

Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA

P.R. Robichaud

USDA-Forest Service, Rocky Mountain Research Station, Forestry Science Laboratory, 1221 South Main Street, Moscow, ID 83843, USA

Received 3 October 1998; accepted 11 May 1999

Abstract

Infiltration rates in undisturbed forest environments are generally high. These high infiltration rates may be reduced when forest management activities such as timber harvesting and/or prescribed fires are used. Post-harvest residue burning is a common site preparation treatment used in the Northern Rocky Mountains, USA, to reduce forest fuels and to prepare sites for natural and artificial tree regeneration. Prescribed burn operations attempt to leave sites with the surface condition of a low-severity burn. However, some of the areas often experience surface conditions associated with a high-severity burn which may result in hydrophobic or water repellent conditions. In this study, infiltration rates were measured after logging slash was broadcast burned from two prescribed burns. The two sites were in Northern Rocky coniferous forests of Douglas-fir/lodgepole pine and ponderosa pine/Douglas-fir. Simulated rainfall was applied to one-square meter plots in three, 30-min applications at 94 mm h^{-1} within the three surface conditions found after the burn: unburned-undisturbed areas, low-severity burn areas and high-severity burn areas.

Runoff hydrographs from the rainfall simulations were relatively constant from the plots that were in unburned-undisturbed areas and in areas subjected to a low-severity burn. These constant runoff rates indicate constant hydraulic conductivity values for these surface conditions even though there was variation between plots. Hydrographs from the rainfall simulation plots located within areas of high-severity burn indicate greater runoff rates than the plots in low-severity burn areas especially during the initial stages of the first rainfall event. These runoff rates decreased to a constant rate for the last 10 min of the event. These results indicate hydrophobic or water repellent soil conditions, which temporarily cause a 10–40% reduction in hydraulic conductivity values when compared to a normal infiltrating soil condition. Since variability was high for these forest conditions, cumulative distribution algorithms of hydraulic conductivity provide a means to account for the inherent variability associated with these hillslopes and different surface conditions cause by fire. Published by Elsevier Science B.V.

Keywords: Water repellent; Rainfall simulation; Forest fire; Hydraulic conductivity

1. Introduction

Water infiltration is defined as the flow of water from the soil surface into the soil profile. The rate at which water is transmitted through soil is highly dependent upon the surface conditions. In forest

environments, various surface conditions can exist and it is important to characterize these conditions and their effect on infiltration.

Runoff from harvested and burned hillslopes varies from extensive to minor. The major determining factor is the amount of disturbance to the surface material which is usually organic debris (commonly referred to as duff or forest floor) that protects the underlying mineral soil. Disturbance may be from

E-mail address: probichaud@fs.fed.us
(P.R. Robichaud).

tree harvesting operations, road building, or fire. All of these activities may impact the protective duff layer. Adverse effects on the duff layer by burning depend upon the severity of fire (Robichaud et al., 1993; Robichaud and Waldrop, 1994; Robichaud, 1996). Post-fire condition of the surface horizons are important because they determine the amount of mineral soil exposed to raindrop splash, overland flow and the development of water repellent soil conditions (DeBano, 1981). Observations from previous studies (Robichaud et al., 1993) suggest there are four different surface/hydrologic conditions to monitor which affect infiltration. These conditions are: (1) areas subjected to high-severity burns (possibly hydrophobic); (2) areas subjected to low-severity burns; (3) areas with bare soil due to log dragging, log landings, skid trails, or roads; and (4) unburned-undisturbed areas.

Numerous observations of water repellent soil conditions have been reported throughout the western USA and the world. Water repellency caused by wildfires has received the most attention in southern California chaparral (DeBano et al., 1967; DeBano and Rice, 1973), although it has been reported after forest wildfires (Megahan and Molitor, 1975; Dyrness, 1976; Campbell, 1977) and on rangelands (Richardson and Hole, 1978; Soto et al., 1994).

In burned soils, severity of water repellency not only depends on soil texture, but is also related to fire intensity, antecedent soil-water content and fuel conditions (DeBano et al., 1976; Robichaud and Hungerford, 2000; Robichaud, 1996). Under field conditions, the water-repellent layer is usually not continuous, so irregular wetting patterns are common (Bond, 1964; Meeuwig, 1971; DeBano, 1981; Dekker and Ritsema, 1995, 1996). Water repellency induced by a low-to-moderate severity prescribed burn is usually of short duration. For example, in southwestern Oregon, soil wettability resulting from a late spring wildfire burn returned to near normal levels after the fall rains began (McNabb et al., 1989). After a late summer wildfire in the Oregon Cascade Mountains, Dyrness (1976) found that soil wettability in stands of lodgepole pine (*Pinus contorta*) experiencing burns of low-severity recovered more rapidly than soils experiencing burns of high-severity. By the sixth year after the

fire, wettability of the soils that experienced both low- and high-severity burns approached that of unburned soil.

The most apparent hydrologic effect of hydrophobic soil conditions is the reduction of infiltration which can induce erosion by overland flow (DeBano et al., 1967). Infiltration curves reflect increasing wettability over time once the soil is placed in contact with water. Infiltration increases with time because the hydrophobic substances responsible for water repellency are slightly water soluble and slowly dissolve, thereby increasing wettability (DeBano, 1981). Researchers have documented persistence of hydrophobic conditions from weeks to years (DeBano et al., 1967; Holzhey 1969). In general, hydrophobicity is broken up, or is sufficiently washed away, within one to two years after a fire.

The objective of this study was to determine infiltration characteristics of forest soils burned at different severities. These calculated hydraulic conductivity values provide important input parameters for use in current erosion prediction models that describe hydrologic responses for various surface conditions typically encountered in forest environments.

2. Methods

2.1. Field sites

The first site, Slate Point (7 ha), was located on the West Fork Ranger District of the Bitterroot National Forest in western Montana, USA. This location has a Douglas-fir (*Pseudotsuga menziesii*)/lodgepole pine (*Pinus contorta*) forest. The habitat type is Douglas-fir/twinflower (*Linnaea borealis*) (Pfister et al., 1977). Slopes within the study area range from 30 to 70% with a northern aspect. Elevation range from 1620 to 1780 m. The soils (83% sand, 12% silt, 5% clay with 33% gravel component) consist of a loamy skeletal mixed Typic Cryoboralf and a loamy skeletal mixed Dystric Cryochrept. Both were formed from weathered rhyolite.

The second site, Hermada (9 ha), was located on the Idaho City Ranger District of the Boise National Forest in central Idaho, USA. This location has a ponderosa pine (*Pinus ponderosa*)/Douglas-fir forest.

Table 1
Selected fire behavior parameters from the Slate Point and the Hermada prescribed fires

Measurement	Slate Point	Hermada
Litter temp. (°C)	633–837	429–915
Duff temp. (°C)	69–612	187–217
Mineral soil surface temp. (°C)	n.a. ^a	119–187
3 mm below mineral soil interface (°C)	38	n.a.
22 mm below mineral soil interface (°C)	30	37–112
Lower duff moisture content (%)	72 ^b	39 ^c
Upper duff moisture content (%)	42	71
Fine fuel moisture content (%)	9	18
Flame length (m)	2–6	1–3
Fireline intensity ^d (kW m ⁻¹)	1160–12,600	260–2800
Ambient temperature (°C)	23	12
Wind speed (km h ⁻¹)	8–11	0–8
Wind direction	N	SE
Relative humidity (%)	22	36

^a n.a. indicates data not available.

^b N = 20 at the Slate Point site.

^c N = 30 at the Hermada site.

^d Fireline intensity is calculated as: $258 \times \text{flame length}^{2.17}$.

The habitat type is Douglas-fir/ninebark (*Physocarpus malvaceus*) (Steele et al., 1981). Slopes within the study area range from 40 to 75% with northeasterly and southeasterly aspects. Elevations range from 1760

to 1880 m. The predominant soil (85% sand, 13%, 2% clay with 12% gravel component) is Typic Cryumbrept, loamy skeletal mixed derived from granitic parent material.

2.2. Field experiment

Duff and fuel characteristics were measured with a geostatistical sampling scheme prior to each burn (Robichaud, 1996; Robichaud and Miller, 2000). The geostatistical sampling scheme used about three-quarters of the sampling points on a grid basis and the remaining sampling points were located close to the grid sampling points to obtain shorter distances between sampling points. To estimate duff thickness and duff reduction by the fire, eight steel pins (200 mm in length) were installed flush with the duff layer (forest floor surface) located in the corners and midpoints of an imaginary 1-m square centered at each sampling point. There were 20 sampling points at the Slate Point site and 30 at the Hermada site. The duff consumed during the fire was determined from the differences between the two surveys (pre- and post-burn measurement).

After the spring burn at the Slate Point site, the area had a mosaic surface pattern indicating variable fire severity. Selected fire behavior parameters are provided in Table 1. This mosaic pattern gave a

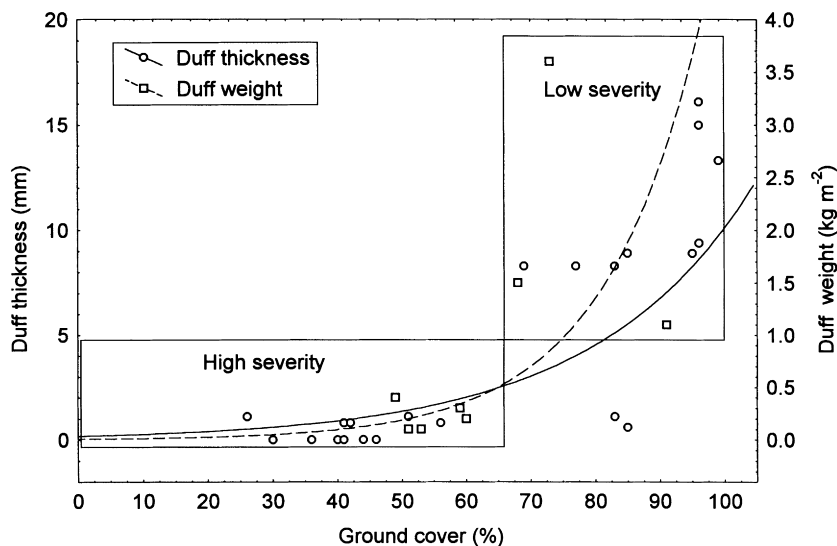


Fig. 1. Ground cover amounts and duff thickness used to classify areas as low- and high-severity burns (Robichaud, 1996).

Table 2

Surface conditions, areas, total runoff and hydraulic conductivity values for the Slate Point and Hermada sites

Surface condition	Total area (%)	No. of plots	Total runoff (mm)			Hydraulic conductivity (mm h ⁻¹)	
			Event 1	Event 2	Event 3	K_{for}^a	$K_{hydrobi}^b$
<i>Slate Point</i>							
Unburned-undisturbed	20	2	4	4	4	77–81	
Low severity burn	65	8	15	9	8	60–89	
High severity burn	15	4	12	14	11		
Non-hydrophobic		2				30–84	
Hydrophobic		4 ^c					23–55
<i>Hermada</i>							
Unburned-undisturbed	40	3	15	17	16	36–62	
Low severity burn	55	3	24	24	22	10–63	
High severity burn	5	5	26	22	20		
Non-hydrophobic		2				22–74	
Hydrophobic		3					15–40

^a Hydraulic conductivity values fitted from the rainfall simulation hydrographs during rain event 3.

^b Hydraulic conductivity for hydrophobic soil conditions fitted from the rainfall simulation hydrographs during the first 10 min of Event 1.

^c Two of the four plots that were hydrophobic were located in areas subjected to the low-severity burns. All others were in areas subjected to high-severity burns.

variety of surface conditions from white ashy (complete combustion) to blackened appearance with minimal destruction of the duff layer, indicating a moderate to light ground char fire as described by Ryan and Noste (1983), or a low- to high-severity burn as described by Phillips and Abercrombie (1987). The fall fire did not burn as expected at the Hermada site. The southern aspect was dryer than the northern aspect but fuel loadings and duff thickness were very variable spatially, thus making it more difficult to carry the fire. After burning the Hermada site, small areas appeared ashy white, whereas the majority of the burn area had a black appearance indicating light ground char (Ryan and Noste, 1983) or low-severity burn (Phillips and Abercrombie, 1987). Surface conditions after the burn were classified on type and severity of disturbance. The four surface conditions were unburned-undisturbed, burns of a low-severity (65–100% ground cover remaining and a duff thickness between 5 and 20 mm), burns of high-severity (0–65% ground cover remaining and a duff thickness less than 5 mm) and skid trails (high disturbance) areas (Robichaud et al., 1993; Robichaud, 1996) (Fig. 1). Skid trails were not used in this analysis.

2.3. Rainfall simulation

Rainfall simulation plots were located randomly in each surface/hydrologic condition area several days after the burn. Fourteen rainfall simulation plots were located at Slate Point site and 11 at the Hermada site (Table 2). Adjustments to plot locations were made for access to water supply and electrical power. Because of fiscal and logistical constraints, rainfall simulation could not take place at each geostatistical sampling location. Since variability within each surface condition was high, as many repetitions as possible were completed as permitted by time and weather. At the Hermada site, most of the area was subjected to a low-severity burn, efforts were made to locate a few plots in areas subjected to high-severity burn to be able to determine the effects of the different surface conditions.

Simulated rainfall events were applied to 1 m² plots with the USDA-Forest Service oscillating nozzle rainfall simulator. These plots were bordered by 150 mm wide sheet metal inserted vertically 50 mm into the mineral soil. The simulator produced a mean rainfall intensity of 94 mm h⁻¹ (SD = 5.5 mm h⁻¹). Each plot received three 30-min rainfall events. Event 1 (dry) was conducted with existing soil moisture condition. After Event 1, the plots were covered with plastic

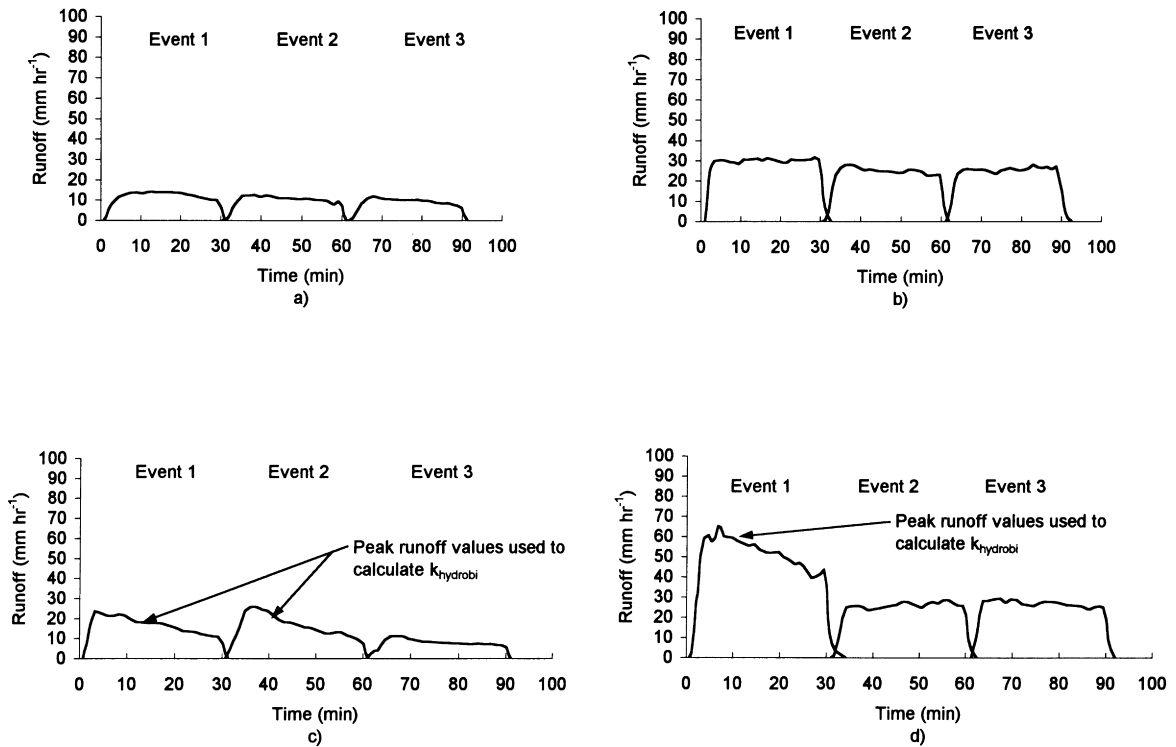


Fig. 2. Hydrographs from the Slate Point site that were within: (a) areas that were unburned-undisturbed; (b) areas subjected to a low-severity burn; (c) areas subjected to a high-severity burn with a slight hydrophobic response; and (d) areas subjected to a high-severity burn with a hydrophobic response.

sheeting and Event 2 (wet) was conducted the following day. Event 3 (very wet) was conducted about 30 min after Event 2. This procedure provided three distinct antecedent moisture conditions. A covered trough at the lower end of each plot carried runoff (water and sediment) through an outlet tube for timed volume samples, collected manually in 500 ml bottles. These data were used to develop hydrographs, total runoff volumes and sediment yields (Robichaud, 1996).

2.4. Analysis methods

Hydrographs show the temporal variation in runoff rate (mm h^{-1}) collected at the outlet of the 1 m^2 plot for three 30-min rainfall events. Runoff amounts can be calculated by the integration of the hydrograph. These hydrographs were used to calculate hydraulic conductivity values by the methods of Luce and Cundy (1994) which determine parameter values for

kinematic wave-Philip's infiltration overland flow equation from the runoff hydrographs. The best fit equation minimizes the error between the observed and synthetic hydrographs by an iterative process of adjusting the values for the sorptivity, conductivity and time to ponding under constant rainfall rate and duration, plot slope and size, and moisture contents. Inputs to saturated hydraulic conductivity (K_{for}) values were fitted from the very wet events when the soil was saturated, since these estimates are more reliable than from the dry or wet events. However, hydraulic conductivity values were also estimated near the beginning of the first rainfall event for determining the hydrophobic hydraulic conductivity (K_{hydrobi}) when the hydrograph had a peaked shape (Figs. 2c,d and 3). When this occurred, the synthetic hydrograph was fitted to the peaked portion of the runoff hydrograph to estimating K_{hydrobi} .

Mean hydraulic conductivity values between the surface conditions were compared by the least

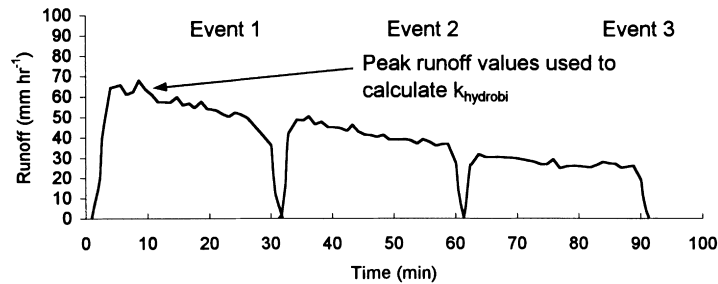


Fig. 3. Hydrographs from the Hermada site that were within areas that were subjected a high-severity burn with a hydrophobic response.

significant difference (LSD) at $\alpha = 0.05$ (StatSoft, 1995). Probability distribution functions were also used to define probabilities of occurrence for values of hydraulic conductivity for each site. Best-fit distribution algorithms were determined by testing various distribution functions (normal, gamma and exponential with an $\alpha = 0.05$) and various number of categories using the Kolmogorov–Smimov one-sample test for goodness-of-fit (McCuen and Snyder, 1986; StatSoft, 1995). This tests the null hypothesis that the cumulative distribution of a variable agrees with the cumulative distribution of some specified probability function at specified α -levels.

3. Results and discussion

3.1. Fire descriptions

Ignition techniques, fuel moisture and weather during the Slate Point burn produced an intense fire concentrated in the center of the unit, whereas the Hermada burn produced a low intensity fire (Table 1). Maximum temperatures within the duff were 69–612°C lasting 3–8 min at the Slate Point site, whereas at the Hermada site maximum temperatures were only 119–187°C in the duff. Spatially varied surface conditions occurred after both prescribed burns. Duff depths averaged 47 mm prior to the fire and 19 mm following the burn at the Slate Point site. Duff depths averaged 36 mm prior to the burn and 29 mm following the burn at the Hermada site. At the Hermada site, the harvest unit did not burn well due to high moisture conditions (71%) of the upper duff, high humidity (36%) and higher fine fuel moisture content (18%) (Table 1).

The fires created mosaic patterns of duff consumption and some unburned areas. These spatial patterns are described in detail in Robichaud and Miller (2000) and Robichaud (1996). The burn sites were divided into three surface conditions: unburned, low severity and high severity surface conditions for rainfall simulation plot locations. The areas subjected to a low-severity burn retained 65–100% of its original ground cover. The area subjected to a high-severity burn retained 0–65% of its original ground cover (Fig. 1). At the Slate Point site, approximately 65% of the area was subjected to a low-severity burn and 15% of the area was subjected to high-severity burn at the top of the slope, where the heat generated during the fire consumed most of the duff layer. Whereas at the Hermada site, approximately 55% of the area was subjected to a low-severity burn and only 5% of the area was subjected to a high-severity burn which occurred on a southern aspect drainage depression (Table 2).

3.2. Slate Point

On the unburned-undisturbed areas, runoff was minimal and constant (4 mm for each event) (Table 2 and Fig. 2a). This low runoff rate resulted because the protective layer of duff (100% ground cover) covering the mineral soil remained intact. The intact duff layer protects the mineral soil from both overland flow and raindrop impact, thereby preventing erosion and increasing infiltration. The duff provided detention storage by allowing water to be released slowly into the underlying mineral soil resulting in high hydraulic conductivity values (77–81 mm h⁻¹). The duff material also acted as a lateral flow path for water moving downslope.

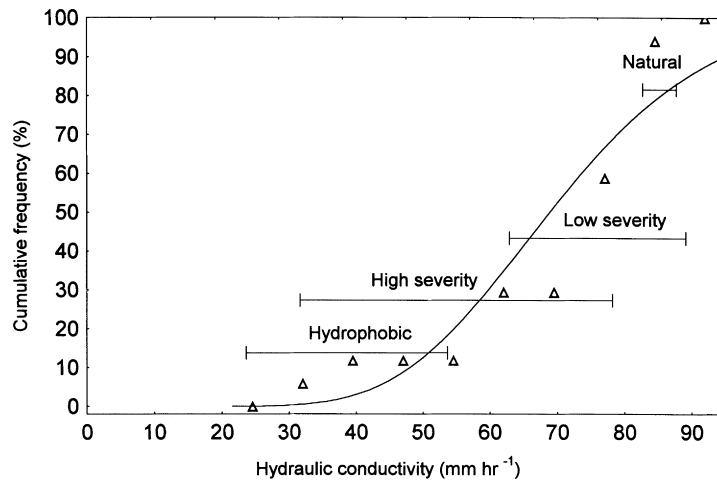


Fig. 4. Cumulative distribution function for hydraulic conductivity at the Slate Point site. Kolmogorov–Smirnov $d = 0.27$ at the $\alpha = 0.05$ level.

An example of a hydrograph from a low-severity burn area indicates a relatively constant runoff rate for all three 30-min rain events (Fig. 2b). Hydraulic conductivity was calculated as 72 mm h^{-1} during Event 3. Total runoff collected, calculated from the area under the hydrograph, were 14, 12 and 12 mm for each successive rainfall event. In contrast, a hydrograph from areas subjected to a high-severity burn indicate high runoff rates during Event 1, decreasing to a constant rate for the last 10 min of each event (Fig. 2c). The shape of a second hydrograph indicates a hydrophobic soil condition was present because runoff decreases with time. Another hydrograph from the same site and surface condition indicates a similar hydrophobic response with a greater magnitude of runoff during the initial portion of the simulated rainfall event and the final runoff rate (Fig. 2d).

3.3. Hermada

Portions of the Hermada site provided another example of a hydrophobic response to simulated rainfall with runoff decreasing with each successive rain event (Fig. 3). Runoff quickly reaches 67 mm h^{-1} and then drops to 30 mm h^{-1} at the end of Event 3. Hydraulic conductivity was estimated at 62 mm h^{-1} at the end of Event 3. At the onset of rain, the hydrophobic hydraulic conductivity was estimated at 35 mm h^{-1} . Thus we can see how hydrophobic

conditions vary as the soil profile becomes wetted and eventually responds as a normal infiltrating soil.

Normal infiltration theory indicates that downward infiltration in an initially unsaturated soil generally occurs under the combined influence of suction and gravity gradients. As the water penetrates deeper and the wetted part of the profile lengthens, the average suction gradient decreases, since the overall difference in the pressure head divides itself along an ever-increasing distance. This trend continues until eventually the suction gradient in the upper part of the profile becomes negligible, leaving the constant gravitational gradient as the only force moving water downward. Since the gravitational head gradient has the value of unity (the gravitational head decreasing at the rate of 1 mm with each millimeter of vertical depth below the surface), it follows that the flux tends to approach the hydraulic conductivity as a limiting value (Hillel, 1982).

3.4. Hydrophobic response

When analyzing a hydrograph such as in Figs. 2c,d and 3, hydraulic conductivity was determined from Event 3, where runoff and infiltration are fairly constant. Data from the beginning of Event 1 represents the hydrophobic hydraulic conductivity. The difference between initial (hydrophobic) hydraulic conductivity and the final hydraulic conductivity when hydrophobic conditions were present. The

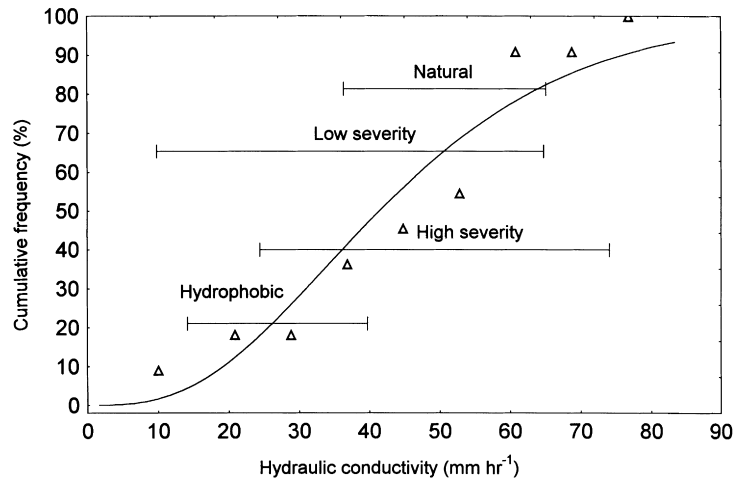


Fig. 5. Cumulative distribution function for hydraulic conductivity at the Hermada site. Kolmogorov–Smirnov $d = 0.16$ at the $\alpha = 0.05$ level.

hydrophobic hydraulic conductivity values were 10–40% of normal saturated hydraulic conductivity. Only 4 out of 14 plots indicated hydrophobicity from Slate Point, and 3 out of 11 plots from Hermada thus indicating that hydrophobic conditions were not extensive especially since only 5% of the total area at the Hermada site was subjected to a high-severity burn. Since hydrophobic substances are water soluble, they can be broken down and destroyed with water, as evident by the declining hydrographs during the third rain event (Figs. 2c,d and 3). The timing or persistence of the hydrophobicity was not measured in this experiment, i.e. repeated rainfall simulation over weeks or months on the same plots was not performed. Researchers have documented persistence from weeks to years. In general, the hydrophobicity is broken up or is sufficiently washed away within one to two years after the fire.

3.5. Cumulative distribution of hydraulic conductivity

Hydraulic conductivity varies within each surface condition (Table 2) and the means were not significantly different by LSD method at $\alpha = 0.05$. For example at the Slate Point site, there was little variation for the unburned-undisturbed hydraulic conductivity; a range of 60–89 mm h⁻¹ for the surface conditions with a low-severity burn; and a range of 30–84 mm h⁻¹ for the surface conditions with a high-severity burn. Therefore, best-fit cumulative

distribution algorithms were used to describe the range of hydraulic conductivity by using all measured hydraulic conductivity for a given field site excluding hydrophobic response conditions (Figs. 4 and 5). Cumulative distribution algorithms combined with spatial distribution (Robichaud and Monroe, 1997) provide methods for estimates of runoff and erosion from spatially-varied forest conditions. This agrees with the finding of Smith and Hebbert (1979), Moore and Clarke (1981) and Hawkins and Cundy (1987) that a single value for hydraulic conductivity for a site is not appropriate for forest conditions.

Hydraulic conductivity values at the Hermada site had larger variations for all treatments and means were significantly smaller by the LSD method when compared with Slate Point (Table 2; Figs. 4 and 5). The differences were due to larger post-fire site variation since much of the site did not burn well as previously described. Overall lower values are probably due to some surface crusting and sealing which have been reported for these soil types. This thin crust can be developed by the beating action of the raindrops, or as a result of the spontaneous slaking and breakdown of the soil aggregates during wetting (Hillel, 1982). This was common on south aspects which have thinner duff. Thus, a single cumulative distribution algorithm for each site should provide reasonable estimates of hydraulic conductivity.

Water drop penetration times, WDPT, (DeBano, 1981) were measured during this study (Robichaud,

1996) using the same geostatistical design described in Robichaud and Miller (2000). These results showed greater repellency in areas subjected to high-severity burns (Robichaud, 1996). Since WDPT were not measured prior to each rainfall simulation, no relations can be made on the expected reduction in infiltration throughout the site based on WDPT. Thus, the reduction in infiltration described here needs additional field evaluation to determine its spatial distribution.

4. Conclusions

Variable surface conditions are common in forest environments especially after prescribed fires. Small-scale rainfall simulation techniques provide a reliable method to determine hydraulic conductivity for these various surface conditions. Two prescribed burns were conducted and both produced variable infiltration rates related to burn severity. When hydrophobic conditions were present, marked changes in the runoff hydrographs over time allowed for the determination of a hydrophobic hydraulic conductivity. When hydrophobic conditions occurred after a high-severity burn, the saturated hydraulic conductivity was reduced between 10 and 40% during the onset of simulated rainfall, thus $K_{\text{hydrobi}} = 0.1\text{--}0.4K_{\text{sat}}$. These hydrophobic hydraulic conductivity values recovered to near saturated hydraulic conductivity values by the third simulated rainfall event for all plots.

In a forest environment, hydraulic conductivity varies by surface condition which is a function of the type and severity of disturbance. Within each surface condition there is also variability. Cumulative distribution algorithms provide a means to account for the inherent variability associated with these hillslopes and surface conditions. Cumulative distribution algorithms and spatial distributions of hydraulic conductivity should be used with erosion prediction models to predict surface runoff and erosion from forest environments.

References

- Bond, R.D., 1964. The influence of the microflora on the physical properties of soils. II. Field studies on water repellent sands. *Aust. J. Soil Res.* 2, 111–122.
- Campbell, I.A., 1977. Stream discharge, suspended sediment and erosion rates in the Red Deer River basin, Alberta, Canada. *Int. Assoc. Hydrol. Sci.* 122, 244–259.
- DeBano, L.F., 1981. Water repellent soils: a state of the art. Gen. Tech. Rpt. PSW-46. USDA For. Serv., Pacific Southwest Forest and Range Exp. Sta., Berkeley, CA, 21pp.
- DeBano, L.F., Rice, R.M., 1973. Water repellent soils: their implications in forestry. *J. Forestry* 71, 220–223.
- DeBano, L.F., Osborn, J.F., Krammes, J.S., Letey, J., Jr., 1967. Soil wettability and wetting agents...our current knowledge of the problem. Gen. Tech. Rpt. PSW-43. USDA For. Serv., Pacific Southwest Forest and Range Exp. Sta., Berkeley, CA, 13pp.
- DeBano, L.F., Savage, S.M., Hamilton, D.A., 1976. The transfer of heat and hydrophobic substances during burning. *Soil Sci. Soc. Am. J.* 40, 779–782.
- Dekker, L.W., Ritsema, C.J., 1995. Fingerlike wetting patterns in two water-repellent loam soils. *J. Environ. Qual.* 24, 324–333.
- Dekker, L.W., Ritsema, C.J., 1996. Preferential flow paths in a water repellent clay soil with grass cover. *Water Resour. Res.* 32, 1239–1249.
- Dyrness, C.T., 1976. Effect of wildfire on soil wettability in the High Cascades of Oregon. Res. Paper PNW-202. USDA For. Serv., Pacific Northwest Forest and Range Exp. Sta. Portland, OR, 18pp.
- Hawkins, R.H., Cundy, T.W., 1987. Steady-state analysis of infiltration and overland flow for spatially-varied hillslopes. *Water Resour. Bull.* 23, 251–256.
- Hillel, D., 1982. *Introduction to Soil Physics*, Academic Press, San Diego, CA (364pp.).
- Holzhey, C.S., 1969. Water-repellent soil in Southern California. In: DeBano, L.F., Letey, J. (Eds.), *Water-Repellent Soils: Proceedings*, Riverside, CA, pp. 31–41.
- Luce, C.H., Cundy, T.W., 1994. Parameter identification for a runoff model for forest roads. *Water Resour. Res.* 30, 1057–1069.
- McCuen, R.H., Snyder, W.M., 1986. *Hydrologic Modeling: Statistical Methods and Applications*, Prentice-Hall, Newark, NJ (568pp.).
- McNabb, D.H., Gaweda, F., Froehlich, H.A., 1989. Infiltration, water repellency, and soil moisture content after broadcast burning a forest site in southwest Oregon. *J. Soil Water Conserv.* 44, 87–90.
- Meeuwig, R.O., 1971. Infiltration and water repellency in granitic soils. Res. Paper INT-111. USDA For. Serv., Intermountain Res. Sta., Ogden, UT, 10pp.
- Megahan, W.F., Molitor, D.C., 1975. Erosional effects of wildfire and logging in Idaho. *Watershed Management Symposium*. Am. Soc. Civil Eng. Irrigation and Drainage Div., Logan, UT, pp. 423–444.
- Moore, R.J., Clarke, R.T., 1981. A distribution function approach to rainfall runoff modeling. *Water Resour. Res.* 17, 1367–1382.
- Pfister, R.D., Kovalchik, B.L., Arno, S.F., Presby, R.C., 1977. Forest habitat types of Montana. Gen. Tech. Rpt. INT-GTR-34. USDA For. Serv., Intermountain Forest and Range Exp. Sta., Ogden, UT, 174pp.
- Phillips, D.R., Abercrombie, J.A., 1987. Pine–hardwood mixtures—a new concept in regeneration. *Southern J. Appl. Forestry* 11 (4), 192–197.

- Richardson, J.L., Hole, F.D., 1978. Influence of vegetation on water repellency in selected western Wisconsin soils. *Soil Sci. Soc. Am. J.* 42, 465–467.
- Robichaud, P.R., 1996. Spatially-varied erosion potential from harvested hillslopes after prescribed fire in the Interior Northwest. PhD Diss., University of Idaho, Moscow, ID, 219pp.
- Robichaud, P.R., Hungerford, R.D., 2000. Water repellency by laboratory burning of four northern Rocky Mountain forest soils. *J. Hydrol.* 231–232, 207–219.
- Robichaud, P.R., Miller, S.M., 2000. Spatial simulations to describe duff consumption of prescribed fire. *Int. J. Wildland Fire* (in press).
- Robichaud, P.R., Monroe, T.M., 1997. Spatially-varied erosion modeling using WEPP for timber harvested and burned hillslopes. ASAE paper No. 97-5015. Amer. Soc. Agric. Eng., Minneapolis, MN, 8pp.
- Robichaud, P.R., Waldrop, T.A., 1994. A comparison of surface runoff and sediment yields from low- and high-severity site preparation burns. *Water Resour. Bull.* 30, 27–34.
- Robichaud, P.R., Luce, C.H., Brown, R.E., 1993. Variation among different surface conditions in timber harvest sites in the Southern Appalachians. International workshop on soil erosion: Proc. Moscow, Russia. Purdue University, West Lafayette, IN, pp. 231–241.
- Ryan, K.C., Noste, N.V., 1983. Evaluating prescribe fires. In: Lotan, J.E., Kilgore, B.M., Fischer, W.C., Mutch, R.W. (Tech. Coord.), Symposium and Workshop of Wilderness Fire: Proc. Gen. Tech. Rpt. INT-182. USDA For. Serv., Intermountain Res. Sta., Ogden, UT, pp. 230–238.
- Smith, R.E., Hebbert, H.B., 1979. A Monte Carlo analysis of the hydrologic effects of spatial variability of infiltration. *Water Resour. Res.* 15, 419–429.
- Soto, B., Basanta, R., Benito, E., Perez R., Diaz-Fierros, F., 1994. Runoff and erosion from burnt soils in northwest Spain. In: Sala, M., Rubio, J.L. (Eds.), *Soil Erosion and Degradation as a Consequence of Forest Fires: Proc. Barcelona, Spain*, pp. 91–98.
- StatSoft, 1995. *Statistica for Windows*. Version 5.1. StatSoft Inc., Tulsa, OK.
- Steele, R., Pfister, R.D., Ryker, R.A., Kittams, J.A., 1981. Forest habitat types of Central Idaho. Gen. Tech. Rpt. INT-GTR-114. USDA For. Serv., Intermountain Res. Sta., Ogden, UT, 138pp.