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Impacts of Wildfire Severity on Hydraulic Conductivity in Forest, Woodland, and Grassland Soils

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1. Introduction

Forest, woodland, and grassland watersheds throughout the world are major sources of high quality water for human use because of the nature of these soils to infiltrate, store, and transmit most precipitation instead of quickly routing it to surface runoff. This characteristic of these wildland soils is due to normally high infiltration rates, porosities, and hydraulic conductivities generated by biological and physical processes (Neary et al. 2009). Many of these ecosystems are subject to prescribed fires and wildfires that affect not only above-ground natural resources but also the soil and hydrologic systems (Ice et al. 2004).

Watershed condition is a term that describes the ability of a watershed system to receive, route, store, and transport precipitation without ecosystem degradation. When a watershed is in good condition, rainfall infiltrates into the soil, and baseflows are sustained between storms. Well-vegetated watersheds in good condition generally do not produce damaging peakflows (flash floods) and large amounts of erosion. However, in some regions of the world, these destructive streamflows are common irrespective of watershed condition. Severe fires, poor harvesting practices, over-grazing, conversion to agriculture and urban uses, and other disturbances alter watershed condition, reducing it to a moderate or poor level (Ffolliott et al. 2003). With poor watershed condition, rainfall infiltration and hydraulic conductivities are reduced significantly. Rainfall then runs over the surface of the soil, and there is little or no baseflow between storms. Erosion is considerable during high stormflows. This process is referred to as desertification and is, unfortunately, all too common in ecosystems currently being subjected to excessive wildfire (Neary 2006).

The surface conditions that determine watershed condition include: 1) the presence or absence of an organic litter layer (<5 mm to > 20 cm) and coarse woody debris, 2) herbaceous, shrub, and woody vegetation (variable cover), and 3) the geologic material (soil and rock). Disturbances like wildfire that destroy, remove, redistribute, or increase plant litter and vegetation, and change soil physical properties, alter the infiltration and percolation capacity of soil (DeBano et al. 2005). When watershed conditions deteriorate, the result is increased flood flows and erosion as watershed condition deteriorates.

Plant litter is a key factor in determining watershed condition (Neary 2002, DeBano and Neary 2005). In a *forest*, the organic "floor" consists of the Oi, Oe, and Oa horizons (also known as the L, F, and H layers; or the O1, O2, and O3 in other nomenclatures; Buol et al.

2003). The Oi layer consists of freshly fallen tree litter (leaves, branches). The Oe layer is made up of partially decomposed litter, and the Oa layer consists of well-decomposed organic matter. The term *woodland* refers to less dense vegetation units with lower vegetative structure that is sometimes referred to as *shrubland* or *scrubland* in the literature. In these ecosystems the distinct Oi, Oe, and Oa layers may occur only under continuous woody vegetation. In grassland ecosystems, easily identifiable layers may not be present and will be much thinner. Mesic grasslands have a complete herbaceous plant cover and well-developed organic soil horizons, but those in semi-arid climates may have only bare soil between plants. Organic material on the soil surface moderates the impact of rain drops, allowing water to infiltrate rather than running off over the surface. Loss of organic material by severe burning, harvesting, respiration, oxidation, site preparation, or other disturbances could result in adverse changes in hydrologic conditions in some instances.

Wildfires affect many water cycle processes. The specific hydrologic processes effects are summarized in Table 1. Changes in baseflow and stormflow definitely affect the quantity of water delivered from forested catchments, and can ultimately alter water quality. The occurrence and magnitude of these effects is a function of the general climate, precipitation, aspect, latitude, severity of fire, and the percentage of a watershed affected. The first three hydrologic processes affected by wildfire (interception, litter storage, and transpiration) listed in Table 1 are due to combustion of tree and herbaceous plant cover. Litter storage is the main process that is linked directly to hydraulic conductivity and infiltration. Loss of the litter layer during combustion is a highly significant process in producing direct effects on infiltration and the resulting watershed responses of streamflow, baseflow, and stormflow (DeBano et al. 1998 Moody et al. 2008). The heat flux during wildfire affects soil structure and porosity and produces water repellency that degrades hydraulic conductivity.

This paper examines the range of hydraulic conductivities measured in forest, woodland, and grassland soils produced by different levels of fire severity. It then discusses reductions in saturated hydraulic conductivities (K_{sat}) produced by degrees of severity-linked water repellency and O horizon destruction.

2. Forest, woodland, and grassland soils

Forests, woodlands, and grassland ecosystems usually develop deep and extensive root networks (Neary et al. 2009). Deposits of leaf, needle, limb, and herbaceous plant litter on the soil surface result in a surface soil horizon with relatively high levels of organic matter. The resulting soil environment produces a diverse micro- and macro-fauna as evidenced by the many invertebrates, insects, and small vertebrates found in these soils. Root growth and decay, cracking due to freeze/thaw and wetting-drying processes, animal burrowing, windthrow of weak trees, subsurface erosion, and other natural processes all increase soil porosity (ratio of void space to total soil volume), the number and size of macropores (>0.06 mm in diameter), and the hydraulic conductivity of the soil. Leaf and herbaceous plant litter on the soil surface dissipates raindrop energy and facilitates rainfall infiltration into the soil. The relatively high organic matter content of wildland soils increases the stability of soil aggregates, thereby preventing soil crusting by reducing detachment of small soil particles. This helps maintain high surface infiltration and hydraulic conductivity rates. For these reasons, most rainfall reaching the organic matter surface horizon infiltrates, and classical Hortonian overland flow occurs only during very intense rainfall events. Surface runoff occurs mainly as variable source area runoff (Hewlett and Troendle 1975) from rock outctrops, shallow soils, or low lying areas such as floodplains, wetlands, and ephemeral stream channnels where the surface water table rises to the soil surface during rainfall. These areas comprise only 5–15% of most wildland landscapes. Most of the infiltrated water either is used for plant transpiration needs or reaches streams by subsurface pathways (Jackson, 2006).

Forest, woodland, and grassland watersheds throughout the world are used as sources of municipal water supplies because of the stability of water yield and quality of the water (Neary 2002). High infiltration rates due to high hydraulic conductivities support baseflow hydrologic regimes that provide adequate supplies for human use.

Hydrologic Process	Type of Change	Specific Effect
1. Interception	Canopy consumed by fire	Moisture storage smaller
		Greater runoff in small storms
		Increased short-term water yield
2. Litter Storage	Litter Consumed	Less water stored (0.5 mm cm^{-1} of litter)
		Mineral soil exposed to raindrop impact
	Litter Scorched	No change
3. Transpiration	Temporary Elimination	Baseflow increased
		Soil moisture increased
4. Infiltration	Reduced	Hydraulic conductivity decreased
		Overland flow increased
5. Streamflow	Changed	Increased in most ecosystems
		Decreased in snow systems
		Decreased in fog-drip systems
6. Baseflow	Changed	Decreased with less infiltration
		Increased with less transpiration
		Summer low flow changes (+ and -)
7. Stormflow	Increased	Volumes greater
		Peakflows larger
		Time of concentration to peakflow shorter
8. Snow accumulation	Changed	Fires <4 ha, increased snowpack
		Fires > 4 ha, decreased snowpack
		Snowmelt rate increased
		Evaporation/sublimation increased

Table 1. A summary of the changes in hydrologic processes after wildfires (Adapted from Neary 2002).

3. Fire effects on ecosystems

3.1 Fire regime

The general character of fire that occurs within a particular vegetation type or ecosystem across long succession time frames, typically centuries, is commonly defined as the characteristic fire regime (Neary et al. 2005). The fire regime describes the typical or modal fire severity that occurs. But it is recognized that, on occasion, fires of greater or lesser severity also occur within a vegetation type. For example, a stand-replacing crown fire is common in long fire-return-interval forests (Figure 1).

The fire regime concept is useful for comparing the relative role of fire between ecosystems and for describing the degree of departure from historical conditions (Hardy et al. 2001, Schmidt et al. 2002). Brown (2000) contains a discussion of the development of fire regime classifications based on fire characteristics and effects, combinations of factors including fire frequency, periodicity, intensity, severity, season, size, pattern, and depth of burn. There are four commonly used fire regime classifications that are aggregated into fire regime groups depending on frequency of fire occurrence (0 to 35 years, 35 to 100+ years, and greater than 200 years) (Neary et al. 2005). *Understory fire regimes* are characterized by fires that are generally nonlethal to the dominant vegetation. They do not substantially change the structure of the dominant vegetation, and have minimal soil hydraulic conductivity effects. *Stand replacement fire regimes* frequently have fires that are lethal to most of the dominant aboveground vegetation. Approximately 80% or more of the vegetation is either consumed or dies as a result of fire, substantially changing the aboveground vegetative structure. Soil properties that influence hydraulic conductivity are frequently affected by this regime. In *mixed fire regimes* the severity of fires varies between nonlethal understory and lethal stand replacement fires with the variation occurring in space or time. Spatial variability occurs within the same fire when fire severity varies, producing a spectrum from fire effects characteristic of understory fire regimes to those of a stand replacement regimes. Hydraulic conductivity is affected in a spatial pattern that reflects the severity. The last fire regime is the *non-fire regime* which occurs in vegetation types that are not prone to fire such as temperate or tropical rain forests. However, hydraulic conductivity can be affected when large accumulations of woody debris burn during periodic droughts.

Fig. 1. High severity, stand replacing wildfire, Apache Sitgreaves National Forest, Arizona. (Photo courtesy of the U.S. Forest Service).

At finer spatial and temporal scales, the effects of a specific fire can be described at the stand and community level (Wells et al. 1979, DeBano et al. 1998, Ryan 2002, Neary et al. 2005). However, the fire regime concept does not work well for describing the soil impacts that alter hydrologic properties such as hydraulic conductivity. The commonly accepted term for describing the ecological effects of a specific fire is *fire severity*. Fire severity describes the magnitude of the disturbance and, therefore, reflects the degree of change in ecosystem components. Thus severity integrates both the heat pulse above ground and the heat pulse transferred downward into the soil. It reflects the amount of energy (heat) that is released by a fire that ultimately affects resources and their functions. Fire severity can be used to describe the effects of fire on the soil and water system, ecosystem flora and fauna, the atmosphere, and society (Simard 1991). It reflects the amount of energy (heat) that is released by a fire that ultimately affects soil hydraulic conductivity.

3.2 Fire intensity and severity

Although the literature historically contains confusion between the terms *fire intensity* and *fire severity*, a fairly consistent distinction between the two terms has been emerging in recent years. Fire managers trained in the United States and Canada in fire behavior prediction systems use the term fire intensity in a strict thermodynamic sense to describe the rate of energy released (Deeming et al. 1977, Stocks, 1991). Fire intensity is concerned mainly with the rate of aboveground fuel consumption and, therefore the energy release rate (Albini 1976, Alexander 1982). The faster a given quantity of fuel burns, the greater the intensity and the shorter the duration (Rothermel and Deeming 1980). Because the rate at which energy can be transmitted through the soil is limited by the soil's thermal properties, the duration of burning is critically important to the effects on soils (Frandsen and Ryan 1986, Campbell et al. 1995). Fire intensity is not necessarily related to the total amount of energy produced during the burning process. Most energy released by flaming combustion of aboveground fuels is not transmitted downward (Packham and Pompe 1971). Only about 5% of the heat released by a surface fire is transmitted into the ground. Therefore, fire intensity is not necessarily a good measure of the amount of energy transmitted downward into the soil, or the associated changes that occur in physical, chemical, and biological properties of the soil. Because one can rarely measure the actual energy release of a fire, the term fire intensity has limited practical application when evaluating ecosystem and soil responses to fire. Fire severity is the preferred measure of the magnitude of negative fire impacts on natural ecosystems and their components (DeBano et al. 1998).

3.3 Fire severity classification

Ryan and Noste (1985) and Ryan (2002) combined fire intensity classes with depth of burn classes to develop a two-dimensional matrix approach to defining fire severity. Their system was based on two components of fire severity: (1) an aboveground heat pulse due to radiation and convection associated with flaming combustion, and (2) a belowground heat pulse. In the literature there is common usage of a one dimension rating of fire severity (Wells et al. 1979, Agee 1993, DeBano et al. 1998, and many others). The single-dimension rating describes the overall severity of the fire and usually focuses primarily on the effects on the soil resource. At the spatial scale of a soil mapping unit, a tree stand, or a plant community, fire severity needs to be based on a sample of the distribution of fire severity classes. All fires produce a matrix of fire severities that cover the range of severity from low to high. The commonly accepted classes, definitions, and visual indicators of fire severity were noted in DeBano et al. (1998) and Neary et al. (2005). The classes are described as:

- Low severity: This class is typically indicated by scorching of smaller trees and seedlings, partial or complete combustion of herbaceous plants, <50% of plant brush canopy consumed, and >50% of trees showing no fire damage. Litter (Oi horizon) is charred or consumed with a 10-15% reduction. The Oe horizon (duff layer) is mostly intact and woody debris just charred. Mineral soil properties are usually unchanged and ash is mostly black. <2% of the area is severely burned, <15% is moderately burned, and the remainder of the area is burned at a low severity or unburned.
- Moderate severity: At this level of severity brush canopies are 60-80% charred or burned and 20-50% of tree canopies exhibit no visible scorch. There is extensive scorching of sapling and small tree crowns. The Oi horizon (litter) is consumed with a 50% reduction of cover and mass. The Oe horizon (duff) is deeply charred or consumed. Woody debris is extensively charred and the mineral soil is mostly unaffected. The signature ash color is gray. <10% of the area is severely burned, but >15% is burned moderately, and the remainder is burned at low severity or unburned.
- High severity: At this level of severity, <90% of brush canopies are charred or burned. Fewer than 20% of tree canopies exhibit no visible scorch, and all saplings and small trees are consumed. The entire organic horizons (Oi, Oe, and Oa) are consumed and woody debris is reduced to ash and charcoal. The mineral soil is often visible and exhibits a reddish or orange color. White ash is commonly found as the signature color. >10 percent of the area has spots that are burned at high severity, >80 percent moderately or severely burned, and the remainder is burned at a low severity.

Fire severity classifications were once done by on-the-ground visual surveys using these general definitions. They are currently being done by remote sensing from aircraft or satellites (van Leeuwen et al. 2010) using a BARC (Burned Area Reflectance Classification) system (Robichaud et al. 2007).

4. Fire severity effects on soils

4.1 General effects

Fire and associated soil heating can destroy soil structure, affecting both total porosity and pore size distribution in the surface horizons of a soil (DeBano et al. 1998). These changes in organic matter decrease both total porosity and pore size, and ultimately infiltration and hydraulic conductivity. Loss of macropores in the surface soil reduces infiltration rates and produces overland flow. Alteration of organic matter can also lead to a water repellent soil condition that further decreases infiltration rates and greatly decreases hydraulic conductivity. The scenario occurring during the destruction of soil structure by fire is:

- The soil structure collapses and increases the density of the soil because the organic matter that served as a binding agent has been destroyed.
- The collapse in soil structure reduces soil porosity (mainly macropores) and hydraulic conductivity.
- The soil surface is further compacted by raindrops when surface soil particles and ash are displaced, and surface soil pores become partially or totally sealed.
- Finally, the impenetrable soil surface reduces infiltration rates into the soil and produces rapid runoff and hillslope erosion. Loss of surface soil horizons leads to

further declines in soil and catchment hydraulic conductivities, and ultimately degradation of water resources.

The energy generated during the ignition and combustion of fuels provides the driving force that is responsible for the changes that occur in the physical, chemical, and biological properties of soils during a fire (DeBano et al. 1998). Mechanisms responsible for heat transfer in soils include radiation, conduction, convection, mass transport, and vaporization and condensation. The heat that is generated by the combustion of surface and above-ground fuels is transferred to the mineral soil surface where it is transferred down into the underlying soil by a series of complex pathways. Quantifying these different pathways for heat flow requires the mathematical modeling of fire behavior, duff ignition and combustion, and the transfer of heat downward to and through moist and dry mineral soil (Dimitrakopoulos and others 1994).

The heat radiated downward during the combustion of aboveground fuels is transferred either to the surface of the forest floor, or directly to the surface of mineral soil if organic surface layers are absent. In most forest ecosystems, heat is usually transferred to an organic layer of litter and duff. When duff is ignited it can produce additional heat that is subsequently transferred to the underlying mineral soil. The depth that heat penetrates a moist soil depends on the water content of the soil, and on the magnitude and duration of the surface heating during the combustion of aboveground fuels, litter, and duff (Frandsen 1987). During long-duration heating, such as that occurring under a smoldering duff fire or when burning slash piles, substantial heating can occur 40 to 50 cm downward in the soil. (Figure 2). This prolonged heating produces temperatures that are lethal to soil organisms and plant roots, and create water repellency that greatly diminishes hydraulic conductivity.

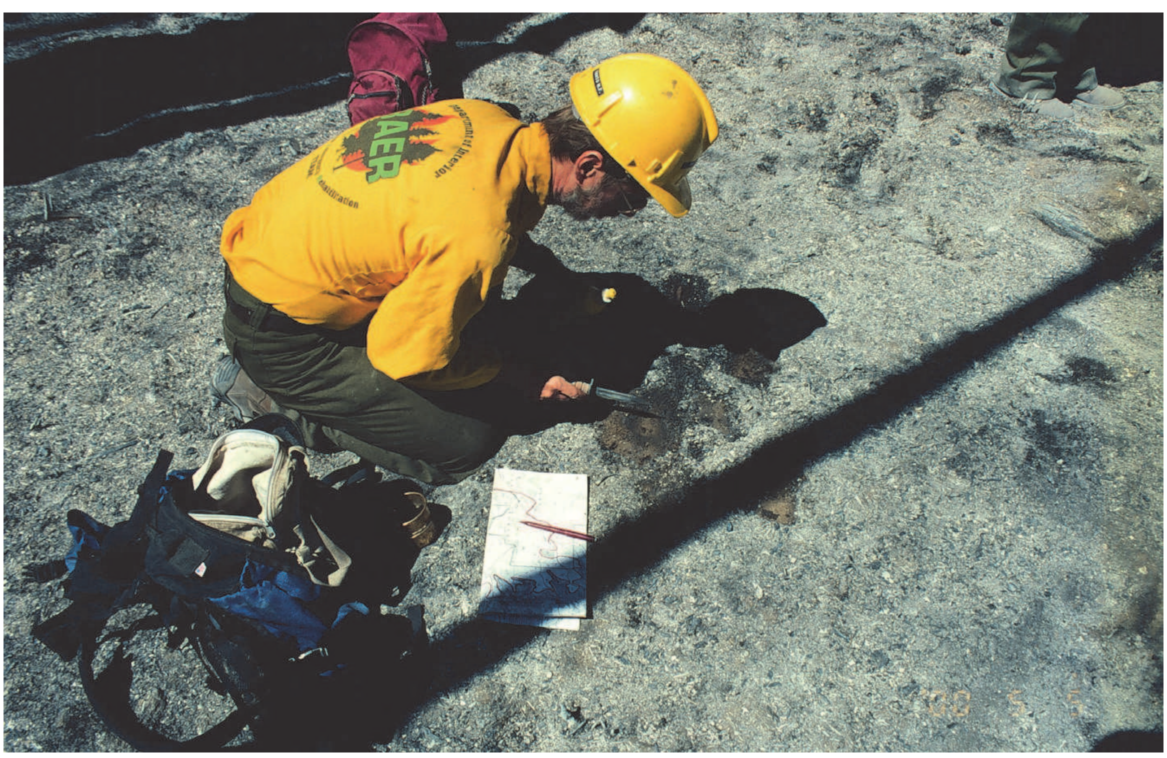

Fig. 2. White and gray ash typical of high severity fire remaining after a spruce-fir stand that was burned at high temperatures for a long duration, Coon Creek Fire of 2000, Tonto National Forest, Arizona. (Photo by Daniel G. Neary).

4.2 Water repellency

The creation of water repellency in soils involves both physical and chemical processes. It is discussed within the context of physical properties because of its strong, influence on infiltration and heat transfer (both physical processes). Although hydrophobic soils were observed in the early 1900s (DeBano 2000a, 2000b), fire-induced water repellency was first identified on burned chaparral watersheds in southern California in the early 1960s. In southern California, both the production of fire-induced water repellency and the loss of protective vegetative cover play a major role in the post-fire runoff and erosion. Normally, dry soils have an affinity for adsorbing liquid and vapor water because there is strong attraction between the mineral soil particles and water. In water repellent soils, however, the water droplet "beads up" on the soil surface where it can remain for long periods and in some cases will evaporate before being absorbed by the soil. Water, however, will not penetrate some soils because the mineral particles are coated with hydrophobic substances that repel water.

Water repellency is produced by soil organic matter and can be found in both fire and non-fire environments (DeBano 2000a, 2000b). Water repellency can result from the following processes involving organic matter: 1) An irreversible drying of the organic matter, 2) The coating of mineral soil particles with leachates from organic materials, 3) The coating of soil particles with hydrophobic microbial byproducts (for example, fungal mycelium), 4) The intermixing of dry mineral soil particles and dry organic matter, and 5) The vaporization of organic matter and condensation of hydrophobic substances on mineral soil particles during fire.

The magnitude of fire-induced water repellency and the reduction in hydraulic conductivity depend upon several parameters, including: 1) The severity of the fire, 2) Type and amount of organic matter present, 3) Temperature gradients in the upper mineral soil, 4) Texture of the soil, and 5) The water content of the soil. The more severe the fire, the deeper the layer, unless the fire is so hot it destroys the surface organic matter. Most vegetation and fungal mycelium contain hydrophobic compounds that induce water repellency. Steep temperature gradients in dry soil enhance the downward movement of volatilized hydrophobic substances that produce water. Early studies in chaparral showed that sandy and coarse-textured soils were the most susceptible to fire-induced water repellency (DeBano 1981). However, more recent studies indicate that water repellency frequently occurs in soils other than coarse-textured ones and that high water repellency may exist prior to wildfires occurring (DeBano 2000a, 2000b; Doerr et al. 2000). Soil water affects the translocation of hydrophobic substances during a fire because it affects heat transfer and the development of steep temperature gradients.

5. Forest, woodland, and grassland soil hydraulic conductivity

5.1 Examples of hydraulic conductivity rates

Table 2 shows the range in K_{sat} for a variety of forest ecosystems across the world. The K_{sat} rates for most undisturbed forests range from 143 to 4990 mm hr^{-1}. The rates for associated pastures that are up to 70 times lower are included for reference purposes. The highest K_{sat} rates in Table 2 are associated with thick Oe or Oa horizons (Lal 1996, Godsey and Elsenbeer 2002, Sauer and Logsdon 2002, Giertz and Diekkrüger 2003, and Sheridan et al. 2007).

5.2 Role of organic horizons in soil hydraulic conductivity

Plant litter is a key factor in determining watershed condition because the relatively deep organic layers have extremely high infiltration rates that exceed all but the most intense rainfall rates (Neary 2002, DeBano and Neary 2005). Organic horizons can range from a few centimeters deep to over 60 cm. Mollisols of grasslands have deep organic rich horizons that function in much the same manner as the O horizons of forest and woodland soils. However their K_{sat} levels are generally lower. Fiedler al. (2002) documented a K_{sat} of 83 mm hr^{-1} in a lightly grazed northern Colorado grassland compared to 8 mm hr^{-1} on a heavily grazed and mostly bare soil. On a mixed species grassland in southern Alberta, Canada, Dormaar et al. (1989) measured a K_{sat} of 45 mm hr^{-1} compared to 33 mm hr^{-1} on a grassland that was used for only short duration grazing. Li and Shao (2006) reported similar K_{sat} levels for climax oak forests and *Acer – Carex* shrubland on the central loess plateau of China (33-34 mm hr^{-1}). Grassland soils were lower at about 14 mm hr^{-1}, but double levels in agricultural fields.

Deep organic horizons found in forests have a profound effect on site hydrology because of their high hydraulic conductivities. The higher K_{sat} rates in Table 2 (e.g. Lal 1996 - 4,990 mm hr^{-1}; Sheridan et al. 2007 - 1,000 mm hr^{-1}; Sauer and Logsdon 2002 – 444 mm hr^{-1}) reflect the presence of these organic horizons. For the most part, these K_{sat} rates are well in excess of peak rainfall intensities. Shallow soils with bedrock, clay-textured horizons, or saturated conditions are the most limiting factors for infiltration and hydraulic conductivity in forest soils. Grace et al. (2006) provided a good example in their study of an organic soil in a hardwood forest of the Tidewater Region of eastern North Carolina. The surface horizon (Oa) of a loam-textured, thermic Terric Medisaprist soil varied between 0 and 60 cm deep. The K_{sat} was measured at 3540 mm hr^{-1}, well in excess of the most intense rainfalls for the humid climate of eastern North Carolina. The A horizon below the organic Oa ranged in depth from 60 to 107 cm, but the K_{sat} drops to 140 mm hr^{-1}. In the B horizon below the A horizon, K_{sat} fell to 40 mm hr^{-1}. The C horizon at 2.1 to 2.5 m below the surface is still above sea level (4.5 m below the soil surface) but it showed diagnostic characteristics of being poorly drained and it often had a shallow water table. The K_{sat} of the C horizon fell to 10 mm hr^{-1}. The impact of a potential wildfire fire on the site described by Grace et al. (2006), especially a high severity fire that consumes the surface organic horizon, is the reduction in the K_{sat} from 3540 to 140 mm hr^{-1}. Without factoring in water repellency or pore sealing by ash, the K_{sat} could be significantly reduced just by the removal of the Oa horizon. The importance of surface organic horizons in forest soils can also be demonstrated by data from Luce (1997). The K_{sat} of lightly disturbed forest soils in a harvested northern Idaho forest stand was reduced from 60 to 80 mm hr^{-1} to 1 mm hr^{-1} by road construction. Deep ripping of the road raised the K_{sat} to 22 to 35 mm hr^{-1}. Adding an artificial organic horizon of mulch raised the K_{sat} up to 80 to 85 mm hr^{-1}.

Woodlands tend to have the lowest hydraulic conductivities because they are less productive ecosystems and their soils are often lithic, shallow, poorly structured, less permeated by roots and soil organisms that develop macroporosity, and lower in organic matter content. The O horizons are thinner and they tend to be discontinuous. Thus the relationships of K_{sat} in these wildland soils is forests > grasslands > woodlands. The importance of surface organic horizons in determining the levels of K_{sat} in forest, woodland, and grassland soils can't be overstated.

Continent/Country		Reference	Hydraulic Conductivity K_{sat}
			mm hr^{-1}
Asia			
Nepal:	Undisturbed Forest	Gilmour et al. 1987	370
	Pasture Converted to Pine		183
	Pasture		39
China:	Forest	Chen et al. 2009	480
	Agriculture		360
	Bare Soil		6
Turkey:	Forest	Gol 2009	83
	Grassland		8
Africa			
Nigeria:	Forest	Lal 1996	4990
	Deforested area		460
Uganda:	Native Forest	Majaliwa et al. 2010	219
	Eucalypt Forest		149
Benin:	Forest	Giertz andDiekkrüger 2003	750
	Pasture		240
Australia			
New South Wales:	Undisturbed Forest	Moore et al. 1986	263
	Logged		19
Capital Territory:	Eucalypt Forest	Talsma and Hallam 1980	926
	Pasture To Pine		147
Western Australia:	Jarrah Forest Sand	Carbon et al. 1980	120
Victoria:	Eucalypt Forest	Sheridan et al. 2007	1000
Europe			
Czech Republic:	Forest Spodosols	Jacka et al. 2011	152
Finland:	Forest Spodosols	Mecke et al. 2000	5
Sweden:	Forest Spodosols	Lind and Lundin 1990	20
North America			
Canada:	Jack Pine	Cuenca et al. 1997	80
USA North Carolina:	Forest	Price et al. 2010	63
	Pasture		8
USA Arkansas:	Forest	Sauer and Logsdon 2002	444
	Pasture		113
South America			
Brazil:	Forest	Godsey and Elsenbeer 2002	250
	Pasture		15
Columbia:	Forest	Martinez and Zink 2004	143
	Pasture		2
Peru:	Forest	Allegre and Cassel 1996	420
	Pasture		41

Table 2. World-wide examples of K_{sat} measurements reported in the literature in surface horizons in forest soils and pastures.

6. Fire effects on hydraulic conductivity

6.1 Observed changes

Fire impacts on watershed hydrology have been reported for many years (DeBano et al. 1998, Neary et al. 2005, Moody et al. 2008). Wildfires exert a tremendous influence on the hydrologic conditions of watersheds in many forest ecosystems in the world depending on a fire's severity, duration, and frequency. Fire in these forested areas is an important natural disturbance mechanism that plays a role of variable significance depending on climate, fire frequency, and geomorphic conditions. This is particularly true in regions where frequent fires, steep terrain, vegetation, and post-fire seasonal precipitation interact to produce dramatic soil impacts (DeBano et al. 1998, Neary et al. 1999). A number of components of the hydrologic cycle can be impacted (Table 1), but K_{sat} reductions are often implicated as a major factor affecting baseflow and stormflow responses of burned watersheds. One clear signature of K_{sat} parameters is that they are highly variable (Doerr et al. 1998, Doerr et al. 2006).

A number of recent studies reporting changes in K_{sat} listed in Table 3 demonstrate clear reductions in conductivity after fires (Parks & Cundy 1989, Greene et al. 1990, Robichaud 2000, Ekinci 2006, Fox et al. 2007, Ekinci et al. 2008, Blake et al. 2009, Novák et al. 2009, and Nyman et al. 2011). Fire severity plays a key role in some of these reductions, but other investigators have demonstrated a surprising lack of correlation with severity (Rab 1996, Valzano et al. 1997, Sheridan et al. 2007, and Blake et al 2009). In the latter case, severity-related reductions in K_{sat} were measured in coniferous forests but not in oak woodlands. K_{sat} reductions of 20 to 48% are commonly reported (Table 3). Blake et al. (2009) also noted K_{sat} reductions of 88 to 92% with high severity wildfire.

An interesting trend emerging out of some of the recent Australian research on the impacts of wildfires on soil hydrologic properties including K_{sat} is that the soil surface K_{sat} values can be similar regardless of severity (Rab 1996 and Nyman et al. 2011) and that natural water repellency may produce K_{sat} values less than those measured in burned soils (Sheridan et al.2007). There also appears to be seasonal effects where natural summer water repellency breaks down and K_{sat} values return to the expected relationship of unburned soils > burned soils in the winter. It is obvious from these results that the fire severity – water repellency – hydraulic conductivity relations are more complex than once believed (DeBano 2000b, Doerr et al. 2000).

6.2 Mechanisms

A number of mechanisms have been discussed as the causative factors in post-wildfire hydrologic changes and K_{sat} reductions (DeBano et al. 1998, Neary et al. 2005, Doerr et al. 2000). The development of water repellency has received the most attention and is a test that is frequently carried out as part of wildfire Burned Area Emergency Response assessments (Keeley 2009, Neary 2009). Other mechanisms that have been suggested as major causes of K_{sat} reduction include pore clogging with fine ash and organic horizon destruction.

6.2.1 Hydraulic conductivity and water repellency

DeBano (1981, 2000a, 2000b) synthesized much of the knowledge about the effects of water repellency after wildfire and prescribed fire on forest, woodland, and grassland soils. Doerr et al (2000) discussed the biological sources of hydrophobic substances, physical factors affecting the formation and persistence of water repellency, temporal variations, and spatial

Location	Reference	Burned Condition Saturated Hydraulic Conductivity K_{sat} Unburned	Burned (Rx/Wf)	Soil Depth
		……………………mm hr⁻¹	………..……	cm
Australia				
	Greene et al. 1990			
	Eucalypt Woodland	92	74	0 - 10
	Nyman et al. 2011			
	Eucalypt Forest			
	Non Repellent Soil	40	30	0 - 05
	Repellent Soil	45	35	2 - 05
	Non Repellent Soil	120	240	>5
	Rab 1996			
	Eucalypts Mod. Sev.	32	34	0 - 10
	Eucalypts High Sev.	32	35	0 - 10
	Sheridan et al. 2007			
	Eucalypts Summer	490	855	0 - 05
	Eucalypts Winter	1409	459	0 - 05
	Valzano et al. 1997			
	Grassland	16	34	0 - 40
France				
	Fox et al. 2007			
	Pine Forest	210	155	0 – 06
Greece				
	Blake et al. 2009			
	Fir (Mod/High Sev.)	505	321/62	0 - 10
	Fir (Mod/High Sev.)	812	510/69	0 - 10
	Oak (Mod/High Sev.)	263	263/289	
Slovakia				
	Novák et al. 2009			
	Pine Forest	432	360	0 - 05
	Grassland	612	972	0 - 05
Turkey				
	Ekinci 2006			
	Oak/Pine Woodland	105	55	0 - 05
	Ekinci et al. 2008			
	Oak/Pine Woodland	48	33	0 - 05
USA				
	Parks & Cundy 1989			
	Douglas Fir& Pine	789	170	0 - 03
	Robichaud 2000			
	Douglas Fir & Pine			
	Low Severity	77 - 81	60 - 89	0 - 05
	High Severity	77 – 81	30 - 84	0 - 05

Table 3. Examples of soil K_{sat} changes after wildfires (Wf) and prescribed (Rx) fires.

variation of water repellent regions both laterally and vertically. As shown in Table 3, fire severity and any resulting water repellency can have a large effect on hydrologic processes including K_{sat} (Blake et al. 2009) or none at all (Rab 1996). The author has personally witnessed these effects during rain events (Ice et al. 2004). Water repellency usually breaks down within 1-3 years due to physical and biological processes (DeBano et al. 1998, Neary et al. 2005). While water repellency is certainly a major factor, other mechanisms can also be important.

6.2.2 Pore clogging

After wildfires, landscapes are blanketed by varying depths of ash until rainstorms remove the ash material in runoff (DeBano et al. 1998, Neary et al. 2005). While there is general concurrence that ash does contribute to post-wildfire hydrologic response, research studies have produced some conflicting results. In some cases ash has resulted in runoff increases but in others the ash increased infiltration (Cerda and Doerr 2008, Woods and Balfour 2008). More recent research by Woods and Balfour (2010) demonstrated that the degree of ash clogging of soil pores is soil texture related. A 1 cm layer of ash clogged pores and reduced infiltration by on a sandy loam soil but not a silt loam soil. The K_{sat} for the sandy loam soil was about 102 mm hr^{-1} pre-fire and dropped to about 30 mm hr^{-1} post-fire. The K_{sat} for the silt loam soil was 6 mm hr^{-1} pre-fire and increased to 8 mm hr^{-1} post-fire. Woods and Balfour (2010) concluded that thin, fine ash layers (1 cm) on a coarse soil with many macropores will clog the pores and increase the site post-fire hydrologic response. The same ash layer on a fine-textured soil with few macropores will have no effect on surface runoff. Thicker ash layers have the potential to delay surface runoff responses unless overwhelmed by intense rainfalls (e.g. 25 mm in 10 or 15 minutes).

6.2.3 O horizon destruction

Loss of the O horizon by combustion in high severity wildfires may play a larger role in post-fire hydrologic responses than previously thought possible. This phenomenon appears to be linked strongly to the loss of the O horizon and not necessarily any reduction in mineral soil K_{sat} values. High severity fires consume the entire O horizon and can decompose soil structure by combusting organic material involved in soil structure development. The example discussed previously of the study by Grace et al. (2006) in eastern North Carolina demonstrates the sharp drop in K_{sat} with the combustion of the surface organic layer (3540 to 140 mm hr^{-1}). A good deal of the large change in the hydrologic response after the Schultz Fire of 2010 in Arizona was most likely due to a similar loss of a 30-60 cm O horizon on steeply sloping soils, not necessarily any significant reduction in K_{sat} (Neary et al. 2011.). Intense rainfall (24 mm in 10 minutes) overwhelmed the infiltration capacity of the severely burned, silty gravel soils.

7. Conclusion

High severity fires produce the largest impacts on the hydrologic functioning of forest, woodland, and grassland soils. Fire severity can have a significant effect on K_{sat} by several mechanisms. These include development of water repellency, sealing of macropores, and combustion of surface organic horizons. High water repellency causes water droplets to sit on the surface of mineral soil, thereby reducing K_{sat} tolow values or even zero (DeBano et al. 1998; Neary et al. 2005) . Fine ash can effectively seal large pores at soil surfaces. The net effect is a reduction in K_{sat} by blocking macropores that are the cause of normally rapid infiltration in wildland soils. Although micropores can still infiltrate water, the rates are significantly reduced. Surface organic horizons have a high degree of porosity and can store, infiltrate, and conduct water at rates that exceed most peak rainfall intensities. Loss of the organic horizon in high severity wildfire is a major cause of K_{sat} reductions. In addition, high severity fires transmit large amounts of heat into the soil that often produce breakdowns in soil structure, leading to macropore size decreases and concomitant K_{sat} rate declines (DeBano et al. 1998).

Although there is a fairly clear correlation between high severity fire and K_{sat} reductions in the literature, some anomalies exist. Researchers in Australia have reported development of water repellency similar to wildfires in completely unburned watersheds. In addition, some moderate and high severity wildfires have not reduced K_{sat} to any significant extent. This could be due to soil physical properties, quality of the vegetation, or fire dynamics peculiar to the specific sites and soils studied or the characteristics of the wildfire. K_{sat} reductions of 20 to 48% are commonly reported after wildfires. Some studies have documented K_{sat} reductions of 88 to 92% with high severity wildfire. Reductions of this magnitude can have significant impacts on post-fire hydrological responses such as stormflows and peakflows.

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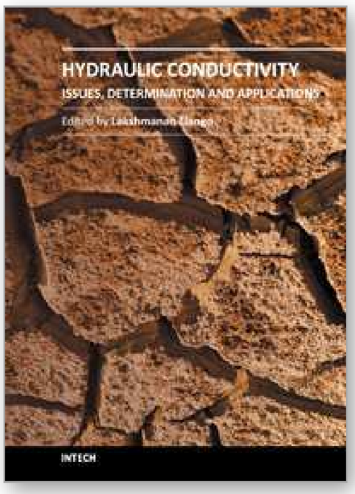

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