The Effect of Wildfire on Soil Properties, Infiltration, and Runoff: Considerations for Hydrologic Modeling

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Extended Abstract

The devastation caused by wildfires is well-known. The post-wildfire effects of flooding and debris flows can also present substantial risk to life, property, and infrastructure. Additionally, the threat of wildfires is expected to increase under changing climatic conditions and as the Wildland Urban Interfaces (WUIs) expand into fire-susceptible areas (Westerling et al. 2006). There is a need to better understand and predict the effect of wildfire on post-wildfire processes and hydrological model parameterization for both emergency and watershed management. Our objective, here, is to provide a brief synthesis of the current state of research and practice of post-wildfire hydrologic modeling.

Wildfires not only effect vegetation, they also directly affect soil properties resulting in changes to infiltration and runoff processes when precipitation occurs. For example, wildfire-induced changes to soil can include the presence of ash, increased water repellency (hydrophobicity), soil crusting, and changes to soil structure. Our analysis focuses on runoff generation processes for post-wildfire event-based hydrological modeling for recently burned areas, specifically on the effect of wildfire-altered soil properties on infiltration. Commonly cited wildfire-induced alterations to soil that affect infiltration include soil water repellency and changes to soil structure. Water repellency is frequently cited as an explanation for increased post-wildfire flood potential while the wildfire-induced changes to soil structure (aggregate deterioration and microaggregate formation) has also been noted (Neary et al. 2005; Parson et al. 2010).

A simple analytical equation used to describe infiltration was introduced by Philip (1957):

$$I = St^{1/2} + At \tag{1}$$

where I is cumulative infiltration (length) over time (t), S is sorptivity (length time$^{-1/2}$), and A (length time^{-1}) is the saturated hydraulic conductivity (K_s) if the surface is covered by a thin but unlimited water supply else the unsaturated hydraulic conductivity (K) of the transmission zone (Tindall et al., 1999). While not a frequently used operational model, the equation does highlight two important points: (a) the introduction of sorptivity, defined as “a measure of the capacity of the medium to absorb or desorb liquid by capillarity” (Philip 1957), and (b) the critical roles of sorptivity and hydraulic conductivity in infiltration.

Recently, Shillito et al. (2020) showed theoretically as well as experimentally how sorptivity, S, is related to water repellency, expressed in terms of γ^*, the effective contact angle of the water in soil:

$$S = \Delta\theta \left[\frac{r^* \sigma \cos\gamma^*}{2\mu}\right]^{1/2} \tag{2}$$

where $\Delta\theta$ is the change in soil moisture, r^* is the effective pore radius of the soil, σ is the surface tension for water and the soil, γ^* is the effective contact angle of the soil, and μ is dynamic viscosity. Surfaces which exhibit a contact angle close to 0^0 are defined as wettable; surfaces that form non-zero contact angles with a liquid are considered water repellent (Figure 1). The higher the value of the contact angle, the higher the degree of water repellency. Contact angle measurements require specialized laboratory equipment. Fortunately, the measurement of sorptivity is easy and quick with commonly available equipment to measure infiltration (e.g., Smith 1999) but also sufficient for most practical purposes, such as quantifying the change in soil water repellency after a fire. Further, sorptivity is a property consistent with commonly used operational infiltration models such as Green and Ampt (Berli and Shillito 2023). Interestingly, however, laboratory tests on water repellent sand indicated water repellency did not significantly affect the saturated hydraulic conductivity, K_s, of the sand (Figure 2).

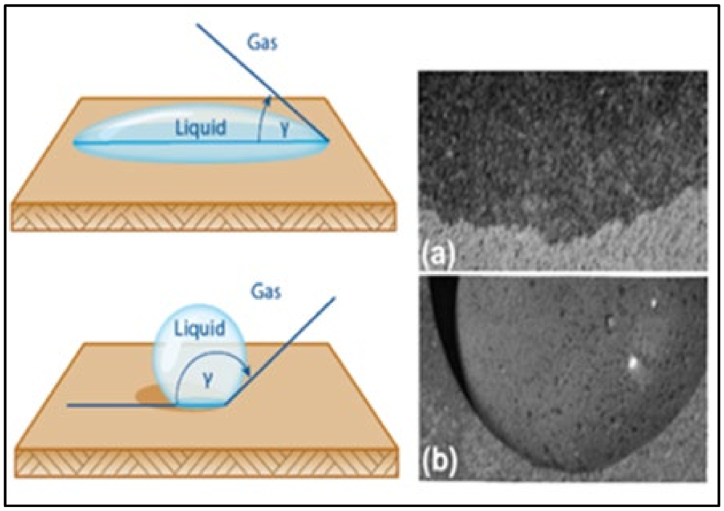


Figure 1. Illustration of the contact angle at a liquid-solid-gas-interface. Photo (a) shows water on a wettable silt soil; photo (b) shows water on a water repellent silt soil (Or et al., 2015; Bachmann et al., 2000).

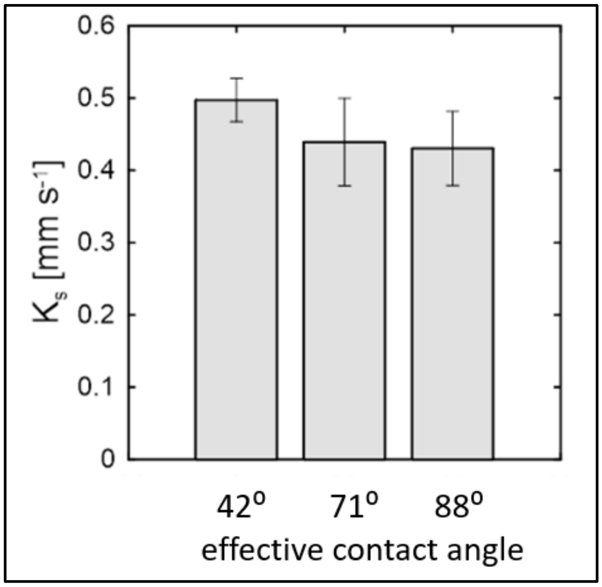


Figure 2. Averaged saturated hydraulic conductivity values for sand samples with increasing levels of water repellency (expressed as contact angles of 42°, 71°, and 88°). Error bars represent the standard deviation (n=5) (Shillito et al., 2020).

The hydraulic conductivity of soil is arguably the most frequently measured and analyzed wildfire-affected physical soil property. The intent of most infiltration measurements is to determine the post-wildfire soil saturated hydraulic conductivity (K_s). As the value of hydraulic conductivity varies over several orders of magnitude for the range of moisture contents soils naturally experience, the value of the hydraulic conductivity at the theoretically measurable point at which the soil is saturated is a critical hydrologic modeling parameter. The variability of post-wildfire hydraulic conductivity data is large and attributed to, for example, nature of the fire, soil characteristics themselves (e.g., texture and structure), the soil moisture status when measured, and measurement method (Moody et al. 2019). However, after fires, soils sometimes have appeared flour-like—the natural aggregates composing surface soil structure have been destroyed (Neary et al. 2005; Parsons et al. 2010).

Recently, a mechanism for the effect of wildfire on soil aggregation has been proposed as this feature may have a significant effect on saturated hydraulic conductivity. Analysis of laboratory measurements of field-collected soil aggregates subjected to known temperature intensities indicated aggregate bonds were weakened or destroyed due to vaporization of pore water (Figure 3) (Albalasmeh et al. 2013; Jian et al. 2018). The destruction of soil aggregates into individual soil particles means the loss of larger pore flow paths resulting in smaller and more tortuous flow paths in the soil—an effect like that of increased soil compaction. In laboratory experiments, Berli et al. (2008) showed changes to soil aggregation by compaction, where larger pores were destroyed, had a particularly strong effect on K_s but not on K associated with the drier soil conditions where smaller pores dominate flow. The influence of aggregation on K_s makes it the ideal parameter to quantify the impact of fire on soil aggregation. It is important to note that for many rain events especially those first events immediately following a wildfire, the soil does not become fully saturated, and infiltration occurs under partially saturated conditions.

Several studies (e.g., Ebel and Martin 2017) therefore proposed using "field-saturated" hydraulic conductivity (K_{fs}) for the calculation of post-wildfire infiltration. As the soil is not fully saturated, K_{fs} can be considerably smaller than K_s, and post-wildfire infiltration can be considerably overestimated when using K_s instead of K_{fs} for infiltration calculations. The conditions for standardizing K for post-wildfire applications are under development. Finally, it must be noted that wildfire can also foster the formation of microaggregates in clay-rich soils (Neary et al. 2005). Following the argument above, this condition would result in an increase in measured post-wildfire K_s.

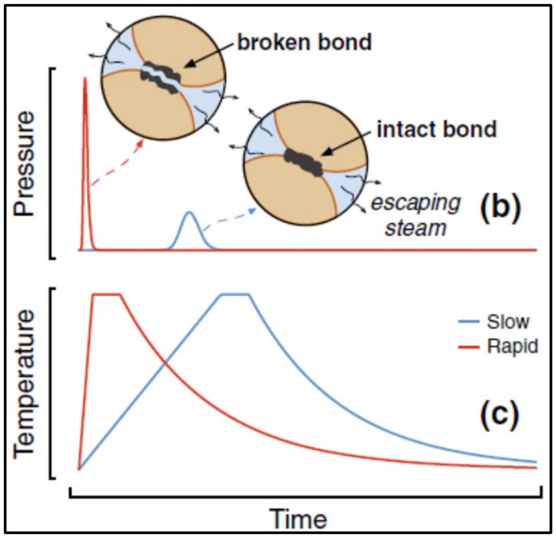
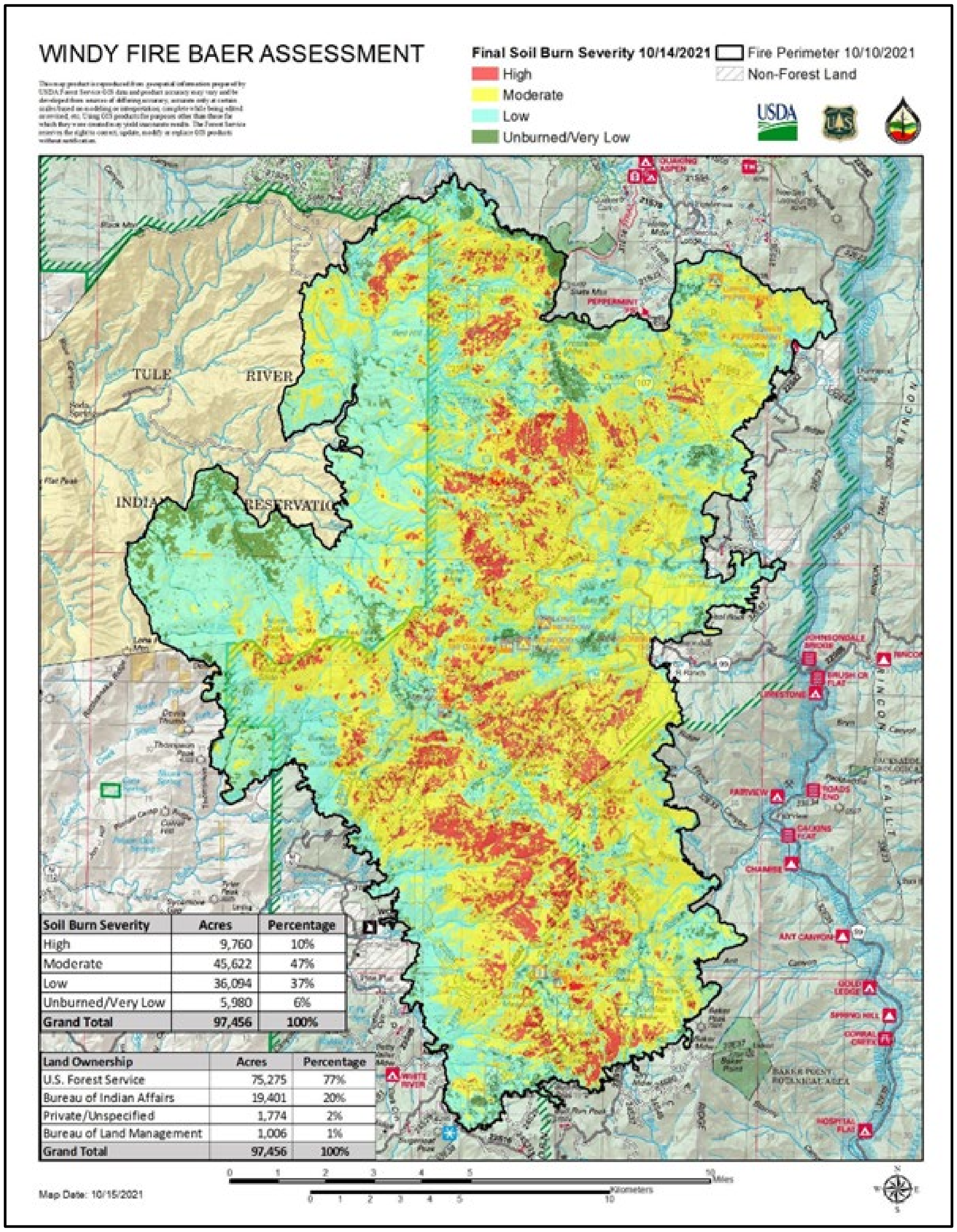


Figure 3. Illustration of the effect of wildfire (temperature intensity) on soil aggregate bonds as measured by changes in pressure in the aggregate (Albalasmeh et al., 2013).

Finally, post-wildfire hydrologic modeling requires the representation of the fire itself. This is supplied by a (Soil) Burn Severity map (Figure 4). The map is created by processing pre- and post-fire satellite infrared imagery, then classifying resultant values into burn severity classes. Burn severity is a qualitative assessment of site-specific effects of a downward-directed heat pulse, but does not explicitly include measurements of fire temperature, intensity, or duration (Parsons et al. 2010; MTBS 2022). The maps are georeferenced and supply information regarding the extent of wildfires, which rarely if ever coincide with hydrologic delineations. The maps also supply information regarding the spatial variability of severity (an assessment of the effect of a downward directed heat pulse on soil and vegetation), a feature necessary in assigning fire-altered hydrologic model parameters to watershed-scale hydrologic models. However, a mechanism explaining the dependence of fire-altered hydraulic conductivity on temperature was discussed above. Further, recent research into the formation of wildfire-induced soil water repellency has also indicated the association between sorptivity and temperature (Samburova et al. 2021). Therefore, the maps do not supply the temperature input needed to quantify fire effects on soil hydrologic properties directly. Current applications regarding fire-altered soil properties are based on mapped burn severity (high, moderate, or low) only, and can contribute to the uncertainty in modeled results.



Soil Burn Severity	Acres	Percentage
High	9,760	10%
Moderate	45,622	47%
Low	36,094	37%
Unburned/Very Low	5,980	6%
Grand Total	**97,456**	**100%**

Land Ownership	Acres	Percentage
U.S. Forest Service	75,275	77%
Bureau of Indian Affairs	19,401	20%
Private/Unspecified	1,774	2%
Bureau of Land Management	1,006	1%
Grand Total	**97,456**	**100%**

Figure 4. (Soil) Burn Severity map for the Windy Fire, CA (October 2021). A (Soil) Burn Severity map indicates the satellite image-based Burn Severity map classifications have been altered and/or verified based on input from trained field personnel, i.e., Burned Area Emergency Response (BAER) teams.

The main objective of our on-going research is to understand the mechanisms describing how fire affects soil and hydrologic parameters necessary for parameterization of post-fire hydrologic models. By understanding these effects, we can better understand what field conditions to look for, what data to measure, and how to use those data in characterizing infiltration. Water repellency, for example, alters soil sorptivity. Changes to soil structure—destruction of soil aggregates and loss of larger soil pores—are reflected in changes to the saturated hydrologic conductivity (K_s). Information regarding soil temperature can allow for the prediction of the degree and distribution of soil changes. This brief description of our ongoing research will ultimately be used to aid in the timely and effective post-wildfire modeling capabilities ranging from real-time emergency response to longer-term watershed management.

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