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Author/s:

Van der Sant, RE;Nyman, P;Noske, PJ;Langhans, C;Lane, PNJ;Sheridan, GJ

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Nyman Petter (Orcid ID: 0000-0002-0366-5548)
 Noske Philip J. (Orcid ID: 0000-0001-5560-3309)

Quantifying relations between surface runoff and aridity after wildfire

René E. Van der Sant^{1,2*}, Petter Nyman¹, Philip J. Noske¹, Christoph Langhans¹,
 Patrick N.J. Lane¹ and Gary J. Sheridan¹

¹The University of Melbourne, ²Melbourne Water Corporation

*Corresponding author:

René E. Van der Sant

Address:

School of Ecosystem and Forest Sciences

The University of Melbourne

Baldwin Spencer Building 113

Parkville, Victoria 3010

Tel:

0412 386 162

E-mail:

rene.vandersant@melbournewater.com.au

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Abstract

Post-wildfire runoff and erosion are major concerns in fire-prone landscapes around the world, but these hydro-geomorphic responses have been found to be highly variable and difficult to predict. Some variation has been observed to be associated with landscape aridity, which in turn can influence soil hydraulic properties. However, to date there has been no attempt to systematically evaluate the apparent relations between aridity and post-wildfire runoff. In this study, five sites in a wildfire burned area were instrumented with rainfall-runoff plots across an aridity index (AI) gradient. Surface runoff and effective rainfall were measured over 10 months to allow investigation of short- (peak runoff) and longer-term (runoff ratio) runoff characteristics, over the recovery period. The results show a systematic and strong relation between aridity and post-wildfire runoff ratio. The average runoff ratio at the driest AI site (33.6%) was two orders of magnitude higher than at the wettest AI site (0.3%). Peak runoff also increased with AI, with up to a thousand fold difference observed during one event between the driest and wettest sites. The relation between AI, peak 15-minute runoff (Q_{15}) and peak 15-minute rainfall intensity (I_{15}) (both in mm h^{-1}) could be quantified by the equation: $Q_{15} = 0.1086I_{15} \times AI^{2.691}$ ($0.6 < AI < 1.8$, $0 < I_{15} < 45$) (adjusted $r^2 = 0.84$). The runoff ratios remained higher at drier AI sites (AI 1.24 and 1.80) throughout the monitoring period, suggesting higher AI also lengthens the window of disturbance after wildfire. The strong quantifiable link which this study has determined between AI and post-wildfire

surface runoff could greatly improve our capacity to predict the magnitude and location of hydro-geomorphic processes such as flash floods and debris flows following wildfire, and may help explain aridity related patterns of soil properties in complex upland landscapes.

Keywords: Fire; surface runoff; landscape aridity; erosion; debris flow

Introduction

Understanding and being able to predict post-wildfire runoff and erosion are major concerns in fire-prone environments around the world (Moody *et al.*, 2013). The timing, severity, and spatial extent of post-wildfire runoff and erosion can influence local stream morphology and ecological habitats (Benda *et al.*, 2003, Miller *et al.*, 2003, Rhoades *et al.*, 2011), sediment budgets (Benda and Dunne, 1997), and landscape evolution (Istanbulluoglu *et al.*, 2004). Negative impacts of post-wildfire runoff and erosion on people can vary from untreatable drinking water (Emelko *et al.*, 2011, Smith *et al.*, 2011, White *et al.*, 2006) to infrastructure destruction and loss of life (Cannon *et al.*, 2008, Jordan and Covert, 2009, Moody *et al.*, 2013, Nyman *et al.*, 2011).

Accordingly, researchers and natural resource managers require information to quantify this spatial variation in post-wildfire runoff and erosion processes to better understand the role of wildfire in a landscape and the potential for post-wildfire hazards and risk (Moody *et al.*, 2013, Nyman *et al.*, 2013). However, these hydro-geomorphic responses of landscapes to fire have been found to be highly variable and difficult to predict.

Following wildfire, hydrological changes such as removal of vegetation protecting the soil surface, increased soil water repellency (DeBano, 2000, Doerr *et al.*, 2000), pore blockage due to fine particle inwash (Larsen *et al.*, 2009), decreased surface roughness (Lavee *et al.*, 1995), or raindrop compaction (Shakesby and Doerr, 2006) can result in a reduced rainfall

threshold for runoff generation. Damaging surface runoff and erosion can, therefore, occur in response to short duration (5, 15, or 30 minute) and/or higher frequency (1, 2, or 5 year return interval) rainfall events (Moody *et al.*, 2013, Nyman *et al.*, 2011). Surface runoff in response to high intensity, short duration rainfall events is particularly important for the generation of debris flows (Gabet and Sternberg, 2008) and flash floods (Cannon *et al.*, 2008) following fire.

The conversion of rainfall to runoff at the point scale is directly controlled by the infiltration-related properties of the soil, which are a function of factors such as structure (porosity), aggregate stability, water repellency, and moisture content. Information on these fine-scale soil properties is frequently unavailable and/or prohibitively resource intensive to collect, particularly in remote catchments. Spatially mappable surrogates for these often unavailable soil properties are therefore extremely valuable for predicting the post-wildfire hydrological responses.

Conceptual models of soil development (Jenny, 1941) and limited observations (Langhans *et al.*, 2016, Noske *et al.*, 2016, Sheridan *et al.*, 2016) indicate that some of the enormous variability in surface runoff generation and post-wildfire erosion is associated with landscape aridity, which is the long-term balance between rainfall and evaporation (Budyko, 1974, Nyman *et al.*, 2014, Prescott, 1949, Priestley and Taylor, 1972). Over long time scales, aridity-induced variation in moisture availability would

primarily be expected to affect soil development, structure, and stability through weathering rates (Atkinson, 2004), biological activity (Jastrow and Miller, 1991), and the input and redistribution of organic matter and minerals (Attiwill and Leeper, 1990). This variation would result in intrinsic differences between soil hydraulic properties due to variation in soil structure (e.g. porosity) and composition (e.g. particle size, organic matter content) (Jenny, 1941). For example, soil depth and structural development is generally greater in wet Eucalypt forests compared with dry Eucalypt forests in south-east (SE) Australia, even though these forests may be only a few kilometres apart (Rees, 1982). Under normal forested conditions aridity-driven variation in soil surface hydrology and runoff generation is likely negligible as vegetation stabilises soil and reduces erosion (Cerdà and Doerr, 2005). Removal of vegetation by wildfire exposes the soil, highlighting differences in soil infiltration capacity. While some studies have observed a homogenisation of soil properties (such as soil moisture retention and soil temperature) by fire (Ebel, 2012a, Ebel, 2012b), observations and anecdotal evidence suggest aridity-driven differences in soil infiltration properties in SE Australian forests is enhanced after burning (Sheridan *et al.*, 2016).

Previous studies of post-wildfire responses have included some features of moisture availability or aridity, but they have not used landscape aridity as a specific index or variable to quantitatively explain the responses. For instance, hillslope aspect can be used to contrast local variation in net radiation and

aridity. A comparison of runoff ratios on opposite aspects in the Mediterranean showed that they were significantly higher (in some case by an order of magnitude) on drier slopes (equatorial facing with higher net radiation) compared with wetter slopes (polar facing with lower net radiation) (Cerdà *et al.*, 1995, Marques and Mora, 1992, Wittenberg *et al.*, 2014, Wittenberg *et al.*, 2007). Ebel (2013) and Ebel *et al.* (2015) observed variation in hydrologic state changes between north- and south-facing slopes in the Colorado front range, USA. Hyde *et al.* (2007) also observed association between basin aspect and post-wildfire gully rejuvenation in this region with the highest rejuvenation overall in west- and southwest-facing basins. In SE Australia, the incidence of post-wildfire debris flows was linked with forest types occurring in drier systems and equatorial facing aspects (Nyman *et al.*, 2011), as well as substantial differences in runoff and erosion response between aspects (Noske *et al.*, 2016).

To date there has been no attempt to systematically evaluate the apparent relation between aridity and post-wildfire runoff. This knowledge gap limits our capacity to use aridity as a landscape-scale predictive tool. The objective of this study was to directly measure and quantify this relation, with emphasis on both the short- (peak runoff) and long-term (runoff ratio) runoff characteristics, from hillslopes following high severity wildfire.

Methods

Hillslope surface runoff plots were established in a wildfire-burnt area across an aridity gradient (holding other factors as constant as possible) to isolate the effect of aridity on post-wildfire runoff. Surface runoff and effective rainfall (rainfall minus interception) were measured over 10 months across five sites of differing aridity. This allowed an investigation of short- (peak runoff) and long-term (runoff ratio) runoff characteristics, along with changes in runoff over the recovery period.

Aridity index

The aridity index (AI) was calculated using equation 1:

$$AI = \frac{Ep}{P} \quad (1)$$

where Ep is potential evaporation and P is annual precipitation. Ep was determined using Priestley-Taylor's model (Priestley and Taylor, 1972). This model of Ep is widely used due to its robust ability to represent evapotranspiration and its simplicity of use (Ai and Yang, 2016, Flint and Childs, 1991). Ep was estimated using net radiation and temperature that were downscaled from regional long-term meteorological observations to produce values at 20m resolution (corresponding to the DEM) (Nyman *et al.*, 2014). This downscaling incorporates the effects of aspect, slope gradient, and elevation on Ep (Nyman *et al.*, 2014). The influence of aspect on aridity is considered during the estimation of direct shortwave radiation. Rainfall was obtained from gridded data (BoM) where point based rainfall records have

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been interpolated using a widely used 3d interpolation algorithm, which accounts for systematic changes in rainfall with elevation (Xu and Hutchinson, 2011). Thus, AI represents variations in aridity due to both the local topographic effects (aspect and slope) as well as larger-scale effects associated with elevation and orographic rainfall. The estimated AI using Priestley-Taylor as the E_p forcing is similar to indices proposed by Budyko (1974) and Prescott (1949), but is better able to incorporate changes in temperature and therefore variation in aridity due to elevation. Budyko's radiative index of dryness was also calculated for each of the sites, obtained from Nyman *et al.* (2014), to provide compatibility with other studies of this type (see Table 1).

Study area

This study was conducted within the burned area from the Aberfeldy wildfire which occurred in 2013 within the Thompson State Forest between Aberfeldy (37.68°S 146.37°E) and Walhalla (37.93°S 146.45°E), Victoria, Australia (Figure 1).

The study area was burnt by a wildfire which started just south of the Aberfeldy township on 17th January 2013. The fire burnt for approximately six weeks and reached a total size of 86,000 ha (DEPI, 2014), with over half the area (44,869 ha) burning within the first 24 hours. The burn severity across the forest was highly variable with unburnt patches occurring adjacent to high severity areas; 46% was burned at high severity (crown burn/scorch), 46% at

medium severity (partial crown scorch and/or understorey burnt) and 8% at low severity (understorey partly unburnt) or unburnt. The fire was brought under control following rainfall (38 mm recorded in Aberfeldy) on 28th February 2013.

Victoria has a warm temperate climate with generally warm, dry summers and cool, wet winters (Kottek *et al.*, 2006). In autumn and winter (March–August), precipitation in the study area is influenced by systems which result in long duration, low intensity rainfall events (BoM, 2014). In summer (December–February), rainfall is often characterised by infrequent, high intensity storms. Monthly rainfall in the study area varies from an average of 70 mm (February) to 112 mm (October) (BoM Erica station 37.98°S 146.37°E). Rainfall during the experimental period was similar to the long term mean of the region (Figure 2). Snowfall below 1200 m is typically light and the ground does not freeze; two light falls were recorded during winter in the study area. Average summer and winter temperature ranges in nearby Erica are 12.4°C/23.2°C and 4.2°C/10.8°C respectively. Mean daily solar radiation exposure at Aberfeldy is 15.1 MJ m⁻² (4.2 kWh m⁻²), daily insolation varies from an average of 24.5 MJ m⁻² (6.8 kWh m⁻²) in January (summer) to 5.9 MJ m⁻² (1.6 kWh m⁻²) in June (winter) (BoM, 2014).

The value of the aridity index varies across the study area as a function of regional scale rainfall patterns, orographic rainfall gradients, and topographic control of solar radiation exposure. Large scale patterns in AI occur due to the

rain shadow created by the Baw Baw Mountains to the west (Parks Victoria, 2012). At smaller scales, strong AI differences are observed between north- and south-facing hillslopes, and between areas of high and low relief (Figure 1).

Vegetation of the study area is dominated by dry mixed species Eucalypt forest (including Mountain Grey Gum *Eucalyptus cypellocarpa*, Messmate *E. obliqua*, Manna Gum *E. viminalis*, Broad-leaf Peppermint *E. dives*, and Narrow-leaf Peppermint *E. radiata*), with an understorey of grasses, bracken fern (*Pteridium esculentum*), and small shrubs (DSE, 2004). In higher rainfall areas (>1000 mm per year), Mountain Ash (*E. regnans*) begins to dominate the overstorey, moving to a pure stand as annual rainfall increases, with an understorey of tree ferns (*Dicksonia antarctica*, *Cyathea australis*) (Costermans, 2009).

The geology of the area is predominantly Palaeozoic (Silurian to early Devonian) sedimentary and metamorphic marine deposits, with some granitic intrusions (Birch *et al.*, 2003). It is part of the East Victorian Uplands (Dissected uplands), an area which was uplifted by slow, periodical, tectonic movements starting in the early Cretaceous (Cochrane *et al.*, 1995). Deep, steep-sided valleys separated by narrow ridges dominate the area due to river downcutting following this uplift. Soils derived from this geology are typically brown earths (Dermosols) and shallow stony loams (Kandosols) (Isbell, 2002).

Disturbances other than bushfire in the study area include tourism, timber harvesting, and mining. No timber harvesting is recorded at the research sites within the period of reliable harvesting records for this area, which extends from approximately 1950 to the present (Vic Forests, 2014, pers. comm., 9 July). Gold mining occurred in parts of the forest from the 1860s, particularly towards the township of Walhalla in the south (Lloyd and Combes, 2010). The sites were not located within an area likely to have been disturbed by registered mines and none of the typical evidence of past gold mining activity was apparent from visual inspection at each of the experimental sites (e.g. abandoned mining structures, collapsed mine-shafts, stone water races).

Site selection and experimental set up

Five sites (20 x 20m) were selected and instrumented within the Aberfeldy burned area to cover a wide range of aridity index (AI) values (Table 1 and Figure 3). Site AI was determined in the field using a real-time GPS-ArcGIS interface with the mapped index. Sites were chosen with the objective of keeping factors other than AI constant or within a narrow range, so that the AI level was the primary difference between the sites. Burn severity was patchy across the burned area and the mapped burn severity based on canopy assessment (satellite or aerial photography) was not always the best indicator of soil burn severity. For example, the lowest AI instrumented site (AI 0.65, see Table 1) was classified as a lower severity burn (class 4 understorey burn), but destruction of biomass indicated that the burn severity near the soil

surface was comparable to the other sites. Burn severity on the ground was considered high where all surface fuels were burnt (material < 2 mm destroyed), understory shrubs had been burnt or scorched, and the canopy had been scorched or flame heights were >15 m. Upper to middle hillslope positions, with a slope of 25–30 degrees were chosen to reduce variation due to topographic position. Sites were located on a planar section of hillslope to avoid i) differences between slope curvature (concave vs convex), and ii) flow direction and channelling effects. All sites were located on sedimentary or metamorphic bedrock according to the Land System of Victoria GIS layer (LSYS250) as detailed in Rees (2000). Field observations suggest soils at AI 0.65 were slightly sandier, being influenced by the nearby igneous granitic intrusion which forms Mt Useful (Mt Useful Granodiorite).

Installation of monitoring equipment at the sites was completed in June 2013, approximately 4 months after the fire, and the sites were active until April of the following year (14 months since fire). At each site, post-wildfire runoff and rainfall was monitored with:

- Two 8m long bounded plots with tipping buckets
- One throughfall trough setup with tipping bucket
- One data logger (Tain Electronics)

Basic site setup is shown in Figure 4. Components of the study were all located within a 20 x 20 m AI pixel and placed to avoid any interference with each other.

Measuring surface runoff and rainfall

Bounded plots (8 x 1.5 m) were constructed using galvanised steel sheet edging (105 x 15 cm, 1.5 mm thickness) (Figure 4). Each plot ended in a collector and pipe connected to a tipping bucket. Plot edging was hammered (using mallets) into the soil to a depth of 3–5 cm, with an overlap at each end of approximately 5 cm. For stability, the sheets were then riveted together and the joins sealed with silicone sealant. Concrete was used to seal the gap between the soil and the downslope edge of the plot and in front of the collector to ensure surface runoff would not undermine or leak through these areas. This method worked well and no undermining was detected during the study. Wire mesh was also placed across the plot above the collector to prevent stones and other large debris from blocking the collector, and drainage lines were dug around the outside of the plots to protect the plots from intrusion of runoff generated further upslope. The box collector was attached to a pipe (50 mm diameter) and flexible tubing which carried water to the tipping buckets. Tipping buckets had a capacity of ~ 500 mL per tip. Each tipping bucket was affixed with screws on top of a concrete slab (40 x 40 cm), the slabs were levelled on soil cuttings in the hillslope.

Effective rainfall (rainfall minus interception) was measured below the canopy at a height of approximately 30 cm using throughfall troughs. Throughfall troughs were constructed from two galvanised steel roofing gutters (7.0 x 0.15 m) running parallel downslope and emptying into a tipping bucket. Two lengths were used to increase the catchment area and allow for the use of a

500 mL tipping bucket. Lengths were suspended just above the ground using wire and steel fence post; this setup allowed the troughs to be close to the ground but unaffected by microtopography, and allowed for flexibility when struck by falling debris (e.g. tree branches). A downpipe at the end of each gutter connected to a Y-shaped pipe, which allowed water to flow together from both lengths. This was then connected to the standard collection pipe and flexible hose leading to a tipping bucket (Figure 4).

The runoff and rainfall data were obtained using a manual counter and a reed switch attached to a data logger (Tain Electronics). Magnets on the sides of the tipping buckets activated both the counter and the reed switch when tipped. The data loggers recorded the number of tips in three minute intervals. The sites were visited at intervals of 15–20 days, over the 10-month monitoring period. At each visit data were recorded from the manual counters and downloaded from the loggers.

Data handling

Manual counter data were checked against logger data to identify problematic periods and they were adjusted before analysis by substituting logger data when there were known to be problems with a manual counter. Logger data quality were also checked by comparing daily rainfall/runoff patterns between sites. Periods of missing or potentially incorrect data were identified and removed from further analysis. At site AI 0.80 rainfall was not recorded by a data logger until 4 months after installation of the plots, in October 2013.

However, as sites AI 0.75 and AI 0.80 were located approximately 500 m apart and had similar vegetation cover, missing rainfall data were estimated using an empirical regression of the existing data. This was checked against manual counter data obtained over the same period.

Data analysis

Logger data recording effective rainfall (beneath the canopy) were analysed to identify all rainfall events over 5 mm, to link peak rainfall with peak runoff.

Data were first summarised by day, then by hour, to identify individual rainfall events with a total of 5 mm. Rainfall events were considered discrete when there was no tipping for a period of an hour, this ensured that long duration, low intensity rainfall events were also included.

To compare between rainfall events, the maximum rainfall intensity over a 15-minute period (I_{15} mm h⁻¹) was used. The average intensity over time is a commonly used metric, but it is important to choose a rainfall descriptor appropriate to the research (Dunkerley, 2010). Intervals between 10 to 30 minutes have been shown to correlate well with rainfall properties driving post-wildfire runoff and erosional response (Moody *et al.*, 2013).

The peak rainfall intensity (I_{15} mm h⁻¹) was calculated using the flow rate from the throughfall troughs. The peak 15-minute runoff (Q_{15} mm h⁻¹) was calculated in a similar manner by identifying the highest flow rate from the plots over a 15-minute period within each rainfall event.

Runoff ratio (RR) for the plots was calculated using the total runoff in mm (Q) of the plots and effective rainfall in mm (P_n) recorded from the throughfall troughs by the following equation:

$$RR = \frac{Q}{P_n} \quad (2)$$

Results

AI and runoff response

Variation in runoff response across the AI gradient could be observed over the entire monitoring period and during individual storm events. The runoff ratio (equation 2) was positively correlated to AI by a power law (equation 3).

$$RR = 0.06394 AI^{2.822} \quad (0.6 < AI < 1.80) \quad (3)$$

where RR is runoff ratio and AI is aridity index.

Equation 3 suggests AI can explain 91% of variability in the data (adjusted r^2 0.91), within the AI range tested ($0.6 < AI < 1.8$) (Figure 5a). This fitted equation was also consistent with runoff ratio data in the first year after fire from Noske *et al.* (2016).

Runoff response during individual storm events, in the form of peak runoff (mm h^{-1}), also showed a strong variation with AI. The change in Q_{15} with increasing I_{15} was more pronounced for higher AI sites compared with lower AI (Figure 5b). A fitted surface model, equation 4, explained 84% of variability in the data (adjusted r^2 0.84).

$$Q_{15} = 0.1086I_{15} \times AI^{2.691} \quad (0.6 < AI < 1.8, 0 < I_{15} < 45) \quad (4)$$

Event-based runoff ratio was similarly correlated with peak rainfall intensity across the aridity gradient, with a fitted surface model resulting in an exponent of $AI^{2.695}$.

Runoff ratio and peak runoff can be highly dependent on rainfall event characteristics, especially intensity (Moody and Martin, 2001). An analysis of rainfall events over 5 mm (24–30 events per site) suggests there were no potentially confounding patterns in the intensity of rainfall events between sites or with time since fire. Given this and other variables affecting runoff response were held constant, observed variation in runoff response could be attributed to aridity (Table 2).

Aridity-driven variation in runoff response was most pronounced during the highest intensity rainfall event (21 March 2014) observed 13 months following fire. Site AI 0.65 experienced the highest rainfall intensity I_{15} 45.6 mm h⁻¹ and the lowest peak runoff Q_{15} 0.0007 mm h⁻¹. In contrast, site AI 1.80 produced the highest peak runoff during this event Q_{15} 0.016 mm h⁻¹ despite having the second lowest rainfall intensity I_{15} 23.3 mm h⁻¹.

Temporal variation of runoff

Aridity-driven variation in runoff remained evident throughout the study despite expected changes in seasonal weather and soil and vegetation recovery (time since fire). Cumulative runoff across the sites showed a strong positive

relation with AI (Figure 6a), with the higher AI sites (e.g. AI 1.80 = 0.336 $\text{mm}_{\text{runoff}}/\text{mm}_{\text{rain}}$) producing ca. 170 times more runoff (per unit rainfall) than the lower AI sites (e.g. AI 0.65 = 0.002 $\text{mm}_{\text{runoff}}/\text{mm}_{\text{rain}}$) (Figure 6a).

Runoff ratio across all sites reduced over time as the sites recovered, but the trend of higher runoff with higher AI continued for the entire period (Figure 6). The average runoff ratio for site 1.80 (33.6%) was substantially higher than all other sites for the entire monitoring period. With similar rainfall conditions at all the sites and no systematic temporal changes in rainfall intensity over this period, this reduction in runoff generation can be attributed to “recovery” (of both soil and vegetation). Results suggest recovery (reduction in runoff generation) is almost complete at lower AI sites by the end of the monitoring period (14 months since fire), while higher AI sites still exhibit substantial runoff generation.

Discussion

Aridity and runoff response

The results show a systematic and extremely strong relation between aridity index (AI) and post-wildfire runoff. The runoff ratio, averaged over the whole monitoring period, at the highest AI site (33.6%) was two orders of magnitude greater than the lowest AI site (0.3%). Peak runoff also increased with AI, with up to a thousand-fold difference observed during the highest intensity rainfall event. This pattern was evident throughout the whole monitoring period, despite variations in seasonal rainfall and post-wildfire recovery. These results

provide a strong empirical linkage between AI and post-wildfire runoff response and quantify these relations across a wide range of AI values. In previous work, these relations have only been opportunistically investigated across a relatively narrow range of AI values. For example, the interpretation of the data presented in Sheridan *et al.* (2016) was limited by different measurement techniques and other confounding variables such as scale and geology. The results from experimental work in the Stony Creek catchments reported by Noske *et al.* (2016) in north-east Victoria showed distinct differences with aridity, but the aridity range studied was very small and limited to only two levels (AI 1.77 (polar facing) and AI 1.60 (equatorial facing)). In their work on predicting debris flows in SE Australia, Nyman *et al.* (2015) found that AI was an important predictor of post-wildfire debris flow occurrence, but that its effect was only apparent in the statistical model when the range of AI was large (AI 0.31-2.59). The current study reinforces the value of the AI as a proxy for post-wildfire hydro-geomorphic processes and, for the first time, uses a controlled experiment to relate rainfall-runoff response to AI after high severity wildfire.

In a global context, a positive relation between aridity and post-wildfire runoff has also been observed and is considered to be linked to a climosequence of soil development. Climosequence studies testing the relation between soil properties and climatic factors often examine landscape scale gradients (Jenny, 1941), but in complex terrain climatic variation may be sufficiently

large over small spatial scales to influence soil properties. The role of a climosequence at local scales is frequently explored by using aspect to generate an aridity gradient (Cerdà *et al.*, 1995, Ebel *et al.*, 2015, Marques and Mora, 1992, Wittenberg and Inbar, 2009, Wittenberg *et al.*, 2014, Wittenberg *et al.*, 2007). For example, Marques and Mora (1992) observed a difference in runoff ratio between aspects, average 5.8% (equatorial facing) compared to 1.5% (polar facing), on burnt hillslopes in the north of Spain. In the north-west United States, aridity-driven effects have been documented across both local (Hyde *et al.*, 2007) and regional (Wondzell and King, 2003) scales. However, it is important to note that the strength of a climosequence or aridity-driven variation in soil development processes will vary depending on the relative range and strength of other variables that influence soil development, such as geologic properties and age, catena position, and topography.

The results of this study seem to indicate that the climosequence (represented by AI) is closely associated with runoff processes and, thus aridity is a primary control on soil hydraulic properties in this domain. Although no direct soil properties or vegetation recovery data are presented here, runoff patterns observed during the study are in line with general theory that soil structural development, soil infiltration capacity, and vegetation growth are lower under more arid conditions (Jenny, 1941, Thompson *et al.*, 2010). For example, Nyman *et al.* (2010) and Nyman *et al.* (2014) found macropores (> 0.5 mm)

contributed substantially to soil infiltration and runoff generation in the post-fire hydrophobic environment, in SE Australia (up to 70% and 95% of the field-saturated and ponded hydraulic conductivity respectively). A more arid environment would be expected to have reduced biologic activity (Ossola and Nyman, 2017), organic matter input (Ebel, 2012a, Moody and Nyman, 2013), and soil development, and consequently reduced formation and stability of pores, especially large pores (Beven and Germann, 1982, Jastrow and Miller, 1991). Similarly, the level of biomass and recovery of vegetation following wildfire would be expected to be lower at higher aridity sites (Wittenberg *et al.*, 2014). Vegetation cover and biomass has been correlated with infiltration capacity (Anderson and Burt, 1990, Dunne, 1978), particularly in water-limited systems such as those experienced in the forests of SE Australia (Thompson *et al.*, 2010, Noske *et al.*, 2016, Lane *et al.*, 2012). The recovery of ground cover following wildfire has also been shown to be important in increasing soil infiltration, and decreasing runoff generation and erodibility (Cerdà and Doerr, 2005, Marques and Mora, 1992, Moody and Nyman, 2013). In line with these results, in the current study, aridity-driven variation in vegetation cover and recovery (Figure 3) corresponds with patterns of runoff ratio (Figure 6 a and b).

The variation between sites is particularly clear immediately following fire. Over time, the runoff ratio of each site decreases, as does the absolute difference between sites (Figure 6b), supporting the interpretation that fire

enhances runoff potential (Sheridan *et al.*, 2016). If runoff measurements at the end of the monitoring period are reflective of unburnt levels, this suggests the background variation in runoff generation between sites, particularly the lower aridity sites, is small. Following fire, runoff generation is substantially enhanced with all sites showing distinctly different runoff generation levels. Runoff levels stabilise approximately 8 months after fire, with the lower aridity sites recovering slightly faster than the higher aridity sites (Figure 6b), which is consistent with observed vegetation patterns (Figure 3). The runoff ratio recovery shown in Figure 6b also suggests that *resistance* to the effects of wildfire is lower at high aridity sites compared with the low aridity sites, while *resilience* to wildfire is high across all aridities. Short-term effects of wildfire which have been shown to be important in runoff generation include soil water repellency (Doerr *et al.*, 2000, Shakesby *et al.*, 2000), vegetation cover (Wittenberg *et al.*, 2007), and soil sealing (Larsen *et al.*, 2009).

The most pronounced aridity-driven variation in runoff and erosion is greatest directly after the fire, and lessens over time as the sites recover. Therefore, accounting for the time after fire might improve the predictive relations determined in this study. The empirical equation determined from our observations (equation 3) already accounts for a large amount of variation (91%), but if a more accurate prediction of post-wildfire runoff were required, including time since fire as a variable would likely be beneficial. This inclusion

may be particularly useful amongst higher AI sites (above 1.24), where absolute change in runoff ratio is highest.

The observed relations between both AI and runoff ratio, and AI and peak runoff with peak rainfall intensity suggests the effect of AI is threshold dependent. Although only five AI levels were measured, the results show a dramatic increase in average runoff ratio between the lower AI sites (0.65 and 0.75) and the higher AI sites (1.24 and 1.80), suggesting a threshold point where AI becomes an important factor in predicting runoff response. Research into post-wildfire debris flow processes also suggests a threshold of runoff is required for initiation (Cannon *et al.*, 2003). Results from this study suggest lower AI sites have a lower initial runoff ratio following fire, and recover to negligible levels of runoff faster than high AI sites. This means lower AI would more often remain below the debris flow runoff initiation threshold, even under high intensity rainfall.

Implications for hydrologic and geomorphic processes

At the landscape scale, aridity-driven variation in post-fire surface runoff could control landscape scale hydrologic and geomorphic processes, including flooding, runoff-initiated debris flows, and long-term erosion rates. Following high severity wildfire, the probability of flash flooding and runoff-initiated debris flow occurrence is considered to be strongly dependent on surface runoff potential and rainfall within the recovery window (Cannon *et al.*, 2008, Jones *et al.*, 2014, Prosser and Williams, 1998). Results of the study show higher AI

is associated with the prolonged generation of substantial surface runoff and peak flows. This is coupled with slower post-wildfire recovery, which increases the probability of an erosive rainfall event occurring within the recovery window. For example, under a rainfall event with a one-year return interval for the area (approximately $I_{15}=38 \text{ mm h}^{-1}$) results suggest the peak runoff from the highest AI site would be 20 times greater than the lowest (0.0008 mm h^{-1} at site AI 0.65 to $> 0.017 \text{ mm h}^{-1}$ at site AI 1.80). Thus, low aridity sites might only pose a major flooding or erosion risk under a 100-year rainfall event, while higher aridity sites might pose a risk under 1–5 year rainfall events. Post-wildfire debris flows in SE Australian forested catchments have been initiated under rainfall events with an I_{30} of 35 mm h^{-1} (Nyman *et al.*, 2011), a rainfall event which has an average return interval of 2–5 years for this area. Aridity-related variation in post-fire surface runoff may also contribute to the longer term evolution of the soil profile in fire-prone forested uplands. Under the same fire regime, lower aridity areas would be expected to have lower potential erosion than higher aridity areas, resulting in a divergence between their erosion rates. In forested environments in the United States, field studies and modelling suggest post-wildfire erosion and debris flow processes contribute a substantial portion of long-term erosion (Istanbulluoglu *et al.*, 2004, Meyer *et al.*, 2001, Pierce *et al.*, 2004). In Australia, Smith *et al.* (2012) calculated a potential depletion of the soil profile of 0.2–1 m in 8,700–43,500 years beneath dry Eucalypt forest due to post-wildfire debris flow processes.

In addition, there is a potential for positive feedback whereby higher fire-related erosion rates result in shallower soils, a more open forest canopy, drier fuels, and as a result, more frequent fire and erosion.

Over the long term this spatial variation in aridity-driven erosion potential could lead to variation in landscape morphology. For example, hillslope asymmetry between polar and equatorial facing slopes has been attributed to differences in insolation and erosional processes (Burnett *et al.*, 2008, Cerdà *et al.*, 1995, Istanbuluoglu *et al.*, 2008, Marques and Mora, 1992, Munro and Huang, 1997, Selkirk *et al.*, 2001). Poulos *et al.* (2012) observed distinct patterns in hillslope asymmetry across mountainous landscapes in the United States, and concluded that specific dominant process controlled asymmetry development within a region. Given the high correlation between AI and post-wildfire runoff potential in SE Australian forests observed in the results of this study, aridity could be a dominant control on hillslope evolution in this region.

Implications for practical application and prediction

With the strong and quantified associations identified in this paper, post-wildfire hillslope surface runoff can now be spatially mapped using AI as a proxy, within the AI range tested ($0.6 < AI < 1.8$). This is the first study to directly investigate these relations in a burnt environment, and the strong relations identified suggest AI provides a means to estimate processes and/or properties which are resource intensive or impractical to determine through field work. Although limited in scope (e.g. burn severity, slope, geology), the

findings of the study could be used to convert an AI layer into one layer showing probable hydrological attributes of the soil surface after fire, including runoff generation potential and potential peak runoff. These characteristics could also be linked to post-wildfire flash flooding and debris flow occurrence probability. Aridity index (and associated relations) could therefore be incorporated into existing models, planning and assessment of soil and water resources, post-wildfire risk assessments, and further research and monitoring tools.

Conclusions

The results show a systematic and strong relation between AI and post-wildfire runoff. These findings have important implications for spatial variation of post-wildfire runoff event sizes and timing, with higher AI resulting in greater probability of substantial erosion impacts, floods, and debris flows following fire. The strong quantifiable link which this study has made between AI and post-wildfire surface runoff greatly improves our capacity to predict and map post-wildfire processes. Although this study has shown empirically that the variation in post-wildfire surface runoff is strongly related to an aridity gradient, the soil hydraulic processes underlying this variation are unknown. Future research should focus on identifying underlying causes and exploring the implications of aridity-driven variation in post-fire soil hydraulic properties to improve and expand our predictive capacity.

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Tables

Table 1: Summary of specific characteristics of instrumented sites in the Aberfeldy fire (2013).

Site aridity index ^a	Location ^b	Elevation ^b	Burn severity ^c	EVC Group ^d	Geology ^e	Soil type ^e
0.65 PT 0.95 BD	37.71° S 146.52° E	1165 m	Understorey burnt (Class 4)	Damp forest	Marine: sandstone, thick to thin bedded, siltstone, shale. Border of Granitic intrusion ^f	Brown earths Dermosol
0.75 PT 1.04 BD	37.83° S 146.50° E	701 m	Tree canopy and understorey burnt (Class 1)	Damp forest	Marine: sandstone, thick to thin bedded, siltstone, minor conglomerate, limestone lenses	Brown earths Dermosol
0.80 PT 1.10 BD	37.83° S 146.50° E	753 m	Tree canopy and understorey burnt (Class 1)	Border of Heathy dry forest and Damp forest	Marine: sandstone, thick to thin bedded, siltstone, minor conglomerate, limestone lenses	Brown earths Dermosol
1.24 PT 1.71 BD	37.85° S 146.47° E	742 m	Tree canopy and understorey burnt (Class 1)	Heathy dry forest	Marine: undifferentiated: sandstone, mudstone, minor conglomerate	Brown earths Dermosol
1.80 PT 2.41 BD	37.76° S 146.42° E	832 m	Tree canopy and understorey burnt (Class 1)	Heathy dry forest	Marine: sandstone, thick to thin bedded, siltstone, minor conglomerate, limestone lenses	Shallow stony loams Kandosol

^a Determined using the Priestley Taylor model (PT) and Budyko model (BD) ^b Recorded in the field using Garmin GPS unit; ^c Fire severity layer for the Aberfeldy-Donnelly Creek fire developed by Department of Environment and Primary Industries (DEPI); ^d Vegetation in Victoria is classified using Ecological Vegetation Classes (EVCs) which represent commonly found species communities and often reflect moisture, soil, and elevation gradients, as well as fire regime (Oates and Taranto, 2001) (DSE, 2004); ^e Land System of Victoria GIS layer (LSYS250) as detailed in Rees (2000) using the Factual Key of Northcote (1975); ^f Based on field observations.

Table 2: Summary of >5 mm rainfall event characteristics at each instrumented site in the Aberfeldy fire (2013).

Aridity Index	Number of events	Median peak I_{15} (mm h ⁻¹)	Minimum peak I_{15} (mm h ⁻¹)	*Maximum peak I_{15} (mm h ⁻¹)
0.65	30	7.22	1.11	45.56
0.75	28	6.67	2.22	34.44
0.80	24	5.86	2.14	31.11
1.24	27	6.67	2.22	16.67
1.80	27	5.56	2.22	23.33

* The maximum I_{15} was recorded during one storm event (21 March 2014), the trend of these across the AI gradient is most likely related to the path followed by the storm compared to the location of sites.

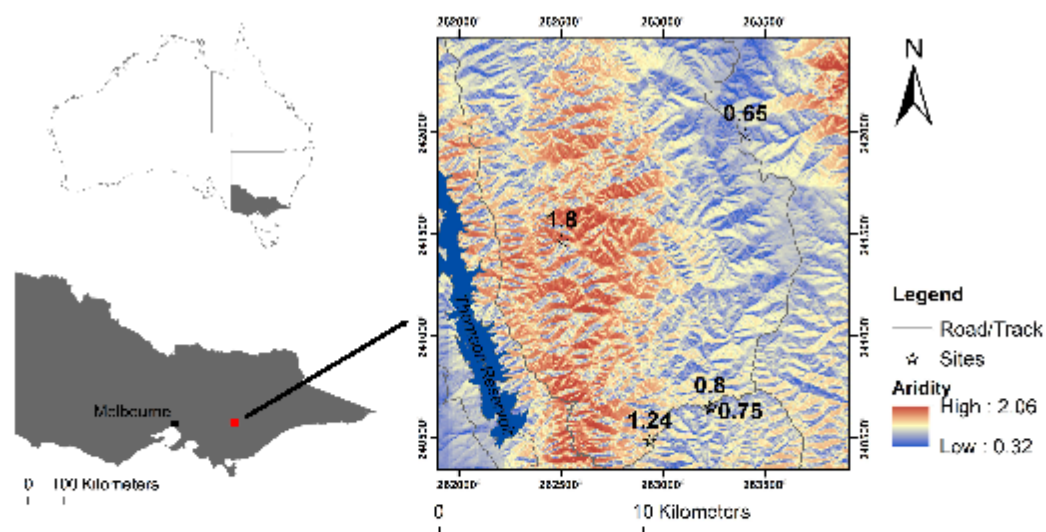


Figure 1

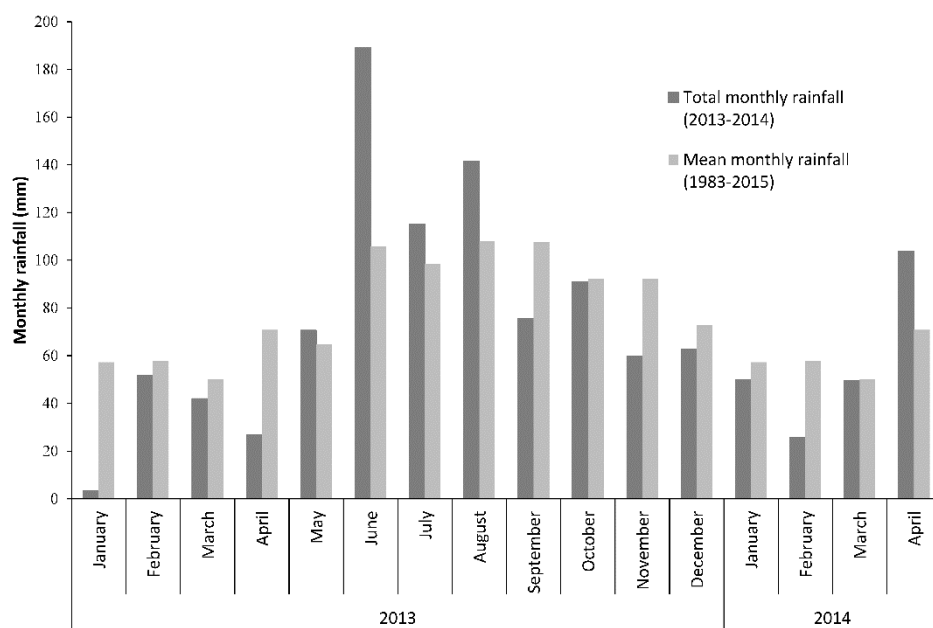


Figure 2

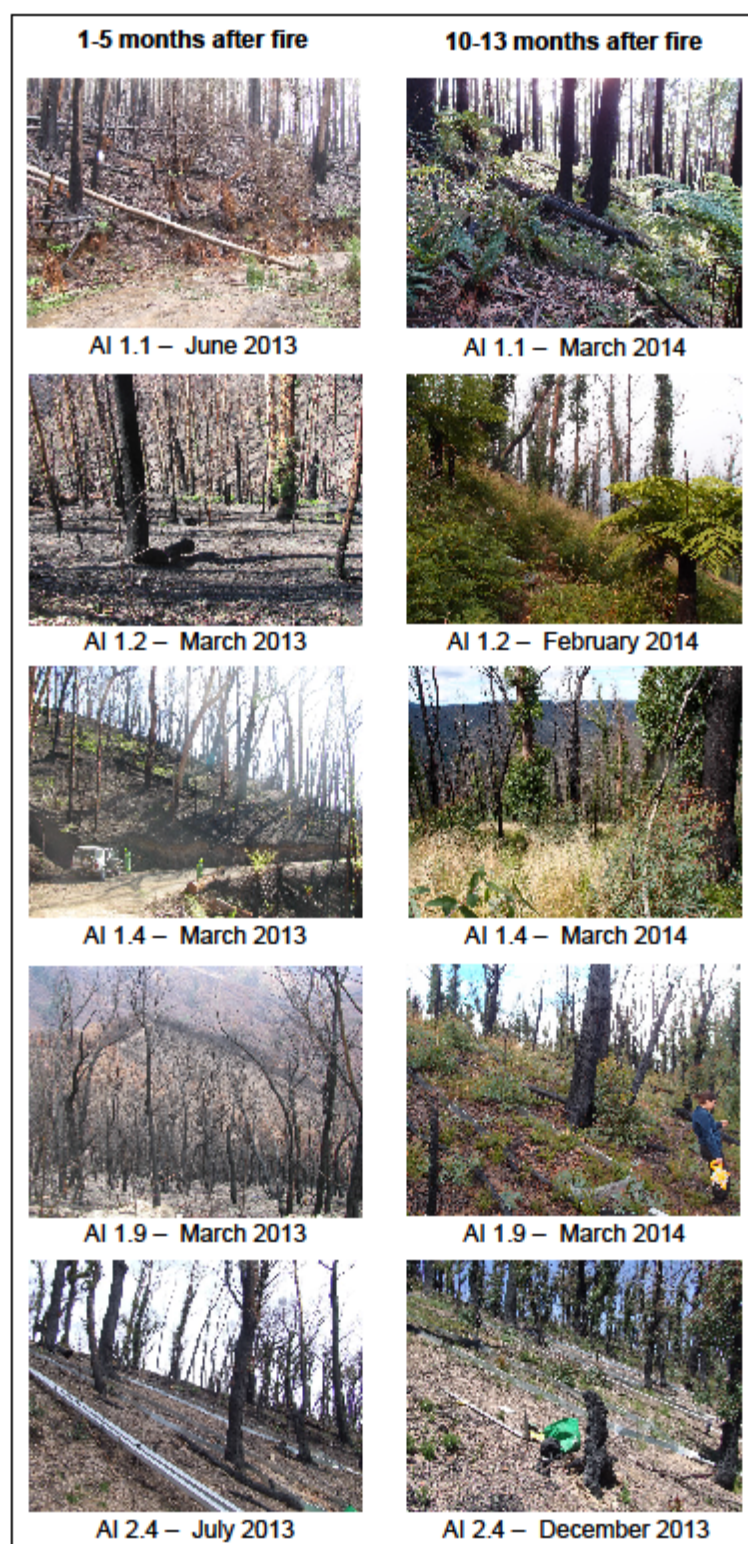


Figure 3

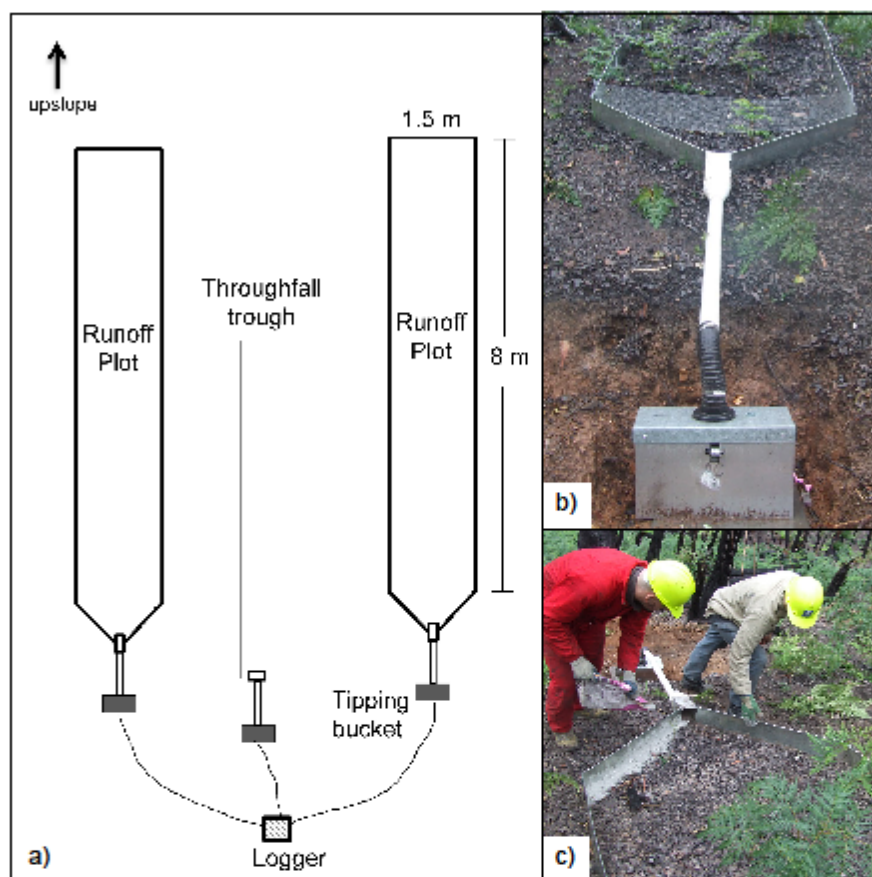


Figure 4

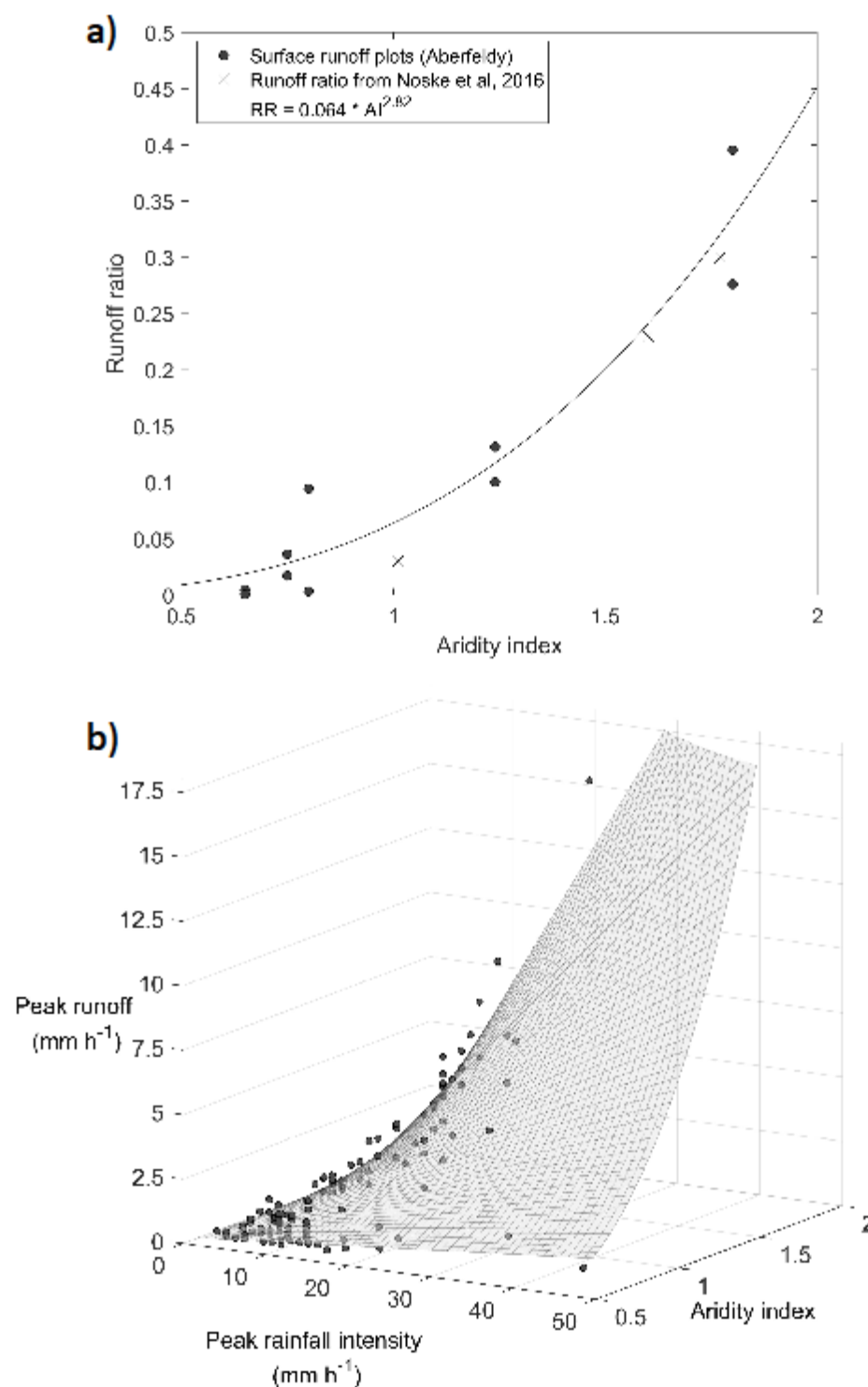


figure 5

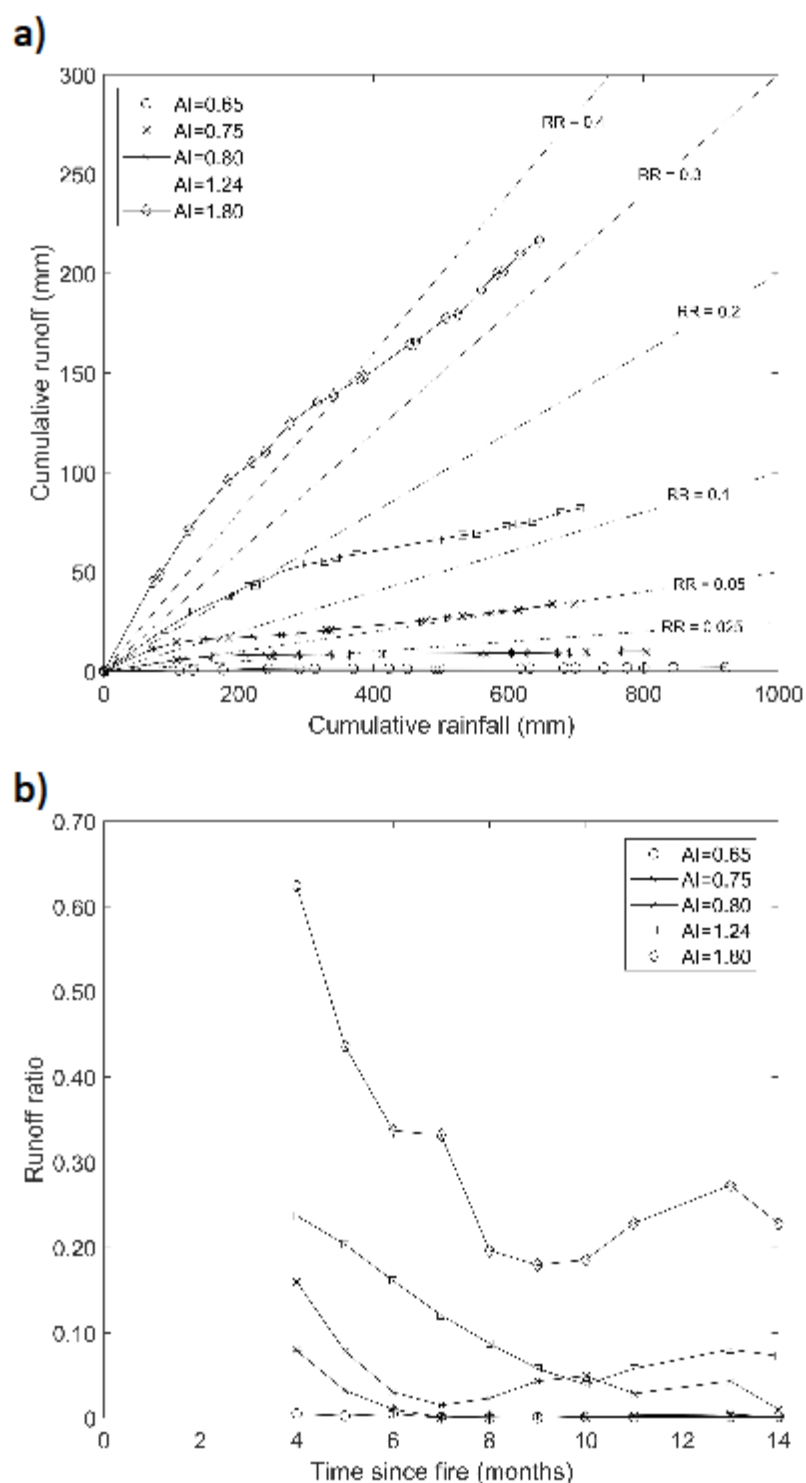


Figure 6