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

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Abstract

As the pressures on water supply from shifting forest disturbance regimes continue to escalate, researchers are being asked to answer increasingly complex questions. However, many questions in wildfire-watershed risk (WWR) research remained unaddressed due to a paucity of relevant datasets. There are, indeed, many fundamental processes we do not understand that require additional data collection to develop risk management frameworks. As such, WWR researchers and managers face a paradox in their need to address critical questions important for the sustainability of socio-hydrological systems while dealing with incomplete information. In many cases, this leads to valuable research ideas being discarded on the account of limited data availability. However, imperfect, incomplete, or limited data should not deter researchers and managers from performing analyses to assess risk. In fact, such analyses improve the research benefit-to-cost ratio of existing data, help unravel gaps in data sources, enable generation of new hypotheses, and highlight where data availability and openness can be improved. If we do not use what we have, how can we know what we need? This issue is of particular interest in Canada, where baseline WWR information for the entire country is generally missing, despite growing concerns about water security in the face of a shifting wildfire regimes. In this commentary, we (a) identify several relevant open geospatial datasets, (b) illustrate how these datasets can be leveraged to produce simple yet relevant risk information, (c) identify some high priority data gaps that require immediate attention, and (d) discuss future avenues towards the creation of baseline Pan-Canadian WWR information.

Résumé

Alors que les changements dans les régimes de perturbations forestières exercent une pression croissante sur l'approvisionnement en eau, les chercheurs doivent répondre à des questions de plus en plus complexes. Pourtant, de nombreuses questions relatives à la recherche sur les risques incendies dans les bassins-versants (RIBV) restent ignorées en raison du manque de données adéquates. Il reste, en effet, de nombreux processus

49 fondamentaux que nous ne comprenons pas et qui requièrent la collecte de données
50 additionnelles, afin de développer des cadres d'analyse appropriés pour la gestion de ces
51 risques. Ainsi, les chercheurs et gestionnaires en RIBV font face à un paradoxe car ils
52 doivent répondre à des questions importantes pour la durabilité des systèmes socio-
53 hydrologiques mais pour lesquelles ils n'ont que des informations incomplètes. Dans de
54 nombreux cas, cela amène au rejet d'idées de recherche du fait de la disponibilité limitée
55 des données. Pourtant, des données limitées, imparfaites, ou incomplètes ne devraient pas
56 dissuader chercheurs et gestionnaires de réaliser des analyses de risques. En fait, de telles
57 analyses améliorent le rapport coût-bénéfice des données existantes, aident à
58 l'identification de lacunes dans les données sources, permettent la génération de nouvelles
59 hypothèses, et mettent en évidence les possibilités d'amélioration dans la disponibilité et
60 l'ouverture des données. Si nous n'utilisons pas ce que nous avons, comment savoir ce
61 dont nous avons besoin ? Ce sujet est d'un intérêt particulier au Canada, où les
62 informations de référence sur les RIBV pour l'entièreté du pays sont généralement
63 manquantes, malgré les inquiétudes grandissantes concernant la sécurité de l'eau dans un
64 contexte de régimes de feux changeants. Dans ce commentaire, nous (a) identifions
65 plusieurs jeux de données pertinents, (b) illustrons la façon dont ces jeux de données
66 peuvent être utilisés à bon escient pour la production d'informations simples mais
67 effectives sur le risque, (c) identifions des lacunes de données prioritaires qui demandent
68 une attention immédiate, et (d) discutons de possibilités futures pour la création d'un
69 référentiel d'information Pancanadien sur les RIBV.

Keywords

water security, watershed management, open data, data fragmentation, risk governance.

Key messages

- Baseline geographic information on wildfire risk to water security in Canada is generally lacking
- Multiple spatial data sources on wildfire and water resources are publicly available
- Many common water security issues occurring post-fire can be explored by combining existing data
- Important data gaps remain to produce Canada-wide baseline WWR information
- The Emergency Management Strategy for Canada can facilitate WWR data collection, management, and openness

Introduction: Incomplete data should not mean untapped information.

Awareness of wildfire risks to water security, or wildfire-watershed risks (WWR) for short, has been growing in Canada (Robinne et al. 2020; Coogan et al. 2019; Pomeroy et al. 2019). Indeed, there is evidence of the convergence of WWR elements nationally, including more seasonal variation in water availability (Ireson et al. 2015; Bonsal et al. 2020), increased occurrence of droughts and extreme precipitation events (Government of Canada 2019), and a changing nature and exacerbating impact of fire activity (Hanes et al. 2019; Coops et al. 2018). Although water resource protection is one of the top priorities for wildfire management agencies across the country (Tymstra et al. 2019), baseline information on the vulnerability of source waters to wildfire remains limited despite the high potential for water supply disruption (Hohner et al. 2019; Martin 2016; Robinne et al. 2021). As hydro-climatic extremes conducive to water security

92 issues will keep growing in magnitude and frequency, access to Pan-Canadian baseline WWR
93 information represents an urgent need towards the development of targeted watershed management
94 strategies.

95 Data—spatial data, in particular—is at the core of modern-day risk governance (Klinke
96 and Renn 2012; Neuvel, Scholten, and van den Brink 2012). Risk governance relies on acquiring
97 knowledge, which itself relies on aggregated information derived from the collection and synthesis
98 of available data sources—an endeavour that depends upon availability and openness of data
99 (Weichselgartner and Pigeon 2015; Månsson, Abrahamsson, and Tehler 2019; Månsson 2018). In
100 this context, access to open data has been increasingly identified as a prerequisite to the production
101 of scientifically-sound information to enable disaster risk reduction policies. With the term open
102 data, we are referring to datasets that are Findable, Accessible, Interoperable, and Reusable, or
103 FAIR (Wilkinson et al. 2016); although the FAIR principles insist on machine-to-machine data
104 transfer and interpretation, they are also applicable to human search and reuse of data. Notably,
105 the Emergency Management Strategy for Canada (EMS), which implements the United Nations
106 Office for Disaster Risk Reduction (UNDRR) recommendations proposed in the Sendai
107 Framework for Disaster Risk Reduction (hereafter, Sendai Framework), strongly promotes data
108 openness to facilitate the production of innovative risk knowledge (Weichselgartner and Pigeon
109 2015; UNISDR 2015; Godsoe, Ladd, and Cox 2019; Public Safety Canada 2019).

110 In recent years, there has been a substantial growth in diversity of both spatial and non-
111 spatial open data provided by different levels of governments in Canada. However, reports of data
112 scarcity continue to emerge both in the fields of water and wildfire science (Tymstra et al. 2019;
113 Garda, Castleden, and Conrad 2017; Mortsch, Cohen, and Koshida 2015). Coupled with decades
114 of data fragmentation, this has impeded the development of a national water strategy, with

consequences for the present needs for protection of water resource from wildfire (Godsoe, Ladd, and Cox 2019; Mamuji and Rozdilsky 2019; Sankey 2018; Johnston et al. 2020; Bakker and Cook 2011). Certainly, we agree on the need for more data to improve our understanding of the variability in post-fire responses and improve our national capacity to deal with growing disaster risks from wildfires. But we also stress that data currently available represent a largely untapped resource to develop valuable baseline information, identify data gaps, and generate hypotheses on WWR in Canada (see recent examples by Robinne et al. 2019a and Robinne 2020). 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 this commentary, we provide a brief critical assessment of Canadian capacity to produce nationally-relevant WWR baseline information using existing open spatial data sources from federal, provincial, and territorial governments (Table S1). In line with the Emergency Management Strategy for Canada (EMS) to “improve understanding of disaster risk” (Public Safety Canada 2019), we discuss several water security topics and explain why wildfires are conducive to water-supply risks. We also provide a series of spatial maps resulting from the integration and aggregation of the spatial datasets we found according to the FAIR principles as examples of how available data sets may be used to develop new risk frameworks. We finally discuss several avenues to improve and leverage this spatial information to inform the production of WWR baseline knowledge, and we provide recommendations on how the EMS can play a pivotal role in advancing WWR governance to fulfil Canadians’ demand for risk reduction (McNie 2007; Henstra, Minano, and Thistlethwaite 2019; Public Safety Canada 2019).

Understanding coupled wildfire-water resource dynamics

The impact of wildfires on water resources is often manifested 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, Niemeyer, Bladon, and Woodsmith 2020; Loiselle et al. 2020). Therefore, a first step in the assessment of wildfire-water risk is the creation of baseline hydrologic datasets, where deviations from the baseline may point to a fire-related disturbance (Hallema et al. 2017). Besides a few rare studies (e.g., Owens et al. 2013), there has not been a retrospective analysis of the records from the >7000 active and non-active hydrometric gauges available in Canada—contained in the HYDAT database—although dedicated analytical methods exist (Hallema et al. 2018; Wine, Cadol, and Makhnin 2018). While the network shows important variations in density over the entire Canadian territory, it is a FAIR dataset, either accessible via the HYDAT 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)). Moreover, gauges that have data that goes back many decades could be combined with data sets of fire regime (Guindon et al. 2020; Hall et al. 2020) to provide unique and unexploited insights into the role of wildfire activity in Canadian watershed hydrology.

Figure 1: (a) Gauged watershed polygons available from Water Survey of Canada (n = 1,675); (b) fire perimeters per decade since 1980 from Natural Resources of Canada (n = 34,341).

An initial exploration of some available data indicates variable spatial overlap between gauged watersheds for which boundaries are available (Figure 1a) and fire activity of the past 40 years (Figure 1b); mismatches in Ontario and Québec are particularly obvious compared to the rest of the country. Specifically, 676 of the 1,675 gauged watersheds available (40.3 %) have experienced a fire in the past four decades. Those fires burned an area of 3.06 km² on average, and a long-term 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 several locations through hydro-statistical analysis (Hallema et al. 2018). 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. Where absence of coverage might remain, applying some of the lessons learned from the previous hydrological decade focused on predictions in ungauged basins can help develop models and predictions in those regions where we do not have overlapping observations (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; Emelko et al. 2011; Pereira and Úbeda 2010). 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 (see Table S1) 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 Authority¹ in Ontario and the Fraser Basin Council in British Columbia². 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.

Preserving aquatic habitats

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 (Brauman et al. 2007; Bixby et al. 2015; Gresswell 1999). Many studies addressing

¹ <https://data.grandriver.ca/downloads.html>

² https://www.fraserbasin.bc.ca/Nicola_Basin_Collaborative.html

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 greater biological activity (Emelko et al. 2016; Cott et al. 2010). The role of fire for sustaining aquatic biodiversity thus remains a matter of debate across the various regions in Canada (Robinne et al. 2020; Carignan and Steedman 2000; Gresswell 1999). 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), which represents a concern in a country where recreational fishing represents CAD \$2.5-billion³. Nevertheless, there is 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)⁴. This network is an Environment and Climate Change Canada (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 Brunswick⁵. 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

³ <https://www.dfo-mpo.gc.ca/stats/rec/can/2015/index-eng.html#4-4-1>

⁴ <https://www.canada.ca/en/environment-climate-change/services/canadian-aquatic-biomonitoring-network.html>

⁵ <https://www.canadianriversinstitute.com/training/cabin/>

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)⁶. 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 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 a visible mismatch between the sampling density of the two datasets, except in the north-western part of the country (Figure 2). Unfortunately, there have almost been no samples collected in areas that have had some of the highest historical area burned in the boreal conifer and mixed-wood forests. 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 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). The DNA metabarcoding

⁶ <https://www.canada.ca/en/environment-climate-change/services/canadian-aquatic-biomonitoring-network/science.html>

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 STREAM project⁷, 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).

⁷ <https://stream-dna.com/>

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.

Protecting community water supply

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 (Table 1); a national assessment of historical fire activity within municipal watersheds only requires spatial data on wildfire activity and spatial boundaries of municipal watersheds, similar to the attempt shown in Figure 3. But past fires are not necessarily a good indication of future fire, especially locally; for example, wildfire activity around Fort McMurray will remain low for decades because of the large 2016 burn (Parks et al. 2018). 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).

Province	Number of MC	Number of burnt MC	Median percentage burned in MC (min - max)
British Columbia	388	244	23 (0.02–100)
Newfoundland Labrador	395	14	9 (0.04–59)
New Brunswick	30	0	0 (NA)

Table 1: Wildfire statistics in Canadian municipal catchments (MC), as presented in Figure 3, for the period 1980–2019. Only those three provinces for which municipal watershed boundaries were available are presented.

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 (Table1, Figure 3). Furthermore, accessing the location of water diversion licences strongly differ by jurisdiction. 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 imminently useful fire hazard metrics for watershed management (Gannon et al. 2019; Jones et al. 2017). That said, ongoing efforts will soon provide a national fire likelihood assessment that builds on established methodologies already used widely at regional scales (Parisien et al. 2019; Stralberg et al. 2018; Thompson et al. 2019; Stockdale et al. 2019), and nation-wide fuel data exist and are available on demand. Still, we do not have enough open data to draw even a simple informative map on the vulnerability of source watersheds to wildfires in Canada, despite a growing demand (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

(Murphy et al. 2020; Burke et al. 2013; Pereira and Úbeda 2010). We thus looked at possible occurrences of contaminated sites burned within municipal watersheds. Using the Federal Contaminated Site Inventory⁸, 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).

⁸ <https://www.tbs-sct.gc.ca/fcsi-rscf/home-accueil-eng.aspx>

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. See Table 1 for further details.

Many other national 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 and adapted to the Canadian context using the federal vector database, or CANVEC, as well as the National Hydro 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. In particular, numerous communities in Canada depend on drinking water, hydroelectricity, flood control, and recreational opportunities coming from reservoirs⁹, and these two datasets can be used to 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 is over 15,000 dams in Canada, although the number of those used for drinking water supply is not available, at least publicly.

Discussion: advancing WWR research 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^{10,11}, and the high value Canadian citizens put on their access to water (Appiah et al. 2016; 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

⁹ We could not find the number of communities, and the answer to several requests sent to different services suggest that this number is actually not known; yet, there is a general agreement—which we support—that it is of significant importance.

¹⁰ <https://www.publicsafety.gc.ca/cnt/rsrscs/pblctns/mtgtn-strtg/index-en.aspx>

¹¹ <https://www.publicsafety.gc.ca/cnt/trnsprnc/brfng-mtrls/trnstn-bndrs/20191120/021/index-en.aspx>

pressures on our water resources (WWF-Canada 2017; Government of Canada 2018; Paquette et al. 2020).

The Sendai Framework for Disaster Risk Reduction is an international effort closely linked to the Sustainable Development Goals (SDG) ¹², whose achievements widely depends on reaching and maintaining water security, as well as protecting forest health, worldwide (Gain, Giupponi, and Wada 2016; Vörösmarty et al. 2018). As a Sendai and SDG signatory member, Canada translated international disaster risk reduction goals into its Emergency Management Strategy for Canada, aiming at “strengthening Canada's ability to assess risks and to prevent/mitigate, prepare for, respond to, and recover from disasters” (Public Safety Canada 2019, p.5). One of the main priorities of the EMS 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 indirect 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.

¹² <https://www.publicsafety.gc.ca/cnt/mrgnc-mngmnt/dsstr-prvntn-mtgtn/pltfm-dsstr-rsk-rdctn/snd-frmwrk-en.aspx>

Although data issues described herein are not new (Tenopir et al. 2018; Boulton et al. 2012), they are particularly limiting when dealing with emerging risks such as wildfire-watershed ones. For instance, the lack of seamless, federally-spanning dataset of WSC 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 (Robinne et al. 2019; Emelko et al. 2011); 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 (Beverly and Bothwell 2011).

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 (van Asselt and Renn 2011; Dunn, Bakker, and Harris 2014; Bakker and Cook 2011; Tymstra et al. 2019; Migliorini et al. 2019; Fisher and Kingma 2001). Linders (2013) explains how information weaknesses and access difficulties to open data complicate 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 was used properly) is fundamentally the same for water security in Canada, where a range of stakeholders provide funds, receive funds, and have a say in watershed planning (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; Paquette et al. 2020)¹³; the Pacific Salmon Explorer¹⁴ is a state-of-the-art platform for the visualization of salmon population data that relies, in part, on numerous ancillary open datasets; finally, the Climate Atlas of Canada¹⁵, powered by the Prairie Climate Centre, 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 capacity to generate baseline risk information regarding wildfire threats to national water resources. Using a subset of pressing wildfire-watershed risk challenges, we gave illustrative examples of research and management questions to be explored urgently. We also highlighted impeding factors such as data gaps, fragmentation, and lack of data openness. Generally speaking, the capacity to produce relevant WWR baseline geographic information covering the entirety of Canada is within reach, as demonstrated by the simple data aggregation results presented above. We showed that, despite existing data(-openness) gaps and mismatches that hinder detailed risk analysis (e.g., on drinking

¹³ <https://watershedreports.wwf.ca/>

¹⁴ <https://www.salmonexplorer.ca/#!/>

¹⁵ <https://prairieclimatecentre.ca/>

water), there is likely enough actionable open data in Canada to advance the task at hand. The framework provided by the Emergency Management Strategy for Canada in a time and age of incredible data wealth is an encouraging sign for WWR researchers and for national water security.

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. The authors confirm that all the data supporting the findings of this study are available within the article and its supplementary materials.

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References

- Albers, Sam. 2017. "Tidyhydat: Extract and Tidy Canadian Hydrometric Data." *The Journal of Open Source Software* 2 (20): 511. <https://doi.org/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). <https://doi.org/10.1142/S2382624X18500200>.

- Appiah, Alfred, Patrick Lloyd-smith, Stephanie Simpson, and Diane P. Dupont. 2016. "On How Much Albertans Value the Reliability of Their Drinking Water Supply Putting a Price Why Did We Do This Research ?" <http://www.cwn-rce.ca/assets/End-User-Reports/Municipal/Adamowicz/CWN-EN-Adamowicz-WEPGN-2016-5Pager-Web.pdf>.
- Asselt, Marjolein B.A. van, and Ortwin Renn. 2011. "Risk Governance." *Journal of Risk Research* 14 (4): 431–49. <https://doi.org/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): 275–89. <https://doi.org/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. <https://doi.org/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 (June): 201. <https://doi.org/10.3389/fenvs.2021.684703>.
- Beverly, Jennifer L., and Peter Bothwell. 2011. "Wildfire Evacuations in Canada 1980-2007." *Natural Hazards* 59 (1): 571–96. <https://doi.org/10.1007/s11069-011-9777-9>.
- 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): 1340–50. <https://doi.org/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): 2359–71. <https://doi.org/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): 217–23. <https://doi.org/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): 528–45. <https://doi.org/10.1139/er-2020-0040>.
- 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. 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. <https://doi.org/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. <https://doi.org/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. <https://doi.org/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): 10131–45. <https://doi.org/10.1007/s10661-013-3318-9>.
- 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. <https://doi.org/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." *Science of The Total Environment* 692 (November): 691–700. <https://doi.org/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. <https://doi.org/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* 9 (May): 1015–23. <https://doi.org/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

- 482 Forests Shows Evidence of Regionally Increasing Trends in the Last Decade.” Edited by
483 Eric Gordon Lamb. *PLOS ONE* 13 (5): e0197218.
484 <https://doi.org/10.1371/journal.pone.0197218>.
- 485 Cott, Peter A., Barry A. Zajdlik, Kelly J. Bourassa, Marc Lange, and Andrew M. Gordon. 2010.
486 “Effects of Forest Fire on Young-of-the-Year Northern Pike, *Esox Lucius*, in
487 the Northwest Territories.” *The Canadian Field-Naturalist* 124 (2): 104.
488 <https://doi.org/10.22621/cfn.v124i2.1046>.
- 489 Dunn, Gemma, Karen J. Bakker, and Leila M Harris. 2014. “Drinking Water Quality Guidelines
490 across Canadian Provinces and Territories: Jurisdictional Variation in the Context of
491 Decentralized Water Governance.” *International Journal of Environmental Research and
492 Public Health* 11 (5): 4634–51. <https://doi.org/10.3390/ijerph110504634>.
- 493 Emelko, Monica B., Uldis Silins, Kevin D. Bladon, and Micheal Stone. 2011. “Implications of
494 Land Disturbance on Drinking Water Treatability in a Changing Climate: Demonstrating
495 the Need for ‘Source Water Supply and Protection’ Strategies.” *Water Research* 45 (2):
496 461–72. <https://doi.org/10.1016/j.watres.2010.08.051>.
- 497 Emelko, Monica B., Micheal Stone, Uldis Silins, Don Allin, Adrian L. Collins, Chris H.S.
498 Williams, Amanda M. Martens, and Kevin D. Bladon. 2016. “Sediment-Phosphorus
499 Dynamics Can Shift Aquatic Ecology and Cause Downstream Legacy Effects after Wildfire
500 in Large River Systems.” *Global Change Biology* 22 (3): 1168–84.
501 <https://doi.org/10.1111/gcb.13073>.
- 502 Fisher, Craig W., and Bruce R. Kingma. 2001. “Criticality of Data Quality as Exemplified in
503 Two Disasters.” *Information & Management* 39 (2): 109–16. [https://doi.org/10.1016/S0378-
504 7206\(01\)00083-0](https://doi.org/10.1016/S0378-7206(01)00083-0).

505 Friberg, Nikolai, Núria Bonada, David C. Bradley, Michael J. Dunbar, Francois K. Edwards,
 506 Jonathan Grey, Richard B. Hayes, et al. 2011. "Biomonitoring of Human Impacts in
 507 Freshwater Ecosystems." In *Advances in Ecological Research*, 44:1–68. Academic Press.
 508 <https://doi.org/10.1016/B978-0-12-374794-5.00001-8>.

509 Gain, Animesh K., Carlo Giupponi, and Yoshihide Wada. 2016. "Measuring Global Water
 510 Security towards Sustainable Development Goals." *Environmental Research Letters* 11
 511 (12): 124015. <https://doi.org/10.1088/1748-9326/11/12/124015>.

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

516 Gannon, Benjamin M., Yu Wei, and Matthew P. Thompson. 2020. "Mitigating Source Water
 517 Risks with Improved Wildfire Containment." *Fire* 3 (3): 1–25.
 518 <https://doi.org/10.3390/fire3030045>.

519 Garda, Chris, Heather Castleden, and Cathy Conrad. 2017. "Monitoring, Restoration, and Source
 520 Water Protection: Canadian Community-Based Environmental Organizations' Efforts
 521 towards Improving Aquatic Ecosystem Health." *Water* 9 (3): 212.
 522 <https://doi.org/10.3390/w9030212>.

523 Godsoe, M., M. Ladd, and R. Cox. 2019. "Assessing Canada's Disaster Baselines and
 524 Projections under the Sendai Framework for Disaster Risk Reduction: A Modeling Tool to
 525 Track Progress." *Natural Hazards* 98 (1): 293–317. [https://doi.org/10.1007/s11069-019-](https://doi.org/10.1007/s11069-019-03599-z)
 526 [03599-z](https://doi.org/10.1007/s11069-019-03599-z).

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

528 Government of Canada.

529 ———. 2019. “Canada’s Changing Climate Report.” www.ChangingClimate.ca/CCCR2019.

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

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

537 Hall, R. J., R. S. Skakun, J. M. Metsaranta, R. Landry, R.H. Fraser, D. Raymond, M. Gartrell, V.
538 Decker, and J. Little. 2020. “Generating Annual Estimates of Forest Fire Disturbance in
539 Canada: The National Burned Area Composite.” *International Journal of Wildland Fire* 29
540 (10): 878. <https://doi.org/10.1071/WF19201>.

541 Hallema, Dennis W., Ge Sun, Peter V. Caldwell, Steven P. Norman, Erika C. Cohen, Yongqiang
542 Liu, Kevin D. Bladon, and Steven G. McNulty. 2018. “Burned Forests Impact Water
543 Supplies.” *Nature Communications* 9 (1): 1307. [https://doi.org/10.1038/s41467-018-03735-](https://doi.org/10.1038/s41467-018-03735-6)
544 6.

545 Hallema, Dennis W., Ge Sun, Peter V. Caldwell, Steven P. Norman, Erika C. Cohen, Yongqiang
546 Liu, Eric J. Ward, and Steven G. McNulty. 2017. “Assessment of Wildland Fire Impacts on
547 Watershed Annual Water Yield: Analytical Framework and Case Studies in the United
548 States.” In *Ecohydrology*, 10:e1794. John Wiley and Sons Ltd.
549 <https://doi.org/10.1002/eco.1794>.

550 Hanes, Chelene C, Xianli Wang, Piyush Jain, Marc-André Parisien, John M. Little, and Mike D.

551 Flannigan. 2019. “Fire-Regime Changes in Canada over the Last Half Century.” *Canadian*
552 *Journal of Forest Research* 49 (3): 256–69. <https://doi.org/10.1139/cjfr-2018-0293>.

553 Henstra, Daniel, Andrea Minano, and Jason Thistlethwaite. 2019. “Communicating Disaster
554 Risk? An Evaluation of the Availability and Quality of Flood Maps.” *Natural Hazards and*
555 *Earth System Sciences* 19 (1): 313–23. <https://doi.org/10.5194/nhess-19-313-2019>.

556 Hohner, Amanda K., Charles C Rhoades, Paul Wilkerson, and Fernando L Rosario-Ortiz. 2019.
557 “Wildfires Alter Forest Watersheds and Threaten Drinking Water Quality.” *Accounts of*
558 *Chemical Research* 52 (5): 1234–44. <https://doi.org/10.1021/acs.accounts.8b00670>.

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

563 Ibrahim, Azhar Al, and Robert J. Patrick. 2017. “Source Water Protection Planning and
564 Management in Metropolitan Canada: A Preliminary Assessment.” *Water* 9 (7): 497.
565 <https://doi.org/10.3390/w9070497>.

566 Ireson, A. M., A. G. Barr, Jill F. Johnstone, S. D. Mamet, G. van der Kamp, C. J. Whitfield, N.
567 L. Michel, et al. 2015. “The Changing Water Cycle: The Boreal Plains Ecozone of Western
568 Canada.” *Wiley Interdisciplinary Reviews: Water* 2 (5): 505–21.
569 <https://doi.org/10.1002/wat2.1098>.

570 Johnston, Lynn M, Xianli Wang, Sandy Erni, Stephen W Taylor, Colin B. McFayden, Jacqueline
571 A Oliver, Chris Stockdale, et al. 2020. “Wildland Fire Risk Research in Canada.”
572 *Environmental Reviews* 23 (0000): 1–23. <https://doi.org/10.1139/er-2019-0046>.

573 Jones, Kelly W., Jeffery B. Cannon, Freddy A. Saavedra, Stephanie K. Kampf, Robert N.

574 Addington, Antony S. Cheng, Lee H. MacDonald, Codie Wilson, and Brett Wolk. 2017.
 575 “Return on Investment from Fuel Treatments to Reduce Severe Wildfire and Erosion in a
 576 Watershed Investment Program in Colorado.” *Journal of Environmental Management* 198
 577 (August): 66–77. <https://doi.org/10.1016/j.jenvman.2017.05.023>.
 578 Klinke, Andreas, and Ortwin Renn. 2012. “Adaptive and Integrative Governance on Risk and
 579 Uncertainty.” *Journal of Risk Research* 15 (3): 273–92.
 580 <https://doi.org/10.1080/13669877.2011.636838>.
 581 Leveque, B., J.-B. Burnet, S. Dorner, and F. Bichai. 2021. “Impact of Climate Change on the
 582 Vulnerability of Drinking Water Intakes in a Northern Region.” *Sustainable Cities and*
 583 *Society* 66 (March): 102656. <https://doi.org/10.1016/j.scs.2020.102656>.
 584 Linders, Dennis. 2013. “Towards Open Development: Leveraging Open Data to Improve the
 585 Planning and Coordination of International Aid.” *Government Information Quarterly* 30
 586 (4): 426–34. <https://doi.org/10.1016/j.giq.2013.04.001>.
 587 Loiselle, Danielle, Xinzhong Du, Daniel S. Alessi, Kevin D. Bladon, and Monireh Faramarzi.
 588 2020. “Projecting Impacts of Wildfire and Climate Change on Streamflow, Sediment, and
 589 Organic Carbon Yields in a Forested Watershed.” *Journal of Hydrology* 590 (August):
 590 125403. <https://doi.org/10.1016/j.jhydrol.2020.125403>.
 591 Luthra, Sonaar. 2019. “We Need to Track the World’s Water like We Track the Weather.”
 592 TED.Com. 2019.
 593 [https://www.ted.com/talks/sonaar_luthra_we_need_to_track_the_world_s_water_like_we_t](https://www.ted.com/talks/sonaar_luthra_we_need_to_track_the_world_s_water_like_we_track_the_weather)
 594 [rack_the_weather](https://www.ted.com/talks/sonaar_luthra_we_need_to_track_the_world_s_water_like_we_track_the_weather).
 595 Mamuji, Aaida A., and Jack L. Rozdilsky. 2019. “Wildfire as an Increasingly Common Natural
 596 Disaster Facing Canada: Understanding the 2016 Fort McMurray Wildfire.” *Natural*

597 *Hazards* 98 (1): 163–80. <https://doi.org/10.1007/s11069-018-3488-4>.

598 Månsson, Peter. 2018. “Mapping Challenges and Opportunities for Aggregating Information on
599 Systemic Risks from Multiple Stakeholders.” *Procedia Engineering* 212 (2017): 736–43.
600 <https://doi.org/10.1016/j.proeng.2018.01.095>.

601 Månsson, Peter, Marcus Abrahamsson, and Henrik Tehler. 2019. “Aggregated Risk: An
602 Experimental Study on Combining Different Ways of Presenting Risk Information.”
603 *Journal of Risk Research* 22 (4): 497–512. <https://doi.org/10.1080/13669877.2017.1391315>.

604 Martin, Deborah A. 2016. “At the Nexus of Fire, Water and Society.” *Philosophical
605 Transactions of the Royal Society B: Biological Sciences* 371 (1696): 20150172.
606 <https://doi.org/10.1098/rstb.2015.0172>.

607 McNie, Elizabeth C. 2007. “Reconciling the Supply of Scientific Information with User
608 Demands: An Analysis of the Problem and Review of the Literature.” *Environmental
609 Science and Policy* 10 (1): 17–38. <https://doi.org/10.1016/j.envsci.2006.10.004>.

610 Migliorini, Massimo, Jenny Sjästad Hagen, Jadranka Mihaljević, Jaroslav Mysiak, Jean-Louis
611 Rossi, Alexander Siegmund, Khachatur Meliksetian, and Debarati Guha Sapid. 2019. “Data
612 Interoperability for Disaster Risk Reduction in Europe.” *Disaster Prevention and
613 Management: An International Journal* 28 (6): 804–16. [https://doi.org/10.1108/DPM-09-
614 2019-0291](https://doi.org/10.1108/DPM-09-2019-0291).

615 Mortsch, Linda, Stewart Cohen, and Grace Koshida. 2015. “Climate and Water Availability
616 Indicators in Canada: Challenges and a Way Forward. Part II – Historic Trends.” *Canadian
617 Water Resources Journal / Revue Canadienne Des Ressources Hydriques* 40 (2): 146–59.
618 <https://doi.org/10.1080/07011784.2015.1006024>.

619 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.” *Science of The Total Environment* 743 (November): 140635. <https://doi.org/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. <https://doi.org/10.1029/2020WR028091>.
- 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. <https://doi.org/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): 1182–97. <https://doi.org/10.1002/hyp.13665>.
- 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: 128–39. <https://doi.org/10.1016/j.geomorph.2013.01.001>.
- Paquette, Catherine, L. Hemphill, A. Merante, and E. Hendriks. 2020. “WWF-CANADA’S 2020 WATERSHED REPORTS: A NATIONAL REASSESSMENT OF CANADA’S FRESHWATER.” Toronto, Ontario, Canada.
- 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

643 Wildfire Risk for Many Communities in the Canadian Boreal Forest.” *Nature*
644 *Communications* 11 (1): 2121. <https://doi.org/10.1038/s41467-020-15961-y>.

645 Parisien, Marc-André, Denyse A. Dawe, Carol Miller, Christopher A. Stockdale, and O. Bradley
646 Armitage. 2019. “Applications of Simulation-Based Burn Probability Modelling: A
647 Review.” *International Journal of Wildland Fire*. <https://doi.org/10.1071/WF19069>.

648 Parks, Sean A., Marc-André Parisien, Carol Miller, Lisa M. Holsinger, and Larry Scott Baggett.
649 2018. “Fine-Scale Spatial Climate Variation and Drought Mediate the Likelihood of
650 Reburning.” *Ecological Applications* 28 (2): 573–86. <https://doi.org/10.1002/eap.1671>.

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

656 Pereira, Paulo, and Xavier Úbeda. 2010. “Spatial Distribution of Heavy Metals Released from
657 Ashes after a Wildfire.” *Journal of Environmental Engineering and Landscape*
658 *Management* 18 (1): 13–22. <https://doi.org/10.3846/jeelm.2010.02>.

659 Perrier, Erika, Megan Kot, Heather Castleden, and Graham A. Gagnon. 2014. “Drinking Water
660 Safety Plans: Barriers and Bridges for Small Systems in Alberta, Canada.” *Water Policy* 16
661 (6): 1140–54. <https://doi.org/10.2166/wp.2014.207>.

662 Pomeroy, John W., Chris M. DeBeer, Phani Adapa, Merrell-Ann Phare, Natasha Overduin,
663 Michael Miltenberger, Tony Maas, Ralph Pentland, Oliver M. Brandes, and Robert W.
664 Sandford. 2019. “Water Security for Canadians - Solutions for Canada’s Emerging Water
665 Crisis.” Saskatoon, SK, Canada: Canadian Water Security Initiative.

<https://www.flowcanada.org/our-work>.

Public Safety Canada. 2019. *Emergency Management Strategy for Canada: Toward a Resilient 2030*. Public Safety Canada. Ottawa, ON: Public Safety Canada.

<https://www.publicsafety.gc.ca/cnt/rsrscs/pblctns/mrgncy-mngmnt-strtgty/index-en.aspx>.

Rieman, Bruce, 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." In *Forest Ecology and Management*, 178:197–211. Elsevier. [https://doi.org/10.1016/S0378-1127\(03\)00062-8](https://doi.org/10.1016/S0378-1127(03)00062-8).

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. <https://doi.org/10.1016/j.dib.2020.105171>.

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. <https://doi.org/10.3390/f10050384>.

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 (November 2019): 124360. <https://doi.org/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*, February, hyp.14086. <https://doi.org/10.1002/hyp.14086>.

- 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. <https://doi.org/10.1086/712232>.
- Sankey, S. 2018. *Blueprint for Wildland Fire Science in Canada (2019-2029)*. Edmonton, Alberta: Natural Resources of Canada - Canadian Forest Service. <https://cfs.nrcan.gc.ca/publications?id=39429>.
- 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 (December): 756–69. <https://doi.org/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): 1508–23. <https://doi.org/10.1002/eco.1474>.
- Spencer, Craig N., Kristin Odney Gabel, and F.Richard Hauer. 2003. "Wildfire Effects on Stream Food Webs and Nutrient Dynamics in Glacier National Park, USA." *Forest Ecology and Management* 178 (1–2): 141–53. [https://doi.org/10.1016/S0378-1127\(03\)00058-6](https://doi.org/10.1016/S0378-1127(03)00058-6).
- 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. <https://doi.org/10.1002/ecs2.2584>.
- Stralberg, Diana, Xianli Wang, Marc-André Parisien, François-Nicolas Robinne, Péter Sóllymos, C. Lisa Mahon, Scott E. Nielsen, and Erin M. Bayne. 2018. "Wildfire-Mediated Vegetation

712 Change in Boreal Forests of Alberta, Canada.” *Ecosphere* 9 (3): e02156.
 713 <https://doi.org/10.1002/ecs2.2156>.

714 Tenopir, C., L. Christian, S. Allard, and J. Borycz. 2018. “Research Data Sharing: Practices and
 715 Attitudes of Geophysicists.” *Earth and Space Science* 5 (12): 891–902.
 716 <https://doi.org/10.1029/2018EA000461>.

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

721 Thompson, Daniel K, Brian Simpson, Ellen Whitman, Quinn E. Barber, and Marc-André
 722 Parisien. 2019. “Peatland Hydrological Dynamics as A Driver of Landscape Connectivity
 723 and Fire Activity in the Boreal Plain of Canada.” *Forests* 10 (7): 534.
 724 <https://doi.org/10.3390/f10070534>.

725 Tymstra, Cordy, Brian J. Stocks, Xinli Cai, and Mike D. Flannigan. 2019. “Wildfire
 726 Management in Canada: Review, Challenges and Opportunities.” *Progress in Disaster
 727 Science*, October, 100045. <https://doi.org/10.1016/j.pdisas.2019.100045>.

728 UNISDR. 2015. “Sendai Framework for Disaster Risk Reduction 2015 - 2030.” Geneva,
 729 Switzerland: United Nations. <https://doi.org/A/CONF.224/CRP.1>.

730 Vörösmarty, Charles J., Vanesa Rodríguez Osuna, Anthony D. Cak, Anik Bhaduri, Stuart E.
 731 Bunn, Fabio Corsi, Jorge Gastelumendi, et al. 2018. “Ecosystem-Based Water Security and
 732 the Sustainable Development Goals (SDGs).” *Ecohydrology & Hydrobiology* 18 (4): 317–
 733 33. <https://doi.org/10.1016/j.ecohyd.2018.07.004>.

734 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.
<https://doi.org/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): 107–16.
<https://doi.org/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.
<https://doi.org/10.1038/sdata.2016.18>.
- Wine, Michael Louis, Daniel Cadol, and Oleg Makhnin. 2018. "In Ecoregions across Western USA Streamflow Increases during Post-Wildfire Recovery." *Environmental Research Letters* 13 (1): 014010. <https://doi.org/10.1088/1748-9326/aa9c5a>.
- WWF-Canada. 2017. "A National Assessment of Canada's Freshwater - Watershed Reports."
<http://watershedreports.wwf.ca>.