# Wildfire impacts on hydrological processes at the catchment-scale: A scoping review

Endi Hajdari,[1,2] Emilia Nietresta[1]

[1] Department of Civil Engineering, McMaster University
[2] Department of Mathematics and Statistics, McMaster University

## Abstract

Wildfires create rippling disturbances throughout the hydrological cycle. The past 2020 fire season was especially dire which saw massive wildfires emerge in California and Australia with little regard by the public of their aftermath. Wildfires can decrease a catchment's interception storage capacity, augment snowmelt through albedo effect, increase flood risks with a rise in surface runoff, and even diminish streamflow while undergoing secondary succession. These post-fire hydrological impacts have been seen to last anywhere from only a few years to over a century. While wildfires pose significant threats on environmental, social, and economic standpoints, research into post-fire effects only began in the last century. This coupled with the transient, highly variable nature of post-fire responses and lack of consistent data, has limited research progress, thereby making it harder to properly mitigate and assess the induced damages. Therefore, there is a need to determine the commonalities and differences between different fire events on a global scale, identify mathematical relationships between the various hydrological processes, as well as develop standard measurement methods so that more effective fire and water resource management systems may be established.

# 1 Introduction

Wildfires are fast moving, wide spreading, burning of a forested area. They disturb the natural equilibrium of the local areas they affect and always generate global interest. Wildfires make headlines every year, especially in parts of North America, South America, Africa, and Australia. They regularly devastate millions of acres of land, generate massive losses in biodiversity, damage structures and infrastructure, and even cause death, costing governments billions of dollars [1]. While the word itself suggests that they are mostly caused by natural events, they are created through both natural or anthropogenic causes, although disproportionally, 85% of wildfires that exist are caused by humans as a result of negligence or arson. The other 15% naturally occur through the combination of dry soil conditions, warm temperature, and lightning [2].

Wildfires are not sustainable and are becoming especially dangerous over time. The ongoing expanding effects of climate change coupled with urban expansion into forested areas not only increases their likelihood of occurrence, but also the level of damage that they leave behind. Australia’s 2020 wildfire season spanning from June 2019 - March 2020 known as the Black Summer, burnt over 46 million acres [3]. The ongoing 2020 fire season in California has seen over 9,279 fires that have burnt almost 5% of the state’s total land area and have included 5 of the 25 largest wildfires in its history [4]. The area burnt by wildfires in Canada has doubled since 1970, averaging more than 26.52 million hectares a year [5].

The impact of wildfires to humans and biodiversity is widely discussed in the media, however the effects of wildfires on water and the hydrological cycle as a whole are often overlooked or seen as unimportant to the general public, water extinguishes fire so it must not be impacted. As counterintuitive as it may seem, wildfires do in fact result in massive impacts to hydrological processes such as precipitation, evapotranspiration, run-off, and streamflow, which will be the focus of this literature review as well as addressing the need for continued research and current and future research focus areas.

# 2 Wildfire Effects on Local Hydrological Processes

## 2.1 Effects on Interception

Wildfires, especially those classified as severe, commonly result in a loss of forest and vegetation cover in a catchment [6]. As a result, a decrease in the catchment's interception storage capacity and an increase in the throughfall (i.e., net amount of precipitation) able to reach the soil surface can be observed immediately after a fire (Figure 1). An increase in the water volume at the upper boundary of the vadose zone, coupled with the changes that wildfires induce on the processes of infiltration and run-off generation, can alter the surface-water balance, thereby shifting the hydrologic response of a catchment [7]. Independent studies conducted by Moody and Martin in 2001, and Kunze and Stednick in 2006, on different forest-covered watersheds following high-severity fires in Colorado, found that post-fire storms with shorter return periods and lower intensity resulted in flooding that would commonly be associated with higher intensity storms with larger return periods [8]. Therefore, the hydrologic response a catchment experiences following a fire is influenced by interception storage capacity, the distribution of precipitation in space, as well as changes in net infiltration and surface run-off [9].

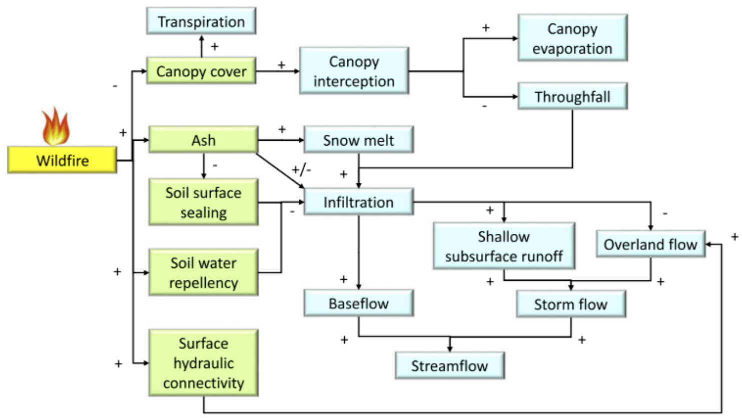


**Figure 1:** Conceptual model of post wildfire hydrologic responses in forest-covered watersheds. The + symbol indicates positive forcing and the − symbol indicates negative forcing in the direction of each arrow [10].

### 2.2 Effects on Evapotranspiration

The loss of canopy cover can induce changes to the surface-energy balance and decrease the annual amount of evapotranspiration that a catchment experiences postfire. For example, a recent 2020 study published in the Journal of Hydrology and conducted by Ma et al., used satellite imagery of 14 watersheds from 1985 to 2017 to track changes in evapotranspiration rates in the Sierra Nevada. While the results they observed varied depending on burn severity, pre-fire canopy density, and the unique topography of each of the sheds, they found that wildfires decreased evapotranspiration rates relative to the pre-fire conditions (Figure 2). Moreover, they reported an average evapotranspiration reduction of 265 mm $yr^{-1}$ (equivalent to 36% of pre-fire evapotranspiration rates) the following year after the fire event, and a reduction of 169 mm $yr^{-1}$ (equivalent to 23% of pre-fire evapotranspiration rates) that persisted over a period of 15 years after the fire [11].

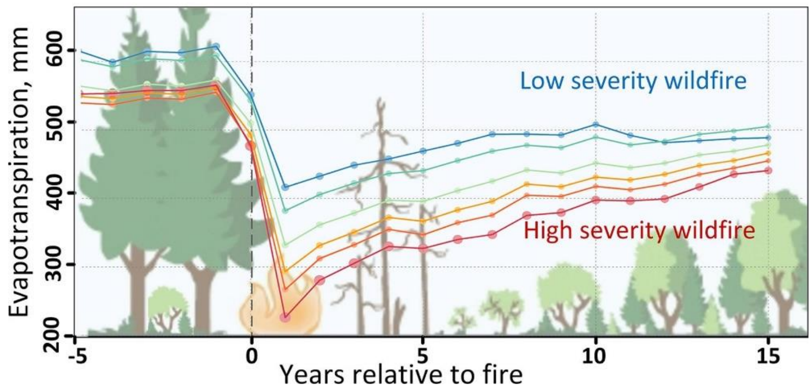


**Figure 2:** Plots of the average evapotranspiration rates observed in different catchments as a function of time and fire severity. Forests that experienced high severity fires experienced the largest reduction in evapotranspiration rates and took longer to recover to pre-fire conditions compared to those burned in lower severity fires [11].

Additionally, the loss of leaf area and increased soil exposure can influence the surface energy balance to be predominantly governed by latent heat flux (i.e., the loss of energy from the ground surface due to evaporation) and sensible heat fluxes (i.e., the loss of energy from the ground surface due to various mechanisms of heat transfer) [12]. For example, a study conducted by Montes-Helu et al., on the hydrological impacts that a high-severity fire had on a forest located in Northern Arizona reported that the burned sites had albedo that was on average 30% greater than that measured at the unburned sites. They associated this increase in albedo and loss of leaf area to the 20% reduction of annual evapotranspiration they observed the year following the fire [13].

However, numerous studies have also shown that the effect albedo has differs with season. In areas that obtain regular snowfall, such as Western Canada and the Northwestern United States, deposition of the pyrogenic carbon particles and debris that wildfires create darken the snow surface. Gleason, Nolin, and Roth found that combined with an increase in solar radiation, the heat absorption and soil temperature of a catchment increases, which accelerates snowmelt in the spring [14]. Overall, these varying observations affect the amount of soil water content, as well as the water available for groundwater recharge and run-off.

### 2.3 Effects on Surface Runoff

Following a wildfire, an increase in surface water runoff has been generally observed by numerous studies both in naturally occurring and artificially modelled wildfire experiments. Campbell et al. found surface runoff to be 8 times higher in a severely burnt 8.1 hectares (ha) catchment when compared to a 17.7ha unburnt catchment, during the first autumn rains following the 1972 Arizona ponderosa pine fire [15]. Moussoulis et al. established an average 112% runoff increase in the first-year post-fire for semi-arid catchments in central Greece as determined by their numerical modelling in agreeance with observed historical data [16].

This significant increase is intimately linked with a few major causes. Primarily, the direct connection fires have in decreasing interception. Wildfires burn ground cover, from large trees to low growing widespread vegetation, resulting in loss of interception material for future incoming precipitation. Often, very little is left to slow the rate at which rain reaches the soil surface, yielding a much earlier time to ponding [17]. The infiltration flux cannot keep up with the new much higher precipitation flux post fire, so runoff ensues. More interestingly however, is the phenomena of hydrophobicity as a catalyst for runoff. Wildfires that burn under high temperatures over an area with a thick layer of ground litter result in vaporization of some organic compounds in the litter. This gas moves its way into the soil condensing as it cools beneath the high temperature surface and forms a waxy coating over surrounding soil particles in a hydrophobic layer (Figure 3) [18]. This layer is variable in thickness and depth, Cory et al. found the layer increases with longer heating time, allowing the gas to seep further into the ground [19]. Hydrophobicity also demands burn temperatures large enough to volatilize ground litter without surpassing maximum extreme temperatures at which hydrophobic properties are destroyed. DeBano et al. found in soils collected in Southern California lost hydrophobicity at temperatures of 280-400°C [19].

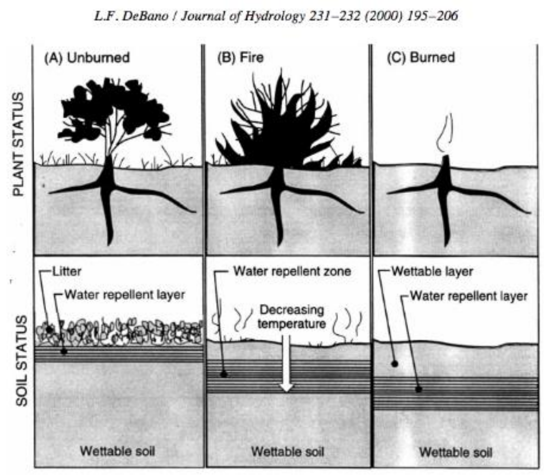


**Figure 3:** Process behind soil hydrophobicity. (A) Litter cover pre-fire. (B) Vaporization and movement of gas during burning. (C) Condensation forming the hydrophobic layer [18].

Conversely, although less studied, it is also important to note the formation of ash cover may delay or even decrease runoff in the short period following a wildfire. Woods and Balfour observed 3 times less runoff in ash covered plots from a Montana study when compared to no ash (Figure 4). The reason for this being the excess time required for precipitation to saturate the 1.9cm ash layer covering the soil with a high porosity of 84%,  before ponding on the surface and finally allowing runoff to occur [20]. This variance between increasing and decreasing runoff post wildfire responses is highly dependent on local climates, soil conditions, and ground cover. Therefore, it is difficult to predict proactively the post fire runoff conditions in an area. There is also complexity in predicting which obstacle will govern the hydrological conditions, be it: less interception, hydrophobicity or ash cover amongst others, research is needed to assess the degree to which each process controls post-fire runoff.

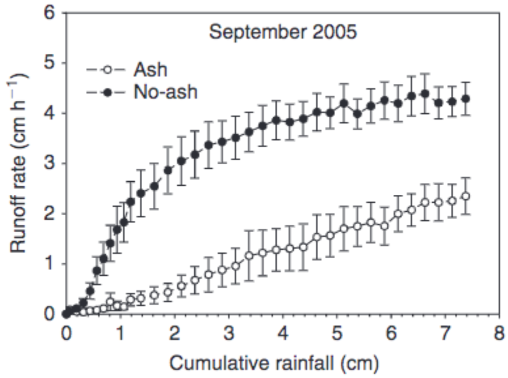


**Figure 4:** Mean Hydrograph from September 2005. Where points represent average runoff rates [20].

### 2.4 Effects on Streamflow

From the large amounts of surface runoff exhibited post wildfire with insufficient stream capacities to allow entrance, as a result peak flow increases dramatically. Neary et al. reported increased flood peak flows of anywhere from 10-100 times those previously recorded after a wildfire when examining historical globally sourced data [21]. However, this impact can increase even further and reach potential peak flood flows of up to 2,300 times pre-wildfire levels as observed by example on a severely burnt Stermer Ridge watershed in Arizona [22]. This high variability in the magnitude of short-term effects is why modelling and assessment of post fire peak flows remain under research, response functions depend on burn severity, terrain roughness, and climate of the area [23].

From a rise in stream flow, flash flooding is likely to occur in the immediate time following the wildfire. The Buffalo Creek fire of 1996 saw an intense post fire rainfall event, with 75 mm of precipitation falling in just over one hour [24]. This generated severe flooding over the burnt area, damaging infrastructure while also causing extreme stress to surface water systems themselves. Water quality within local streams is degraded, due to likely increase in contaminants entering from surface runoff and aquatic habitats suffer, due to the destructive nature debris flow has while being driven through streams [23]. Surface water contains and drives many extremely important local ecosystems, so these negative effects are crucially important to recognize and hopefully research to mitigate them in future events.

As a temporal comparison, although we see such a large spike in peak flow in the first few years after the fire, a gradual decrease in stream flow to a minimum is observed occurring 20-40 years after the fire [25]. The process behind this decline is due to secondary succession of the forest. Once new seedlings germinate and begin the stages of intensive regeneration of the forest cover, interception and transpiration increase rapidly for the following several years. During this phase the forest's water demand reaches a maximum and stream flow a minimum, lasting for decades while regeneration continues. In a study conducted by the Melbourne Water Corporation for Catchment Hydrology for the 1939 bushfires, Marcar et al. discovered over several decades, 11 annual stream flows declined to as low as 50% of pre-fire stream flow levels, a minimum of 600mm/year (Figure 5). The recovery of pre wildfire streamflow conditions is expected to take as long as 150 years [25]. These long-term recovery periods highlight the magnitude disturbance wildfires have in both short- and long-term effect to stream flow. Considering the numerous high-profile wildfires observed in 2020, there will need to be another century of observations to fully assess the damages these fires have left behind.

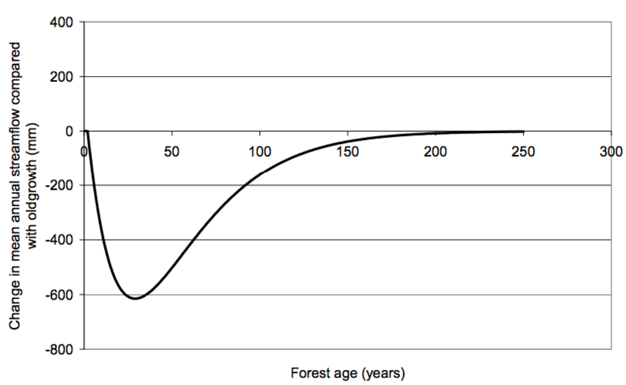


**Figure 5:** Annual Streamflow change with increasing forest age (years) for the 1939 Australian Bushfires [25].

## 3 Methodologies

Double catchment methods are used to assess post-wildfire hydrological effects. One catchment is burnt, either purposefully through artificial experimentation or by unexpected wildfire disturbances, while the other area remains intact and unburnt. These two catchments must exhibit similar pre-fire conditions in terms of: topography, ground cover, soil type, and absolute location to yield effective results. Both catchments are then monitored using rain gauge and other instruments in the time post fire to observe differences in their hydrological responses. The unburnt catchment’s data is treated as pre-fire conditions for the burnt catchment, eliminating the need for its pre-fire hydrological data, which often is unavailable, unreliable or old to begin with. Challenges with this approach are with locating appropriate similar unburnt catchments near the fire area, however many successes of this method have been documented. Heath et al. examined 4 burnt and 3 unburnt catchments within the Sydney Basin and found appropriate results in their experiment, in accordance with available pre-fire data [26].

## 4 Conclusions

### 4.1 Gaps in the Literature

The impacts wildfires have on hydrology are increasing in magnitude and longevity due to climate change which poses significant risks on water quality, human health and safety, and flooding. However, research into post-wildfire effects only began in the last century [27]. As a result, there is more work that needs to be done. Moreover, there are no standard measurements methods that have been developed to measure the post-fire hydrological impacts which are required for the comparison and the creation of computer models that can better predict future behaviour of these processes. Also, there is a lack of data available to build computer models and difficult accessing existing data. A better understanding of post-fire hydrological processes and how they are related is required to establish more effective water resource management systems, which could save governments millions of dollars in the near future [27].

### 4.2 Current Research Priorities

Postfire hydrologic responses at a local scale are generally transient, vary in time and space, as well as depend on factors such as climate, topography, geology, vegetation, and characteristics of the fire itself – all of which are measured by different methods [27]. These characteristics tend to hinder research progress as different studies apply varying methodologies. Thus, the research issues that must be prioritized include: (1) Determining re-occurring patterns that can explain the relations between varying processes through the organization of similarities and differences in post-fire hydrologic responses observed in various climates and geographies; (2) Identifying mathematical relations between hydrological processes such as precipitation, basin morphology, runoff, watershed storage, and soil characteristics required to predict the timing, magnitudes, and duration of floods and debris flows from unburned basins; (3) Developing standard measurement methods that will ensure that the collection of uniform and comparable data. Resolving these key issues will aid in improving current numerical models [27].

## References

[1] Thomas, D., Butry, D., Gilbert, S., Webb, D., & Fung, J. (2017). The costs and losses of wildfires: A literature survey. doi:10.6028/nist.sp.1215

[2] Wolters, C. (2020, July 02). Here's how wildfires get started-and how to stop them. Retrieved from https://www.nationalgeographic.com/environment/natural-disasters/wildfires/

[3] Burton, J. (2020, February 07). 'It was a line of fire coming at us': Firefighters return home. Retrieved from https://www.busseltonmail.com.au/story/6620313/it-was-a-line-of-fire-coming-at-us-firefighters-return-home/

[4] 2020 California fires are the worst ever. Again. (2020, September 15). Retrieved from https://www.latimes.com/projects/california-fires-damage-climate-change-analysis/

[5] What's behind the 'unprecedented' wildfires ravaging California | CBC News. (2020, September 12). Retrieved from https://www.cbc.ca/news/technology/california-wildfires-climate-change-1.5659909

[6] Hallema, DW, Sun, G, Bladon, KD, et al. Regional patterns of postwildfire streamflow response in the Western United States: The importance of scale-specific connectivity. *Hydrological Processes*. 2017; 31: 2582– 2598. https://doi.org/10.1002/hyp.11208

[7] Winkler, R. D., Moore, R. D., Redding, T. E., Spittlehouse, D. L., Smerdon, B. D., Carlyle-Moses, D. E. (2010). The effects of forest disturbance on hydrologic processes and watershed response. In: R. G. Pike, T. E. Redding, R. D. Moore, R. D. Winker, K. D. Bladon (eds), 2010. Compendium of forest hydrology and geomorphology in British Columbia. B.C. Min. For. Range, For. Sci. Prog., Victoria, B.C. and FORREX Forum for Research and Extension in Natural Resources, Kamloops, B.C. Land Manag. Handb. 66.

[8] Moody, J. A., & Martin, D. A. (2001). Post-fire, rainfall intensity–peak discharge relations for three mountainous watersheds in the western USA. Hydrological Processes, 15(15), 2981–2993

[9] Maina, FZ, Siirila-Woodburn, ER. Watersheds dynamics following wildfires: Nonlinear feedbacks and implications on hydrologic responses. *Hydrological Processes*. 2020; 34: 33– 50. https://doi.org/10.1002/hyp.13568

[10] Ebel, B. A., and Moody, J. A. Synthesis of soil-hydraulic properties and infiltration timescales in wildfire-affected soils. *Hydrological Processes*. 2017; 31: 324– 340. doi: 10.1002/hyp.10998.

[11] Qin Ma, Roger C. Bales, Joseph Rungee, Martha H. Conklin, Brandon M. Collins, Michael L. Goulden, Wildfire controls on evapotranspiration in California's Sierra Nevada, Journal of Hydrology, Volume 590, 2020, 125364, ISSN 0022-1694

[12] Niemeyer, RJ, Bladon, KD, Woodsmith, RD. Long-term hydrologic recovery after wildfire and post-fire forest management in the interior Pacific Northwest. *Hydrological Processes*. 2020; 34: 1182– 1197. https://doi.org/10.1002/hyp.13665

[13] Dore, Sabina & Kolb, Thomas & Montes-Helu, Mario & Eckert, S & Sullivan, B & Hungate, Bruce & Kaye, J & Hart, Stephen & Koch, George & Finkral, A.. (2010). Carbon and water fluxes from ponderosa pine forests disturbed by wildfire and thinning. Ecological applications : a publication of the Ecological Society of America. 20. 663-83. 10.1890/09-0934.1.

[14] Gleason, K. E., Nolin, A. W., and Roth, T. R. (2013), Charred forests increase snowmelt: Effects of burned woody debris and incoming solar radiation on snow ablation, *Geophys. Res. Lett.*, 40, 4654– 4661, doi:10.1002/grl.50896.

[15] Campbell, R. E.; Baker, Jr., M. B.; Ffolliott, P. F.; Larson, F. R.; Avery, C. C. 1977. Wildfire effects on a ponderosa pine ecosystem: An Arizona case study. USDA For. Serv. Res. Pap. RM-191. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experimental Station. 12 p.

[16] Moussoulis, E., Mallinis, G., Koutsias, N., and Zacharias, I. (2015) Modelling surface runoff to evaluate the effects of wildfires in multiple semi-arid, shrubland-dominated catchments. *Hydrol. Process.*, 29: 4427– 4441. doi: 10.1002/hyp.10509.

[17] Brian A. Ebel, Temporal evolution of measured and simulated infiltration following wildfire in the Colorado Front Range, USA: Shifting thresholds of runoff generation and hydrologic hazards, Journal of Hydrology, Volume 585, 2020, 124765, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2020.124765.

[18] L.F DeBano, The role of fire and soil heating on water repellency in wildland environments: a review, Journal of Hydrology, Volumes 231–232, 2000, Pages 195-206, ISSN 0022-1694, https://doi.org/10.1016/S0022-1694(00)00194-3.

[19] Kalendovsky MA , Cannon SH (1997) Fire-induced water-repellent soils: An annotated bibliography. *US Geological Survey Open-File Report* **97–720**. US Geological Survey, Denver, CO. 41 pp. (Website: http://geohazards.cr.usgs.gov/html_files/landslides/ofr97-720/biblio.html).

[20] Woods Scott W., Balfour Victoria N. (2008) The effect of ash on runoff and erosion after a severe forest wildfire, Montana, USA. *International Journal of Wildland Fire* **17**, 535-548. https://doi.org/10.1071/WF07040

[21] Neary, Daniel & Gottfried, Gerald & Ffolliott, Peter. (2003). Post-wildfire watershed flood responses.

[22] Gottfried, G. J., Neary, D. G., Baker Jr, M. B., & Ffolliott, P. F. (2003, October). Impacts of wildfires on hydrologic processes in forest ecosystems: two case studies. In Proceedings, First Interagency Conference on Research in the Watersheds (pp. 27-30).

[23] Neary, Daniel G.; Koestner, Karen A.; Youberg, Ann. 2011. Hydrologic impacts of high severity wildfire: Learning from the past and preparing for the future. Paper presented at the 24th Annual Symposium of the Arizona Hydrological Society; Watersheds near and far: Response to changes in climate and landscape; September 18-20, 2010; Flagstaff, AZ. 8 p.

[24] Elliott, J.G. and Parker, R.S. (2001), Developing a post-fire flood chronology and recurrence probability from alluvial stratigraphy in the Buffalo Creek watershed, Colorado, USA. Hydrol. Process., 15: 3039-3051. https://doi.org/10.1002/hyp.390

[25] Marcar, N., Benyon, R., Polglase, P., Paul, K., Theiveyanathan, T. & Zhang, L. (2006). Predicting the hydrological impacts of bushfire and climate change in forested catchments of the River Murray Uplands: A review.

[26] Heath, J. T., Chafer, C. J., van Ogtrop, F. F., and Bishop, T. F. A., "Post-wildfire recovery of water yield in the Sydney Basin water supply catchments: An assessment of the 2001/2002 wildfires", <i>Journal of Hydrology</i>, vol. 519, pp. 1428–1440, 2014. doi:10.1016/j.jhydrol.2014.09.033.

[27] John A. Moody, Richard A. Shakesby, Peter R. Robichaud, Susan H. Cannon, Deborah A. Martin, Current research issues related to post-wildfire runoff and erosion processes, Earth-Science Reviews, Volume 122, 2013, Pages 10-37, ISSN 0012-8252.