Manaaki Whenua
Landcare Research

Assessment of post-fire debris flow hazard, Hillend Station, Wanaka

Prepared for: Otago Regional Council

May 2018

Assessment of post-fire debris flow risk, Hillend Station, Wanaka

Contract Report: LC3162

Hugh Smith, Les Basher

Manaaki Whenua – Landcare Research

Reviewed by:	*Approved for release by:*
Andrew Neverman	Chris Phillips
Scientist – Geomorphology	Portfolio Leader – Managing Land & Water
Manaaki Whenua – Landcare Research	Manaaki Whenua – Landcare Research

Contents

Summary

Project and Client

- Otago Regional Council approached Manaaki Whenua – Landcare Research (MWLR) to provide an assessment of the risk of post-fire debris flows for the Hillend Station burn area near Wanaka.

Objectives

- Review the international and local literature on the occurrence and controlling factors for debris flow and mudflow initiation following fire.
- Review local literature on the occurrence of debris flows in Otago.
- Undertake a field inspection of the burnt site and characterise site and soil conditions that might contribute to increased hazard from debris flows and mudflows, including an assessment of water repellency and surface soil strength on burnt and unburnt slopes.
- Report results of the study and determine whether the hazard from debris flow and mudflow originating in the burnt area has been increased due to the fire.

Methods

- A literature search was undertaken to identify relevant international and local literature on the occurrence and controlling factors for post-fire debris flow and mudflow initiation.
- A 2-day site inspection was completed in late March 2018 to assess whether the debris flow hazard had increased following the fire.
- This field assessment examined vegetation and surface soil conditions, identified key erosion processes affecting the slope, and assessed whether there was evidence of previous debris flows or mudflows. Diagnostic tests for soil water repellency and surface soil shear strength were undertaken on both burnt and unburnt slopes.

Results

- Evidence of localised post-fire rill erosion was observed in several places but its extent was very limited. The ephemeral channel at the southern end of the burn area appears to have carried small debris flows before the fire. Small levees characteristic of debris flow deposits were observed and a small debris flow fan is present at the base of this channel.
- The burn severity was considered low across much of the burn area with the exception of a small area on the lower slope with higher burn severity resulting from the presence of woody vegetation. Evidence of localised overland flow and rill erosion was notable in this area affected by higher burn severity with sediment deposits observed a short distance downslope.
- By the time the site was visited in late March vegetation was beginning to recover (grass, weeds and fern) but there was still extensive bare ground.

- The literature review summarised post-fire debris flow generation processes and controlling factors, including topography and lithology, burn severity and soil impacts, and characteristic rainfall conditions that trigger debris flows after fire. Post-fire debris flows may be initiated either by surface runoff and progressive downslope sediment entrainment leading to a debris flow or by landsliding on burnt slopes that may trigger a debris flow in the channel network.
- Runoff-generated debris flows after fire are typically initiated in steep, convergent headwater catchments burnt at high severity with erodible and low-infiltrating surface soils. This type of debris flow is usually triggered by short duration, high intensity storm rainfall within 1–2 years after fire.
- By contrast, mass failure-generated debris flow tend to occur 5–10 years or longer after fire and are associated with an increase in soil saturation and a loss of tree root cohesion due to widespread fire-related tree mortality. These debris flows are generally initiated by long duration, high magnitude rainfall events.

Conclusions and recommendations

- Based on consideration of available scientific literature and the site inspection, the hazard from debris or mudflows originating in the burn area on Hillend Station is unlikely to have increased due to the fire.
- The hazard associated with runoff-generated debris flow after fire appears to be low. This conclusion is based on the low burn severity and its negligible impact on soils across most of the burn area.
- Fire can increase the availability of erodible, non-cohesive surface sediments. This is an important factor in post-fire susceptibility to runoff-generated debris flow. Surface soil shear strength measurements provide an indication of changes in soil erodibility. These measurements showed negligible difference in surface soil shear strength between burnt and unburnt areas.
- Fire can also enhance soil water repellency and increase overland flow, contributing to increased risk of runoff-generated debris flow. However, no soil water repellency was observed in either burnt or unburnt areas.
- Analysis of depth-duration-frequency statistics from the burn area indicated that rainfall of sufficient intensity and duration to produce runoff-generated debris flow from burnt landscapes in south-east Australia and the western United States could occur over the Hillend Station burn area. However, this assumes comparable landscape susceptibility. Site observations suggest that the susceptibility of the burn area to runoff-generated debris flow is low.
- There is evidence of pre-fire debris flow activity associated with shallow landsliding. It seems unlikely that the fire will have increased this pre-existing hazard. The absence of forest cover indicates that changes in the soil water balance and soil cohesion resulting from the fire are likely to be minimal. It is therefore unlikely that fire has increased the hazard associated with mass failure-generated debris flow.
- There is limited need for specific measures to reduce the risk of debris flow activity related to the fire. The most suitable approach would involve promoting rapid surface vegetation recovery. This may involve seeding and temporarily reducing grazing intensity to support vegetation regrowth.

1 Introduction

On 3 January 2018 a fire was started at the base of Mt Alpha near Lake Wanaka and burnt about 200 ha of steep hillslopes covered in grassland and scrub, destroying the vegetation and leaving much ash and bare ground at the surface. As the steep hillslope lies immediately above part of Wanaka township, Otago Regional Council (ORC) were concerned about the increased hazard of erosion (debris flow and mudflow) due to the fire and its possible impact on the houses below.

Streams to either side of the burnt area (Stoney Creek and Waterfall Creek – see Fig. 1) have historically carried debris flows (ORC 2011) and immediate post-fire inspection of the burn area showed evidence of highly localised soil movement by rill erosion as well as by possible mudflow (Fig. 2). These may have been triggered by the dumping of water from monsoon buckets during firefighting.

Figure 1 View of the burn area (outlined by red line) and adjacent catchments of Stoney Creek and Waterfall Creek.

Figure 2 Evidence of localised small mudflow soon after the fire (Photo: Ben Mackey).

Otago Regional Council approached Manaaki Whenua – Landcare Research (MWLR) to provide an assessment of:

1 Has the hazard from mud/debris flows originating in the burnt area been increased due to the fire?
2 What is the characteristic rainfall that is likely to generate mud/debris flows in the burnt area?
3 Are there characteristic mud/debris flow initiation sites or likely pathways for flows to take?
4 What is the likely duration of any elevated hazard, and what are the key factors that control this? (vegetation regrowth, rainfall patterns, soil response?)
5 Can measures be taken to reduce the probability of future flows, until hillslope conditions have stabilised? (targeted planting, initiating controlled flows?)
6 Have any other hazards increased as a result of the fire? (e.g., rockfall, mass movement, clearwater flooding?)
7 What are the likely characteristics of any flows that reach the base of the slope – runout path and distance, volume, water/sediment ratio?

MWLR responded with a proposal to address questions 1–6 but considered question 7 should be addressed if an initial investigation determined the fire had increased the hazard of debris flows or mudflows.

2 Objectives

- Review the international and local literature on the occurrence and controlling factors for debris flow and mudflow initiation following fire.
- Review local literature on the occurrence of debris flows in Otago.
- Undertake a field inspection of the burnt site and characterise site and soil conditions that might contribute to increased hazard from debris flows and mudflows, including an assessment of water repellency and surface soil strength on burnt and unburnt slopes.
- Report results of the study and determine whether the hazard from debris flow and mudflow originating in the burnt area has been increased due to the fire.

3 Literature review

Post-fire debris flows have been a common occurrence in parts of Australia (e.g. Nyman et al. 2011, 2015) and the USA (Cannon et al, 2008, 2010; see https://landslides.usgs.gov/hazards/) where they have been well studied, but are not well known in New Zealand. Most debris flows in New Zealand occur in areas of steep slopes, high sediment supply, high storm rainfalls, and are often associated with the input of sediment to stream channels from landsliding (McSaveney & Davies 2005; McSaveney et al. 2005; Bowman & Davies 2008; Welsh & Davies 2010; Bowman & Kailey 2010; Kailey 2013). By contrast, many post-fire debris flows are associated with increased overland flow and sediment supplied by surface erosion processes rather than mass movement (e.g. Smith et al., 2012; Nyman et al. 2011, 2015; Cannon et al. 2000). Mudflows have rarely been reported in New Zealand other than from volcanoes (lahars).

Post-fire debris flow research has predominantly occurred in North America and, to a lesser extent, in Australia. We could locate no published studies or reports of post-fire debris flows occurring in New Zealand. Hence, this review focuses on our understanding of post-fire debris flow processes based on international scientific literature. This literature does not distinguish between debris flow and mudflow processes. Instead, these post-fire processes tend to be viewed on a continuum between flood flows to hyperconcentrated flows with increasing sediment loads that transition into debris flows (Costa 1998; Pierson, 2005). Typically, a combination of processes occur in a given burnt catchment where surge-driven behaviour may lead to alternating flow processes, which also vary longitudinally along the channel with changes in slope and sediment entrainment (Cannon et al. 1998; Hungr et al. 2001; Kean et al. 2013). Most field studies rely on interpretation of depositional evidence (e.g. unsorted levee deposits, matrix supported clasts, convex surface morphology of deposits, severe channel scour) to identify debris flow processes, although more recent work in instrumented catchments (including videos) has directly measured debris flow events (Kean et al. 2013).

This literature review considers the mechanisms driving initiation of post-fire debris flows, the landscape factors influencing susceptibility, and the characteristics of triggering rainfall events. We also examine the occurrence of debris flow in the Otago region to give a regional context. We will draw on this literature review when assessing the potential post-fire debris flow hazard for the Hillend Station burn area.

3.1 Post-fire debris flow generation processes

Post-fire debris flow may be generated by either surface runoff or mass failure mechanisms (Cannon 2001; Meyer et al. 2001). Runoff-generated debris flows are initiated by elevated levels of surface runoff from recently burnt hillslopes where progressive entrainment of ash and sediment downslope leads to the formation of debris flows either on hillslopes or once flows reach channels (Wells, 1987; Cannon et al., 2001; Gabet & Sternberg 2008). This generation mechanism involves increased post-fire surface runoff due to reduced plant interception and surface hydraulic roughness as well as the presence of post-burn soil water repellency (Neary et al. 2005; Shakesby 2011; Nyman et al. 2014). Higher runoff combines with fire-induced increases in surface soil erodibility (Nyman et al. 2013) contributing to higher detachment rates, rill erosion and hillslope debris flow processes (Gabet. 2003; Langhans et al. 2017). In convergent zero-order headwaters, flows may incise channels and debris flow processes may continue downstream, depending on changes in slope, flow rheology and channel form (Kean et al. 2013; Staley et al. 2014; Nyman et al. 2015).

In contrast, mass failure-generated debris flows may occur in response to soil saturation and reduced tree root cohesion following stand-replacing wildfire (Benda & Dunne 1997; Wondzell & King 2003). Mass failure-generated debris flows tend to occur in response to high magnitude, long-duration storm events (24–48 h), and are most frequently observed following storms with recurrence intervals in the order of 50–100 years (Meyer et al., 2001; Wondzell & King 2003). The reduction in evapotranspiration with fire-related tree mortality leads to increases in soil water content and pore water pressures (Swanston 1971; Wondzell & King 2003). This reduces the storm magnitude threshold required to reach soil saturation. The loss of mechanical cohesion as the roots of fire-killed trees decompose decreases soil strength and increases susceptibility to shallow failures (McNabb & Swanson 1990; Wondzell & King 2003). Increases in landslide activity have been reported 5–10 years after wildfire, which appears consistent with the timing for root decay (Gray & Megahan 1981).

Comparison of runoff versus mass failure-generated debris flows suggests that runoff-generated debris flows are more frequent and contribute larger quantities of material in recently burnt catchments (Cannon & Gartner 2005; Cannon et al. 2010; Nyman et al. 2011). For example, runoff-generated debris flows accounted for 76% of 210 debris flows observed after fire in the western United States (Cannon & Gartner 2005). This partly reflects differences in the timing of landscape responses to fire that affect the two debris flow generation mechanisms. Runoff-generated debris flows tend to occur within 1–3 years of fire, whereas mass failure-generated events typically occur 5–10 years after fire (Meyer et al. 2001). Rapid surface soil and vegetation recovery tend to reduce the risk of runoff-generated debris flows in the short-term by increasing infiltration and surface roughness and reducing the available surface sediment supply (Nyman et al. 2015; Langhans et al. 2016). In contrast, there is a post-fire lag in the time taken for loss of root cohesive strength to increase the risk of mass failure generated debris flows before this risk decreases as tree seedlings grow and establish root networks, which may take up to 20 years (Meyer et al. 2001).

The following discussion focuses on factors influencing the initiation of runoff-generated debris flows, namely (1) topography and lithology, (2) burn severity and soil impacts, and (3) characteristic rainfall. Mass failure-generated debris flows have been observed following stand-replacing forest fires where decreased evapotranspiration and reduced tree root strength with widespread tree kill are important factors associated with increased risk of this type of post-fire debris flow. The absence of forest cover across the Hillend Station burn area implies that the hazard associated with mass failure-generated debris flow is unlikely to be affected by the fire.

3.2 Topography and lithology

Slope steepness and convergent topography are important susceptibility factors influencing the likelihood of post-fire debris flow occurrence. Analysis of debris flows in the forested highlands of Victoria, Australia, suggests that slopes >25° in at least 30% of first- and second-order headwater catchments will increase susceptibility (Nyman et al. 2011). Convergent headwaters are another important factor. The average area above debris flow scoured channel initiation points was 1.9 ha (range 0.31–11 ha) in the Victorian highlands (Nyman et al. 2015), which was notably similar to the contributing areas for channel initiation reported by Cannon et al, (2001) for post-fire debris flow affected catchments in Colorado. The effect of convergent topography is evident in Figure 3, which shows burnt and debris flow affected landscapes in Victoria following the 2009 wildfires. Figure 3B and 3C clearly show flow lines and rills converging within headwaters towards channel initiation points.

Lithology exerts a control on debris flow susceptibility through its influence on sediment availability and topographic form. In the Victorian highlands, sedimentary (mostly mudstone and siltstone) and metamorphic geologies were both found to be susceptible to post-fire runoff-generated debris flows (Nyman et al. 2011). In contrast, these authors found that catchments underlain by granitic geology exhibited flash flood responses and did not display the characteristic depositional evidence of debris flow processes. The granitic terrain differs from adjacent sedimentary catchments in terms of resistance to weathering and topography, with steep cliffs and large areas of exposed bedrock, thereby limiting sediment availability (Nyman et al. 2011). A similar observation was reported for canyons in Utah where weathering-resistant terrain was less susceptible to fire-related debris flows (Larsen et al. 2006). In this environment, sediment supply limitation reduced post-fire debris flow susceptibility in contrast to transport-limited environments with regolith-mantled hillslopes (Larsen et al. 2006).

The larger fraction of sand and gravel in granite-dominated catchments versus the more silt-clay dominated soils formed in sedimentary catchments could also influence the formation of runoff-generated debris flows (Nyman et al. 2011). The supply of fine material has been identified as an important factor contributing to progressive entrainment processes on hillslopes that are associated with the initiation of runoff-generated debris flows after fire (Meyer & Wells 1997; Gabet & Sternberg 2008). Fine sediment also contributes to debris flow processes via its contribution to shear strength through cohesion in clays and interparticle friction (Costa 1988). Hence, the limited supply of fines could impede post-fire debris flow initiation.

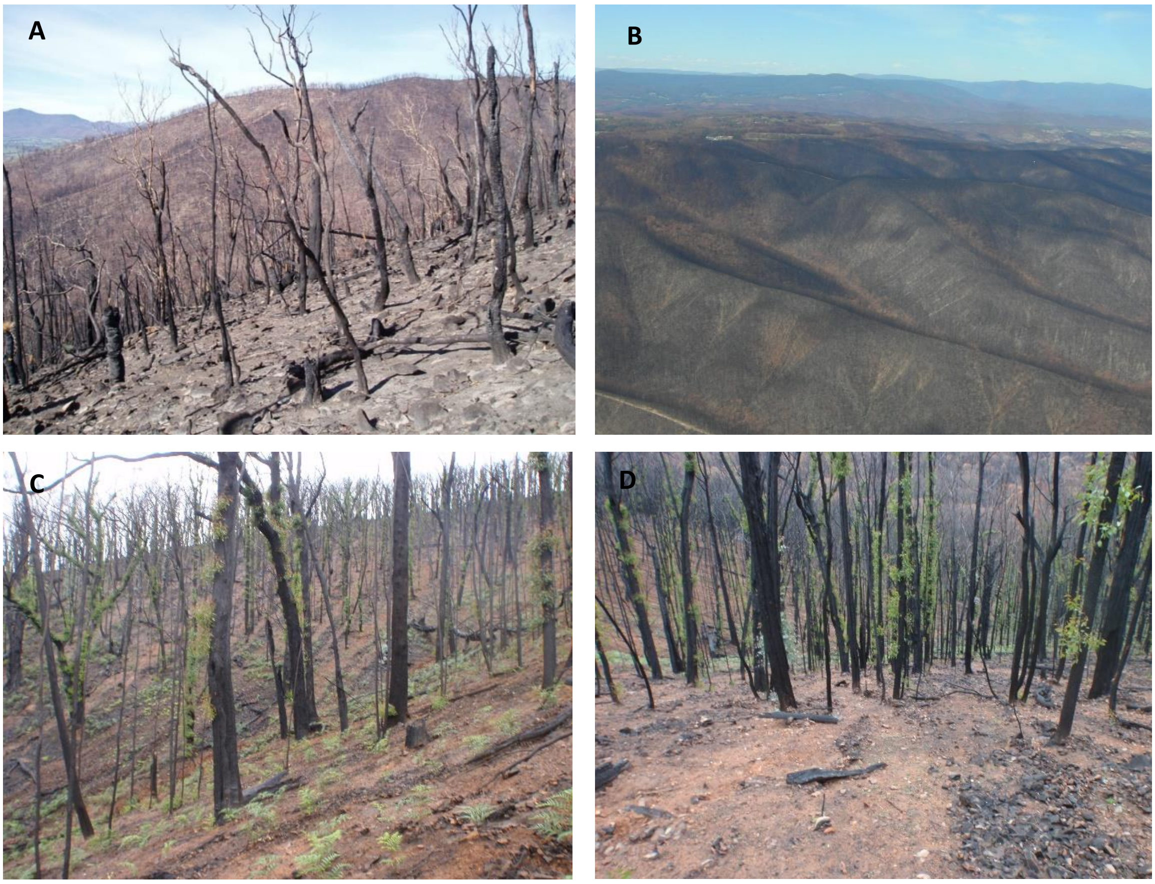

Figure 3 Post-fire landscapes that produce runoff-generated debris flows in Victoria, Australia. These photographs are included here to highlight the contrast with the Hillend Station burn area in terms of burn severity, soil surface condition, and visual evidence of hillslope surface erosion. Note the evidence of convergent surface runoff in zero order headwater catchments.

3.3 Burn severity and soil impacts

Landscape-scale analysis of post-fire debris flow susceptibility showed that burn severity was the strongest predictor of debris flow occurrence based on data from the forest highlands of Victoria (Nyman et al. 2015). These authors quantified debris flow susceptibility using logistic regression with an inventory of 315 post-fire debris flow fans deposited within 12 months of two large wildfires. Significant predictors in the model were burn severity, local slope, radiative index of dryness, and rainfall intensity (Nyman et al, 2015). Likewise, empirical analysis using stepwise multiple regressions of variables influencing post-fire debris flow occurrence in the western United States showed that the catchment area with slope greater than 30% (S), area burned at moderate and high severity (B), and total rainfall (R) could explain most of the variance (R^2 = 0.83, sample n = 50) in measured debris flow volumes (V), where $\ln(V) = 7.2 + 0.6\ln(S) + 0.7B^{0.5} + 0.2R^{0.5}$ (Gartner et al. 2008). Both these empirical analyses highlight the importance of burn severity and its impact on soils for the initiation of runoff-generated debris flows after fire.

Burn severity (measured by vegetation change) provides an indirect measure of the potential fire effect on the soil. Although it does not directly capture the level, depth, and duration of soil heating during the passage of a fire, recent work has shown that burn severity, measured by comparing pre- and post-fire satellite imagery and computing the difference Normalised Burn Ratio (*dNBR*), can be quantitatively related to changes in soil hydraulic conductivity (Moody et al. 2016). These authors showed that field-saturated hydraulic conductivity decreases with increasing *dNBR* (when *dNBR* > 400). The causal processes were not directly addressed but probably relate to physical changes in soil porosity, the extent of soil sealing and the strength of soil water repellency (Moody et al. 2016). Soil water repellency reduces the infiltration capacity of soil (Doerr et al. 2000). Fires may induce or increase soil water repellency (DeBano 2000; Doerr et al, 2004), although background water repellency can also be present in unburnt soils (Crockford et al. 1991; Doerr et al. 2009). Water repellency is known to be common in some New Zealand soils (e.g. Wallis et al. 1991; Müller et al. 2010; Deurer et al. 2011) but the relationship with fire is not known.

Wildfire-related combustion of surface soil organics and fine roots can reduce surface soil cohesion and may produce an erodible, non-cohesive surface layer comprising both ash and mineral soil of variable depth (Nyman et al. 2013). An example of the fire effect on soil shear strength with depth is given in Figure 4. This shows a recovery trend of increasing soil shear strength in the 0–5 cm depth range with time since fire (0.5–3 years) for burnt sites in Victoria, Australia (Nyman et al. 2013). These authors found that all sampled non-eroded points within 0.5 years of fire were classed as non-cohesive (i.e. τ_v < 5 kPa), and within 1 year this reduced to 17–54% of sampled points. These findings have important implications for runoff-generated debris flow susceptibility. As noted previously, the availability of readily entrained fine material is an important factor in debris flow initiation. High severity fire can produce an extensive non-cohesive surface layer, which, combined with reduced infiltration linked to increased soil water repellency, may provide both the enhanced surface runoff generation and the sediment availability needed to generate post-fire debris flow.

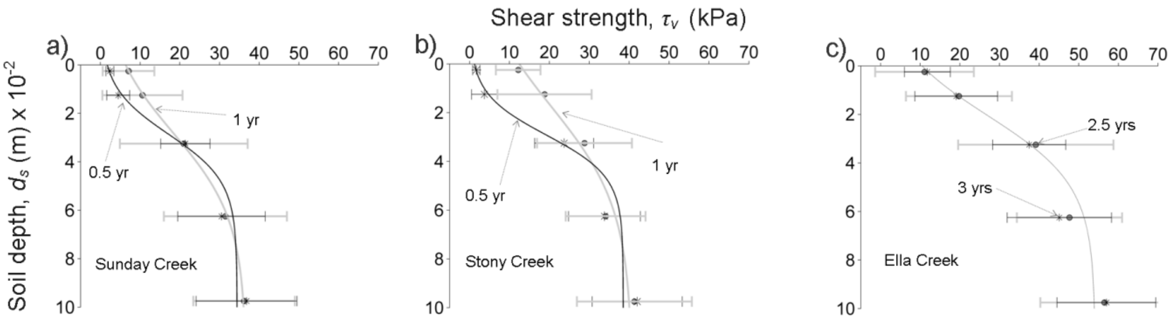

Figure 4 Changes in soil shear strength (τ_v) with soil depth (d_s) at different stages of recovery (0.5–3 years) after high severity wildfire at three sites in Victoria, Australia (source: Nyman et al, 2013).

The recovery in soil properties and vegetation cover after fire is an important factor in reducing susceptibility to runoff-generated debris flow initiation (Langhans et al. 2016). In Victoria, the observed decline in the erodible surface soil layer is consistent with the observed decline in runoff-generated debris flow initiation with time since fire. All observed debris flows occurred within 12 months of fire in a survey of events across the Victoria highlands (Nyman et al. 2011), while in the western United States most runoff-generated debris flow activity occurred within 2 years after fire (Gartner et al. 2004). The post-fire recovery period also corresponds with increasing soil infiltration capacity linked to declining soil water repellency and increasing macroporosity (Nyman et al. 2014). The latter effect may reflect initial ash blocking of macropores that temporarily reduces macropore flow (Woods & Balfour 2010). Surface vegetation regrowth may also provide increased hydraulic roughness that reduces overland flow velocities and sediment entrainment (Moody & Martin 2001).

3.4 Characteristic rainfall for post-fire debris flow generation

The two post-fire debris flow generation mechanisms exhibit contrasting magnitude-frequency characteristics in triggering rainfall events. Runoff-generated debris flows tend to occur in response to more frequent, short-duration, high-intensity storm events with average recurrence intervals of <2–10 years (Cannon et al. 2008; Nyman et al. 2015). This pattern has been observed in both the forest highlands of southeast Australia and in the western United States, although longer duration frontal storms also generated debris flows in burnt, chaparral dominated catchments in southern California (Cannon et al. 2008). Post-fire, mass failure-generated debris flows generally occur in response to high magnitude, long duration events, typically with much longer recurrence intervals (Wondzell & King 2003; Cannon & Gartner 2005). As a result of this difference in rainfall characteristics, there is a higher likelihood that the more frequent, high-intensity storm events will occur during the short post-fire window of increased susceptibility to runoff-generated debris flow initiation. This is consistent with post-fire observations of debris flow events (Nyman et al. 2011).

Storm events observed to have triggered runoff-generated debris flows were characterised by average 15- and 30-minute rainfall intensities ranging from 35 to 85 and 17 to 60 mm h^{-1}, respectively, in Victoria, Australia (Nyman et al. 2015). In a study of rainfall characteristics for runoff-generated debris flows in recently burnt catchments in Colorado and California, Cannon et al. (2008) found that 80% of storms that generated debris flows lasted less than 3 hours, with most rainfall falling within less than 1 hour in Colorado. These storms exhibited average storm intensities of 1–32 mm h^{-1} and 10 minute peak intensities of 6–63 mm h^{-1}. Longer duration frontal storms were also found to produce runoff-generated debris flows in southern California, where storms ranged from 5.5 to 30 h in duration, exhibited storm average intensities of 1.3–20 mm h^{-1}, and peak 30 minute intensities of 8–37 mm h^{-1} in the first year after fire (Cannon et al. 2008). A limitation of this analysis is the variable distance between rain gauges and debris flow-affected catchments, which may lead to underestimation of rainfall totals and intensities.

Subsequent work in southern California emphasised the importance of short duration (<= 30 mins), high intensity rainfall for triggering post-fire debris flows using instrumented catchments to directly capture post-fire debris flow response (Kean et al. 2011). The authors reported a range in 15-minute rainfall intensities of 12–69 mm h^{-1} that were observed to produce 24 runoff-generated debris flows after fire. A strength of the findings presented by Kean et al. (2011) is the availability of rainfall data from catchments affected by debris flows rather than more distant locations. In summary, studies to date show that the characteristic rainfall likely to produce runoff-generated debris flows is of short duration and high intensity. Such rainfall is necessary to produce the rapid overland flow and associated sediment entrainment on hillslopes that form part of the initiation process for runoff-generated debris flows in susceptible burnt catchments.

3.5 Debris flow occurrence in the Otago region

Debris flows occur widely in the Otago region (de Scally et al. 2010; ORC 2011). Most investigations of debris flow in the region focus on fan deposits. ORC (2011) report that over 2,000 alluvial fan areas have been mapped in Otago, which equates to 6% of the total land area. This was based on fan mapping across the Otago region by Opus (2009) with the aim of characterising the risk to communities associated with alluvial fans, including from debris flows. The mapping classified fans into debris, composite and floodwater-dominated categories.

Debris flows in the region are typically triggered by landsliding initiated by localised, intense rainfall that often follows significant antecedent rainfall (McSaveney & Glassey 2002; Baum & Godt 2011). For example, McSaveney and Glassey (2002) examined a debris flow in a small tributary of the Rees River, west Otago, that resulted in one fatality in January 2002. In this event, it appears that high intensity rainfall associated with a localised convective storm triggered shallow landslides in loose, weathered rock debris overlying schist bedrock, which travelled down the stream network as a debris flow. The daily rainfall totalled 240 mm (estimated 2–3 year recurrence interval), so the authors reasoned that a short period (perhaps 5–10 minutes) of very high intensity rainfall triggered the landsliding on already saturated debris.

Debris flow activity has been reported in catchments adjacent to the Hillend Station burn. Stoney and Waterfall Creeks are incised into the West Wanaka ranges and located either side of the burn area (Fig. 1). In the Stoney Creek catchment, extensive slope instability, including shallow landsliding, present a debris flow hazard (ORC 2011). Large storm events in 1999 and 2004 generated debris flows that deposited material across roads (Opus 2009). The 2004 storm was estimated at less than a 50-year recurrence interval. Following the magnitude 6.7 earthquake west of Milford Sound on 16 October 2007, surficial debris flows were generated by the sudden release of water from the headscarp of a pre-existing large landslide (Woods 2007). As in Stoney Creek, there is widespread slope instability present in Waterfall Creek catchment, and past debris flow deposits were observed during a site visit in November 2007 (ORC 2011). This report also notes the potential for formation of a landslide debris dam in this catchment, potentially triggered by a large seismic or high intensity storm event leading to slope failure impounding the channel.

Debris flows have also been investigated elsewhere in the Otago region. McSaveney (1995) reported on several large debris flows that destroyed a bridge and its replacement structure in January 1983 and again in January 1994. These events occurred on a different Waterfall Creek that crosses SH6 and also drains into Lake Wanaka. The 1983 debris flow occurred in response to an extended rain period with an estimated recurrence interval of 3 years that led to slope failure with an approximate volume of 20,000 m^3 (McSaveney 1995). The 1994 debris flow occurred in response to a very high magnitude rainfall event with an estimated recurrence interval of 200 years (McSaveney 1995). This event did not have a well-defined initiation point and was instead initiated by many debris flows throughout the Waterfall Creek catchment that coalesced down the main channel. McSaveney (1995) speculates that the debris flow probably occurred during a brief period of very high intensity rainfall and lasted a matter of minutes rather than hours. In another nearby example, large debris flows occurred in the Pipson Creek catchment and affected SH6 on six occasions between 1989 and 2004 (Opus 2004). The 2004 debris flow event resulted from upstream landsliding from two main sources totalling 580,000 m^3 with an estimated 10–20,000 m^3 available for future release (Opus 2004).

The general view of debris flow occurrence in New Zealand emphasises the importance of steep slopes and high sediment supply, where high magnitude rainfall often provides the triggering mechanism that frequently involves shallow landslides initiating debris flows in the channel network (McSaveney & Davies 2005). This is consistent with reports of debris flows in the Otago Region, where the role of earthquakes as a triggering mechanism has also been noted. These mechanisms for debris flow generation represent an important contrast with the occurrence of post-fire debris flow. For runoff-generated debris flow, which are more frequently observed after fire than mass failure-generated debris flow, antecedent rainfall is not a significant factor in predicting debris flow occurrence (Cannon & Gartner 2005). Instead, this process is dominated by infiltration-excess overland flow from burnt and often water repellent soils where there is an abundant supply of non-cohesive ash and loose soil that enables debris flows to form on hillslopes and in channels (Nyman et al. 2015; Langhans et al. 2017).

4 Methods

The Hillend Station burn area was closely inspected during a 2-day field visit to examine vegetation and surface soil conditions, identify key erosion processes affecting the slope, and assess whether there was evidence of previous debris flows or mudflows. Diagnostic tests for soil water repellency and surface soil shear strength were undertaken on both burnt and unburnt slopes. These diagnostic measurements provided an indication of the increased potential for surface runoff generation and a possible increase in the erodibility of surface soils, both important factors in the initiation of runoff-generated debris flows after fire (Nyman et al. 2011, 2013).

The test for soil water repellency involved placing individual water droplets on the soil surface and observing the time taken for the drop to penetrate the soil. This Water Drop Penetration Time (WDPT) test has been previously used to investigation water repellency of New Zealand soils (Wallis et al. 1991) and has been widely used internationally to characterise the strength of water repellency of fire-affected soils (e.g. Doerr et al. 1998, 2009). In this investigation, soils were considered non-repellent when drop penetration times were <2 seconds, slightly repellent at 10–60 seconds, and strongly repellent at >60 seconds (Doerr et al. 1998).

Soil shear strength was measured using a shear vane (Gilson HM-504A pocket shear vane set with range 0–2.5 kg cm^{-2}). The shear vane measures the internal resistance of the surface soil (5 mm depth) to an applied rotation force. Previous studies have used shear vanes to quantify soil erodibility (Leonard & Richard 2004), including following wildfire (Nyman et al. 2013). Changes in soil erodibility with burning may result from heating and combustion of surface soil organic matter and fine roots that provide cohesive strength to the soil. Here, we follow a simplified approach based on Nyman et al. (2013) focusing on measuring surface soil shear strength at burnt and unburnt locations. In total, we sampled eight burnt and six unburnt locations with five measurements at each location.

Using the literature review and field data the hazard factors for debris flows were identified and an assessment made as to whether they have increased following the fire.

5 Results

5.1 Site description

The fire occurred on a steep, north-east facing slope below Mt Alpha and between Stoney Creek and Waterfall Creek. The slope is an ice-smoothed valley wall that has, and is, being modified by large-scale gravitational mass movement (creeping landslides). Mean slope is about 26° with a maximum slope of up to 45°. Rock outcrops are extensive in places but for the most part the slope is mantled in colluvium. The slope is weakly dissected with one prominent ephemeral channel towards the southern end. In places it is hummocky reflecting slope movement.

Soils are mapped as Pedal Immature Pallic soils of the Arrow Steepland soil set. Examination at several places on the slope showed these are weakly developed, moderately stony soils with weakly developed soil structure in both the topsoil and subsoil (Fig. 5). Soil depth is highly variable but typically appeared to be 0.5–1 m deep near rock outcrops, and on ridges soils were very shallow (<0.5 m). While no measurements of soil hydrologic properties are available, they probably have high infiltration and permeability rates. Areas with shallow soils would be prone to saturation during large storms.

Figure 5 Typical soil on the burnt slope.

Table 1 Depth-duration-frequency statistics extracted from HIRDs for the burn site (https://hirds.niwa.co.nz/)

	Duration									
ARI* (yr)	10 min	20 min	30 min	1 hr	2 hr	6 hr	12 hr	24 hr	48 hr	72 hr
1.58	3	4	6	9	14	27	42	66	82	93
2	3	5	6	10	15	29	45	70	87	99
5	4	6	8	13	19	37	56	84	105	120
10	5	8	10	15	22	43	64	96	119	136
20	6	9	12	18	26	49	73	108	135	153
30	7	10	13	20	29	53	79	116	144	164
40	7	11	14	21	31	57	83	121	152	173
50	8	11	15	22	33	59	86	126	157	179
60	8	12	15	23	34	61	89	130	162	185
80	8	13	16	25	36	65	94	136	170	194
100	9	14	17	26	38	68	98	142	177	202

* Annual recurrence interval

Annual rainfall at Wanaka is relatively low at 680 mm. Data extracted for NIWAs High Intensity Design Rainfall System provide an analysis of rainfall intensity data for the site (Table 1). Rainfalls in November 1999 and 30 January 2004 produced debris flows in Stoney Creek. While the date of the 1999 event is not known, rainfall data supplied by ORC show a rainfall event over 4 days produced a storm rainfall total of 202 mm that was probably responsible for the debris flow. Rainfall data for January 2004 suggest a low storm rainfall of 39 mm, although there was also about 50 mm of rain 3 days before this event.

A large, deep-seated landslide is present at the southern end of the burnt area (Fig. 6) and it appears to have been recently active with several scarps present in the middle section of the landslide (Fig. 7). This recent instability appears similar to that described in Stoney Creek as a result of the October 2007 Fiordland earthquake (ORC 2011) and may have been triggered by the same earthquake.

Figure 6 Burn area and location of large deep seated landslide.

Figure 7 Recent scarps with shallow slumping on the landslide shown in Figure 4.

Evidence of localised post-fire rill erosion was observed in several places but its extent was very small (Fig. 8). There was also some evidence of localised small-scale rockfall from rock bluffs, and one shallow translational failure was seen (Fig. 9) – it is not known if this post-dates the fire. The ephemeral channel at the southern end of the burnt area appears to have carried small debris flows prior to the fire (Fig. 10). In its lower reaches there are small levees and the exposed sediments show a poorly sorted, matrix-supported deposit with very large clasts characteristic of debris flows (Fig. 10). There is a small debris flow fan at the base of this channel that extends to within about 50 m of the nearest house.

Figure 8 Localised small scale rill erosion.

Figure 9 Shallow translational landslide.

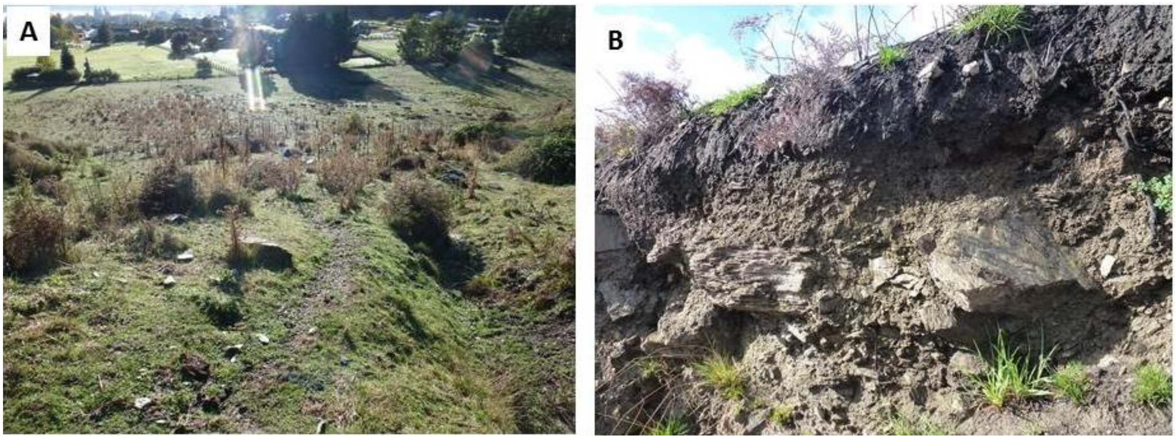

Figure 10 Evidence for debris flow in ephemeral channel. (A) small levee adjacent to the channel and large surface rocks; (B) matrix-supported deposit with large clasts.

Immediately after the fire much of the burnt area was completely denuded of vegetation but there were also areas that were less affected, particularly towards the upper limit of the burn, or which did not burn at all (Fig. 11). There was a small area on the lower slope with higher burn severity resulting from woody vegetation that fuelled higher burn temperatures (Fig. 12). Evidence of localised overland flow and rill erosion was notable in the area affected by higher burn severity with sediment deposits observed a short distance downslope (Fig. 13). By the time the site was visited in late March vegetation was beginning to recover (grass, weeds and fern) but there was still extensive bare ground (Figs 14, 15).

Figure 11 Range of vegetation condition immediately after the burn. Most of the slope was completely denuded (A) but burn severity was lower, particularly towards the margins of the burn (B) (Photo: Ben Mackey).

Figure 12 Area of high burn severity where soil surface has been scorched and tree roots have been completely burnt (Photo: Ben Mackey).

Figure 13 Evidence of localised post-fire overland flow and sediment deposition below the area of higher burn severity shown in Figure 10.

Figure 14 Convergent slopes in the headwater of the ephemeral channel at the southern end of the burn area.

Figure 15 Vegetation condition in late March.

5.2 Field measurements

Soil water repellency

No evidence of soil water repellency was observed in either burnt or unburnt locations. All water drop penetration times were less than 2 seconds. Fire may enhance soil water repellency and this may contribute to increased surface runoff after fire (Doerr et al. 2000), which has been identified as a factor contributing to the increased risk of runoff-generated debris flows. In steep, forested terrain in Australia, the combination of poorly structured shallow soils and strong soil water repellency contributes to the generation of large amounts of surface runoff that may initiate debris flows in headwater catchments after fire (Nyman et al. 2011). The absence of any evidence of soil water repellency on the Hillend station burn area suggests that the fire has probably not altered the hydraulic properties of the soil that may lead to increased surface runoff.

New Zealand soils are prone to developing water repellency under field moisture conditions (Wallis et al. 1991). The presence of water repellency is highly dependent on soil moisture levels and may exhibit patterns in response to wetting and drying (Doerr & Thomas 2000; MacDonald & Huffman 2004). Therefore, it is plausible that under drier conditions some soil water repellency may be observed across the Hillend Station burn area, but it would probably also be present in unburnt areas, in the absence of a possible fire effect on water repellency.

Surface soil shear strength

Soil shear strength measurements indicated no significant difference between burnt and unburnt locations on Hillend station. Shear vane readings in kg cm^{-2} were converted to kPa for comparison with international literature. The mean burnt and unburnt soil shear strengths were 11.0 ± 2.8 and 12.6 ± 11 kPa, respectively. We observed higher variability on the unburnt than the burnt terrain. This may partly reflect the need to target unvegetated patches on the unburnt slope for shear strength measurements. Such locations may be subject to other forms of disturbance (e.g. sheep trampling).

We sought to characterise possible fire-related changes to the internal resistance of the surface soil. This resistance depends on inter-particle cohesion and the contribution of fine roots to soil strength (Nyman et al. 2013), and not the effect of above-ground vegetation. The results indicate that the fire is unlikely to have had much effect on the erodibility of the soil. This finding is consistent with our field observations, which indicated that the fine root layer present within the upper few centimetres of the burnt soil remained largely intact (Fig. 16).

Figure 12 Intact fine roots were observed in surface soils on the burn area.

The soil shear strength measurements from Hillend station burn area may also be compared with equivalent data from burnt soils in Victoria, Australia (Nyman et al. 2013). In the Australian study, the temporal changes in surface soil shear strength were assessed by comparing multiple sites 0.5 to 3 years following high severity wildfire. Both our investigation and the study by Nyman et al. (2013) employed pocket shear vanes manufactured to equivalent specifications. Nyman et al. (2013) report shear strength measurements at the soil surface (5 mm depth) of 1.2–1.7, 7.1–12, and 11.4 kPa within 0.5, 1 and 3 years after fire, respectively. The burnt and unburnt measurements from Hillend station are comparable to those recorded at the Australian sites 1–3 years after fire. The purpose of this comparison is to demonstrate the extent to which fire may reduce surface soil shear strength (and increase soil erodibility) in the short term. Such an effect was not observed at Hillend Station. Moreover, 93% of individual measurements at Hillend station exceed the threshold of 5 kPa defining noncohesive soils (i.e. noncohesive < 5 kPa) identified by Nyman et al. (2013). This suggests a low availability of readily entrained, fine-grained material at the soil surface within the burn area.

5.3 Hazard assessment

The hazard from debris flow is unlikely to have increased within the burn area due to the fire. This assessment is based on the following considerations:

Debris flow processes

The post-fire debris flow hazard is associated with surface runoff or mass failure triggering mechanisms, and sometimes a combination of both. There is evidence of pre-fire shallow landsliding on the burn area and deposits associated with small pre-burn debris flows. Mass failure-generated debris flows are generally associated with stand-replacing fires that result in (1) increased soil saturation due to a temporary reduction in forest evapotranspiration and (2) loss of tree root cohesive strength when there is widespread tree kill. Therefore, in the absence of forest cover on the burn area, it is unlikely that the fire will alter the pre-existing level of hazard associated with landsliding and debris flow.

Landscape susceptibility to runoff-generated debris flow after fire typically depends on (1) steep, convergent topography, (2) high burn severities, and (3) fire-modified soil properties, with triggering by intense rainfall that generates overland flow. These factors are considered below.

Topography

Slopes within the burn area are steep and exceed the estimated threshold slope (approximately >25°) observed in landscapes susceptible to post-fire debris flows. However, most of the burn area lacks convergent slopes, with the exception of an ephemeral channel located towards the southern end (Fig. 14).

Burn severity

The burn severity was insufficient to affect soil properties that influence post-fire debris flow susceptibility. Burn severity has been identified as a key predictor of post-fire debris flow susceptibility, as discussed in the literature review (section 3). Much of the burn area appears to have burnt at low severity with only a small area with woody vegetation burning at a higher severity (Fig. 11). There was a notable difference in the extent of visible evidence for overland flow and erosion between these two areas, with more signs of erosion and sediment deposition associated with the higher severity burn area (Figs 12, 13). This field observation underscores the importance of burn severity for impacts on soil properties that affect the potential for post-fire runoff generation and soil erosion.

Soil properties

The lack of forest cover or other woody vegetation across the burn area significantly limited the intensity of the fire and hence the extent and duration of soil heating. As a result, there appears to have been a minimal effect of the fire on soil across most of the burn area. Field measurements indicated the absence of soil water repellency and negligible differences in surface soil shear strength between burnt and unburnt areas. Both these soil properties have been identified as important factors in landscape susceptibility to runoff-generated debris flows after fire. Moreover, we noted that fine roots remained intact in the upper soil profile. Fine roots provide additional cohesion to the surface soil. Loss of these roots through heating and combustion during fire increases surface soil erodibility.

Characteristic rainfall

Runoff-generated debris flows after fire typically occur in response to short duration and high intensity rainfall. Data from debris flow affected catchments in southeast Australia and southern California show ranges in 15 minute intensities of 35–85 and 12–69 mm h^{-1}, respectively. The reported 30 minute intensity for southeast Australia ranges from 17 to 60 mm h^{-1} (section 3). For context, debris flow triggering rainfall intensities are compared with the depth-duration-frequency statistics for the Hillend Station burn area by converting rainfall depths (mm) in Table 1 to units of mm h^{-1} and interpolating between the 10 and 20 minute durations. The range in 15-minute intensities from southeast

Australia equates to a recurrence interval of close to 30 to >100 years, while the 30-minute intensity range equates to 5–10 to >100 years. In contrast, the 15-minute intensity range from southern California equates to recurrence intervals of approximately <1.58 to >100 years at the Hillend Station burn site.

This comparison highlights the difference in triggering intensities between southeast Australia and southern California, and demonstrates that this information cannot be readily translated to different post-fire landscapes. Too many other factors influence debris flow initiation after fire. In the absence of any data on rainfall and post-fire debris flow occurrence in New Zealand, it is impossible to reach a firm conclusion about possible threshold intensities. However, given the low burn severity and minimal soil impact of the Hillend Station fire, it seems plausible that possible triggering rainfall intensities would conceivably need to be towards the upper end or exceed the reported ranges from Australia and California, which implies possible recurrence interval in the order >100 years. The likelihood of such infrequent, short-duration but high-magnitude storm rainfall occurring during a 1 or 2 year post-fire recovery window is low.

6 Conclusions and recommendations

Post-fire debris flows may be initiated either by surface runoff and progressive downslope sediment entrainment leading to a debris flow, or by landsliding that triggers a debris flow, or sometimes a combination of these processes.

The assessment of debris flow hazard across the Hillend Station burn area revealed evidence of pre-fire debris flow activity associated with shallow landsliding. It seems unlikely that the fire will have increased this pre-existing hazard. The absence of forest cover across the burn area suggests changes in soil water balance and soil cohesion resulting from the fire are likely to be minimal. Hence, it is improbable that the fire will have affected the level of pre-existing landsliding and debris flow hazard.

The hazard from runoff-generated debris or mudflows originating in the burn area on Hillend Station is unlikely to have increased due to the fire. Runoff-generated debris flow are typically initiated in steep, convergent headwaters burnt at high severity with erodible and low-infiltrating surface soils and are usually triggered by short duration (<1 hour), high intensity storm rainfall within 1–2 years after fire. At Hillend Station the hazard associated with runoff-generated debris flow after fire appears to be low, based on the low burn severity and its negligible impact on soil shear strength or water repellency across most of the burn area.

The pre-existing hazard associated with debris flows across the Hillend Station burn area is unlikely to have changed significantly due to the fire. Moreover, the fire is unlikely to have sufficiently modified the soil to introduce a new hazard associated with runoff-generated debris flows. Therefore, there is limited need for specific measures to reduce the risk of debris flow activity related to the fire. The most suitable approach would be to promote rapid surface vegetation recovery. This may involve seeding and perhaps temporarily excluding or reducing grazing to further promote surface cover regrowth.

7 Acknowledgements

Otago Regional Council provided funding for this study. Thanks to Ben Mackey for providing the local reports and immediate post-fire photos, and for discussing the site with us. We thank Joseph Fraser for assisting with access to the site, and Mike Scurr for allowing access to Hillend Station.

8 References

Baum RL, Godt JW 2010. Early warning of rainfall-induced shallow landslides and debris flow in the USA. Landslides 7: 259–272.

Benda L, Dunne T 1997. Stochastic forcing of sediment supply to channel networks from landsliding and debris flow. Water Resources Research 33(12): 2849–2863.

Bowman E, Kailey P 2010. Debris flow mechanics for New Zealand mountain catchments. Report for EQC by University of Canterbury.

Bowman E, Davies T 2008. The recognition and identification of debris flow hazards for proposed development sites in New Zealand. In: Chin CY ed. Proceedings of 18 NZGS Geotechnical Symposium on Soil-Structure Interaction. 18th New Zealand Geotechnical Society (NZGS) Symposium, 4–6 September 2008 NZGS Symposium (34), Auckland.

Cannon SH 2001. Debris-flow generation from recently burned watersheds. Environmental & Engineering Geoscience 7(4): 321–341.

Cannon SH, Powers PS, Savage WZ 1998. Fire-related hyperconcentrated and debris flows on Storm King Mountain, Glenwood Springs, Colorado, USA. Environmental Geology 35: 210–218.

Cannon SH, Reneau S 2000. Conditions for generation of fire-related debris flows, Capulin Canyon, New Mexico. Earth Surface Processes and Landforms 25: 1103–1121.

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

Cannon SH, Gartner JE 2005. Wildfire-related debris flow from a hazards perspective. In: Hungr O, Jacob M eds Debris flow hazards and related phenomena. Berlin: Praxis, Springer-Verlag. Pp. 363–385.

Cannon SH, Gartner JE, Wilson RC, Bowers JC, Laber JL (2008. Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California. Geomorphology 96(3–4): 250–269.

Cannon SH, Gartner JE, Rupert MG, Michael JA, Rea AH, Parrett C 2010. Predicting the probability and volume of postwildfire debris flows in the intermountain western United States. Geological Society of America Bulletin 122: 127–144.

Costa JE 1988. Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows. In: Baker VR, Kochel RC, Patten PC eds Flood geomorphology. New York: Wiley-Intersciences. Pp. 113–122.

Crockford H, Topalidis S, Richardson DP 1991 Water repellency in a dry sclerophyll eucalypt forest—measurements and processes. Hydrological Processes 5: 405–420.

DeBano LF 2000. The role of fire and soil heating on water repellency in wildland environments: a review. Journal of Hydrology 231–232: 195–206.

De Scally FA, Owens IF, Louis J 2010. Controls on fan depositional processes in the schist ranges of the Southern Alps, New Zealand, and implications for debris-flow hazard assessment. Geomorphology 122: 99–116.

Deurer M, Müller K, Van Den Dijssel C, Mason K, Carter J, Clothier BE 2011. Is soil water repellency a function of soil order and proneness to drought? A survey of soils under pasture in the North Island of New Zealand. European Journal of Soil Science 62: 765–779.

Doerr SH (1998) On standardizing the ''water drop penetration time'' and the ''molarity of an ethanol droplet'' techniques to classify soil hydrophobicity. A case study using medium textured soils. Earth Surface Processes and Landforms 23(7): 663–668.

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 2000. Soil water repellency: its causes, characteristics and hydro-geomorphological significance. Earth-Science Reviews 51: 33–65.

Doerr SH, Blake WH, Shakesby RA, Stagnitti F, Vuurens SH, Humphreys GS, Wallbrink P 2004. Heating effects on water repellency in Australian eucalypt forest soils and their value in estimating wildfire soil temperatures. International Journal of Wildland Fire 13(2): 157–163.

Doerr SH, Woods SW, Martin DA, Casimiro M 2009. 'Natural background' soil water repellency in conifer forests of the north-western USA: its prediction and relationship to wildfire occurrence. Journal of Hydrology 371: 12–21.

Gabet E (2003) Post-fire thin debris flows: sediment transport and numerical modelling. Earth Surface Processes and Landforms 28(12): 1341–1348.

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.

Gartner JE, Bigio ER, Cannon SH 2004. Compilation of post wildfire runoff-event data from the western United States: U.S. Geological Survey Open-File Report 2004–1085. http://pubs.usgs.gov/of/2004/1085/

Gartner JE, Cannon SH, Santi PM, Dewolfe VG 2008. Empirical models to predict the volumes of debris flows generated by recently burned basins in the western U.S. Geomorphology 96: 339–354.

Gray DH, Megahan WF 1981. Forest vegetation removal and slope stability in the Idaho Batholith. United States Department for Agriculture Forest Service Research Paper INT-271, 23 p.

Hungr O, Evans SG, Bovis MJ, Hutchinson JN 2001. A review of the classification of landslides of the flow type. Environmental & Engineering Geoscience 7: 221–238.

Kailey P 2013. Debris flows in New Zealand Alpine Catchments. Unpublished PhD thesis, University of Canterbury, Christchurch, New Zealand.

Kean JW, Staley DM, Cannon SH 2011. In situ measurements of post-fire debris flows in southern California: comparisons of the timing and magnitude of 24 debris-flow events with rainfall and soil moisture conditions. Journal of Geophysical Research. Earth Surface 116 (F04019).

Kean JW, McCoy SW, Tucker GE, Staley DM, Coe JA 2013. Runoff-generated debris flows: observations and modeling of surge initiation, magnitude, and frequency. Journal of Geophysical Research. Earth Surface 118: 2190–2207.

Langhans C, Smith HG, Chong DMO, Nyman P, Lane PNJ, Sheridan GJ 2016. A model for assessing water quality risk in catchments prone to wildfire. Journal of Hydrology 534: 407–426.

Langhans C, Nyman P, Noske PJ, Van der Sant RE, Lane PNJ, Sheridan GJ 2017. Post-fire hillslope debris flows: evidence of a distinct erosion process. Geomorphology 295: 55–75.

Larsen IJ, Pederson JL, Schmidt JC 2006. Geologic versus wildfire controls on hillslope processes and debris flow initiation in the Green River canyons of Dinosaur National Monument. Geomorphology 81: 114–127.

Léonard J, Richard G 2004. Estimation of runoff critical shear stress for soil erosion from soil shear strength. Catena 57: 233–249.

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

McNabb DH, Swanson FJ (1990) Effects of fire on soil erosion. In: Walsad JD, Radosevich SR, Sandberg DV eds Natural and prescribed fire in the Pacific Northwest forests. Corvallis, OR: Oregon State University Press. Pp. 159–176.

McSaveney MJ 1995. Debris flow and bridge loss at Waterfall Creek, SH6 at Lake Wanaka, New Zealand. Institute of Geological & Nuclear Sciences. Science Report 95/21. 35 p.

McSaveney MJ, Glassey PJ 2002. The fatal Cleft Peak debris flow of 3 January 2002, Upper Rees Valley, West Otago. Institute of Geological and Nuclear Science Report 2002/03. 28 p.

McSaveney MJ, Davies TR 2005. Engineering for debris flows in New Zealand. In: Jakob M, Hungr O eds Debris-flow hazards and related phenomena. Berlin: Springer. Pp. 635–658.

McSaveney MJ, Beetham RD, Leonard GS 2005. The 18 May 2005 debris flow disaster at Matata: causes and mitigation suggestions. Institute of Geological and Nuclear Sciences Client Report 2005/71.

Meyer GA, Wells SG 1997. Fire-related sedimentation events on alluvial fans, Yellowstone national park, USA. Journal of Sedimentary Research 67(5): 776–791.

Meyer GA, Pierce JL, Wood SH, Jull AJT 2001. Fire, storms, and erosional events in the Idaho batholith. Hydrological Processes 15(15): 3025–3038.

Moody JA, Martin DA 2001. Initial hydrologic and geomorphic response following a wildfire in the Colorado Front Range. Earth Surface Processes and Landforms 26: 1049–1070.

Moody JA, Ebel BA, Nyman P, Martin DA, Stoof CR, McKinley R 2016. Relations between soil hydraulic properties and burn severity. International Journal of Wildland Fire 25: 279–293.

Müller K, Deurer M, Slay M, Aslam T, Carter JA, Clothier B 2010. Environmental and economic consequences of soil water repellency under pasture. Proceedings of the New Zealand Grassland Association 72: 207–210.

Neary DG, Ryan KC, DeBano LF 2005. Wildfire fire in ecosystems: effects of fire on soils and water. Gen. Tech. Report. RMRS-GTR-42-vol. 4. Ogden, UT: United States Department of Agriculture, Forest Service, Rocky Mountain Research Station. 250 p.

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

Nyman P, Sheridan GJ, Moody J, Smith HG, Noske P, Lane PNJ 2013. Sediment availability on burned hillslopes. Journal of Geophysical Research. Earth Surface 118: 1–17.

Nyman P, Sheridan GJ, Smith HG, Lane PNJ 2014. Modeling the effects of surface storage, macropore flow and water repellency after wildfire. Journal of Hydrology 513: 301–313.

Nyman P, Smith HG, Sherwin CB, Langhans C, Lane PNJ, Sheridan GJ 2015. Predicting sediment delivery from debris flows after wildfire. Geomorphology 250: 173–186.

Opus 2004. Pipson Creek debris-flow hazard assessment SH6 RP828/3.65. Report No. 1081. Report prepared for Transit New Zealand.

Opus 2009. Otago alluvial fans project. Internal report #1205 – version 2. Report prepared for Otago Regional Council, Dunedin.

Otago Regional Council 2011. Otago alluvial fans high hazard fan investigation. Internal report. Dunedin: Otago Regional Council.

Pierson TC 2005. Distinguishing between Debris Flows and Floods from Field Evidence in Small Watersheds. USGS Fact Sheet 2004-3142. Vancouver, WA: U.S. Department of the Interior.

Shakesby RA 2011. Post-wildfire soil erosion in the Mediterranean: review and future research directions. Earth-Science Reviews 105: 71–100.

Smith HG, Sheridan GJ, Nyman P, Child DP, Lane PNJ, Hotchkis MAC, Jacobsen GE 2012. Quantifying sources of fine sediment supplied to post-fire debris flows using fallout radionuclide tracers. Geomorphology 139–140: 403–415.

Staley DM, Wasklewicz TA, Kean JW 2014. Characterizing the primary material sources and dominant erosional processes for post-fire debris-flow initiation in a headwater basin using multi-temporal terrestrial laser scanning data. Geomorphology 214: 324–338.

Swanston DN 1971. Principal soil movement processes influenced by roadbuilding, logging and fire. In: Proceedings of the Symposium on Forest Land Uses and Stream Environment. Corvallis, OR: Oregon State University. Pp. 29–40.

Wallis MG, Scotter DR, Horne DJ 1991. An evaluation of the intrinsic sorptivity water repellency index on a range of New Zealand soils. Australian Journal of Soil Research 29: 353–362.

Wells G 1987. The effects of fire on the generation of debris flows in southern California. Reviews in Engineering Geology 7: 105–114.

Welsh A, Davies T 2010. Identification of alluvial fans susceptible to debris flow hazards. Landslides 8: 183–194.

Wondzell SM, King JG 2003. Postfire erosional processes in the Pacific Northwest and Rocky Mountain regions. Forest Ecology and Management 178(1–2): 75–87.

Woods R 2007. Stoney Creek slip site inspection and review. Otago Regional Council, File Note EN70, EN09SC. 14 p.

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.