The Influence of Wildfire on Water Quality and Watershed Processes: new insights and Remaining challenges

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Abstract

This short paper provides the framework and introduction to a Special Issue entitled 'Forests, Flames and Faucets: The Influence of Wildfire on Water Quality and Watershed Processes'. It's eight papers were selected from those presented at two consecutive conferences held in 2018 in Europe and the USA that focused on the impacts of wildfire on factors that regulate streamflow, water quality, sediment transport, and aquatic habitats. Despite decades of watershed research, our understanding of the effects of wildfires on the processes that regulate clean water supply remains limited. Here we summarise the key challenges and research needs in this interdisciplinary field and evaluate the contributions the eight special issue papers make to improved understanding of wildfire impacts on watershed processes. We also outline research priorities aimed at improving our ability to predict and, where necessary, mitigate wildfire impacts on watersheds. Achieving these advances is all the more pressing given the increasing extent and severity of wildfires in many areas that are the source of clean water for major population centres.

Keywords: water contamination, pollutants, drinking water, water supply,

Introduction

Wildfires influence watersheds from top to bottom, altering the ecosystem processes that regulate streamflow and the delivery of clean water (Shakesby & Doerr 2006; Nunes et al. 2018). Although the global area burned by wildland fires has declined in the past two decades, due predominantly to the conversion of savannah and grassland to agriculture (Andela et al. 2017), changing climate, forest conditions and land-use patterns have increased the frequency, extent, and severity of forest wildfires in many parts of the world (Dennison et al. 2014; Jolly et al. 2015; Westerling 2016; Radeloff et al. 2018). The associated extensive loss of life and destruction of property from recent wildfires in, for example, western North America, Portugal, Greece and elsewhere stunned the public and amplified global awareness of their destructive potential (e.g. BBC 2017; Jergler 2018) and it is widely accepted that climate and land use changes will continue the observed increase in the extent and severity of forest wildfires in the future (Flanningan et al. 2013; Knorr et al. 2016).

These changes have crucial implications for the capacity of watersheds to conserve aquatic biodiversity and sustain drinking water supply (Bladon et al. 2014; Martin 2016). Learning to adapt to severe wildfires and determine how best to reduce not only threats to human life and property but also to drinking water supplies have emerged as pressing global challenges (Hallema et al. 2018; Robinne et al. 2018).

Both wildfire behavior and watershed processes are spatially and temporally complex, and post-fire water quality and watershed responses elude simple generalization. For example, observations of short-term effects of wildfires on aquatic biota, sediment, ash and nutrient losses are widespread, but only recently have we begun to recognize that some of these responses may persist for many years (Rust et al. 2018; Rhoades et al. 2019). Recent studies have helped increase appreciation that post-fire nutrient enrichment, carbon (C) and metal mobilization create challenges for water treatment operations (Emelko et al. 2011; Bladon et al. 2014; Martin 2016; Hohner et al. 2019). Yet despite decades of watershed research, our understanding of the effects of wildfires on the processes that regulate clean water supply remains limited. Our need to adapt to future increases in wildfire size and severity (Flanningan et al. 2013; McWethy et al. 2019) requires new analytical approaches, and evaluation of various spatial and temporal scales across multiple fuel types and hydrologic regimes.

This Special Issue entitled ‘Forests, Flames and Faucets: The Influence of Wildfire on Water Quality and Watershed Processes’ addresses this need by presenting new insights from research conducted in Europe, North America and Australia with the shared objective of advancing understanding of how wildfires influence watersheds and water quality. The eight papers it contains emerged from international conferences conducted in Lisbon, Portugal (EU COST Action ES1306 Connecteur and the H2020 PLACARD project, February 2018; Nunes et al. 2018) and Missoula, Montana, USA (Forests-Flames-Faucets; Association for Fire Ecology and International Association of Wildland Fire, May 2018). The Lisbon meeting was convened in response to multiple extreme wildfires in 2017 that threatened Portuguese watersheds, water storage and treatment utilities and included researchers and water resource managers from Europe, the US, Canada, Australia and Israel, as well as water managers, drinking water treatment specialists and the public. Both conferences presented research on the consequences of wildfire on the factors that regulate streamflow, water quality, sediment transport, aquatic habitat and other attributes of forest watersheds. The studies included here provide new insights from wild and prescribed fires conducted at hillslope, stream and catchment scales. They highlight the links between upland, riparian and aquatic environments and surface water quality. Though much historic fire information derives from short-term studies of individual fires, this issue features four papers that evaluate water quality changes over 4 to 10-year time frames and includes papers that make comparisons involving 6 to 153 individual fires.

Linking Specific Contaminants and Water Quality Assets

The research presented here helps to advance understanding of coupled response of post-fire changes in nutrients, carbon, metal, or other contaminants with aquatic ecosystem, drinking water reservoir, treatment operations, or other water assets. Harper et al. (2019) aimed to disentangle which individual or combined chemical constituents influence a common aquatic indicator species (*Daphnia magna*). They evaluated the toxicity of ash from wildfires that burned six distinct vegetation types collected around the world. Toxic ash had high pH, nitrate, chloride and conductivity compared to other ash types that were harmless to *D. magna*. Neither water-soluble metal or polycyclic aromatic hydrocarbon concentrations contributed to ash toxicity. Though the study provided insights about variability in ash toxicity, the authors were unable to pinpoint the specific chemical constituents directly responsible for those effects. Martens et al.

(2019), using a multiple-taxa approach in southern Alberta, Canada, evaluated changes in the stream macroinvertebrate assemblage in response to persistent post-fire changes in stream nutrients, temperature and other resources. They found that a wildfire influenced not only water chemistry, but also the stream macroinvertebrate community for eight years. Both the composition and abundance of stream macroinvertebrates differed between burned and long unburned reference streams. Unburned streams had lower overall macroinvertebrate abundance and greater occurrence of disturbance-sensitive taxa (i.e., stoneflies). In contrast, burned streams and salvage-logged areas both had higher macroinvertebrate abundance and higher dominance of chironomids and caddisflies. The lasting post-fire effects were attributed to sustained increases in stream resources (e.g., stream temperature, dissolved organic C (DOC), sediment and soluble reactive phosphorus (P).

Analytical advances continually uncover new contaminants of concern and help increase understanding of their post-fire responses and downstream consequences. Two papers from forests of the southeastern USA apply novel laboratory (Majidzadeh et al. 2019) and field approaches (Olivares et al. 2019) to study chemical attributes of DOC and their post-fire responses that have implications for drinking water treatment. Similar to wildfires, the release of pyrogenic C and DOC following prescribed fires are synchronized with the initial post-fire rainstorms. However, detection of these short-lived C releases is complicated by abundant particulate charred material, suspended sediment, and high background stream DOC concentrations. New *in situ* ultraviolet-visible absorption (UV-VIS) sensors offer the possibility to capture storm events and provide a more complete temporal record of post-fire DOC dynamics. Olivares et al. (2019) evaluated this technology following a prescribed fire at the Francis Marion Experimental Forest, in South Carolina, USA. The sensors captured rapid fluctuations in DOC associated with individual storm events in burned and long unburned catchments, though the low-severity prescribed burn had little measurable effect on C release. The consequences of post-fire dissolved organic matter export, including both DOC and DON, have become crucial to drinking water utilities following enactment of regulations and monitoring for specific disinfection by-products. The *in situ* DOC sensor evaluated by Olivares et al. (2019) provides an example of how new analytical approaches may better address the temporal fluctuations and spatial complexity of forest watersheds to deliver timely and cost-effective water quality information to downstream users.

Contaminant Mobilization and Transport

The processes that mobilize and transport sediment, nutrients, C and other constituents vary widely among watersheds and fires and further complicate assessment of post-fire water quality change (Nunes et al. 2018). As opposed to targeting disconnected watershed processes, a coupled evaluation of potential contaminant sources and their retention in short and long-term vegetation, soil and burned landscape sinks may better characterize post-fire responses. Evaluation of biologic and physical nutrient retention within stream channels, hyporheic zones and flood plains have helped advance understanding of forest watersheds (Triska et al., 1989; Hall et al. 2002; Covino et al. 2010), though these approaches have rarely been applied to post-fire conditions. Silins et al. 2014 and the study presented here by Martens et al. (2019) found that retention of particulate-P in stream sediments following wildfire in the Canadian Rockies has led to sustained, elevated P in stream water and contributed to long-term shifts in the macroinvertebrate community.

Slow post-fire vegetation recovery likely dampens nutrient demand and retention and has been credited for persistent, elevated stream nutrients (Rhoades et al. 2019). Here, Rust et al. (2019) use publicly available stream water and wildfire data from more than 150 fires in the western US, and identified fire severity, post-fire vegetation recovery and site-specific soil properties as key contributors to post-fire stream nutrient and metal responses. The study by Williams et al. (2019) examining the impacts of wildfire in the southern Canadian Rockies further demonstrates that the rate of vegetation recovery determines how long wildfires will alter precipitation inputs, which in turn drive the hydrologic processes that mobilize and transport potential contaminants. Specifically, by reducing canopy foliage, crown fires reduce the proportion of precipitation that is intercepted and sublimated from the forest canopy, thus increasing the precipitation reaching the soil. The authors observed reduced rainfall interception and increased rain and snow inputs that combined to augment annual precipitation by 51%. The slow post-fire recovery of the subalpine forest canopy at that site prolonged these hydrologic effects of the wildfire for a decade. These studies suggest that, overall, a more spatially integrated assessment of retention and release processes will provide a better assessment of the likelihood that potential post-fire water quality contaminants will be delivered to receiving water bodies.

Reducing Wildfire Impacts on Watersheds and Water Quality

There is widespread agreement of the need to adapt to the growing number, size and severity of wildfires, especially in areas with high-population density and around valuable water sources and storage and treatment infrastructure (McWethy et al. 2019). There are also numerous opportunities to manage watershed risks both before and after wildfires (Nunes et al. 2018). However, our limited current understanding of the probability of wildfire occurrence, fire behavior and watershed responses prevent specific determination of where and when to invest in pre-fire fuel reduction treatments. Here Gannon et al. (2019) present an optimization model they developed and evaluated for identifying treatment locations to reduce watershed vulnerability. Their model determined that mechanical fuel reduction treatments conducted on relatively small portions of steep watersheds may be sufficient to reduce risks of post-fire erosion. However, the costs of mechanical treatment projects were prohibitively high and could not be justified solely by the potential cost savings from reduced soil erosion.

Additional information to help monetize potential benefits of mechanical and prescribed fire treatments aimed at reducing risks to aquatic ecosystems, other water quality attributes, watershed conditions and water treatment operations might alter the economic balance of pre-fire management. As one example presented here Majidzadeh et al. (2019), report that periodic prescribed burning in coastal plain forests reduced DOC leaching and potentially hazardous disinfection by products (DPBs) precursor formation, a previously unaccounted benefit of management. Prescribed fire is commonly promoted as a strategy for avoiding the negative watershed and water quality consequences of severe wildfire (Gannon et al. 2019). By restricting their timing, size and intensity, managed fires are expected to limit extensive loss of vegetation cover and exposure of mineral soils. However, detailed information about how to balance reduction of hazardous fuels and restoration of desired stand structure and composition with protection of source water supply and watershed condition remains sparse. Better understanding and tools are needed to help land managers compare the small, but potentially chronic, water quality changes from repeated prescribed burning and fuel-reduction activities with the dramatic effects of severe wildfire. Here, Majidzadeh et al. (2019) report that repeated prescribed burning contributed to reduced forest floor mass and decreased DOC concentration

relative to an adjacent unmanaged catchment. It also influenced the abundance of aromatic C compounds in forest floor leachate and stream water and reduced the potential to form (DBPs) during drinking water treatment.
Not surprisingly, there has been considerable examination of post-fire erosion control activities (Robichaud et al. 2000; Shakesby & Doerr 2006). Such treatments can reduce soil loss under some conditions but may also benefit other water quality attributes and enhance soil productivity and ecosystem recovery. For example, Pierson et al. (2019) report here that by reducing post-fire erosion mulching treatments may also limit C and N mobilization and transport and downslope losses. They also found that eroded C and N declined within a few years. There is, however, growing evidence that post-fire stream nutrient changes may persist longer where revegetation is slow (Rhoades et al. 2019; Rust et al. 2019) and there has been little effort to date to rehabilitate lingering wildfire effects using in-stream, riparian or upland rehabilitation treatments.

Persistent and Emerging Knowledge Gaps

Tremendous progress has been made in the past three decades in our understanding of post-fire watershed and water quality responses and on mitigating their impacts. New conceptual frameworks have recently been brought forward by Nunes et al. (2018) and Hallema et al. (2019) with the aim to accelerate progress by bridging gaps in scales, approaches and relevant disciplines. However, there remains a need to conceptualize responses across fire-sensitive hydro-climatic-geologic settings globally (Moody et al. 2013) and better practical knowledge is required to manage wildfire threats to drinking water supply and infrastructure. The immediate, catastrophic watershed effects of wildfires are well recognized, but their long-term consequences have only recently become apparent. Links between post-fire vegetation recovery and persistent post-fire water quality responses highlight the value of considering these disturbances from an ecosystem perspective. For example, both short- (Riggan et al. 1994; Rhoades et al. 2011) and longer-term wildfire effects on stream nutrients (Rust et al. 2019) relate to the extent of high-severity wildfire, and these conditions, in turn, influence post-fire vegetation recovery (Chambers et al. 2016; Malone et al. 2018). Advances in understanding of the coupled hillslope, stream-reach and catchment-scale biogeochemical processes that regulate plant and soil nutrient and C uptake and release are needed to determine the threats of potential post-fire contaminants to downstream resources. There is also growing awareness of overlapping disturbances, such as repeated wildfires, fires following insect outbreaks or associated with drought or harvesting (Harvey et al. 2014; 2016a; 2016b; Stevens-Rumann et al. 2017; Rhoades et al. 2018), but little information about how these may impact watershed processes or water quality. The link between long-term watershed responses and vegetation dynamics have logical implications for post-fire watershed restoration. While great effort has gone into studying short-term, post-fire erosion control (Robichaud et al. 2000), virtually nothing is known about what revegetation or stream restoration approaches are best suited to resolving lingering post-wildfire water quality concerns.

Linking the formation of contaminants and their downstream mobilization is a continual challenge to predicting and managing the threats of wildfires on aquatic resources and water treatment (Nunes et al. 2018). For example, recent research identified storm sewer inputs of fire-transformed contaminants from residential, commercial, and light industrial settings as a pathway of concern for municipal water supply (Burke et al. 2012; Stein et al. 2013), though little else is currently known about this water quality threat. Wildfire impacts to groundwater also remain poorly understood. Furthermore, understanding of how complex fire behavior burning under distinct forest and climatic conditions creates, transforms and degrades C and N-based precursors to the disinfection by products formed during water treatment (Hohner et al. 2019) remains limited. The societal and ecological impacts of wildfires on water supply and aquatic ecosystems will become an increasingly critical environmental concern in coming decades (Robinne et al. 2018; Hallema et al. 2019). Current knowledge of the combined complexities of current and anticipated future wildfire behavior and watershed responses remains too limited to adequately predict where to expect risks and how to best mitigate them. To face this challenge future research needs to focus on these persistent and emerging knowledge gaps and linkages between changing forest and fuel conditions, wildfire behavior and watershed and water quality responses as well as their effect on downstream users and water treatment utilities.

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