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INVITED COMMENTARY

Assessing water contamination risk from vegetation fires: Challenges, opportunities and a framework for progress

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1 | THE CHALLENGE

Water crises—defined as significant declines in water quality and quantity—top the global risks list compiled by the World Economic Forum (2015) that have the greatest potential impacts on society. Vegetation fires are amongst the most hydrologically significant landscape disturbances (Ebel & Mirus, 2014) and affect ~4% of the global vegetated land surface annually (Giglio, Randerson, & van der Werf, 2013). Fire-prone or fire-managed ecosystems (forests, grass-, and peatlands) also provide ~60% of the water supply for the world's 100 largest cities (Martin, 2016). Accordingly, fire is increasingly acknowledged as a serious threat to water supply globally (Martin, 2016; Robinne et al., 2016). Whilst the global area burned declined by ~20% over the last two decades mainly due to agricultural expansion (Andela et al., 2017), many areas critical for water supply are exposed to increasing fire risk (Doerr & Santin, 2016; Sankey et al., 2017). This is due to increases in fire weather severity (Flannigan et al., 2013) and extended fire season in many regions (Westerling, Hidalgo, Cayan, & Swetnam, 2006), as well as fuel build-up due to fire suppression, afforestation, land abandonment, and a trend towards more extensive fires (Doerr & Santin, 2016).

A substantial body of hydrological research exists on fire impacts on soil-, hillslope- and, to a lesser extent, catchment-scale processes with a focus on infiltration, runoff, erosion, and water yield (Moody, Shakesby, Robichaud, Cannon, & Martin, 2013; Shakesby & Doerr, 2006; Shakesby, Moody, Martin, & Robichaud, 2016). However, despite the concerns highlighted above, research has only recently focused on linkages between on-site and downstream impacts of fire on water quality (Abraham, Dowling, & Florentine, 2017; Bladon, Emelko, Silins, & Stone, 2014; Smith, Sheridan, Lane, Nyman, & Haydon, 2011) and treatability of contaminated water following fire (Emelko, Silins, Bladon, & Stone, 2011). Presence of highly erodible ash, combined with enhanced runoff and erosion responses following fire, can rapidly transfer sediment, nutrients, and contaminants of health concern, such as polycyclic aromatic hydrocarbons (PAHs) and heavy metals into stream networks (Bodí et al., 2014; Verkaik et al., 2013), impacting aquatic ecosystems (Silva et al., 2015) and drinking water supplies (Smith et al., 2011). These impacts can be exacerbated

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following drought due to reduced contaminant dilution at low water levels. Such events have led to drinking-water restrictions affecting large cities (e.g., Denver, 1996, 2002; Canberra, 2003; Belfast, 2011) and substantial direct costs for restoring ecosystem services and managing drinking water treatment, e.g., $26 Mill. Denver and $38 Mill. Canberra (Denver Water, 2010; White et al., 2006). Climate change will likely increase risks of water contamination events through increases in droughts, fire frequency, intensity and extent, and intensity of rainfall events (IPCC, 2014; Sankey et al., 2017).

Despite their economic and environmental significance, it is still difficult to sufficiently predict the probability and magnitude of post-fire contaminant exports to enable (a) reliable water contamination risk assessments in fire-prone catchments and (b) support effective mitigation strategies (Shakesby, 2011; Shakesby et al., 2016; Verkaik et al., 2013). Research in this area has recently gained momentum, but the body of research is still relatively small with enormous variability in the reported drivers of post-fire contamination events (type of pollutants and mobilization processes; Moody et al., 2013) and location- or end user-specific questions (e.g., White et al., 2006; Emelko et al., 2011; Campos et al., 2012; Santín, Doerr, Otero, & Chafer, 2015; Santos, Sanches Fernandes, Pereira, Cortes, & Pacheco, 2015a, 2015b; Langhans et al., 2016). As a result, both the type and extent of knowledge are limited and regionally diverse. The emerging field of post-fire water contamination research has thus not yet developed a coherent framework that supports addressing regional and universal knowledge gaps.

This commentary introduces such a framework within which we highlight (a) the dominant limitations to our capacity to evaluate post-fire water contamination risk and (b) recent advances towards addressing them across a range of post-fire environments. This framework embodies the science required to broaden the scope and maximize the utility of such investigations, whilst enabling meaningful comparison between studies and addressing site-specific and end user-focused priorities.

2 | A FRAMEWORK FOR PREDICTING POST-FIRE WATER CONTAMINATION RISKS

Post-fire water contamination risks are governed by the potential generation, mobilization, and accumulation of contaminants in aquatic environments. Whilst fire and fuel characteristics determine their generation (i.e., their availability after fire), hydrological processes (precipitation, infiltration, runoff, and erosion) drive their mobilization and delivery to water bodies. Mitigation opportunities exist at several stages (Figure 1): (a) effective fuel management can reduce risk before fires occur (Elliot, Miller, & Audin, 2010), (b) fire suppression might limit the spread of fires into particularly sensitive zones, (c) post-fire emergency measures can mitigate the mobilization and transport of contaminants to water assets (Robichaud, Elliot, Pierson, Hall, & Moffet, 2007), and (d) treatment plants can be modified to meet specific decontamination needs. The hydrological research community therefore has a central role in water contamination risk assessment in fire-prone landscapes. To do this, a simple tiered framework for evaluating post-fire water contamination risk is proposed (Figure 1), which includes

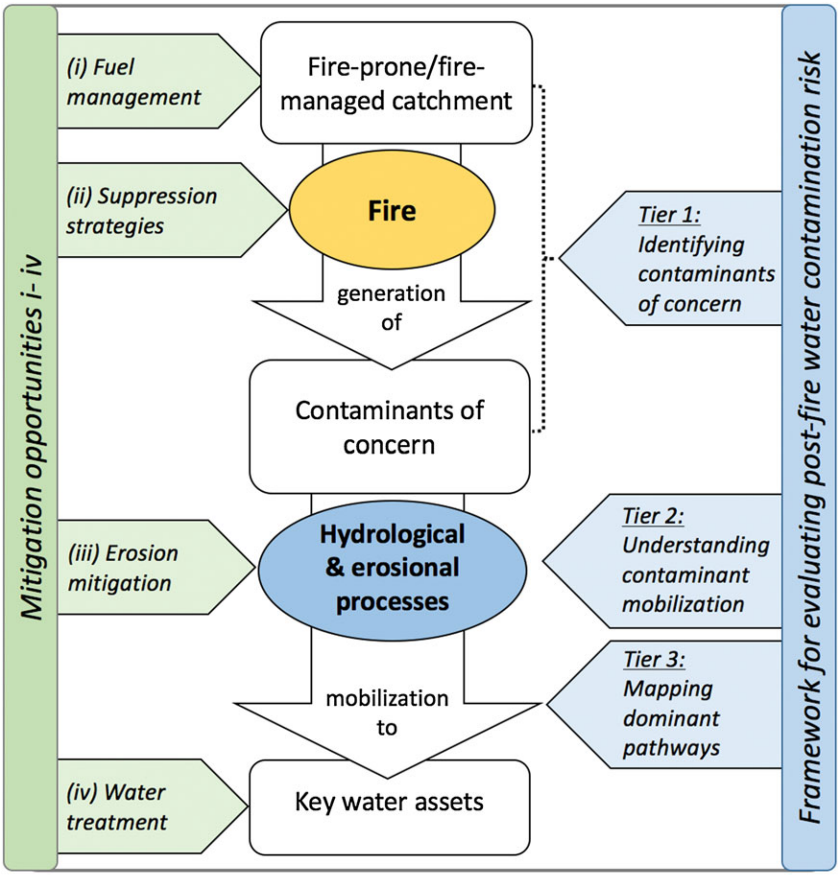

FIGURE 1 Visual representation of the proposed framework with three main tiers for evaluating post-fire water contamination risk. Opportunities for mitigation at different stages before, during, and after fire events are highlighted

1. Identifying contaminants and water assets of concern;
2. Understanding the dominant processes that govern contaminant mobilization; and
3. Mapping the dominant pathways linking contaminants to areas of concern.

2.1 | Identifying contaminants and water assets of concern

Post-fire water erosion can mobilize a multitude of constituents with contamination potential in dissolved and particulate forms or adsorbed to sediments (Smith et al., 2011). However, whether a *constituent* is deemed a *contaminant* depends on the ecosystem service evaluated (e.g., human consumption, industrial use, and aquatic ecosystem health; Calkin et al., 2007). Both the asset at risk (river, reservoir, or aquifer) and the contaminant of concern need to be clearly defined to focus research efforts. For example, Bladon et al. (2008) and Silins et al. (2014) reported elevated nutrient levels following snowmelt impacting stream ecosystems in burned catchments in Canada; White et al. (2006) reported water treatment problems immediately post-fire driven by turbidity in the Australian Bendora reservoir and subsequent releases of dissolved metals from reservoir bottom sediments; Campos et al. (2012) found acute toxic effects in Portuguese river ecosystems from PAHs dissolved in ash-laden runoff; and major additional treatment costs arose from changes in dissolved organic carbon (DOC) following the 2016 Fort McMurray wildfire, Canada (Thurton, 2017). These examples demonstrate that identification of the key contaminant(s) of concern for a particular water asset is critical and linked to end-user priorities. For each case, this process constrains the possible approaches in subsequent post-fire contamination assessment; therefore, contaminants are best identified at the outset, or better still, identified by managers of sensitive watersheds in fire prone ecosystems before a fire occurs (Elliot, Miller, & Enstice, 2016).

2.2 | Understanding the dominant processes that govern contaminant mobilization

Contaminants can be mobilized by wind and water erosion, debris flow, mass failure, and dissolution in water (Bodí et al., 2014; Smith et al., 2011). However, a specific process is often dominant in a particular landscape (Moody et al., 2013) and can be responsible for the majority of contaminant mobilization and delivery to water systems. For example, Jackson and Roering (2009) reported that debris flows in the Oregon Coast Range (USA) triggered by saturation-based mass failure were responsible for the majority of post-fire sediment production. In contrast, Nyman, Sheridan, Smith, and Lane (2011) showed that runoff-generated debris flows dominated burned catchments in SE Australia; while in the Mediterranean, Shakesby (2011) noted the absence of both mass failure and debris flows, implying the dominance of interill processes (Prats, Wagenbrenner, Santos Martins, Malvar, & Keizer, 2016). The dominant processes that govern contaminant mobilization are often controlled by higher-order factors, for example, aridity controlling debris flows occurrence in Australia (Sheridan et al., 2016) or mobilization being affected by land use patterns (Nunes et al., 2017).

As highlighted above, transport by water erosion plays a dominant role for contaminant delivery to surface water bodies. Pollutants can be mobilized by surface-runoff or saturation-based processes, which are controlled by different system properties. For example, runoff-related processes such as inter-rill and rill erosion and runoff-generated debris flows require knowledge on local weather patterns, topography, fire severity, and soil hydrological and erosional characteristics. Their occurrence is often driven by high-intensity, short-duration rainfall events (Kean, Staley, & Cannon, 2011). Saturation-based processes, such as post-fire mass failure processes common in steep landscapes of western North America, result from increased soil saturation and decreased soil bulk strength. They are therefore sensitive to tree mortality, gradual root decay, and high-volume rainfall events (Jackson & Roering, 2009). These contrasting processes may also erode distinct parts of the landscape. For example, spatially widespread rill and inter-rill erosion processes can mobilize the ash that blankets soil after fire (Moody et al., 2013), whereas channel erosion processes may release colluvial, bank, or bed stores of clay-sized or clay-adsorbed contaminants (Smith et al., 2011; Stone, Emelko, Droppo, & Silins, 2011). Both processes can also dominate at different times. For example, in northern temperate regions, channel erosion often governs mobilization during the snowmelt period, whereas rainfall dominates more widespread mobilization later in the season (Owens et al., 2013; Silins, Stone, Emelko, & Bladon, 2009). Non-erosional processes include the subsurface mobilization of dissolved contaminants such as DOC, phosphorous, and nitrate in some regions, which is also governed by saturation processes (Elliot, Brooks, Traeumer, & Dobre, 2015; Mast & Clow, 2008; Olefeldt, Devito, & Turetsky, 2013).

Different mobilization processes are associated with characteristic thresholds, and therefore, the dominant process in a given environment can be considered as a first-order control on the magnitude and frequency of contamination events. Thus, research should focus on the contaminants to which water assets are most vulnerable and mobilization processes most relevant to them. For example, the mobilization of ash and other associated components has been recently assessed in depth (e.g., Bodí et al., 2014; Campos, Abrantes, Keizer, Vale, & Pereira, 2016). These works offer a wealth of information and strategies for describing mobilization processes in specific environments which, combined with emerging methods to determine ash loads and their movement across landscapes (Santín et al., 2015; Chafer, Santín, & Doerr, 2016; Neris, Elliot, Doerr, & Robichaud, 2017), represent a promising step towards simulation of ash mobilization in burnt areas.

2.3 | Mapping the dominant pathways linking contaminants to areas of concern

This step is perhaps the most challenging element of the proposed framework, particularly when considering entire catchments. It will differ between transport pathways (connectivity on hillslopes, percolation to groundwater, transport in channel networks, and movement in water bodies) and is also related to the properties of the contaminants, including their potential transformation in the environment.

Hydrological contaminant transport can be partitioned into the parts where land surface properties dominate, and where properties of the water body dominate. For example, land surface properties including burn severity, surface roughness, slope, and topographic convergence control the connectivity of overland flow transport processes, which in turn affect contaminant delivery to receiving waters (Moody et al., 2013). In contrast, aquatic environment properties such as volume, flow regime, temperature, and stratification dominate processes including contaminant dilution, attenuation, transformation, and breakdown (Samuels, Amstutz, Bahadur, & Pickus, 2006; Smith et al., 2011). Groundwater contamination has also been observed in some areas (Mansilha, Carvalho, Guimarães, & Espinha, 2014; Olefeldt et al., 2013), but subsurface transport remains poorly studied.

Surface transport pathways can differ between mobilization processes. Their connectivity in the landscape for a given process is controlled by factors such as geomorphology, rainfall, or soil properties (Bracken et al., 2013; Bracken, Turnbull, Wainwright, & Bogaart, 2015). However, the impacts of fire on vegetation cover and soils change connectivity of transport pathways immediately after fire and throughout the recovery period, with controls including fire severity, burn patchiness, ash characteristics, soil water repellency, and vegetation recovery (Moody et al., 2013; Jordán et al., 2015). Human factors, such as forest tracks, terraces, and post-fire management add further complication (Shakesby, 2011; Wagenbrenner, MacDonald, Coats, Robichaud, & Brown, 2015). The spatial and temporal heterogeneities of these factors have complex impacts. For example, Ferreira, Coelho, Ritsema, Boulet, and Keizer (2008) showed runoff connectivity to be controlled by water repellency patterns in Portugal and disrupted by forestry operations, with stronger connectivity in the dry season (Nunes, Malvar, Benali, Rial Rivas, & Keizer, 2016). In contrast, Williams et al. (2016) highlighted the importance of prefire landscape degradation in the western USA, with bare patches generating runoff and erosion enhanced by fires and heavy rainfall. Wagenbrenner and Robichaud (2014) provided catchment-scale and nested data, quantifying declining sediment delivery with increasing scale, and substantial advances have been made in modelling fire affected landscapes (Elliot, 2013; Flanagan, Frankenberger, Cochrane, Renschler, & Elliot, 2013; Miller, Elliot, Billmire, Robichaud, & Endsley, 2016; Robichaud et al., 2007); yet a major challenge still remains in quantifying contaminant amounts available for transport and delivery to receiving waters.

A diverse body of research concerns contaminant transport in aquatic environments, especially in streams, which often highlight high-magnitude but short duration contamination pulses following fire (Smith et al., 2011). However, there is often a lack of connection between contaminant delivery from the land surface and within-stream transport processes (Moody et al., 2013). The latter is complicated by remobilization of contaminants inside the stream network, which depends on particle size and streamflow properties, and can lead to a lagged post-fire response (Bladon et al., 2014; Elliot, 2013; Smith et al., 2011). There are fewer studies focusing on lakes, where particle size and density, lake bathymetry, and stratification affect contaminant attenuation and second-order impacts such as nutrient-induced eutrophication (Smith et al., 2011). As an example of links between hillslopes and water supply systems, White et al. (2006) reported high turbidity and metals in streams draining burnt Australian watersheds, depositing at the bottom of a reservoir and resuspending periodically, leading to lasting water quality issues; while Santos et al. (2015b) discussed a similar problem in Portugal, caused by phosphorus exports adsorbed to sediment, enhancing eutrophication during the summer dry season. These latter linkages have been associated with biostabilization of fire-affected river bed sediments and have resulted in larger post-fire contaminant pulses with resuspension (Stone et al., 2011). They also resulted in lasting legacy effects and downstream transport of post-fire contaminants in larger river basins (Emelko et al., 2016).

Given that quantifying transport processes at the land surface is already difficult, with complexity increasing with scale, the variability in contaminant transport and fate in channels and lakes and potential lags and remobilization on land and in water provide a major challenge. However, linking contaminant transport from the land surface to streams, reservoirs, and aquifers is a critical step in assessing water contamination risks after fire. At the landscape level, recent advances in hydrological and sediment connectivity theory (Bracken et al., 2013, 2015; Nunes et al., 2017) allow the development of better models (Elliot, 2013; Flanagan et al., 2013; Miller et al., 2016) and spatial indices to map risk areas and eventually facilitate post-fire interventions (Robichaud & Ashmun, 2013). Contaminant source tracing and apportionment techniques also provide valuable insights into characterizing both upstream sources and downstream fate of fire-affected sediments and contaminants in larger river basins downstream of fire (Stone, Collins, Silins, Emelko, & Zhang, 2014). Finally, there is a wealth of historical water quality data for streams and reservoirs which can be explored to study the relation between fires and contamination (Emelko et al., 2016; Rhoades, Entwistle, & Butler, 2011; Santos et al., 2015a).

3 | THE FRAMEWORK IN PRACTICE

The framework outlined above can be used to support a post-fire contamination vulnerability assessment (*sensu* Adger, 2006). For example, the sensitivity of a water asset, that is, the likelihood of it being affected by an important contamination event, can be evaluated by the probability of specific events occurring. This will depend on (a) the combined probability of occurrence of fires with relevant severity that produce significant contaminant loads and of contamination-inducing storms during the window of disturbance period and (b) landscape- and water asset properties, such as their transport pathways, residence time of contaminants, and the dilution capacity of water bodies. In cases of drinking water supply priorities, treatability risk assessment frameworks can be informed by vulnerability assessments conducted using this framework.

For each case, the choice of contaminant(s) of concern and potential impacts constrain the possible approaches for post-fire contamination assessment, and therefore, they should be identified at the outset. Recent studies have focused on determining the sensitivity to post-fire contamination and range from relatively simple spatial indices (e.g., Robinne et al., 2016 at the global scale) to more complex assessments based on the probability of occurrence of both fire and the post-fire contamination events (Langhans et al., 2016; Santos et al., 2015a; Thompson et al., 2013). Advances in post-fire erosion risk modelling (Neris et al., 2017;

Robichaud et al., 2007) may serve to provide a foundation for more complex contamination models, but science advancements are still needed to support the development of these higher level predictive tools.

The following two examples illustrate limitations in existing approaches following fire and the potential benefit of applying the proposed framework to assess contamination risk:

As in 2017, extensive fires in 2003 and 2005 threatened the main water water supply reservoir of Lisbon (Portugal) with high concentrations of fine sediments (Coelho, Almeida, & Mateus, 2011). This fire-prone region has seen substantial research on post-fire erosion rates at the plot to slope scale but much less on sediment transport at the catchment scale (Ferreira et al., 2008). Contaminant studies in the stream network in this region have focused on ecotoxic contaminants (Mansilha et al., 2017) and nutrients (Santos et al., 2015b) due to their potential environmental significance. Coelho et al. (2011) argued that existing data were insufficient to connect post-fire erosion risk with larger-scale stream contamination risk, with different yet supposedly reasonable assumptions on transport processes in a water quality model leading to contamination estimates ranging from none to severe. This exemplifies a situation where a large research focus on sediment mobilization (Tier 2 of the framework presented here) was not combined with a similar focus on transport (Tier 3 of the framework). This has recently been addressed by developing models which can account for the seasonal dynamics of hydrological connectivity in burnt areas (Nunes et al., 2016, 2017; van Eck, Nunes, Vieira, Keesstra, & Keizer, 2016). These go some way in improving our ability to assess post-fire contamination risk; a major uncertainty in adapting the Lisbon water supply to a changing environment (Groot, Rovisco, & Lourenço, 2014).

The severe 2016 wildfire around Fort McMurray, Alberta, Canada was catastrophic for the city and the most expensive disaster in Canadian history (Insurance Bureau of Canada, 2016). It burnt extensive upstream Boreal forest regions and raised many concerns, including the unknown threat to drinking water provision. While periods of source water quality deterioration, especially shifts in DOC, challenged treatment and led to the >$1 million (Can.) increases in associated costs in the first year after the fire (Thurton, 2017), potentially catastrophic treatment failure was averted. While operational expertise and wise infrastructure investment largely enabled this success, rapid identification of water contamination and treatment risks was informed by previous long-term, post-fire, catchment-scale hydrological research (Emelko et al., 2011, 2016; Silins et al., 2009) that was conducted in the different hydrologic, geologic, and physiographic settings of Alberta's south-eastern, steep-sloped Rocky Mountains. This example underscores the foundational nature of the first tier of the proposed framework in appropriately linking contamination risks and end-user priorities. For example, while heavy metals may pose significant threats to ecosystem health, they can be effectively removed by most conventional and advanced drinking water treatment processes (see Emelko et al., 2011 for links of contaminants of concern to drinking water infrastructure typologies). Here, the identified need to focus on relatively subtle changes in DOC after wildfire both enabled appropriate—albeit costly—water treatment responsiveness (Tier 1 of the framework) and identified key knowledge gaps related to contaminant mobilization in low relief northern landscapes with highly variable hydrologic connectivity (Tier 2 of the framework).

Predicting the risk of post-fire water contamination is critical to enabling effective mitigation strategies for safeguarding water quality and treatability, particularly given increased water scarcity and fire risk in many regions. Current approaches to risk assessment are often site-specific because of differences in dominant mobilization and transport processes, as well as vulnerability of priority water assets. In the case of drinking water, while contaminants of concern are often known and have been broadly linked to infrastructure needs, operational capacity during challenge periods such as the hydrologic events discussed herein remains largely undescribed—both factors must be considered in treatment risk assessment. Further identification of contaminants of concern for priorities such as ecosystem health is more difficult due to complex interactions between contaminants and effects on trophic chains (Silins et al., 2014). The lack of systematic frameworks for assessing risks has made it difficult to generalize research findings from specific studies and develop adaptation strategies in our changing environment. Risk is the probability that a hazard will result in adverse consequences; thus, the framework presented herein prioritizes post-fire water contamination hazard identification (Tier 1) and evaluation of the probability of adverse consequence through predictive modelling of contaminant mobilization and transport (Tiers 2 and 3). While there is a clear need for more data collection and basic research to advance this framework, it can nonetheless help structure existing and future research, with the ultimate goal of contributing to the development of simplified, but effective tools, for watershed asset management by predicting and mitigating post-fire contamination risks.

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