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Foreword

Synthesising empirical results to improve predictions of post-wildfire runoff and erosion response

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Abstract. Advances in research into wildfire impacts on runoff and erosion have demonstrated increasing complexity of controlling factors and responses, which, combined with changing fire frequency, present challenges for modellers. We convened a conference attended by experts and practitioners in post-wildfire impacts, meteorology and related research, including modelling, to focus on priority research issues. The aim was to improve our understanding of controls and responses and the predictive capabilities of models. This conference led to the eight selected papers in this special issue. They address aspects of the distinctiveness in the controls and responses among wildfire regions, spatiotemporal rainfall variability, infiltration, runoff connectivity, debris flow formation and modelling applications. Here we summarise key findings from these papers and evaluate their contribution to improving understanding and prediction of post-wildfire runoff and erosion under changes in climate, human intervention and population pressure on wildfire-prone areas.

Additional keywords: ash, climate change, hydraulic conductivity, hydrology, overland flow, precipitation, scale.

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Introduction and context

Sufficient understanding for reliable and accurate prediction of the underlying controls on post-wildfire hydrology and erosion remains an ambitious goal, with new research often revealing increasing complexity. Recognition of the influences of soil water repellency (SWR) and ash serve as illustrations. Until the last 15 years or so, a somewhat simple view of the behaviour of SWR and its impact on soil hydrology in burned terrain was accepted; severe fire behaviour created water-repellent soil conditions, resulting in increased post-fire runoff and decreased infiltration. More recent research, however, has revealed a variety of possible repellency characteristics in post-fire soil, ranging, for example, from induced SWR in previously entirely wettable soil to reduced SWR after fire, with possible effects ranging from negligible to significant. Nevertheless, the importance of SWR relative to other fire effects, such as loss of litter and duff layers, decreased surface roughness and soil disaggregation remains poorly quantified (Doerr *et al.* 2009; Doerr and Shakesby 2013). Until recently, ash was viewed simply as a by-product of burning, with a mostly minor and transient impact on runoff and erosion. Ash is now recognised, however, as potentially having a substantial effect on hydraulic conductivity, water storage, overland flow and erosion. Moreover, through incorporation into the soil, ash possibly plays a significant role in carbon sequestration (e.g. Santín *et al.* 2012; Bodí *et al.* 2014). The increasing complexity in the understanding of post-wildfire processes and outcomes and their transient nature has made the task of predicting post-wildfire runoff and erosion using models increasingly challenging. Modellers have mostly opted for one of two prediction pathways: estimating the quantities of runoff or soil removed given particular scenarios, or providing probabilities and amounts of runoff and erosion.

Greater interaction and collaboration over the last 15 years or so between geographically isolated groups of post-wildfire field researchers have proved important in fostering new lines of investigation and in recognising that certain regionally distinctive factors can play a prominent role in post-wildfire hydrogeomorphic responses. These interactions and collaborations, however, have not always included meteorologists and modellers, whose interests are highly relevant to post-wildfire research. We convened an American Geophysical Union Chapman Conference in August 2013 that specifically aimed to include representatives from these other research areas. The overall goal was to explore ways of improving the predictive capabilities of post-wildfire runoff and erosion models. Improved prediction is important not only for intrinsic scientific reasons but also because better accuracy of models is vital in helping decision-makers take the most appropriate and timely action to minimise soil loss, damage to stream courses and property together with problems arising from flooding, rapid mass movements, reduced water quality and threats to life. A pre-meeting review paper (Moody *et al.* 2013) identified research priorities and formed the basis for organisation of the conference sessions. Each paper in this present special issue relates to one of the six main conference topic sessions: *Identification and classification of post-wildfire domains*; *Temporal and spatial variability of precipitation*; *Infiltration*; *Runoff processes and connectivity across different spatial scales*; *Variation in erosion responses between post-wildfire domains*; and *Predictive post-wildfire runoff and erosion modelling.*

Identification and classification of post-wildfire domains

The aim of this topic was to explore the feasibility of classifying post-wildfire responses into domains in order to improve model predictions. Post-wildfire response domains may be viewed as areas or regions characterised by distinctive patterns or sets of environmental controlling factors (Moody *et al.* 2013). However, discussions clearly showed that: (1) the previously preferred parameter for differentiating domains – fire regimes – was not appropriate because humans and climate change have significantly altered them; and (2) in some regions, a single locally distinctive factor or group of such factors (e.g. existence of dry ravel, influence of post-burn bioturbation activity, legacy of historical soil degradation) may be superimposed on a universal set of parameters and potentially have a significant effect on the hydrological and erosional outcomes (e.g. Shakesby and Doerr 2006; Shakesby *et al.* 2007; Shakesby 2011). In this special issue, Sheridan *et al.* (2016) show that a comparatively simple aridity classification that differentiates between wet–damp and dry *Eucalyptus* forest in the eastern Victorian uplands of south-east Australia may be a very useful post-wildfire erosion predictor. High aridity is associated with low post-fire infiltration capacities and high overland flow and therefore greater chances of high-magnitude erosion by debris flow, whereas the opposite is true for low-aridity areas. They reason that fire-enhanced SWR and low macroporosity account for low post-fire infiltration capacity. That such a simple domain-specific metric alone can broadly indicate post-wildfire erosion quantities in this region is not only a novel finding but also indicates the possible high-order status of this or other domain-specific controls in other regions worldwide. Exploring the roles of these controls in explaining post-wildfire effects could represent a highly promising way of improving model calibration and prediction.

Temporal and spatial variability of precipitation

Rainfall ranks as the most important post-wildfire driver of runoff and erosion. How to satisfactorily measure and represent its critical temporal and spatial characteristics (intensity, duration, intermittency, spatial variability and profile) remains a challenge especially for whole landscapes affected by wildfire (e.g. Huff 1967; Dunkerley 2012, 2015). Sidman *et al.* (2016*a*) address the problem of accurate representation of spatiotemporal variation in post-wildfire rainfall in models. Poor temporal resolution in rainfall data inevitably leads to poor explanation of runoff and erosion measured in the field. Sidman *et al.* run the Kinematic Runoff and Erosion Model/Automated Geospatial Watershed Assessment (KINEROS2/AGWA) model with uniform rainfall characteristics and several temporally varying rainfall distributions more closely resembling actual rainfall data collected via radar. They conclude that the latter simulated data can provide far more accurate peak flow predictions than when spatially uniform rainfall is used. Importantly, however, even without accurate prediction of high-intensity rainfall, likely locations of high flood risk remain unchanged, so that managers can still obtain useful predictions of at-risk locations with only comparatively poor-quality rainfall data. The results of Sidman *et al.* confirm, therefore, what the post-wildfire research community has long realised but been largely unable to resolve – that the required data for characterising rainfall may not be available. Identifying the best spatiotemporal metrics and scale to represent rainfall remains a critical research priority (Moody *et al.* 2013). Sidman *et al.* demonstrate why this is so, but it is encouraging to learn that prediction based on more typically available data can still be useful to managers.

Infiltration

One key issue addressed at the conference was identification of easily transferable metrics that best quantify post-wildfire soil hydraulic properties modified by soil structural changes, removal of litter and duff layers, alteration of soil texture, and changed water-repellency characteristics. At present, the effects of burn severity on runoff are frequently described by qualitative terminology (high, medium and low burn severity) (Parsons *et al.* 2010) and by measurements of SWR that are not readily transformed into quantitative metrics for predicting fire-induced changes of soil hydraulic properties, which are essential inputs to soil infiltration models. Moody *et al.* (2016) address this problem by determining quantitative empirical relations between soil hydraulic properties (field saturated hydraulic conductivity and sorptivity) and a quantitative metric of burn severity (remotely sensed change in normalised burn ratio) in controlled laboratory experiments using small tension infiltrometers and a large set of replicate soil cores collected from a wildfire-affected area with different burn severities. The experiments were conducted in part during the conference by participants. Although site-specific, these empirical relations presented in the paper by Moody *et al.* (2016) provide the first quantitative links between burn severity and soil hydraulic properties that can be used in existing infiltration models to improve the prediction of post-wildfire runoff and erosion. Additional measurements from other sites worldwide (using the outcomes of this research as a guide) would create a useful database from which generalities and further insights could be extracted. A second key issue addressed concerned the role of ash. Despite doubts (Gabet and Sternberg 2008) and a lack of experimental data, reduced infiltration and increased overland flow due to clogging of pores by ash has been a generally accepted effect (e.g. Larsen *et al.* 2009). Stoof *et al.* (2016) use laboratory experiments to explore whether this process does occur, but find that, at least for the sand used in their experiments, the presence of ash in the pores would be unlikely to promote enhanced overland flow. They discuss other mechanisms by which ash can affect post-fire hydrology, and present results demonstrating the important hydrological effect of ash on saturated hydraulic conductivity.

Runoff processes and connectivity across different spatial scales

Key issues considered for this topic were: (1) the operation of runoff processes at different scales; and (2) connectivity between overland flow generation and channel flow. Although wildfires are known mostly to cause enhanced runoff at all scales, the ability to predict responses even at small scales, as used in most research (Shakesby and Doerr 2006), has not been without difficulties. At large scales, few results have been published on post-wildfire runoff response. Furthermore, very few studies have involved more than one scale, so that, for example, how runoff-generating patches link to streamflow in burned basins remains largely unexplored. Williams *et al.* (2016) focus on the need to consider runoff and erosion at different scales within a hillslope in order to understand their structural (relating to surface conditions) and functional (relating to processes) connectivity. They apply a novel approach in which rainfall simulation of fine- (0.5-m^2) and coarser-scale (13-m^2) effects of post-wildfire vegetation and surface conditions on rainsplash and overland flow processes are determined, and they combine this measurement approach with hillslope-scale modelling to estimate runoff and erosion. This combination of manageable direct measurement for small scales and modelling at the far more difficult larger scale offers a promising solution to the problem of assessing across-scale connectivity of runoff and erosion processes provided the model is sufficiently robust.

Variation in erosion responses between post-wildfire domains

Differences in the nature of erosion responses between post-wildfire domains, as defined under topic 1 (*Identification and classification of post-wildfire domains*), were discussed at the conference. Although wildfire typically leads to enhanced erosion through exposing areas of bare soil (often protected only by charred remains of vegetation and ash), the nature and magnitude of the erosion response can vary considerably from one domain to another as a result of domain-specific controls. Research into post-wildfire erosion in different domains continues to reveal unusual erosion responses, many of which can only be satisfactorily explained when domain-specific factors are included. An illustration is provided in this special issue by Jordan (2016) who focusses on post-wildfire debris flows in the southern interior of British Columbia, Canada. Factors controlling debris flow formation are poorly understood, particularly outside of western USA (Nyman *et al.* 2015). Unlike in most domains considered in the literature, post-wildfire processes (and specifically debris flows) in British Columbia are greatly affected by large accumulations of winter snow. Debris flows are found to have little preference for season as they occur in spring, summer and fall. Their occurrence in the latter two seasons is explained respectively by high-intensity and low-intensity rainstorms, but their occurrence in spring is associated with snowmelt-induced elevated groundwater levels. Jordan's paper, therefore, demonstrates the importance of understanding the influence of domain-specific factors, in this case snowmelt, in providing improved post-wildfire hazard prediction.

Predictive post-wildfire runoff and erosion modelling

Several predictive models incorporating elements of the above five topics were presented at the conference. The two papers concerned with models selected for this special issue adopt different modelling approaches to predicting the impacts of wildfire on hillslope hydrogeomorphic processes for different mitigation scenarios. Robichaud *et al.* (2016) validate hillslope sediment yield predictions made by a probabilistic erosion model (the Erosion Risk Management Tool – ERMiT) with field data collected from eight paired watersheds in the intermountain west of the USA. This model predicts erosion for individual rainfall or snowmelt events rather than long-term averages. For decision-makers, the likelihood of erosion and variability in magnitude predicted in this type of model are more important than annual erosion estimates, such as would be predicted with a deterministic model. The authors compare observed and predicted sediment yields from control plots and from plots with different mitigation treatments for severely burned hillslopes. Sidman *et al.* (2016*b*) apply a two-stage modelling approach to predict the hydrogeomorphic impacts of fuel treatments (mechanical thinning and prescribed fire) in two national parks in Utah, USA. Their first stage involves assessing fuel treatment effectiveness by modelling wildfires on treated and untreated terrain. In the second stage, fire severity information from the first stage and other relevant field data, including soil and vegetation parameters, together with digital elevation models, are entered into the KINEROS2/AGWA model to determine runoff and erosion for typical high-intensity-rainfall events. Model outputs are obtained for combinations of untreated and treated, and burned and unburned scenarios. Comparison with actual wildfire effects shows that their approach provides realistic fire severity and erosion predictions. Importantly, however, the authors caution that for their two study locations, fuel treatment policy is driven primarily by the desire to reduce fire activity and improve forest health: mitigation of post-wildfire runoff and erosion has a much lower priority. Both these papers join an increasing body of literature (e.g. Miller *et al.* 2011; Rulli *et al.* 2013; Moussoulis *et al.* 2015; Notario del Pino and Ruiz-Gallardo 2015) demonstrating the value of adopting a modelling approach in post-wildfire erosion and hydrology research.

Future research priorities

The spatial scales at which critical post-wildfire processes are investigated or modelled in these eight papers are small relative to those associated with other agents of disturbance such as hurricanes and earthquakes. The impacts of these post-wildfire processes can, however, be disproportionately large relative to the sizes of burned areas affected and have far-reaching consequences for infrastructure and property, water quality downstream (e.g. Johansen *et al.* 2003) and possible effects on precipitation (Chen *et al.* 2001; Tryhorn *et al.* 2008). The spatial patterns of burn severity and fire-affected soil hydraulic properties are intricate and closely associated with the distribution pattern of prefire vegetation. Superimposed on these patterns are topographic variations at different spatial scales together with stochastic rainfall variations at different spatiotemporal scales. Thus, a key challenge for predicting wildfire erosion and runoff responses is linking the range and scale of controlling processes operating over different scales. Future improvements in post-wildfire prediction will require elegant solutions to the parameterisation of these multiscale processes based on field measurements that can be feasibly carried out given time, cost and safety constraints. In addition to conventional field techniques, use of tracers might provide invaluable insight into sediment sources and connectivity of processes operating over whole hillslopes and drainage basins (e.g. Owens *et al.* 2012). Modellers should try to: (1) incorporate the variability found from field measurements and from remote sensing data; (2) make their models applicable to locations outside the area where calibration has been carried out (Chen *et al.* 2013); and (3) continue to improve prediction of erosion and runoff responses following wildfires to inform post-fire assessment teams, and emergency and land managers. Furthermore, modellers may want to consider using predicted modifications of fire regimes and rainfall characteristics caused by human intervention and climate change to model longer-term hydrogeomorphic responses (Jones *et al.* 2014).

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