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Rethinking infiltration in wildfire-affected soils

Brian A. Ebel[1]* and
John A. Moody[2]

[1] *Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado at Boulder, Boulder, CO, 80309-0216, USA*
[2] *U.S. Geological Survey, National Research Program, 3215 Marine St. Ste. E-127, Boulder, CO, 80303, USA*

*Correspondence to: Brian A. Ebel, Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado at Boulder, Boulder, CO 80309-0216, USA.
E-mail: brian.ebel@colorado.edu

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Motivations

Wildfires frequently result in natural hazards such as flash floods (Yates *et al.*, 2001) and debris flows (Cannon *et al.*, 2001a,b; Gabet and Sternberg, 2008). One of the principal causes of the increased risk of post-wildfire hydrologically driven hazards is reduced infiltration rates (e.g. Scott and van Wyk, 1990; Cerdà, 1998; Robichaud, 2000; Martin and Moody, 2001). Beyond the reduction in peak infiltration rate, there is mounting evidence that the fundamental physics of infiltration in wildfire-affected soils is different from unburned soils (e.g. Imeson *et al.*, 1992; Moody *et al.*, 2009; Moody and Ebel, 2012).

Understanding post-wildfire hydrology is critical given the increasing wildfire incidence in the western USA (Westerling *et al.*, 2006) and elsewhere in the world (Kasischke and Turetsky, 2006; Holz and Veblen, 2011; Pausas and Fernández-Muñoz, 2012). Wildfire is a disturbance event with global distribution (Bowman *et al.*, 2009; Krawchuk *et al.*, 2009; Pechony and Shindell, 2010; Moritz *et al.*, 2012), and with increasing populations moving into fire-prone areas, understanding post-wildfire infiltration is of increasing importance for predicting post-wildfire consequences. Runoff is generally controlled by the infiltration-excess mechanism in fire-affected soils (e.g. Mayor *et al.*, 2007; Onda *et al.*, 2008; Kinner and Moody, 2010). It is essential that the fire community have conceptual models, physical equations and tools (i.e. numerical models) to predict infiltration and thus excess rainfall (after Horton, 1933), which can provide estimates of peak discharge, start of runoff, time to peak and total runoff for hydroclimatic scenarios after wildfires. Reductions in saturated hydraulic conductivity K_{sat} $[\mathrm{L\,T}^{-1}]$ are common for fire-affected soils, and the relatively low values observed explain the elevated flash flood hazards (e.g. K_{sat} of 1–100 $\mathrm{mm\,h}^{-1}$, Robichaud, 2000; Yates *et al.*, 2000; Martin and Moody, 2001; Robichaud *et al.*, 2007; Moody *et al.*, 2009; Neary, 2011; Nyman *et al.*, 2011).

Traditional Infiltration Theory

Traditional infiltration theory is based upon a hydraulic gradient with gravitational and capillary components (Philip, 1957a). Early-time infiltration is dominated by capillarity, and late-time infiltration is largely dominated by gravity (Philip, 1957b). This leads to a monotonically decreasing infiltration rate with time as infiltration progresses. Models based on traditional theory (Green and Ampt, 1911; Philip, 1957c; Smith and Parlange, 1978) predict that the maximum infiltration rate corresponds to the driest soil conditions (Philip, 1957c). This results in 'worst-case' scenarios, in terms of flash flood potential, for wet initial conditions of high soil–water contents, θ $[\mathrm{L}^3\,\mathrm{l}^{-3}]$. Traditional theory has been used to better understand the effects of ash (Woods and Balfour, 2008) and for specific studies of post-wildfire floods (Yates *et al.*, 2000). For both cases, a limitation was not knowing the appropriate hydraulic parameters (wetting front suction and hydraulic conductivity, K $[\mathrm{L\,T}^{-1}]$, respectively) for fire-affected soils. One approach (Robichaud, 2000) was to adapt an infiltration model (Philip, 1969; Luce and Cundy, 1994) coupled to the kinematic-wave equation to estimate soil parameters (time-to-start of runoff, sorptivity, and hydraulic conductivity) by minimizing the fit between simulated and observed hydrographs under constant rainfall. Modified forms of some traditional infiltration models have been incorporated into basin-scaled runoff models as options (Feldman and Goldman, 1984) to predict maximum runoff for unburned basins, but these models have faced the same problem of not knowing appropriate soil-hydraulic parameters for fire-affected soils. In general, most post-wildfire predictions of peak discharge have used regional regression models for fire-affected basins or the curve number method (Foltz *et al.*, 2009), but again have had difficulty because needed parameter values for fire-affected areas are unknown. Although it is often assumed that traditional infiltration theories apply in fire-affected soils, these theories and numerical models of infiltration that express them are seldom tested with field measurements during actual rainstorms.

How Fire-Affected Soils are Different

Infiltration processes are not well understood in fire-affected soils whose soil-hydraulic properties and soil–water content have been altered by the heat from a wildfire. Previous field studies have documented that soil surface sealing by ash (Onda *et al.*, 2008; Larsen *et al.*, 2009) and fine sediments (Neary *et al.*, 1999; Larsen *et al.*, 2009), needle cast (Pannkuk and Robichaud, 2003; Cerda and Doerr, 2008), and ash cover (Woods and Balfour, 2010; Ebel *et al.*, 2012) have measurable effects on post-wildfire runoff. However, the most frequently cited cause of reduced infiltration rates, and thus increased runoff, in fire-affected areas is the increase in soil–water repellency (DeBano, 2000; Doerr *et al.*, 2000; Letey, 2001) above the existing level present in unburned soils (e.g. Doerr *et al.*, 1998; Doerr and Moody, 2004; Varela *et al.*, 2005; Stoof *et al.*, 2011). Soils with coarser grain-size distributions are more prone to developing soil–water repellency (DeBano, 1981). Soil–water repellency also depends on hydrologic states. Lower soil–water repellency is found in wet soils compared with dry soils, and a fairly well-established soil–water content threshold exists above which repellency is minimal (Dekker and Ritsema, 1994; Doerr and Thomas, 2000; MacDonald and Huffman, 2004). Soil–water repellency can, however, be re-established when wet soil dries below the soil–water content threshold (Shakesby *et al.*, 1993).

The complexity of infiltration in fire-affected soils was shown by Imeson *et al.* (1992), who documented four typical patterns (types) of time-variable infiltration rates observed during rainfall simulation experiments (Figure 1). Type 1 is the expected infiltration rate from traditional theory, and type 2 is only slightly different, with the most salient feature being the linear decline in infiltration rate with time as the soil wets up and the capillarity contribution to the hydraulic gradient declines. Type 3 and type 4 in Figure 1 have initially low infiltration rates that increase as the soil wets up and then decline with increased wetting; these patterns are not explained by traditional theory (type 1). Imeson *et al.* (1992) attributed the type 3 and type 4 responses to soil–water repellency, which causes low infiltration rates at the low soil–water contents typical of early-time infiltration. The 'levelling off' of infiltration rate with time for type 4 in Figure 1 was attributed to macropore flow by Imeson *et al.* (1992), which is likely highly spatially variable (Nyman *et al.*, 2010).

Beyond the unexpected temporal characteristics of infiltration in wildfire-affected soils, new evidence has documented that the infiltration rate at very low soil–water contents may approach zero (i.e. essentially impermeable) rather than very large rates. Near-zero infiltration rates into fire-affected soils with $\theta < 0.02$ $\mathrm{cm}^3\,\mathrm{cm}^{-3}$ were documented immediately after a wildfire and before substantial rain (Moody and Ebel, 2012). These conditions were termed 'hyper-dry' by Moody and Ebel (2012) and are probably present after many wildfires. *A minimum in infiltration rate at hyper-dry conditions, where traditional infiltration theory predicts a maximum, points to the need for rethinking infiltration processes in wildfire-affected soils*. This is important because this minimum may provide an explanation why catastrophic floods after wildfire are often associated with the first substantial rain before possible sealing effects. In particular, these observations document a disconnection between the hydrologic processes at the surface and the capillarity portion of the gradient that should result from the strong spatial contrasts in matric potential in the subsurface that develop during infiltration. This decoupling depends, in part, on wildfire-enhanced soil–water repellency. If this decoupling exists and removes the contribution of capillarity from infiltration, then initial infiltration

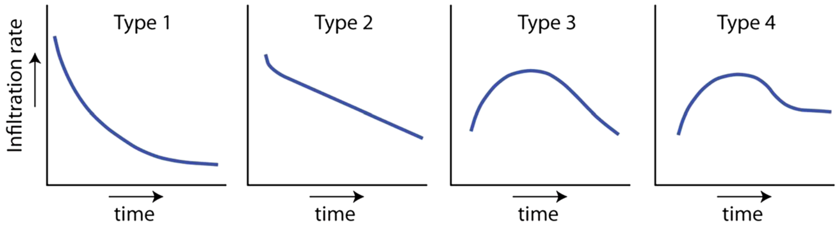

Figure 1. Four types of infiltration rate as a function of time during the simulated rainfall experiments of Imeson *et al.* (1992). Type 1 is the 'standard type' with exponentially decreasing infiltration rate with time. Type 2 is a linear decrease in infiltration rate with time. Type 3 has initially high soil–water repellency that initially results in a low infiltration rate, but as the soil wets, infiltration rate increases to a maximum and then declines exponentially with time. Type 4 is like type 3 except that the infiltration rate eventually levels off to a constant value because of macropore flow (after Imeson *et al.*, 1992)

rates would be controlled by gravity, which results in minimal flow because of the very low hydraulic conductivities at such low soil–water contents. Adsorption of water vapour is too slow to impact infiltration processes at the 20- to 60-min timescale of typical convective storms (Moody and Ebel, 2012). No physical process is substantial enough to move water at short timescales of seconds to tens of minutes in hyper-dry soils, which enhances soil–water repellency, directly contradicting traditional infiltration models.

One major problem with characterizing infiltration in wildfire-affected soils is that certain measurement techniques appear to bias results. For example, Ebel *et al.* (2012) found that ponded head (several cm) measurements of infiltration using single ring infiltrometers (Nimmo *et al.*, 2009) overwhelmed soil–water repellency and gave infiltration rate estimates that were similar to unburned soils. Similar biases from ponded head measurements were found by Cerdà (1996) and Nyman *et al.* (2010). In contrast, infiltration estimates using a tension infiltrometer (Decagon Devices Mini Disk) at an applied pressure head of -1 cm showed that fire-affected soils were essentially impermeable (Ebel *et al.*, 2012) at the timescale of typical convective storms (i.e. 20–60 min). Tension infiltrometers can be challenging to use in wildfire-affected soils, which are often coarse textured, because it is difficult to have a reliable interface between the infiltrometer and the soil surface. Making infiltration measurements in a fire-affected environment where flux is near zero is an extremely difficult task as negligible errors for large infiltration rates become large errors for near-zero fluxes.

Ways Forward

Field evidence is suggesting that the hyper-dry domain, where $\theta < 0.02\ \mathrm{cm^3\,cm^{-3}}$, is important for understanding post-wildfire infiltration–runoff response. Traditional infiltration theories have not focused on this domain and cannot provide accurate quantitative predictions for soils affected by wildfire in this hyper-dry domain. This problem likely extends to other unburned soils with substantial soil–water repellency, an issue that is increasingly observed (Dekker *et al.*, 2005), especially under drought conditions (Goebel *et al.*, 2011). Modification of existing traditional infiltration models needs to incorporate the effects of soil–water repellency. Specifically, future research needs to determine how soil–water repellency affects the relations between θ and the matric potential ψ [L], that is, soil–water retention curves (e.g. Goebel *et al.*, 2004; Regalado and Ritter, 2005; de Jonge *et al.*, 2007), and the relation between K and θ, that is, the hydraulic conductivity function. Recent work has generated models for soil–water repellency characteristic curves (i.e. water repellency metrics *vs* θ and *vs* ψ) for unburned soils (Bachmann *et al.*, 2007; Karunarathna *et al.*, 2010a, b). Once the effects of soil–water repellency are established for these two soil–water repellency characteristic curves, they can be used in unsaturated zone simulation (Deurer and Bachmann, 2007) and potentially accurately estimate infiltration (near zero) for hyper-dry conditions. However, these two soil–water repellency characteristic curves need to be combined into a family of soil–water retention curves (ψ *vs* θ) for each value of soil–water repellency. Additionally, it is not yet clear if the typical (Mualem, 1976) relations (K *vs* θ) accurately represent the hydraulic conductivity function for unsaturated water-repellent soils. Only a few field measurements attempting to estimate a hydraulic conductivity function in wildfire-affected soils have been made (Robichaud, 2000) using the method described by Luce and Cundy (1994). Laboratory experiments are needed that measure hydraulic conductivity as a function of soil–water content for wildfire-affected soils to address this concern.

Another approach, based on the observation that post-wildfire runoff and erosion respond to short-duration, high-intensity rain, suggests that sorptivity $[\mathrm{L\,T^{1/2}}]$ should be important at these time scales (Smith, 2002). Simpler infiltration models (e.g. Philip, 1957b) could utilize sorptivity measurements of the type presented by Moody *et al.* (2009), who showed that sorptivity was non-monotonic, decreasing to smaller values at hyper-dry ($\theta < 0.02$) and very wet conditions ($\theta > 0.2\ \mathrm{cm^3\,cm^{-3}}$), and increasing to a maximum value near θ of 0.05 to 0.1 $\mathrm{cm^3\,cm^{-3}}$. Alternatively, this disequilibrium between the surface and subsurface, in terms of the decoupling of the capillarity portion of the hydraulic gradient, could be simulated in fully coupled surface water/groundwater models that use first-order exchange coefficients by using a large coupling length scale, as suggested by Ebel *et al.* (2009). There is definitely a need for more field measurements and controlled laboratory measurements to resolve the effects of wildfire on the soil-hydraulic functions, which will provide the basis for modifying traditional infiltration theory to meet the needs of predicting post-wildfire floods and debris flows.

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References

Bachmann J, Deurer M, Arye G. 2007. Modeling water movement in heterogeneous water-repellent soil: 1. Development of a contact angle dependent water-retention model. *Vadose Zone Journal* 6: 436–445.

Bowman DMJS, Balch JK, Artaxo P, Bond WJ, Carlson JM, Cochrane MA, D'Antonio CM, DeFries RS, Doyle JC, Harrison SP, Johnston FH, Keeley JE, Krawchuk MA, Kull CA, Marston JB, Moritz MA, Prentice IC, Roos CI, Scott AC, Swetnam TW, van der Werf GR, Pyne SJ. 2009. Fire in the earth system. *Science* 324: 481–484.

Cannon SH, Kirkham RM, Parise M. 2001a. Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado. *Geomorphology* 39: 171–188.

Cannon SH, Bigio ER, Mine E. 2001b. A process for fire-related debris flow initiation, Cerro Grande fire, New Mexico. *Hydrological Processes* 15: 3011–3023.

Cerdà A. 1996. Seasonal variability of infiltration rates under contrasting slope conditions in southeast Spain. *Geoderma* 69: 217–232.

Cerdà A. 1998. Changes in overland flow and infiltration after a rangeland fire in a Mediterranean scrubland. *Hydrological Processes* 12: 1031–1042.

Cerda A, Doerr SH. 2008. The effect of ash and needle cover on surface runoff and erosion in the immediate post-fire period. *Catena* 74: 256–263.

DeBano LF. 1981. Water repellent soils: a state of the art. General Technical Report PSW-46. U.S. Dept. of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station. 21 pp.

DeBano LF. 2000. Water repellency in soils: a historical overview. *Journal of Hydrology* 231–232: 4–32.

Dekker LW, Ritsema CJ. 1994. Fingered flow: the creator of sand columns in dune and beach sands. *Earth Surface Processes and Landforms* 19: 153–164.

Dekker, LW, Oostindie K, Ritsema CJ. 2005 Exponential increase of publications related to soil water repellency. *Soil Research* 43: 403–441.

Deurer M, Bachmann J. 2007. Modeling water movement in heterogeneous water-repellent soil: 2. A conceptual numerical simulation. *Vadose Zone Journal* 6: 446–457.

Doerr SH, Moody JA. 2004. Hydrological effects of soil water repellency: on spatial and temporal uncertainties. *Hydrological Processes* 18: 829–832.

Doerr SH, Thomas AD. 2000. The role of soil moisture in controlling water repellency: new evidence from forest soils in Portugal. *Journal of Hydrology* 231–232: 134–147.

Doerr SH, Shakesby RA, Walsh RPD. 1998. Spatial variability of soil hydrophobicity in fire-prone eucalyptus and pine forests, Portugal. *Soil Science* 163: 313–324.

Doerr SH, Shakesby RA, Walsh RPD. 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth-Science Reviews* 51: 33–65.

Ebel BA, Mirus BB, Heppner CS, VanderKwaak JE, Loague K. 2009. First-order exchange coefficient coupling for simulating surface water–groundwater interactions: parameter sensitivity and consistency with a physics-based approach. *Hydrological Processes* 23: 1949–1959.

Ebel BA, Moody JA, Martin DA. 2012. Hydrologic conditions controlling runoff generation immediately after wildfire. *Water Resources Research* 48: W03529.

Feldman AD, Goldman DM. 1984. *Infiltration and Soil Moisture Redistribution in HEC-1*. U.S. Army Corps of Engineers, Institute for Water Resources, Davis, CA, 20 p.

Foltz RB, Robichaud PR, Rhee H. 2009. A synthesis of post-fire road treatments for BAER Teams: methods, treatment effectiveness, and decision making tools for rehabilitation. *General Technical Report*, RMRS-GTR-228, Fort Collins, CO, USDA, Forest Service, Rocky Mountain Research Station, 152 p.

Gabet EJ, Sternberg P. 2008. The effects of vegetative ash on infiltration capacity, sediment transport and the generation of progressively bulked debris flows. *Geomorphology* 101: 666–673, doi:10.1016/j.geomorph.2008.03.005

Goebel M-O, Bachmann J, Woche SK, Fischer WR, Horton R. 2004. Water potential and aggregate size effects on contact angle and surface energy. *Soil Science Society of America Journal* 68: 383–393.

Goebel M-O, Bachmann J, Reichstein M, Janssens IA, Guggenberger G, 2011. Soil water repellency and its implications for organic matter decomposition – is there a link to extreme climatic events?. *Global Change Biology* 17: 2640–2656.

Green WA, Ampt GA. 1911. Studies on soil physics: 1. The flow of air and water through soils. *Journal of Agricultural Science* 4: 1–24.

Holz A, Veblen TT. 2011. Variability in the Southern Annular Mode determines wildfire activity in Patagonia. *Geophysical Research Letters* 38: L14710, doi:10.1029/2011GL047674

Horton RE. 1933. The role of infiltration in the hydrologic cycle. *Trans. Am. Geophys. Union* 14: 446–460.

Imeson AC, Verstraten JM, van Mulligen EJ, Sevink J. 1992. The effects of fire and water repellency on infiltration and runoff under Mediterranean type forest. *Catena* 19: 345–361.

de Jonge LW, Moldrup P, Jacobsen OH. 2007. Soil–water content dependency of water repellency in soils: effect of crop type, soil management, and physical-chemical parameters. *Soil Science* 172: 577–588.

Karunarathna AK, Kawamoto K, Moldrup P, de Jonge LW, Komatsu T. 2010a. A simple beta-function model for soil–water repellency as a function of water and organic carbon contents. *Soil Science* 175: 461–468.

Karunarathna AK, Moldrup P, Kawamoto K, de Jonge LW, Komatsu T. 2010b. Two-region model for soil water repellency as a function of matric potential and water content. *Vadose Zone Journal* 9: 719–730.

Kasischke ES,Turetsky MR. 2006. Recent changes in the fire regime across the North American boreal region – spatial and temporal patterns of burning across Canada and Alaska. *Geophysical Research Letters* 33: L09703. doi:10.1029/2006GL025677

Kinner DA, Moody JA. 2010. Spatial variability of steady-state infiltration into a two-layer soil system on burned hillslopes. *Journal of Hydrology* 381: 322–332.

Krawchuk MA, Moritz MA, Parisien M-A, Van Dorn J, Hayhoe K. 2009. Global Pyrogeography: the Current and Future Distribution of Wildfire. *PLoS One* 4(4): e5102.

Larsen I, MacDonald LH, Brown E, Rough D, Welsh MJ, Pietraszek JH, Libohava Z, Benavides-Solorio JD, Schaffrath K. 2009, Causes of post-fire runoff and erosion: water repellency, cover, or soil sealing?. *Soil Science Society of America Journal* 73: 1393–1407.

Letey J. 2001. Causes and consequences of fire-induced water repellency. *Hydrological Processes* 15: 2867–2875.

Luce CH, Cundy TW. 1994. Parameter identification for a runoff model for forest roads. *Water Resources Research* 30(4): 1057–1069.

MacDonald LH, Huffman EL. 2004. Post-fire soil water repellency: persistence and soil moisture thresholds. *Soil Science Society of America Journal* 68: 1729–1734.

Martin DA, Moody JA. 2001. Comparison of soil infiltration rates in burned and unburned mountainous watersheds. *Hydrological Processes* 15: 2893–2903.

Mayor AG, Bautista S, Llovet J, Bellot J. 2007. Post-fire hydrological and erosional responses of a Mediterranean landscpe: seven years of catchment-scale dynamics. *Catena* 71: 68–75.

Moody JA, Ebel BA. 2012. Hyper-dry conditions provide new insights into the cause of extreme floods after wildfire. *Catena* 93: 58–63.

Moody JA, Kinner DA, Ubeda X. 2009. Linking hydraulic properties of fire affected soils to infiltration and water repellency. *Journal of Hydrology* 379: 291–303.

Moritz MA, Parisien M-A, Batllori E, Krawchuk MA, Van Dorn J, Ganz DJ, Hayhoe K. 2012. Climate change and disruptions to global fire activity. *Ecosphere* 3:art49.

Mualem Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research* 12: 513–522.

Neary DG. 2011. Impacts of wildfire severity on hydraulic conductivity in forest, woodland and grassland soils. In *Hydraulic Conductivity – Issues, Determination, and Application*, Elango L. (ed) InTech Publishers, Rijeka, Croatia, Chap. 7, 123–142.

Neary DG, Klopatek CC, DeBano LF, Ffolliott PF. 1999. Fire effects on belowground sustainability: a review and synthesis. *Forest Ecology and Management* 122: 51–71.

Nimmo JR, Schmidt KM, Perkins KS, Stock JD. 2009. Rapid measurement of field saturated hydraulic conductivity for areal characterization. *Vadose Zone Journal* 8: 142–149.

Nyman P, Sheridan G, Lane PNJ. 2010. Synergistic effects of water repellency and macropore flow on the hydraulic conductivity of a burned forest soil, south-east Australia. *Hydrological Processes* 24: 2871–2887.

Nyman P, Sheridan G, Smith HG, Lane PNJ. 2011. Evidence of debris flow occurrence after wildfire in upland catchments of south-east Australia. *Geomorphology* 125: 383–401.

Onda Y, Dietrich WE, Booker F. 2008. Evolution of overland flow after a severe forest fire, Point Reyes, California. *Catena* 72: 13–20.

Pannkuk CD, Robichaud PR. 2003. Effectiveness of needle cast at reducing erosion after forest fires. *Water Resources Research* 39: 1333, doi:10.1029/2003WR002318

Pausas J, Fernández-Muñoz S. 2012. Fire regime changes in the Western Mediterranean Basin: from fuel-limited to drought-driven fire regime. *Climatic Change* 110: 215–226.

Pechony O, Shindell DT. 2010. Driving forces of global wildfires over the past millennium and the forthcoming century. *Proceedings of the National Academy of Sciences* 107: 19167–19170.

Philip JR. 1957a. The theory of infiltration: 1: the infiltration equation and its solution. *Soil Science* 83: 345–357.

Philip JR. 1957b. The theory of infiltration: 4: sorptivity and algebraic infiltration equations. *Soil Science* 84: 257–264.

Philip JR. 1957c. The theory of infiltration: 5: the influence of initial moisture content. *Soil Science* 84: 257–264.

Philip JR. 1969. Theory of infiltration. Advances in Hydroscience 5, Academic, San Diego, CA: 215–296.

Regalado CM, Ritter A. 2005. Characterizing water dependent soil repellency with minimal parameter requirement. *Soil Science Society of America Journal* 69: 1955–1966.

Robichaud PR. 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. *Journal of Hydrology* 231–232: 220–229.

Robichaud PR, Elliot WJ, Pierson FB, Hall DE, Moffet CA, Ashmun LE. 2007. Predicting postfire erosion and mitigation effectiveness with a web-based probabilistic erosion model. *Catena* 71: 229–241.

Scott DF, van Wyk DB. 1990. The effects of wildfire on soil wettability and hydrological behaviour of an afforested catchment. *Journal of Hydrology* 121: 239–256.

Shakesby RA, Coelho COA, Ferreira AD,Terry JP, Walsh RPD. 1993. Wildfire impacts on soil erosion and hydrology in wet Mediterranean forest, Portugal. *International Journal of Wildland Fire* 3: 95–110.

Smith RE. 2002. Infiltration theory for hydrologic applications. *Water Resources Monograph* Smettem, K.R.J., Broadbridge, P., and Woolhiser, D.A. (eds) 15, American Geophysical Union, Washington, D.C. 212.

Smith RE, Parlange J-Y. 1978. A parameter efficient hydrologic infiltration model. *Water Resources Research* 14: 533–538.

Stoof CR, Moore D, Ritsema CJ, Dekker LW. 2011. Natural and fire-induced soil water repellency in a Portuguese shrubland. *Soil Science Society of America Journal* 75: 2283–2295.

Varela ME, Benito E, de Blas E. 2005. Impact of wildfires on surface water repellency in soils of northwest. Spain. *Hydrological Processes* 19: 3649–3657.

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW. 2006. Warming and earlier spring increase Western U.S. forest wildfire activity. *Science* 313: 940–943.

Woods SW, Balfour VN. 2008. The effect of ash on runoff and erosion after a severe forest wildfire, Montana, USA. *International Journal of Wildland Fire* 17: 535–548.

Woods SW, Balfour VN. 2010. The effects of soil texture and ash thickness on the post-fire hydrological response from ash covered soils. *Journal of Hydrology* 393: 274–286.

Yates DN, Warner TT, Leavesley GH. 2000. Prediction of a flash flood in complex terrain. Part II: a comparison of flood discharge simulations using rainfall input from radar, a dynamic model, and an automated algorithmic system. *Journal of Applied Meteorology* 39: 815–825.

Yates D, Warner TT, Brandes EA, Leavesley GH, Sun J, and Mueller CK. 2001. Evaluation of flash-flood discharge forecasts in complex terrain using forecast and radar-observed precipitation, and the impact of wildfire burn on flood severity. *Journal of Hydrologic Engineering* 6: 265–274.