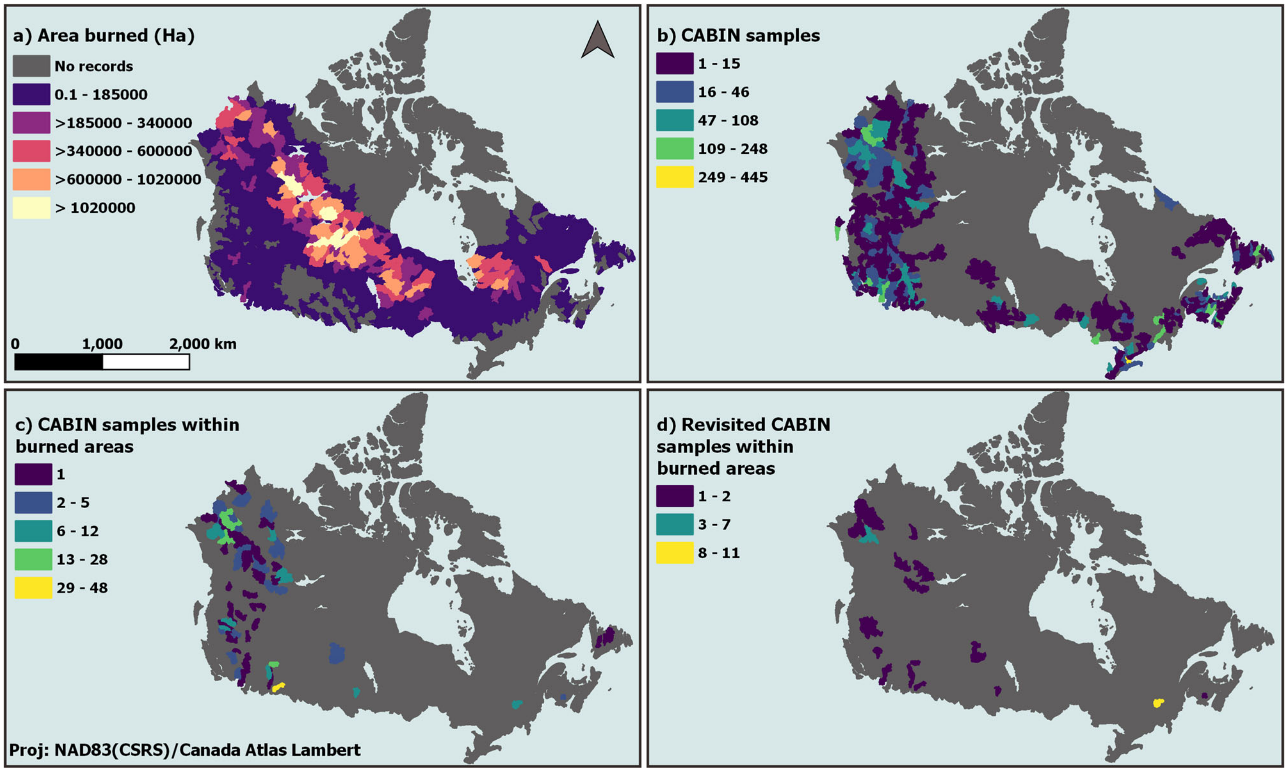

Figure 2. Map set illustrating wildfire activity and aquatic biomonitoring sampling across Canada, with (a) the recorded cumulative area burned per watershed within the National Hydrographic Network (NHN) since 1980, (b) the number of CABIN samples per NHN watershed since 1987, (c) the number of CABIN samples overlapping with recorded burned perimeters within NHN watersheds, and (d) the number of revisited CABIN samples overlapping with recorded burned perimeters within NHN watersheds. Source: Author.

23% (20% being the threshold at which post-fire hydrological effects are likely to occur (Bosch and Hewlett 1982; Hallema et al. 2018)). However, past fires are not necessarily a good indication of future fire, especially locally (Parks et al. 2018; Parisien et al. 2020); for example, wildfire activity around Fort McMurray should remain low for decades because of the large 2016 burn, granted the fact that sparse burning in longer-fire return systems makes it difficult to infer fire hazard from the short period of modern observations. There have been efforts in North-America to map fire likelihood at a high-resolution, allowing for analysis investigating worst-case wildfire scenarios that can impact source-water quantity or degrade water quality for many years after the fire (Gannon et al. 2019; Gannon, Wei, and Thompson 2020). Additionally, analyses may also focus on the coupled impact of wildfire and climate change on source-water quantity and quality (Loiselle et al. 2020).

Unfortunately, most provinces and territories do not offer an open access to spatial data relative to municipal watersheds; for instance, municipal watershed boundaries that contribute source water for communities are mostly unavailable (Figure 3). Furthermore, accessing the location of water diversion licences (also called permits) strongly differ by jurisdiction. Often, fear of terrorism motivates jurisdictions to keep community source water information concealed for security purposes (Gleick 2006). When accessible, these datasets present numerous discrepancies, thereby underlining the nature of water allocation as a provincial responsibility, which can make data aggregation and analysis challenging. Statistics Canada regularly publishes the Biennial drinking water plants survey (Statistics Canada 2021), a survey of the state of drinking water production and demand in Canada based on detailed accounts provided by provinces and water providers; public results, however interesting, are only made available aggregated at the provincial level. The access to the disaggregated source data—or microdata—is restricted and its cost can be prohibitive depending on the time necessary for the envisioned analysis. An alternative addressing security concerns while guaranteeing a decent level of spatial precision would be the creation of an aggregated dataset of essential drinking water variables (i.e., volume diverted and population served) at the HUC-12 subwatershed scale (Hydrological Unit Code

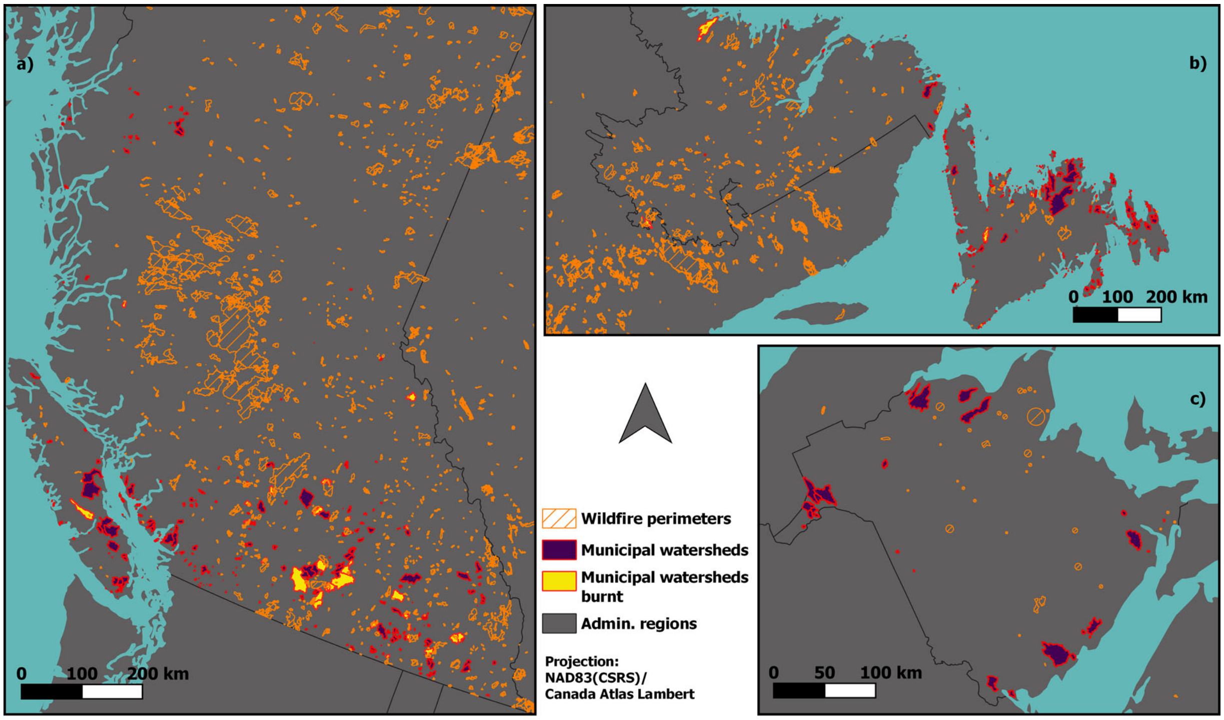

Figure 3. Map set showing the location of municipal watersheds for which spatial boundaries are available, and historical fire perimeters from 1980 to 2019. Frame (a) displays data for British Columbia, frame (b) for Newfoundland-Labrador, and frame (c) for New Brunswick. Source: Author.

– 12 digits, around 100 km^2), although this level of precision does not exist yet in the NHN.

A number of data that could help map the fire environment within these source watersheds are not available either. Specifically, this includes data sets describing fuel types and fire probabilities, which are both eminently useful fire hazard metrics for watershed management (Jones et al. 2017; Gannon et al. 2019). That said, ongoing efforts will soon provide a national fire likelihood assessment that builds on established methodologies already used widely at regional scales (Stralberg et al. 2018; Parisien et al. 2019; Stockdale et al. 2019; Thompson et al. 2019), and nation-wide fuel data at a 250 m spatial resolution derived from the MODIS satellite sensors exist and are available on demand (Beaudoin et al. 2014). Although we do not have the necessary open data to devise detailed vulnerability assessments of source watersheds across Canada at the moment, the growing demand for such information can partially be satisfied by the production of simple yet informative risk indicators at local or regional scales (Scott et al. 2012; Thompson, Scott, Kaiden, et al. 2013; Pomeroy et al. 2019; Robinne et al. 2019; Leveque et al. 2021).

Contamination of sites in municipal watersheds constitute a major threat to downstream water supply; several studies, indeed, showed that wildfires and post-fire runoff can lead to mobilization of dangerous toxicants, such as heavy metals, into downstream water resources (Pereira and Úbeda 2010; Burke et al. 2013; Murphy et al. 2020). We thus looked at possible occurrences of contaminated sites burned within municipal watersheds. Using the Federal Contaminated Site Inventory (Treasury Board of Canada Secretariat 2021), we identified one site in British Columbia (not shown) matching our research criteria, located on Reserve lands of the Tk'emlúps te Secwépemc First Nation near Kamloops. This site is located within the perimeter of a fire that burned in August 2003. It is listed as high priority for action given the presence of polycyclic aromatic hydrocarbons (PAHs) and metalloids in the soil; we cannot, however, draw any conclusion regarding potential post-fire quality issues that may have happened, given the basic level of analysis. That said, this type of approach is needed to identify sites throughout Canada's catchments used for municipal supply, given the grave implications for human health from contaminated drinking water (Shakoor et al. 2017).

Many other national FAIR datasets containing water- and forest-related information can also be leveraged to produce general yet important information on wildfires within freshwater environments. For instance, a recent study calculated temporal changes in river lengths impacted by fire in the Western US (Ball et al. 2021), and such work could be easily reproduced an adapted to the Canadian context using the Canadian vector database, or CANVEC, as well as the National Hydrographic Network, or NHN. In particular, CANVEC and NHN provide information to several water elements, natural and manmade, that could even generate more ideas for scientific studies, or even simple risk assessments. For instance, Robinne (2020) used watershed boundaries from the NHN to look at historical fire activity at the sub-sub-watershed level. There is also a general agreement that numerous communities in Canada depend on drinking water, hydroelectricity, flood control, and recreational opportunities coming from reservoirs, yet the number and location of these communities remain unknown; CANVEC and NHN can be used to provide such important information and help explore reservoir vulnerability, which is of increasing concern (Bonansea and Fernandez 2013; Terêncio et al. 2020; Basso et al. 2021). According to the Canadian Dam Association, there are over 15,000 dams in Canada, although the number of those used for drinking water supply is not available, at least publicly.

Risk reduction opportunities within the Emergency Management Strategy for Canada

The convergence of threats from global environmental change, the tremendous growth of open data access, the engagement of the Canadian government to reduce disaster risks (Public Safety Canada 2019), and the high value Canadian citizens put on their access to water (Adamowicz et al. 2016; Appiah et al. 2019) all combine to provide an enabling environment towards the rapid accumulation of WWR knowledge. The acquisition of such knowledge increasingly feels like an emergency, considering the increasing pressures on our water resources and the increasing frequency of disastrous fire seasons (WWF-Canada 2017; Government of Canada 2018; WWF-Canada 2020).

The Sendaï Framework for Disaster Risk Reduction is an international effort closely linked to the Sustainable Development Goals (SDG), whose achievements widely depend on reaching and maintaining water security, as well as protecting forest health, worldwide (Gain, Giupponi, and Wada 2016; Vörösmarty et al. 2018). As a Sendaï and SDG signatory member, Canada translated international disaster risk reduction goals into its EMS. The aim of EMS is the "strengthening [of] Canada's ability to assess risks and to prevent/mitigate, prepare for, respond to, and recover from disasters" (Public Safety Canada 2019, 5). One of its priorities is to improve disaster risk awareness within the Canadian society through the production of accurate risk information. But oft-cited issues of data openness, harmonization, and modernization by the public opinion (Linders 2013; Wilkinson et al. 2016; Weerakkody et al. 2017) points at data governance issues to be addressed promptly; the harmonization and opening of wildfire and water data can indeed help communicate on several priority topics described above. The Blueprint for wildland fire science in Canada (Sankey 2018) clearly stresses the need for open data to raise public awareness on wildfire risks, including secondary risks to water supply. But data availability is only the first building-block of effective risk communication (Weichselgartner and Pigeon 2015): a recent analysis of flood maps in Canada reads like a warning, as their generally-low quality and high complexity hinders efforts to improve risk literacy (Henstra, Minano, and Thistlethwaite 2019), pointing at more general issues of transparency and collaboration within risk management initiatives.

Although data issues described herein are not new (Boulton et al. 2012; Tenopir et al. 2018), they are particularly limiting when dealing with emerging risks such as WWR. For instance, the lack of seamless, federally-spanning dataset of Water Survey of Canada's watersheds seriously hinders knowledge production on the role of fire disturbances in shaping Canadian hydrology (Robinne et al. 2020); the case of municipal watersheds and the difficulty to access water rights data are other important limitations to drinking water risk assessment and source water protection, as they preclude the identification of priority areas in need of better risk assessment (Emelko et al. 2011; Robinne et al. 2019); finally, the difficulty to find data on water supply to First Nation communities is surprising, as many of those face the double exposure of poor water supply (Bradford et al. 2016) and high fire activity (Erni et al. 2021).

In line with numerous calls for extended collaboration in the risk management sector, we argue that developing WWR research through the EMS can help identify the variety of actors involved in forest conservation and water management: drinking water providers, First Nations, watershed councils, forestry companies, municipalities and provincial agencies responsible for water resource management, and federal agencies involved in forest research and water science, among others (Robinne et al. 2021). Such collaboration, with data creation and openness as a core objective, is paramount to the production of risk information (Table 1) (Fisher and Kingma 2001; Bakker and Cook 2011; van Asselt and Renn 2011;

Dunn, Bakker, and Harris 2014; Migliorini et al. 2019; Tymstra et al. 2020). Linders (2013) explains how information weaknesses and access difficulties to open data complicates the proper allocation of funding, generates redundancy and thus money wasting, and limits accountability. Although Linders describes these issues in the context of international aid, the problem at stake (i.e., who receives the money, why, how much, and if it was used properly) is fundamentally the same for water security in Canada, where a range of stakeholders provides funds, receive funds, and have a say in watershed planning (Simms and de Loë 2010; Simms, Lightman, and de Loë 2010; Bakker and Cook 2011). We showed that it is possible to create useful WWR information with what is readily available, and we argue that so much more could be done with better data openness, without reinventing the "data wheel." Several noteworthy examples of data aggregation in Canada provide, in this respect, ample inspiration for what WWR national products could look like: the Watershed Reports of WWF-Canada regarding the state of our water resources is one of the best examples to date of extensive data compilation and aggregation for effective risk communication (WWF-Canada 2017, 2020); the Pacific Salmon Explorer (Salmon Watersheds Program 2020) is a state-of-the-art platform for the visualization of salmon population data that relies on numerous ancillary open datasets; finally, the Climate Atlas of Canada (University of Winnipeg and Prairie Climate Centre 2019) offers an immersive experience into climate change in Canada, with the possibility for users to download locally-relevant data.

Conclusion

In this commentary, we provided a critical overview of Canada's ability to generate baseline risk information regarding wildfire threats to national water resources. Using a subset of pressing wildfire-watershed risk challenges, we illustrated several research and management questions that should be explored urgently. We also highlighted limiting factors such as data gaps, fragmentation, and lack of data openness. Generally, the capacity to produce relevant WWR baseline geographic information covering the entirety of Canada is within reach, as demonstrated by the data availability overview presented. We showed that current data is sufficient for coarse-scale analyses of WWR, but there are deficiencies in data depth, quality, and completeness that create challenges for quantifying absolute risks for many community watersheds. The framework provided by the EMS for Canada in a time and age of incredible data wealth is an encouraging sign for WWR researchers and for national water security.

Acronyms

CABIN Canadian Aquatic Biomonitoring Network (Government of Canada)
CANLABS Canadian Landsat Burned Severity (Government of Canada)
CANVEC Canadian Vector database (Government of Canada)
DNA Deoxyribonucleic acid (NA)
ECCC Environment and Climate Change Canada (Government of Canada)
EMS Emergency Management Strategy (Government of Canada)
FAIR Findable, accessible, interoperable, reusable (GOFAIR Initiative)
FCSI Federal Contaminated Site Inventory (Government of Canada)
HYDAT Hydrometric data (database) (Government of Canada)
HUC Hydrological Unit Code (NA)
NFDB National Fire Database (Government of Canada)
NBAC National Burned Area Composite (Government of Canada)
NGS Next generation sequencing (NA)
NHN National Hydrographic Network (Government of Canada)
PAH Polycyclic aromatic hydrocarbons (NA)
SARA Species at Risk Act (Government of Canada)
SDG Sustainable Development Goals (United Nations)
STREAM Sequencing the Rivers for Environmental Assessment and Monitoring (Government of Canada)
UNDRR United Nations Office for Disaster Risk Reduction (United Nations)
WWF-Canada Word Wildlife Fund Canada (Word Wildlife Fund)
WWR Wildfire-watershed risk (NA)
WSC Water Survey of Canada (Government of Canada)

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Data availability

The data that support the findings of this study are available on the Open Science Framework at this address: https://osf.io/yw8vp/ [DOI: 10.17605/OSF.IO/YW8VP]. These data were derived from resources available in the public domain, as listed in the supplementary table (https://mfr.ca-1.osf.io/render?url=https://osf.io/kemc7/?direct%26mode=render%26action=download%26mode=render). The authors confirm that all the data supporting the findings of this study are available within the article and its supplementary materials.

References

Adamowicz, Wiktor L., Alfred Appiah, Patrick Lloyd-Smith, Stephanie Simpson, and Diane P. Dupont. 2016. "Putting a Price on How Much Albertans Value the Reliability of Their Drinking Water Supply." http://www.cwn-rce.ca/assets/End-User-Reports/Municipal/Adamowicz/CWN-EN-Adamowicz-WEPGN-2016-5Pager-Web.pdf.

Al-Ibrahim, Azhar, and Robert J. Patrick. 2017. "Source Water Protection Planning and Management in Metropolitan Canada: A Preliminary Assessment." *Water* 9 (7): 497. doi:10.3390/w9070497.

Albers, Sam. 2017. "Tidyhydat: Extract and Tidy Canadian Hydrometric Data." *The Journal of Open Source Software* 2 (20): 511. doi:10.21105/joss.00511.

Appiah, Alfred, Wiktor Adamowicz, Patrick Lloyd-Smith, and Diane Dupont. 2019. "Reliability of Drinking Water: Risk Perceptions and Economic Value." *Water Economics and Policy* 5 (2): 1850020. doi:10.1142/S2382624X18500200.

van Asselt, Marjolein B. A., and Ortwin Renn. 2011. "Risk Governance." *Journal of Risk Research* 14 (4): 431–449. doi:10.1080/13669877.2011.553730.

Bakker, Karen J., and Christina Cook. 2011. "Water Governance in Canada: Innovation and Fragmentation." *International Journal of Water Resources Development* 27 (2): 275–289. doi:10.1080/07900627.2011.564969.

Ball, Grady, Peter Regier, Ricardo González-Pinzón, Justin Reale, and David Van Horn. 2021. "Wildfires Increasingly Impact Western US Fluvial Networks." *Nature Communications* 12 (1): 2484. doi:10.1038/s41467-021-22747-3.

Basso, Marta, Marcos Mateus, Tiago B. Ramos, and Diana C. S. Vieira. 2021. "Potential Post-Fire Impacts on a Water Supply Reservoir: An Integrated Watershed-Reservoir Approach." *Frontiers in Environmental Science* 9: 201. doi:10.3389/fenvs.2021.684703.

Beaudoin, A., P. Y. Bernier, L. Guindon, P. Villemaire, X. J. Guo, G. Stinson, T. Bergeron, S. Magnussen, and R. J. Hall. 2014. "Mapping Attributes of Canada's Forests at Moderate Resolution through k NN and MODIS Imagery." *Canadian Journal of Forest Research* 44 (5): 521–532. doi:10.1139/cjfr-2013-0401.

Bixby, Rebecca J., Scott D. Cooper, Robert E. Gresswell, Lee E. Brown, Clifford N. Dahm, and Kathleen A. Dwire. 2015. "Fire Effects on Aquatic Ecosystems: An Assessment of the Current State of the Science." *Freshwater Science* 34 (4): 1340–1350. doi:10.1086/684073.

Bladon, Kevin D., Uldis Silins, Michael J. Wagner, Micheal Stone, Monica B. Emelko, Carl A. Mendoza, Kevin J. Devito, and Sarah Boon. 2008. "Wildfire Impacts on Nitrogen Concentration and Production from Headwater Streams in Southern Alberta's Rocky Mountains." *Canadian Journal of Forest Research* 38 (9): 2359–2371. doi:10.1139/X08-071.

Bonansea, M., and R. L. Fernandez. 2013. "Remote Sensing of Suspended Solids Concentration in a Reservoir with Frequent Wildland Fires on Its Watershed." *Water Science and Technology* 67 (1): 217–223. doi:10.2166/wst.2012.560.

Bonsal, Barrie R., Rajesh R. Shrestha, Yonas Dibike, Daniel L. Peters, Christopher Spence, Lawrence Mudryk, and Daqing Yang. 2020. "Western Canadian Freshwater Availability: Current and Future Vulnerabilities." *Environmental Reviews* 28 (4): 528–545. doi:10.1139/er-2020-0040.

Bosch, J. M., and J. D. Hewlett. 1982. "A Review of Catchment Experiments to Determine the Effect of Vegetation Changes on Water Yield and Evapotranspiration." *Journal of Hydrology* 55 (1–4): 3–23. doi:10.1016/0022-1694(82)90117-2.

Boulton, Geoffrey, Philip Campbell, Brian Collins, Peter Elias, Wendy Hall, Graeme Laurie, Onora O'Neill, Michael Rawlins, J. Thornton, and Patrick Vallance. 2012. *Science as an Open Enterprise*. London: The Royal Society.

Bradford, Lori E. A., Lalita A. Bharadwaj, Udoka Okpalauwaekwe, and Cheryl L. Waldner. 2016. "Drinking Water Quality in Indigenous Communities in Canada and Health Outcomes: A Scoping Review." *International Journal of Circumpolar Health* 75 (1): 32336. doi:10.3402/ijch.v75.32336.

Brauman, Kate A., Gretchen C. Daily, T. Ka'eo Duarte, and Harold a Mooney. 2007. "The Nature and Value of Ecosystem Services: An Overview Highlighting Hydrologic Services." *Annual Review of Environment and*

Resources 32 (1): 67–98. doi:10.1146/annurev.energy.32.031306.102758.

Brown, Alice E., Lu Zhang, Thomas A. McMahon, Andrew W. Western, and Robert A. Vertessy. 2005. "A Review of Paired Catchment Studies for Determining Changes in Water Yield Resulting from Alterations in Vegetation." *Journal of Hydrology* 310 (1–4): 28–61. doi:10.1016/j.jhydrol.2004.12.010.

Burke, Megan P., Terri S. Hogue, Alicia M. Kinoshita, J. Barco, C. Wessel, and Eric D. Stein. 2013. "Pre- and Post-Fire Pollutant Loads in an Urban Fringe Watershed in Southern California." *Environmental Monitoring and Assessment* 185 (12): 10131–10145. doi:10.1007/s10661-013-3318-9.

Bush, E., and D. S. Lemmen. eds. 2019. *Canada's Changing Climate Report*. Ottawa, ON: Government of Canada. www.changingclimate.ca/CCCR2019.

Canadian Rivers Institute. 2021. "Canadian Aquatic Biomonitoring Network (CABIN)." Accessed July 14, 2021. https://www.canadianriversinstitute.com/training/cabin/.

Canadian Soil Information Service. 2013. "Soil Texture by Ecodistrict." Agriculture and Agri-Food Canada. https://open.canada.ca/data/en/dataset/0b88062f-ebbe-46c6-ab19-54fd226e9aa7.

Carignan, Richard, and Robert J. Steedman. 2000. "Impacts of Major Watershed Perturbations on Aquatic Ecosystems." *Canadian Journal of Fisheries and Aquatic Sciences* 57 (S2): 1–4. doi:10.1139/f00-172.

Carvalho, Francisco, Arunava Pradhan, Nelson Abrantes, Isabel Campos, Jan Jacob Keizer, Fernanda Cássio, and Cláudia Pascoal. 2019. "Wildfire Impacts on Freshwater Detrital Food Webs Depend on Runoff Load, Exposure Time and Burnt Forest Type." *The Science of the Total Environment* 692: 691–700. doi:10.1016/j.scitotenv.2019.07.265.

Chadd, Richard, and Chris Extence. 2004. "The Conservation of Freshwater Macroinvertebrate Populations: A Community-Based Classification Scheme." *Aquatic Conservation: Marine and Freshwater Ecosystems* 14 (6): 597–624. doi:10.1002/aqc.630.

Coogan, Sean C. P., François-Nicolas Robinne, Piyush Jain, and Mike D. Flannigan. 2019. "Scientists' Warning on Wildfire—A Canadian Perspective." *Canadian Journal of Forest Research* 49 (9): 1015–1023. doi:10.1139/cjfr-2019-0094.

Coops, Nicholas C., Txomin Hermosilla, Michael A. Wulder, Joanne C. White, and Douglas K. Bolton. 2018. "A Thirty Year, Fine-Scale, Characterization of Area Burned in Canadian Forests Shows Evidence of Regionally Increasing Trends in the Last Decade." *PLoS One* 13 (5): e0197218. doi:10.1371/journal.pone.0197218.

Cott, Peter A., Barry A. Zajdlik, Kelly J. Bourassa, Marc Lange, and Andrew M. Gordon. 2010. "Effects of Forest Fire on Young-of-the-Year Northern Pike, Esox Lucius, in the Northwest Territories." *The Canadian Field-Naturalist* 124 (2): 104. doi:10.22621/cfn.v124i2.1046.

Dunn, Gemma, Karen J. Bakker, and Leila M. Harris. 2014. "Drinking Water Quality Guidelines across Canadian Provinces and Territories: Jurisdictional Variation in the Context of Decentralized Water Governance." *International Journal of Environmental Research and Public Health* 11 (5): 4634–4651. doi:10.3390/ijerph110504634.

Edge, Thomas A., Donald J. Baird, Guillaume Bilodeau, Nellie Gagné, Charles Greer, David Konkin, Glen Newton, et al. 2020. "The Ecobiomics Project: Advancing Metagenomics Assessment of Soil Health and Freshwater Quality in Canada." *The Science of the Total Environment* 710: 135906. doi:10.1016/j.scitotenv.2019.135906.

Elliot, William J., Mary Ellen Miller, and Nic Enstice. 2016. "Targeting Forest Management through Fire and Erosion Modelling." *International Journal of Wildland Fire* 25 (8): 876–887. doi:10.1071/WF15007.

Emelko, Monica B., Uldis Silins, Kevin D. Bladon, and Micheal Stone. 2011. "Implications of Land Disturbance on Drinking Water Treatability in a Changing Climate: Demonstrating the Need for 'Source Water Supply and Protection' Strategies." *Water Research* 45 (2): 461–472. doi:10.1016/j.watres.2010.08.051.

Emelko, Monica B., Micheal Stone, Uldis Silins, Don Allin, Adrian L. Collins, Chris H. S. Williams, Amanda M. Martens, and Kevin D. Bladon. 2016. "Sediment-Phosphorus Dynamics Can Shift Aquatic Ecology and Cause Downstream Legacy Effects after Wildfire in Large River Systems." *Global Change Biology* 22 (3): 1168–1184. doi:10.1111/gcb.13073.

Environment and Climate Change Canada. 2018. "Science of Aquatic Biomonitoring." https://www.canada.ca/en/environment-climate-change/services/canadian-aquatic-biomonitoring-network/science.html.

Environment and Climate Change Canada. 2019. "Canadian Aquatic Biomonitoring Network." https://www.canada.ca/en/environment-climate-change/services/canadian-aquatic-biomonitoring-network.html.

Environment and Climate Change Canada. 2021. "Canadian Centre for Climate Services." https://www.canada.ca/en/environment-climate-change/services/climate-change/canadian-centre-climate-services/display-download.html.

Environment and Climate Change Canada and University of Guelph. 2019. "Sequencing the Rivers or Environmental Assessment and Monitoring (STREAM)." https://stream-dna.com/.

Erni, Sandy, Lynn Johnston, Yan Boulanger, Francis Manka, Pierre Bernier, Brian Eddy, Amy Christianson, Tom Swystun, and Sylvie Gauthier. 2021. "Exposure of the Canadian Wildland–Human Interface and Population to Wildland Fire, under Current and Future Climate Conditions." *Canadian Journal of Forest Research* 51 (9): 1357–1367. doi:10.1139/cjfr-2020-0422.

Fekete, Alexander, Katerina Tzavella, Iuliana Armas, Jane Binner, Matthias Garschagen, Carlo Giupponi, Vahid Mojtahed, Marcello Pettita, Stefan Schneiderbauer, and Damien Serre. 2015. "Critical Data Source; Tool or Even Infrastructure? Challenges of Geographic Information Systems and Remote Sensing for Disaster Risk Governance." *ISPRS International Journal of Geo-Information* 4 (4): 1848–1869. doi:10.3390/ijgi4041848.

Fisher, Craig W., and Bruce R. Kingma. 2001. "Criticality of Data Quality as Exemplified in Two Disasters." *Information & Management* 39 (2): 109–116. doi:10.1016/S0378-7206(01)00083-0.

Fisheries and Ocean Canada. 2020. “Survey of Recreational Fishing in Canada, 2015.” https://www.dfo-mpo.gc.ca/stats/rec/can/2015/index-eng.html#4-4-1.

Fraser Basin Council. 2021. “Nicola Basin Collaborative.” https://www.fraserbasin.bc.ca/Nicola_Basin_Collaborative.html.

Friberg, Nikolai, Núria Bonada, David C. Bradley, Michael J. Dunbar, Francois K. Edwards, Jonathan Grey, Richard B. Hayes, et al. 2011. “Biomonitoring of Human Impacts in Freshwater Ecosystems.” *Advances in Ecological Research* 44: 1–68. doi:10.1016/B978-0-12-374794-5.00001-8.

Gain, Animesh K., Carlo Giupponi, and Yoshihide Wada. 2016. “Measuring Global Water Security towards Sustainable Development Goals.” *Environmental Research Letters* 11 (12): 124015. doi:10.1088/1748-9326/11/12/124015.

Gannon, Benjamin M., Yu Wei, Lee H. MacDonald, Stephanie K. Kampf, Kelly W. Jones, Jeffery B. Cannon, Brett H. Wolk, Antony S. Cheng, Robert N. Addington, and Matthew P. Thompson. 2019. “Prioritising Fuels Reduction for Water Supply Protection.” *International Journal of Wildland Fire* 28 (10): 785. doi:10.1071/WF18182.

Gannon, Benjamin M., Yu Wei, and Matthew P. Thompson. 2020. “Mitigating Source Water Risks with Improved Wildfire Containment.” *Fire* 3 (3): 1–25. doi:10.3390/fire3030045.

Garda, Chris, Heather Castleden, and Cathy Conrad. 2017. “Monitoring, Restoration, and Source Water Protection: Canadian Community-Based Environmental Organizations’ Efforts towards Improving Aquatic Ecosystem Health.” *Water* 9 (3): 212. doi:10.3390/w9030212.

Gleick, Peter H. 2006. “Water and Terrorism.” *Water Policy* 8 (6): 481–503. doi:10.2166/wp.2006.035.

Godsoe, M., M. Ladd, and R. Cox. 2019. “Assessing Canada’s Disaster Baselines and Projections under the Sendai Framework for Disaster Risk Reduction: A Modeling Tool to Track Progress.” *Natural Hazards* 98 (1): 293–317. doi:10.1007/s11069-019-03599-z.

Government of Canada. 2018. *Water Quality in Canadian Rivers*. Gatineau, Québec: Government of Canada.

Grand River Conservation Authority. 2020. “Grand River Information Network (GRIN).” https://data.grandriver.ca/about.html.

Gresswell, Robert E. 1999. “Fire and Aquatic Ecosystems in Forested Biomes of North America.” *Transactions of the American Fisheries Society* 128 (2): 193–221. > 2.0.co;2. doi:10.1577/1548-8659(1999)128 < 0193:faaeif.

Guindon, Luc, P. Villemaire, F. Manka, H. Dorion, R. Skakun, R. St-Amant, and S. Gauthier. 2020. “Canada Landsat Burned Severity Product 1985-2015 (CanLaBS).” doi:10.23687/b1f61b7e-4ba6-4244-bc79-c1174f2f92cd.

Guindon, Luc, Sylvie Gauthier, Francis Manka, Marc-André Parisien, Ellen Whitman, Pierre Bernier, Andre Beaudoin, Philippe Villemaire, and Rob Skakun. 2020. “Trends in Wildfire Burn Severity across Canada, 1985 to 2015.” *Canadian Journal of Forest Research*. doi:10.1139/cjfr-2020-0353.

Hall, R. J., R. S. Skakun, J. M. Metsaranta, R. Landry, R. H. Fraser, D. Raymond, M. Gartrell, V. Decker, and J. Little. 2020. “Generating Annual Estimates of Forest Fire Disturbance in Canada: The National Burned Area Composite.” *International Journal of Wildland Fire* 29 (10): 878. doi:10.1071/WF19201.

Hallema, Dennis W., Ge Sun, Kevin D. Bladon, Steven P. Norman, Peter V. Caldwell, Yongqiang Liu, and Steven G. McNulty. 2017. “Regional Patterns of Postwildfire Streamflow Response in the Western United States: The Importance of Scale-Specific Connectivity.” *Hydrological Processes* 31 (14): 2582–2598. doi:10.1002/hyp.11208.

Hallema, Dennis W., Ge Sun, Peter V. Caldwell, Steven P. Norman, Erika C. Cohen, Yongqiang Liu, Eric J. Ward, and Steven G. McNulty. 2017. “Assessment of Wildland Fire Impacts on Watershed Annual Water Yield: Analytical Framework and Case Studies in the United States.” *Ecohydrology* 10 (2): e1794. doi:10.1002/eco.1794.

Hallema, Dennis W., Ge Sun, Peter V. Caldwell, Steven P. Norman, Erika C. Cohen, Yongqiang Liu, Kevin D. Bladon, and Steven G. McNulty. 2018. “Burned Forests Impact Water Supplies.” *Nature Communications* 9 (1): 1307. doi:10.1038/s41467-018-03735-6.

Hanes, Chelene C., Xianli Wang, Piyush Jain, Marc-André Parisien, John M. Little, and Mike D. Flannigan. 2019. “Fire-Regime Changes in Canada over the Last Half Century.” *Canadian Journal of Forest Research* 49 (3): 256–269. doi:10.1139/cjfr-2018-0293.

Henstra, Daniel, Andrea Minano, and Jason Thistlethwaite. 2019. “Communicating Disaster Risk? An Evaluation of the Availability and Quality of Flood Maps.” *Natural Hazards and Earth System Sciences* 19 (1): 313–323. doi:10.5194/nhess-19-313-2019.

Hohner, Amanda K., Charles C. Rhoades, Paul Wilkerson, and Fernando L. Rosario-Ortiz. 2019. “Wildfires Alter Forest Watersheds and Threaten Drinking Water Quality.” *Accounts of Chemical Research* 52 (5): 1234–1244. doi:10.1021/acs.accounts.8b00670.

Hrachowitz, M., H. H. G. Savenije, G. Blöschl, J. J. McDonnell, M. Sivapalan, J. W. Pomeroy, B. Arheimer, et al. 2013. “A Decade of Predictions in Ungauged Basins (PUB)—A Review.” *Hydrological Sciences Journal* 58 (6): 1198–1255. doi:10.1080/02626667.2013.803183.

Ireson, A. M., A. G. Barr, Jill F. Johnstone, S. D. Mamet, G. van der Kamp, C. J. Whitfield, N. L. Michel, et al. 2015. “The Changing Water Cycle: The Boreal Plains Ecozone of Western Canada.” *WIREs Water* 2 (5): 505–521. doi:10.1002/wat2.1098.

Johnston, Lynn M., Xianli Wang, Sandy Erni, Stephen W. Taylor, Colin B. McFayden, Jacqueline A. Oliver, Chris Stockdale, et al. 2020. “Wildland Fire Risk Research in Canada.” *Environmental Reviews* 28 (2): 164–173. doi:10.1139/er-2019-0046.

Jones, Kelly W., Jeffery B. Cannon, Freddy A. Saavedra, Stephanie K. Kampf, Robert N. Addington, Antony S. Cheng, Lee H. MacDonald, Codie Wilson, and Brett Wolk. 2017. “Return on Investment from Fuel Treatments to Reduce Severe Wildfire and Erosion in a Watershed Investment Program in Colorado.” *Journal of Environmental Management* 198 (Pt 2): 66–77. doi:10.1016/j.jenvman.2017.05.023.

Kennedy, Maureen C., Donald McKenzie, Christina Tague, and Aubrey L. Dugger. 2017. “Balancing Uncertainty and

Complexity to Incorporate Fire Spread in an Eco-Hydrological Model." *International Journal of Wildland Fire* 26 (8): 706. doi:10.1071/WF16169.

Klinke, Andreas, and Ortwin Renn. 2012. "Adaptive and Integrative Governance on Risk and Uncertainty." *Journal of Risk Research* 15 (3): 273–292. doi:10.1080/13669877.2011.636838.

Leveque, B., J.-B. Burnet, S. Dorner, and F. Bichai. 2021. "Impact of Climate Change on the Vulnerability of Drinking Water Intakes in a Northern Region." *Sustainable Cities and Society* 66: 102656. doi:10.1016/j.scs.2020.102656.

Linders, Dennis. 2013. "Towards Open Development: Leveraging Open Data to Improve the Planning and Coordination of International Aid." *Government Information Quarterly* 30 (4)JAI: 426–434. doi:10.1016/j.giq.2013.04.001.

Loiselle, Danielle, Xinzhong Du, Daniel S. Alessi, Kevin D. Bladon, and Monireh Faramarzi. 2020. "Projecting Impacts of Wildfire and Climate Change on Streamflow, Sediment, and Organic Carbon Yields in a Forested Watershed." *Journal of Hydrology* 590: 125403. doi:10.1016/j.jhydrol.2020.125403.

Luthra, Sonaar. 2019. "We Need to Track the World's Water like We Track the Weather." *TED.Com*. https://www.ted.com/talks/sonaar_luthra_we_need_to_track_the_world_s_water_like_we_track_the_weather.

Mamuji, Aaida A., and Jack L. Rozdilsky. 2019. "Wildfire as an Increasingly Common Natural Disaster Facing Canada: Understanding the 2016 Fort McMurray Wildfire." *Natural Hazards* 98 (1): 163–180. doi:10.1007/s11069-018-3488-4.

Månsson, Peter. 2018. "Mapping Challenges and Opportunities for Aggregating Information on Systemic Risks from Multiple Stakeholders." *Procedia Engineering* 212: 736–743. doi:10.1016/j.proeng.2018.01.095.

Månsson, Peter, Marcus Abrahamsson, and Henrik Tehler. 2019. "Aggregated Risk: An Experimental Study on Combining Different Ways of Presenting Risk Information." *Journal of Risk Research* 22 (4): 497–512. doi:10.1080/13669877.2017.1391315.

Martin, Deborah A. 2016. "At the Nexus of Fire, Water and Society." *Philosophical Transactions of the Royal Society B: Biological Sciences* 371 (1696): 20150172. doi:10.1098/rstb.2015.0172.

Marushka, Lesya, Malek Batal, Constantine Tikhonov, Tonio Sadik, Harold Schwartz, Amy Ing, Karen Fediuk, and Hing Man Chan. 2021. "Importance of Fish for Food and Nutrition Security among First Nations in Canada." *Canadian Journal of Public Health = Revue Canadienne de Sante Publique* 112 (Suppl 1): 64–80. doi:10.17269/s41997-021-00481-z.

McNie, Elizabeth C. 2007. "Reconciling the Supply of Scientific Information with User Demands: An Analysis of the Problem and Review of the Literature." *Environmental Science & Policy* 10 (1): 17–38. doi:10.1016/j.envsci.2006.10.004.

Migliorini, Massimo, Jenny Sjåstad Hagen, Jadranka Mihaljević, Jaroslav Mysiak, Jean-Louis Rossi, Alexander Siegmund, Khachatur Meliksetian, and Debarati Guha Sapir. 2019. "Data Interoperability for Disaster Risk Reduction in Europe." *Disaster Prevention and Management* 28 (6): 804–816. doi:10.1108/DPM-09-2019-0291.

Miller, M. E., W. J. Elliot, M. Billmire, Peter R. Robichaud, and K. A. Endsley. 2016. "Rapid-Response Tools and Datasets for Post-Fire Remediation: Linking Remote Sensing and Process-Based Hydrological Models." *International Journal of Wildland Fire* 25 (10): 1061–1073. doi:10.1071/WF15162.

Mortsch, Linda, Cohen, Stewart and Grace Koshida. 2015. "Climate and Water Availability Indicators in Canada: Challenges and a Way Forward. Part II—Historic Trends." *Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques* 40 (2): 146–159. doi:10.1080/07011784.2015.1006024.

Murphy, Sheila F., Jeffrey H. Writer, R. Blaine McCleskey, and Deborah A. Martin. 2015. "The Role of Precipitation Type, Intensity, and Spatial Distribution in Source Water Quality after Wildfire." *Environmental Research Letters* 10 (8): 084007. doi:10.1088/1748-9326/10/8/084007.

Murphy, Sheila F., R. Blaine McCleskey, Deborah A. Martin, JoAnn M. Holloway, and Jeffrey H. Writer. 2020. "Wildfire-Driven Changes in Hydrology Mobilize Arsenic and Metals from Legacy Mine Waste." *The Science of the Total Environment* 743: 140635. doi:10.1016/j.scitotenv.2020.140635.

Nearing, Grey S., Frederik Kratzert, Alden Keefe Sampson, Craig S. Pelissier, Daniel Klotz, Jonathan M. Frame, Cristina Prieto, and Hoshin V. Gupta. 2021. "What Role Does Hydrological Science Play in the Age of Machine Learning?" *Water Resources Research* 57 (3): e2020WR028091. doi:10.1029/2020WR028091.

Neary, Daniel G., George G. Ice, and C. Rhett Jackson. 2009. "Linkages between Forest Soils and Water Quality and Quantity." *Forest Ecology and Management* 258 (10): 2269–2281. doi:10.1016/j.foreco.2009.05.027.

Neris, Jonay, Cristina Santin, Roger Lew, Peter R. Robichaud, William J. Elliot, Sarah A. Lewis, Gary Sheridan, et al. 2021. "Designing Tools to Predict and Mitigate Impacts on Water Quality following the Australian 2019/2020 Wildfires: Insights from Sydney's Largest Water Supply Catchment." *Integrated Environmental Assessment and Management* 17 (6): 1151–1161. doi:10.1002/ieam.4406.

Neuvel, Jeroen M. M., Henk J. Scholten, and Adri van den Brink. 2012. "From Spatial Data to Synchronised Actions: The Network-Centric Organisation of Spatial Decision Support for Risk and Emergency Management." *Applied Spatial Analysis and Policy* 5 (1): 51–72. doi:10.1007/s12061-010-9059-z.

Niemeyer, Ryan J., Kevin D. Bladon, and Richard D. Woodsmith. 2020. "Long-Term Hydrologic Recovery after Wildfire and Post-Fire Forest Management in the Interior Pacific Northwest." *Hydrological Processes* 34 (5): 1182–1197. doi:10.1002/hyp.13665.

Nunes, Joao P., Stefan H. Doerr, Gary Sheridan, Jonay Neris, Cristina Santín, Monica B. Emelko, Uldis Silins, Peter R. Robichaud, William J. Elliot, and Jacob Keizer. 2018. "Assessing Water Contamination Risk from Vegetation Fires: Challenges, Opportunities and a Framework for Progress." *Hydrological Processes* 32 (5): 687–694. doi:10.1002/hyp.11434.

Owens, Philip N., Timothy R. Giles, Ellen L. Petticrew, M. S. Leggat, R. D D. Moore, and Brett C. Eaton. 2013. "Muted Responses of Streamflow and Suspended Sediment Flux in a Wildfire-Affected Watershed." *Geomorphology* 202: 128–139. doi:10.1016/j.geomorph.2013.01.001.

Parisien, Marc-André, Denyse A. Dawe, Carol Miller, Christopher A. Stockdale, and O. Bradley Armitage. 2019. "Applications of Simulation-Based Burn Probability Modelling: A Review." *International Journal of Wildland Fire* 28 (12): 913. doi:10.1071/WF19069.

Parisien, Marc-André, Quinn E. Barber, Kelvin G. Hirsch, Christopher A. Stockdale, Sandy Erni, Xianli Wang, Dominique Arseneault, and Sean A. Parks. 2020. " "Fire Deficit Increases Wildfire Risk for Many Communities in the Canadian Boreal Forest." *Nature Communications* 11 (1): 2121. doi:10.1038/s41467-020-15961-y.

Parks, Sean A., Marc-André Parisien, Carol Miller, Lisa M. Holsinger, and Larry Scott Baggett. 2018. "Fine-Scale Spatial Climate Variation and Drought Mediate the Likelihood of Reburning." *Ecological Applications* 28 (2): 573–586. doi:10.1002/eap.1671.

Pawlowski, Jan, Mary Kelly-Quinn, Florian Altermatt, Laure Apothéloz-Perret-Gentil, Pedro Beja, Angela Boggero, Angel Borja, et al. 2018. "The Future of Biotic Indices in the Ecogenomic Era: Integrating (e)DNA Metabarcoding in Biological Assessment of Aquatic Ecosystems." *Science of the Total Environment* 637–638: 1295–1310. doi:10.1016/j.scitotenv.2018.05.002.

Pereira, Paulo, and Xavier Úbeda. 2010. "Spatial Distribution of Heavy Metals Released from Ashes after a Wildfire." *Journal of Environmental Engineering and Landscape Management* 18 (1): 13–22. doi:10.3846/jeelm.2010.02.

Perrier, Erika, Megan Kot, Heather Castleden, and Graham A. Gagnon. 2014. "Drinking Water Safety Plans: Barriers and Bridges for Small Systems in Alberta, Canada." *Water Policy* 16 (6): 1140–1154. doi:10.2166/wp.2014.207.

Pomeroy, John W., Chris M. DeBeer, Phani Adapa, Merrell-Ann Phare, Natasha Overduin, Michael Miltenberger, Tony Maas, Ralph Pentland, Oliver M. Brandes, and Robert W. Sandford. 2019. *Water Security for Canadians—Solutions for Canada's Emerging Water Crisis*. Saskatoon, SK: Canadian Water Security Initiative. https://www.flowcanada.org/our-work.

Public Safety Canada. 2019. *Emergency Management Strategy for Canada: Toward a Resilient 2030*. Ottawa, ON: Public Safety Canada. https://www.publicsafety.gc.ca/cnt/rsrcs/pblctns/mrgncy-mngmnt-strtgy/index-en.aspx.

Rieman, Bruce E., Danny Lee, Dave Burns, Robert Gresswell, Michael Young, Rick Stowell, John Rinne, and Philip Howell. 2003. "Status of Native Fishes in the Western United States and Issues for Fire and Fuels Management." *Forest Ecology and Management* 178 (1–2): 197–211. doi:10.1016/S0378-1127(03)00062-8.

Rieman, Bruce E., and Jim Clayton. 1997. "Wildfire and Native Fish: Issues of Forest Health and Conservation of Sensitive Species." *Fisheries* 22 (11): 6–15. doi:10.1577/1548-8446(1997)022<0006:WANFIO>2.0.CO;2.

Robinne, François-Nicolas. 2020. "A Geospatial Dataset Providing First-Order Indicators of Wildfire Risks to Water Supply in Canada and Alaska." *Data in Brief* 29 (April): 105171. doi:10.1016/j.dib.2020.105171.

Robinne, François-Nicolas, Dennis W. Hallema, Kevin D. Bladon, and James M. Buttle. 2020. "Wildfire Impacts on Hydrologic Ecosystem Services in North American High-Latitude Forests: A Scoping Review." *Journal of Hydrology* 581: 124360. doi:10.1016/j.jhydrol.2019.124360.

Robinne, François-Nicolas, Dennis W. Hallema, Kevin D. Bladon, Mike D. Flannigan, Gabrielle Boisramé, Christian M. Bréthaut, Stefan H. Doerr, et al. 2021. "Scientists' Warning on Extreme Wildfire Risks to Water Supply." *Hydrological Processes* 35 (5): hyp.14086. doi:10.1002/hyp.14086.

Robinne, François-Nicolas, Kevin D. Bladon, Uldis Silins, Monica B. Emelko, Mike D. Flannigan, Marc-André Parisien, Xianli Wang, Stefan W. Kienzle, and Diane P. Dupont. 2019. "A Regional-Scale Index for Assessing the Exposure of Drinking-Water Sources to Wildfires." *Forests* 10 (5): 384. doi:10.3390/f10050384.

Robinson, Chloe V., Teresita M. Porter, Michael T. G. Wright, and Mehrdad Hajibabaei. 2021. "Propylene Glycol-Based Antifreeze is an Effective Preservative for DNA Metabarcoding of Benthic Arthropods." *Freshwater Science* 40 (1): 77–87. doi:10.1086/712232.

Salmon Watersheds Program. 2020. "Pacific Salmon Explorer." https://www.salmonexplorer.ca/#!/.

Sankey, S. 2018. *Blueprint for Wildland Fire Science in Canada (2019–2029)*. Edmonton, AB: Natural Resources of Canada, Canadian Forest Service. https://cfs.nrcan.gc.ca/publications?id=39429.

Scott, Joe, Don Helmbrecht, Matthew P. Thompson, David E. Calkin, and Kate Marcille. 2012. "Probabilistic Assessment of Wildfire Hazard and Municipal Watershed Exposure." *Natural Hazards* 64 (1): 707–728. doi:10.1007/s11069-012-0265-7.

Shakesby, Richard A., and Stefan H. Doerr. 2006. "Wildfire as a Hydrological and Geomorphological Agent." *Earth-Science Reviews* 74 (3–4): 269–307. doi:10.1016/j.earscirev.2005.10.006.

Shakoor, Muhammad Bilal, Rab Nawaz, Fida Hussain, Maimoona Raza, Shafaqat Ali, Muhammad Rizwan, Sang-Eun Oh, and Sajjad Ahmad. 2017. "Human Health Implications, Risk Assessment and Remediation of as-Contaminated Water: A Critical Review." *Science of the Total Environment* 601–602: 756–769. doi:10.1016/j.scitotenv.2017.05.223.

Silins, Uldis, Kevin D. Bladon, Erin N. Kelly, Evan Esch, John R. Spence, Micheal Stone, Monica B. Emelko, et al. 2014. "Five-Year Legacy of Wildfire and Salvage Logging Impacts on Nutrient Runoff and Aquatic Plant, Invertebrate, and Fish Productivity." *Ecohydrology* 7 (6): 1508–1523. doi:10.1002/eco.1474.

Simms, G., and R. C. de Loë. 2010. "Challenges for Water Governance in Canada: A Discussion Paper Governance for Source Water Protection in Canada." Governance for Source Water Protection in Canada Report No. 2.

Simms, G., D. Lightman, and R. de Loë. 2010. "Tools and Approaches for Source Water Protection in Canada." Canadian Water Network. http://poliswaterproject.org/sites/default/files/WPGG_SWPG_No.1.pdf.

Soil Landscapes of Canada Working Group. 2010. "Soil Landscapes of Canada Version 3.2." Agriculture and Agri-Food Canada. https://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html.

Spence, Christopher, Newell Hedstrom, Suzanne E. Tank, William L. Quinton, David Olefeldt, Stefan Goodman, and Nicole Dion. 2020. "Hydrological Resilience to Forest Fire in the Subarctic Canadian Shield." *Hydrological Processes* 34 (25): 4940–4958. doi:10.1002/hyp.13915.

Spencer, Craig N., Kristin Odney Gabel, and FRichard Hauer. 2003. "Wildfire Effects on Stream Food Webs and Nutrient Dynamics in Glacier National Park, USA." *Forest Ecology and Management* 178 (1–2): 141–153. doi:10.1016/S0378-1127(03)00058-6.

Statistics Canada. 2021. "Biennial Drinking Water Plants Survey (DKWP)." Surveys and Statistical Programs. https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&Id=1260950.

Stockdale, Christopher A., Neal McLoughlin, Mike Flannigan, and S. Ellen Macdonald. 2019. "Could Restoration of a Landscape to a Pre-European Historical Vegetation Condition Reduce Burn Probability?" *Ecosphere* 10 (2): e02584. doi:10.1002/ecs2.2584.

Stralberg, Diana, Xianli Wang, Marc-André Parisien, François-Nicolas Robinne, Péter Sólymos, C. Lisa Mahon, Scott E. Nielsen, and Erin M. Bayne. 2018. "Wildfire-Mediated Vegetation Change in Boreal Forests of Alberta, Canada." *Ecosphere* 9 (3): e02156. doi:10.1002/ecs2.2156.

Tenopir, C., L. Christian, S. Allard, and J. Borycz. 2018. "Research Data Sharing: Practices and Attitudes of Geophysicists." *Earth and Space Science* 5 (12): 891–902. doi:10.1029/2018EA000461.

Terêncio, Daniela Patrícia Salgado, Rui Manuel Vitor Cortes, Fernando António Leal Pacheco, João Paulo Moura, and Luís Filipe Sanches Fernandes. 2020. "A Method for Estimating the Risk of Dam Reservoir Silting in Fire-Prone Watersheds: A Study in Douro River, Portugal." *Water* 12 (11): 2959. doi:10.3390/w12112959.

Thompson, Daniel K., Brian Simpson, Ellen Whitman, Quinn E. Barber, and Marc-André Parisien. 2019. "Peatland Hydrological Dynamics as a Driver of Landscape Connectivity and Fire Activity in the Boreal Plain of Canada." *Forests* 10 (7): 534. doi:10.3390/f10070534.

Thompson, Matthew P., Joe H. Scott, Jeffrey D. Kaiden, and Julie W. Gilbertson-Day. 2013. "A Polygon-Based Modeling Approach to Assess Exposure of Resources and Assets to Wildfire." *Natural Hazards* 67 (2): 627–644. doi:10.1007/s11069-013-0593-2.

Thompson, Matthew P., Joe Scott, Paul Langowski, Julie Gilbertson-Day, Jessica Haas, and Elise Bowne. 2013. "Assessing Watershed-Wildfire Risks on National Forest System Lands in the Rocky Mountain Region of the United States." *Water* 5 (3): 945–971. doi:10.3390/w5030945.

Treasury Board of Canada Secretariat. 2021. "Federal Contaminated Sites Inventory." https://www.tbs-sct.gc.ca/fcsi-rscf/home-accueil-eng.aspx.

Turcotte, Audrey, Natalie Kermany, Sharla Foster, Caitlyn A. Proctor, Sydney M. Gilmour, Maria Doria, James Sebes, Jeannette Whitton, Steven J. Cooke, and Joseph R. Bennett. 2021. "Fixing the Canadian Species at Risk Act: Identifying Major Issues and Recommendations for Increasing Accountability and Efficiency." *FACETS* 6: 1474–1494. doi:10.1139/facets-2020-0064.

Tymstra, Cordy, Brian J. Stocks, Xinli Cai, and Mike D. Flannigan. 2020. "Wildfire Management in Canada: Review, Challenges and Opportunities." *Progress in Disaster Science* 5: 100045. doi:10.1016/j.pdisas.2019.100045.

United Nations International Strategt for Disaster Reduction (UNISDR). 2015. "Sendai Framework for Disaster Risk Reduction 2015–2030." Geneva, Switzerland: United Nations. doi:A/CONF.224/CRP.1.

University of Winnipeg and Prairie Climate Centre. 2019. "Climate Atlas of Canada." https://prairieclimatecentre.ca/.

Vörösmarty, Charles J., Vanesa Rodríguez Osuna, Anthony D. Cak, Anik Bhaduri, Stuart E. Bunn, Fabio Corsi, Jorge Gastelumendi, et al. 2018. "Ecosystem-Based Water Security and the Sustainable Development Goals (SDGs)." *Ecohydrology & Hydrobiology* 18 (4): 317–333. doi:10.1016/j.ecohyd.2018.07.004.

Weerakkody, Vishanth, Zahir Irani, Kawal Kapoor, Uthayasankar Sivarajah, and Yogesh K. Dwivedi. 2017. "Open Data and Its Usability: An Empirical View from the Citizen's Perspective." *Information Systems Frontiers* 19 (2): 285–300. doi:10.1007/s10796-016-9679-1.

Weichselgartner, Juergen, and Patrick Pigeon. 2015. "The Role of Knowledge in Disaster Risk Reduction." *International Journal of Disaster Risk Science* 6 (2): 107–116. doi:10.1007/s13753-015-0052-7.

Wilkinson, Mark D., Michel Dumontier, IJsbrand Jan Aalbersberg, Gabrielle Appleton, Myles Axton, Arie Baak, Niklas Blomberg, et al. 2016. "The FAIR Guiding Principles for Scientific Data Management and Stewardship." *Scientific Data* 3 (1): 160018. doi:10.1038/sdata.2016.18.

Wine, Michael Louis, and Daniel Cadol. 2016. "Hydrologic Effects of Large Southwestern USA Wildfires Significantly Increase Regional Water Supply: Fact or Fiction?" *Environmental Research Letters* 11 (8): 085006. doi:10.1088/1748-9326/11/8/085006.

Wine, Michael L., Daniel Cadol, and Oleg Makhnin. 2018. "In Ecoregions across Western USA Streamflow Increases during Post-Wildfire Recovery." *Environmental Research Letters* 13 (1): 014010. doi:10.1088/1748-9326/aa9c5a.

WWF-Canada. 2017. "A National Assessment of Canada's Freshwater—Watershed Reports." Toronto, Ontario, Canada. http://watershedreports.wwf.ca.

WWF-Canada. 2020. "WWF-Canada's 2020 Watershed Reports: A National Reassessment of Canada's Freshwater." Toronto, Ontario, Canada.