Effects of forest fires on watershed ecosystems

Summary of the state of research and essential references

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Date: April 2024
Version: 1.3

Written for the Water Resources Division of the Government of Northwest Territories

Version	Date	Reviewers	Description of changes
1.0	2024/03/18		Initial draft
1.1	2024/04/19		Addition of a section, “fire effects on vegetation”
1.2	2024/05/02		Accepted final version. Watermark removed and suggested citation added.
1.3	2024/05/06		Minor edits: figure numbering + typos

Suggested citation: F.-N. Robinne, “Effects of forest fires on watershed ecosystems — Summary of the state of research and essential references”, prepared for the Government of Northwest Territories, 2024.

Preamble

According to the Government of Canada, from May to October 2023, the Northwest Territories (NWT) experienced over 300 wildfires that burned over four million hectares, leading to the evacuation of multiple communities, together representing nearly 70% of the NWT's population. This was the largest wildfire season on record for the Territories. Last November, the Insurance Bureau of Canada estimated the damages to the communities of Behchokǫ̀-Yellowknife and Hay River to be over $60 million in insured damages. Already, multiple media are reporting worries regarding the upcoming 2024 fire season, with drought conditions persisting from abnormally dry to extremely dry on a large portion of the NWT, and multiple communities surrounded by overstocked forests.

Many of the communities impacted by the 2023's wildfires depend on nearby lakes, reservoirs, and rivers for their water supply, their food security, and their economic activities. Many of these water bodies saw a significant part of their watersheds burn, thereby raising multiple water security concerns, such as water pollution hazards and the possibility of aquatic ecosystem degradation.

This document offers a list of key references on various topics of concern listed by the Government of the Northwest Territories. The first section provides multiple important references that are often general in scope (i.e., they cover multiple post-fire aspects of watershed ecology) and global or regional in scale. Section 1 provides an overview of fire effects on vegetation, sections 2 to 5 focus on providing context and references regarding abiotic changes to watershed ecosystems post-fire, whereas section 6 focuses on biotic changes (i.e., the food web). Finally, section 7 focuses on risks to water supply—drinking water in particular—when source catchments are impacted by wildfires. While treated separately, the elements discussed in different sections will combine together in the post-fire environment to create water security concerns.

Note that the effects of wildfires on watershed ecology in the Northwest Territories have started to receive attention recently. As much as possible, the references listed thereafter describe studies that were conducted in ecosystems broadly similar to those found in the Territories (e.g., the boreal forest) but elsewhere in Canada or in the world, and whose results may nonetheless provide important insights for managing watersheds and water supplies impacted by wildfires in the NWT.

1) Large-scope references

The past two decades have seen a significant increase in the number of publications on wildfire effects on watershed ecology and water resources worldwide, with a net acceleration these past ten years. This acceleration seems related to the growing interest in ecosystem services coming from forests combined with increased occurrences of extreme wildfire events—events partly fueled by climate change—and a better acknowledgment of their widespread effects on watersheds and freshwater environments. The growing number of research studies has naturally led to the release of several literature reviews, commentaries, and conceptual papers.

Multiple comprehensive reviews and technical reports have been published; they usually cover all the aspects of watershed ecology that can be impacted by a fire and, increasingly, explain how those impacts can lead to post-fire hazards that have the potential to harm downstream social, economic, and environmental values. Neary et al. 2005, Smith et al. 2011, and Bladon et al. 2014 are often cited. The latter review displayed a figure that conveys very well the current understanding of wildfire effects on watershed ecosystems and their services (figure 1).

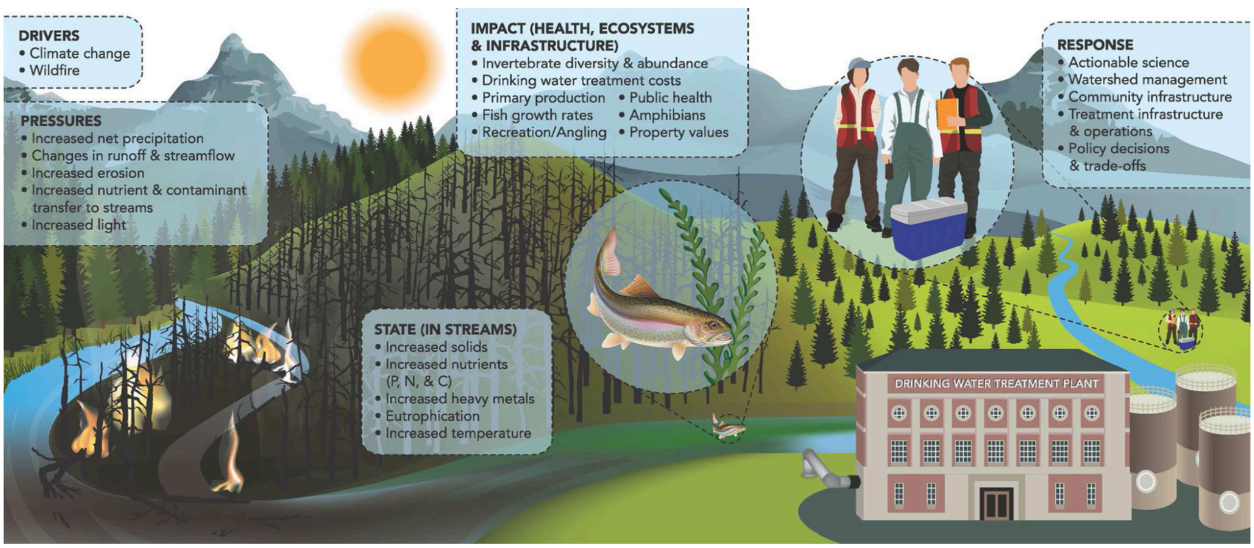

Figure 1: Water supply pressures, state, and impact due to wildfire, including potential responses to mitigate the impacts in the future (Bladon et al. 2014).

Several commentaries and conceptual papers have also stressed water security risks from wildfires. Simply put, water security refers to the capacity of an individual or a society to safely access sufficient quantities of clean water to meet their daily needs. Understanding where wildfire fits within the water security paradigm has led to multiple recent commentaries that essentially invite society as a whole to consider changing fire regimes as a serious threat to social and economic stability. The papers by Martin 2016, Murphy et al. 2018, Robinne et al. 2021, and Belongia et al. 2023 offer important perspectives on this issue.

As mentioned above, exploring wildfire through the lens of risks to ecosystem services has gained traction. The concept of ecosystem services indeed provides a useful connector between wildfires and water security issues. Ecosystem services are those contributions from nature that benefit human wellbeing; the concept of watershed or hydrological services specifically refers to those ecosystem services coming from watersheds, perhaps most importantly drinking water supply and flood control. The 2016 review by Thom and Seidl is noteworthy and offers a strong introduction to the topic, even if not only limited to freshwater; it was followed by several similar reviews that have all helped build a strong case for the study of wildfire risks to ecosystem services. The term “ecosystem services” is now regularly used in wildfire studies, with a recent increase in the number of studies specifically focusing on quantifying wildfire risks to various types of ecosystem services. Generally speaking, large and severe wildfires have the greatest negative impact on watershed ecosystems and their services, while prescribed fires offer an interesting tool to protect or even enhance watershed ecosystem services.

The number of large-scope references with a strong focus on Canada remains limited. In 2000, Carignan et al. published “Impacts of Major Watershed Perturbations on Aquatic Ecosystems”, and in 2002 Pinel-Alloul et al. published “Watershed Impacts of Logging and Wildfire: Case Studies in Canada”; the latter is a review based on multiple publications that came out of several Canadian projects focused on the effect of forest disturbances on boreal and shield lake ecosystems. More Canadian publications related to wildfires and watersheds appeared after 2010, and two reviews were published in 2020, one by Robinne et al. with a general approach on wildfires and watershed services, and the other by Holloway et al. dealing more generally with the effects of fire on permafrost, including changes to runoff and water quality.

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2) Fire effects on vegetation

Summary on the state of research

The first obvious effect of fire on a forested watershed is on the vegetation cover. Depending on the fire regime of the vegetation (the fuel) covering the watershed of interest, geographic features (e.g., geology, hydrology), as well pre-existing watershed disturbances (e.g., forestry, pest infestation), fire effects on vegetation and its recovery within and among burnt sites may vary greatly. These variations have, over millennia, created a mosaic of uneven-aged forest patches across the boreal. As the saying goes, “pyrodiversity begets biodiversity”, and the boreal forest ecosystems of Canada are very much fire-prone and fire-adapted (i.e., pyrophilic), to a point where scientists refer to co-evolution to describe this interdependence of vegetation and fire in the boreal forest.

The fire regime concept describes the historical pattern of fire—both temporal and spatial—in a given area. While all fire regime parameters, such as fire season and area burned, may influence vegetation patterns, it is fire intensity and its corollary, fire severity, that have the most evident direct ecological effects, thereby greatly influencing post-fire regeneration trajectories. Low intensity fires are running fire with small flame length and very shallow depth of burn, resulting in low severity with ecological effect limited to clearing the undergrowth, without or with only superficial damages to trees. Moderate intensity fires lead to mixed severity burns with clearing of the undergrowth with a mix of scorched and dead trees. High intensity fires are crown fires; those have the highest severity, with virtually all trees dead, no vegetation left, and a high depth of burn. These fires are stand-replacing, meaning that a forest stand will restart from an early seral stage of the ecological succession. Again, these three types of fires and their resulting severity usually happen all at once within the same fire perimeter; furthermore, many islands of unburned vegetation—called fire refugia—remain (figure 2).

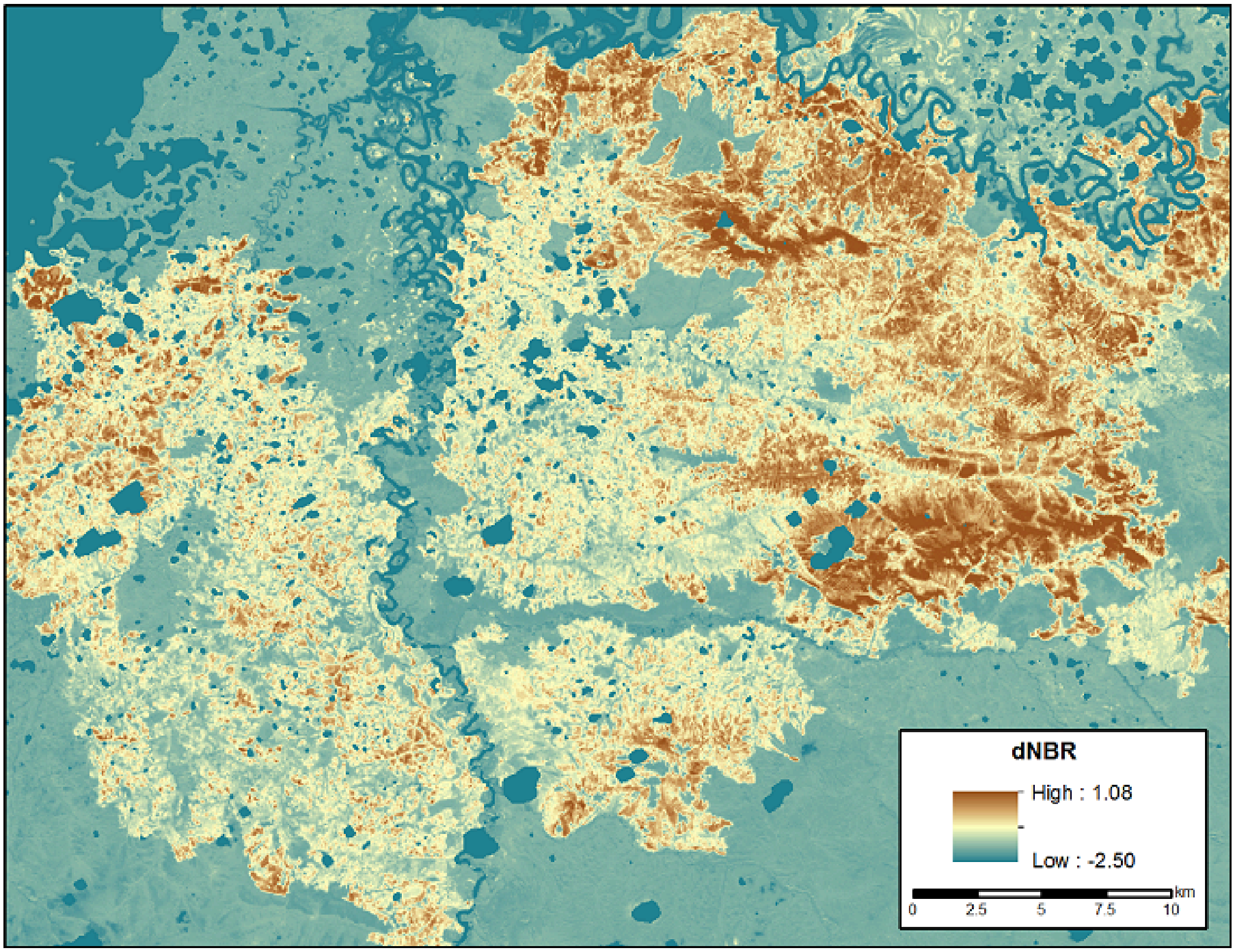

Figure 2: Illustrating the landscape mosaic resulting from variable burn severity within a fire perimeter. The differenced Normalized Burned Ratio (dNBR) for a burn scar from fires in 2015 within ABoVE grid tile Bh05Bv03. A higher dNBR indicates a higher fire severity. From https://daac-news.ornl.gov/content/wildfire-burn-severity-across-alaska-and-canada

Knowledge of post-fire vegetation recovery in boreal environments is rather well known. Vegetation in Canada will recover from fire through two essential processes: seeding and suckering, with vegetation well reestablished within 15 years post-fire. Conifer forests tend to experience higher intensity and thus higher severity compared to other vegetation types; even lower fire intensity may be damaging to species like Black Spruce, but the functional adaptation to fire through serotiny—the release of seeds from the cone when exposed to heat—have made such species prolific post-fire colonizers. Aspen, a deciduous species characteristic of the boreal mixedwood forest, is also a prolific post-fire colonizer, mostly through vegetative suckering (i.e., asexual reproduction), although seed colonization can happen in areas displaying high fire severity. While the boreal forest may be seen as a low biodiversity biome, the diversity of post-fire ecosystem trajectories is high; while post-fire recovery mechanisms are well known, predicting future vegetation is not trivial and depends on many factors such as pre-fire vegetation type, structure, and health, fire severity, proximity to fire refugia, post-fire climatic conditions, and local landscape features.

This complexity is being made even greater with ongoing climate change coupled to anthropogenic disturbances—anything from fire exclusion to O&G exploration. Those are indeed disrupting fire regimes and post-fire regeneration patterns, and vegetation shifts have been observed across the country, including in the NWT. Scientists are now increasingly referring to regeneration failure, and wildfires might very well make these changes happen more rapidly, with a general shift towards more deciduous forests and more open stands. Drier forests will lead to more severe fires happening more often, thereby hindering tree maturation and the production of a new see bank; when coupled with a drier post-fire environment, vegetation may not be able to establish, and soil will remain exposed to erosion. Intense fires happening earlier in the season or at higher elevations might also alter vegetation composition in burned stands. Our understanding of the meaning of these changes to long term watershed functioning remains limited.

The past decades have shown the tremendous benefits of remote sensing for the monitoring of fire severity, as well post-fire trajectories and recovery trends in changing environmental conditions. The development of remote-sensing capabilities, especially through artificial intelligence, is revolutionizing our capacity to map and track wildfire effects on the boreal landscape. Multiple datasets, frameworks, and algorithms now exist to study this biome.

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3) Post-fire hydrology

Summary on the state of research

Forests act as sponges: trees intercept water from precipitation, store it in their canopy and soils, and water is then redistributed downstream through various surface, sub-surface and groundwater flows. This sponge effect has a direct impact on the functioning of a watershed, first and foremost because it stabilizes high and low flows. There are obviously regional variations in this storage capacity, but there is consensus that forests are an essential component of water security. There is also an increased acknowledgement of the role of disturbances, such as fire, to avoid forest overgrowth to a point where competition for water limits downstream supply.

Large and severe fires can significantly alter this storage capacity by removing vegetation and organic topsoils. Water infiltration capacity might be severely limited by the lack of interception from vegetation, by the change in soil bulk density decreasing soil porosity, by the existence of a thick ash layer clogging soil pores, and by the creation or strengthening of a hydrophobic (or water-repellent) layer (figure 3). The decrease in interception and in soil infiltration can lead to a substantial increase in net precipitation and thus in runoff and finally in peakflow. Such an effect will usually be more pronounced in small, steep watersheds where changes to water concentration time can lead to flashy behavior and floods.

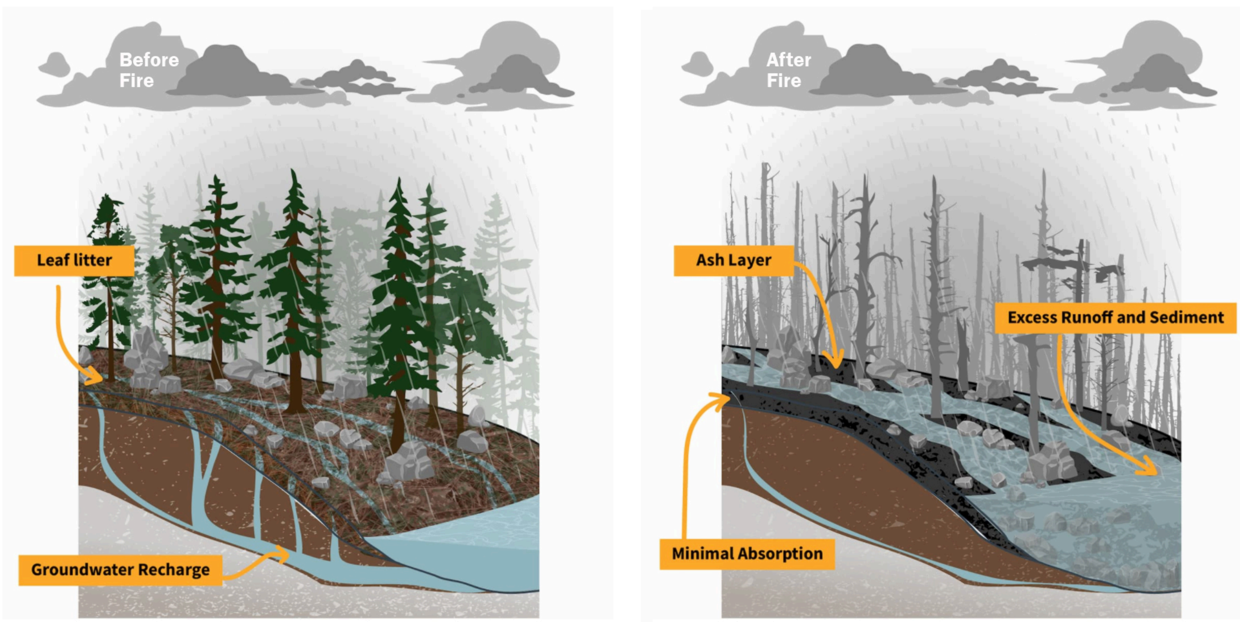

Figure 3: Fire hydrology data viz story, USGS Water Resources Mission Area, 2020 (https://www.usgs.gov/media/images/fire-hydrology-data-viz-story-carousel)

While burned watersheds often tend to display general increases in water yield, the general behavior described above will be mediated by three important factors: the watershed area burned, the severity of the fire, and the occurrence of post-fire precipitation. It is common to use a 20% rule of thumb for watershed area burned, several papers having shown that this is a common threshold after which hydrological effects start to appear. Several recent papers have challenged this rule by showing that effects can appear with 10% of the watershed burned, whereas it can take more than 30% watershed area burned to see effects. Differences in watershed specificities (size, steepness, wetland cover, underlying permafrost) and fire severity patterns certainly play an important role in post-fire hydrological behavior, but post-fire precipitation seems to have an overarching role. It is indeed possible for post-fire hydrological response to be null or negative if no significant precipitation happens.

If annual water yield often shows a general increase in burnt watersheds, a fire might also lead to a decrease in low flows during the dry season, as vegetation regrows and water demand from saplings is high. This is a phenomenon that has been documented in Australia for decades and that has only started to be studied in detail in North America. In regions underlain by permafrost, wildfire might lead to deep thaw, allowing water to infiltrate deeper underground, with the effect of lowering baseflow.

Finally, the timing of flow will also be altered by fire. This is particularly obvious in watersheds where snow represents an important part of the annual streamflow. While snow might accumulate in deeper layers in burned areas, it will also melt earlier in Spring and at a faster rate, thereby displacing the timing of the Spring freshet and of the dry season low flows, which both can have important effects on aquatic ecology and water supply.

The effects described above can last anywhere from a few weeks or months for hydrophobicity to years or even decades in the case of low and peak flows.

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4) Post-fire geomorphology

Summary on the state of research

Forests act like a shield, in the sense that they protect soils from erosion by intercepting precipitation, thus dissipating energy and limiting physical weathering due to raindrop impact and runoff velocity. Forest soils rich in organic matter also present a structure more resistant to erosion, and trees’ root systems contribute to this resistance by holding soils together.

Parallel to hydrological changes, large and severe wildfires alter watershed erosion patterns and rates (figure 4). As runoff increases in volume and velocity, hillslope erosion processes become more powerful, and rills and gullies might rapidly form during precipitation. Both post-fire hydrological and erosional processes may combine to generate various types of intense phenomena such as gullies, debris flows, and landslides, in particular when the fire is quickly followed by intense rainstorm. Such phenomena can cause significant damages to (infra)structures and threaten life (figure 4).

Figure 4: Photos of damage from major postfire debris flows during the last two decades in southern California: (a) December 25, 2003, Devore, San Bernardino County (Old/Grand Prix fires); (b) February 6, 2010, La Cañada-Flintridge, Los Angeles County (2009 Station fire); (c) and (d) January 9, 2018, Montecito, Santa Barbara County (2017 Thomas fire). Photo credits: USGS.

Sediments, rocks, and logs from hillslopes will eventually reach the river system. River banks might become unstable, especially if riparian vegetation was burnt, adding to eroded material from hillslopes. Furthermore, stormflow might increase erosion within the riverbed. All these effects combine to modify river morphology, possibly for decades. These changes will modify the river's sediment transport capacity, flood regime, and aquatic habitats. While these changes are often natural and may be seen as necessary for river health, their occurrence in watersheds used for drinking water supply or river hosting sensitive aquatic species may not be desirable.

Post-fire changes to erosion dynamics and the hazards they represent might last for several years, although with decreasing intensity as vegetation regrows and debris stored in the river system stabilizes. That said, intense rainstorms over the burned watershed might still produce excess sediments and debris as stabilized in-channel material gets remobilized by storm flows. In southern British Columbia, landslides were observed 25 years after the fire, a delay likely due to the time needed for the root system to fully degrade.

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5) Post-fire water quality

Summary on the state of research

Forests act as natural water filters, with forest soils retaining many of the natural and human-made chemicals present in the atmosphere, in the soil, and in living organisms; many of them like carbon, phosphorus, and nitrogen are essential building blocks for life. Forests also help regulate watershed air temperature and water storage, which have a direct influence on the stability of freshwater temperature. Good water quality promotes healthy aquatic ecosystems, recreational uses, and facilitates the drinking water treatment process, making it cheaper.

Accelerated hydrological and erosional processes post-fire will often combine to degrade water quality (figure 5), especially in the event of rainstorms soon following the fire. Excess ash and sediments can lead to excess water turbidity, while the increased amount of direct sunlight reaching the ground will increase water temperature; in combination, these will enhance biological activity and reduce dissolved oxygen levels, which can compromise the survival of aquatic life.

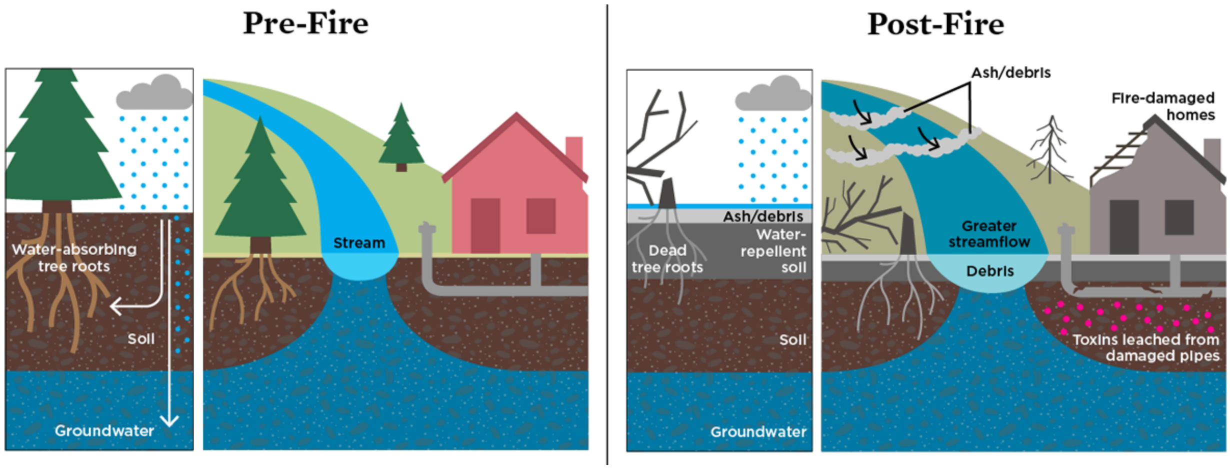

Figure 5: Wildfire impacts on water quality - Union of Concerned Scientists 2022.

Nutrient concentration for nitrogen and phosphorus typically increases after a fire, further leading to decrease in water quality. Nitrogen and phosphorus are limiting nutrients, meaning that they are generally found in low concentration in ecosystems, thereby limiting biological activity and biomass growth. After a fire, ash and sediments will contribute to increases in both nutrients, leading to water enrichment; smoke deposition on water bodies will also contribute nitrogen. Combined to the increase in water temperature, water enrichment will often lead to strong increases in phytoplankton, periphyton, and algae. This sudden increase in primary production has created concerns around the possible development of harmful algal bloom and eutrophication, which can be detrimental to human health and wildlife; while toxic cyanobacteria have been observed in waterways downstream of burned areas, and while post-fire algal bloom sightings have been reported, it remains unclear how much of a risk harmful algal blooms represent by lack of dedicated studies in freshwater environments (post-fire algal blooms have been observed in the ocean).

Carbon concentration—in the form of dissolved organic carbon (DOC)—will also often increase post-fire. High DOC concentration turns water dark brown (often compared to the color of a strong tea) and limits light entering the water column, which can counteract the effect of enrichment mentioned above. Higher DOC concentrations are a typical response in waterways surrounded by burned peatlands. While high DOC concentration does not represent a hazard, it might make water less attractive for recreational purposes, or make people worry that water is polluted. While these concerns cannot be discarded, the real hazard coming from DOC happens during the water treatment process, when DOC reacts with chlorine to create carcinogenic disinfection byproducts (see section 7).

There has been increased attention in wildfire-caused water pollution from human-made (infra)structures. High levels of arsenic and selenium—toxic heavy metals—have been observed downstream of legacy mining sites and former industrial sites caught in wildfires. Wildland-urban interface fires lead to the combustion of material such as plastic, metal, detergents, treated wood, etc… that can generate toxic compounds such as Polycyclic Aromatic Hydrocarbons (PAH) and Volatile Organic Compounds (VOC) that can find their way to water through storm runoff or smoke deposition. Forests may also contain important concentrations of toxicants such as mercury or polychlorinated biphenyls (PCB) from human activities and industrial emissions, toxicants that can be remobilized by a fire and be eroded or deposited onto water bodies. Mercury is of particular concern, especially its bioaccessible form, methylmercury, that can bioaccumulate and biomagnify to levels making fish dangerous to human consumption.

Finally, firefighting can be a source of water pollution, mostly related to the use of retardant foam. Retardant foam can essentially be seen as a fertilizer: it contains high levels of phosphate, ammonia, and sulfate. While it seems that no specific regulation exists regarding the use of retardants near waterways in Canada, foam directly entering water will most likely happen by accident. In such cases, first-hand observers have reported near-immediate fish kills and water pollution several days after the facts. The state of the science regarding the danger of retardant foam with respect to water pollution points to a very low level of concern, especially when considered relatively to the other sources of pollution coming from a large fire. Some foam also contains per- and polyfluorinated substances (PFAS, also called forever chemicals) that can create a suite of health issues for aquatic life and be complex to treat for drinking water purposes, although those don't seem to be used for wildland firefighting in Canada.

The duration of the effects described above can be limited to a few days for retardant foam in water to several years. Higher nutrient concentrations and excess sediments have been reported 15 years post-fire, reports that seem driven by the occurrence of heavy upstream precipitation and delays in vegetation recovery.

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6) Post-fire aquatic ecology

Summary on the state of research

Forested watersheds are often associated with thriving aquatic ecosystems. Many iconic fishes, like salmonids, thrive in forested streams and lakes. While the aquatic ecosystems of Canada are likely resilient to wildfire activity, it remains important to understand the effects of fire activity on aquatic food webs, especially as widespread watershed degradation and climate change are leading to changes in fire regimes.

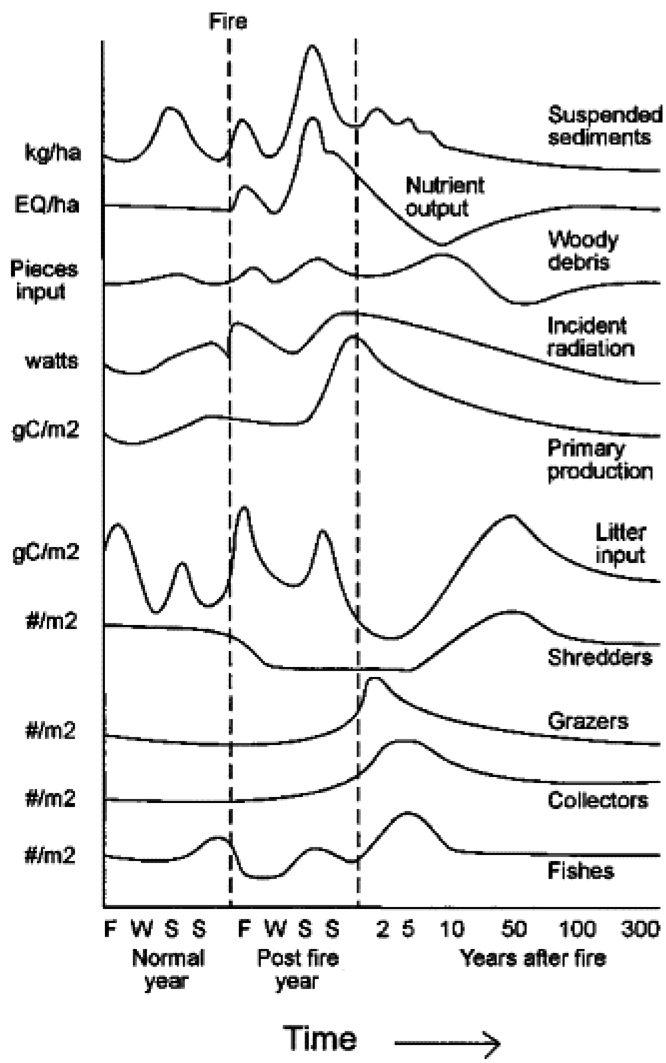

Figure 6: A generalized temporal sequence of selected events in response of aquatic ecosystems to fire (Gresswell 1999)

The effects of wildfires on aquatic ecosystems can vary tremendously, and it is difficult to generalize. While wildfires might have an immediate detrimental effect on many components of an aquatic ecosystem, long-term effects (over a decade or more) can be neutral or even seen as beneficial (figure 6). It seems that primary production is the main beneficiary from post-fire inputs such as nutrients and sediments; increases in chlorophyll-a from phytoplankton biomass is a common sign of water enrichment post fire. However, this enrichment can mean various things for different levels of the trophic chain, and whether it happens within a lake or a river. The literature shows that there will be winners and losers depending on the level of specialization of some species and their capacity to endure post-fire changes to water quality, streamflow, and flow timing.

Salmonids have received a significant amount of attention. While post-fire fish kills have been documented—excess sediments and ash can clog fish gills, leading to suffocation—, such events are likely limited to a short window of time after the fire when heavy rainfall triggers the first “flush”. It has been shown that watersheds with well connected river and lake systems allow for fish to find refuge after disturbance and to recolonize afterwards. Several studies have reported enhanced aquatic habitat salmonids after a fire, and even the colonization of new streams within the burned perimeter. Work done at the Southern Rockies Watershed Project in Alberta reported increased trout growth in the years after the 2003 Lost Creek fire.

Other fishes studied in Canada such as Yellow Perch and White Sucker did not show significant population changes in lakes affected by wildfires, although wildfire parameters (e.g., fire severity, percent watershed burned) are admittedly not always well reported. A 2010 study done in the NWT suggested that the rejuvenation of riparian vegetation burned in a fire was beneficial to young Northern Pike.

Given the tremendous variations in aquatic ecosystem response to fire, the longevity of these effects, when significant, will also vary in great levels. Several studies focusing on Canadian lakes reported a limited effect for a few years only, while some other studies done in the US and Canadian Rocky Mountains have reported noteworthy effects still detectable over 15 years after the fire.

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7) Wildfire risks to potable water supply

Summary on the state of research

When source watersheds are burned by a large and severe fire, the changes to watershed functioning described above combine and cascade downstream, creating risks to communities depending on upstream water supply for food, recreation, and drinking water supply. The study of wildfire risk to drinking water supply has gained a lot of attention these past 10 years. In Canada, the 2016 Horse River fire in Fort McMurray and its aftermath created high levels of concerns for water treatment and distribution capacities, and the municipality was put under a three-month boil water advisory out of precaution. The recent Black Summer in eastern Australia led to more than half of source catchment experiencing some level of burning. Post-fire risks to potable water supply are now commonly mentioned in news reports, including in Canada.

The first issue that water treatment and distribution structures will face is the possibility of damages from excess erosion (hillslope scour and gullies) and debris flows (mud flows, woody debris, or landslides). The amount of eroded material coming from burned areas can also accumulate in reservoirs used for water supply, which can cause excess sedimentation. Dredging reservoirs is costly: after the 2002 Hayman fire in Colorado, the city of Denver spent nearly $30M USD in reservoir cleaning. In case of damages to the drinking water treatment plant’s intakes, a locality might have to rely on existing clean water storage, which may be limited to a few days only if there is no alternate water source.

The decrease in water quality entering the treatment plant usually leads to challenges to the production of potable water (figure 7). Excess sediments and nutrients will strain the treatment line, with higher production of by-products that will have to be cleaned and disposed of. Changes to water quality can also vary rapidly and in great levels, making it harder to adjust the dosage of elements such as alum, an essential element of the water treatment process. Some toxicants, such as heavy metals, can be hard to remove. A particular concern comes from higher DOC concentrations in source water: DOC reacts with chlorine—the most common product used in conventional water treatment—to create disinfection by-products (or DBP), such as trihalomethanes, that have been shown to be carcinogenic. Lower water quality means a higher use of chemicals for water treatment, which also comes at a cost. Treated water going to distribution will be safe, but the time, cost of production, and stress on operators will be higher. There have been examples of plant shutdown when the water cannot be treated, as well as cases where a treatment plant will have to be retrofitted or fully built to accommodate changes to source water.

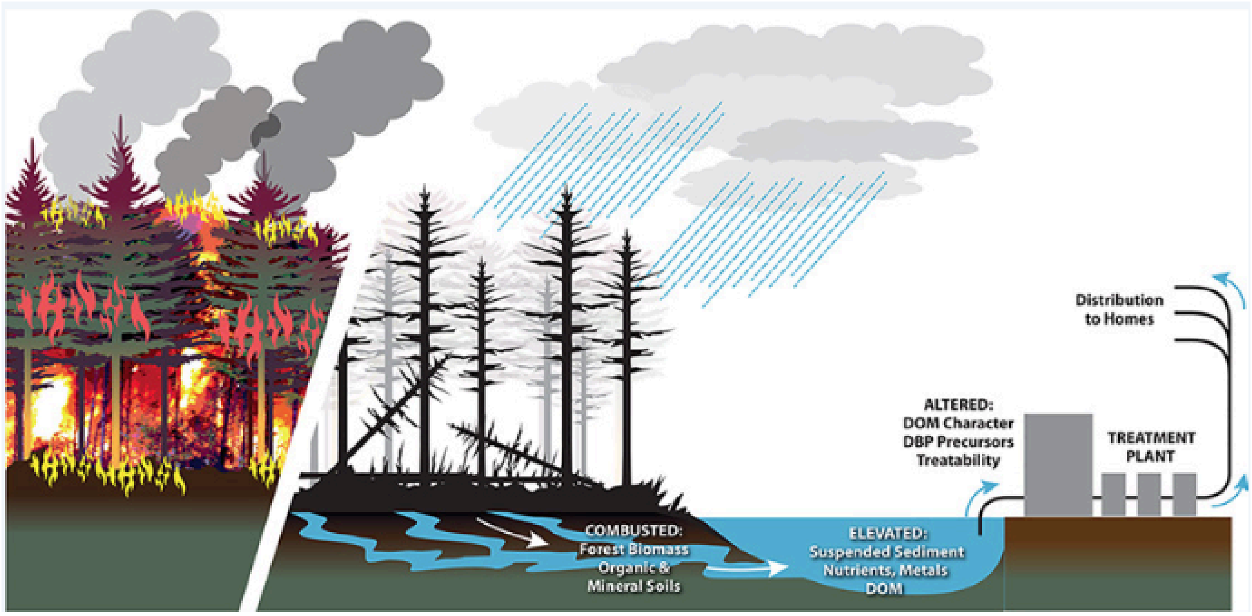

Figure 7: Drinking water treatment challenges from wildfire-polluted water (Hohner et al. 2019).

There has been a recent focus on water pollution in the distribution system of wildland-urban interfaces. While water getting out of the treatment plant is clean, existing pollution from fires in the wildland-urban interface can contaminate pipes carrying water to homes. Depressurization during a fire can suck in toxicants derived from plastic into the pipes, leading to high levels of VOCs, which are carcinogenic. It is advised that tap water coming to residential areas be tested for such toxicants, including water coming from private wells. The costs associated with such type of pollution might reach several dozens of millions of US dollars, as per estimation done in the USA after the 2017-2018 fire seasons.

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