Sedimentary Geology 364 (2018) 286–301

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Special Issue Contribution: SEDIMENTARY EVIDENCE OF GEOHAZARDS

A combined morphometric, sedimentary, GIS and modelling analysis of flooding and debris flow hazard on a composite alluvial fan, Caveside, Tasmania

Claire L. Kain [a,*], Edward H. Rigby [b], Colin Mazengarb [a]

[a] Geological Survey Branch, Mineral Resources Tasmania, Department of State Growth, Tasmanian Government, 30 Gordons Hill Road, Rosny Park, Tasmania 7018, Australia
[b] Rienco Consulting, 5 Pelham Street, Sorell, Tasmania 7172, Australia

ARTICLE INFO

Article history:
Received 11 May 2017
Received in revised form 15 September 2017
Accepted 7 October 2017
Available online 12 October 2017

Keywords:
Alluvial fan
Flood modelling
Sediment transport
RiverFlow-2D
Debris flow

ABSTRACT

Two episodes of intense flooding and sediment movement occurred in the Westmorland Stream alluvial system near Caveside, Australia in January 2011 and June 2016. The events were investigated in order to better understand the drivers and functioning of this composite alluvial system on a larger scale, so as to provide awareness of the potential hazard from future flood and debris flow events. A novel combination of methods was employed, including field surveys, catchment morphometry, GIS mapping from LiDAR and aerial imagery, and hydraulic modelling using RiverFlow-2D software. Both events were initiated by extreme rainfall events (<1% Annual Exceedance Probability for durations exceeding 6 h) and resulted in flooding and sediment deposition across the alluvial fan. The impacts of the 2011 and 2016 events on the farmland appeared similar; however, there were differences in sediment source and transport processes that have implications for understanding recurrence probabilities. A debris flow was a key driver in the 2011 event, by eroding the stream channel in the forested watershed and delivering a large volume of sediment downstream to the alluvial fan. In contrast, modelled flooding velocities suggest the impacts of the 2016 event were the result of an extended period of extreme stream flooding and consequent erosion of alluvium directly above the current fan apex. The morphometry of the catchment is better aligned with values from fluvially dominated fans found elsewhere, which suggests that flooding represents a more frequent future risk than debris flows. These findings have wider implications for the estimation of debris flow and flood hazard on alluvial fans in Tasmania and elsewhere, as well as further demonstrating the capacity of combined hydraulic modelling and geomorphologic investigation as a predictive tool to inform hazard management practices in environments affected by flooding and sediment movement.

1. Introduction

Hydrogeomorphic processes in alluvial fan systems can involve a combination of fluvial, hillslope and mass movement processes, as part of a larger erosion-deposition system (e.g., Bull, 1977; Blair and McPherson, 1994; Harvey et al., 2005). Extreme flooding, landslides and debris flows are known to cause significant problems for property owners and infrastructure managers in such environments. As such, an understanding of alluvial hydrogeomorphic processes is important for determining the progression of flooding and sediment movement on alluvial fans, interpreting their impacts, and assessing the probability of and risk from potential future flooding and sediment movement.

Alluvial fans are cone or fan-shaped deposits of sediment that occur adjacent to mountain fronts, where streams or debris flows exit a confined area (Allen, 1965; Bull, 1977; Blair and McPherson, 1994; Harvey et al., 2005). Alluvial fans are formed by stream flow, hyperconcentrated flow, debris flows or a combination of processes (Bull, 1977; Harvey et al., 2005). Moreover, some fans may have been formed by debris flows under different climatic regimes but are now controlled by stream flooding and sedimentation (Bull, 1977). The relative contribution of the aforementioned processes affects the morphology of the fan, alongside large-scale variables such as tectonics, climate and base level (Bull, 1977; Viseras et al., 2003; Harvey et al., 2005), and thus exerts physical controls on the nature of flooding hazard (NRC, 1996). Most importantly, the hazard associated with alluvial fans relates not only to water inundation, but includes sediment erosion and deposition processes that require different consideration and remediation methods than water floods (Hungr et al., 1984; He et al., 2003; Jakob and Hungr, 2005; Davies and McSaveney, 2008). Debris flow fans are considered more hazardous than fluvially dominated fans, due to the higher peak discharge and sediment load associated with debris flows (Hungr et al., 2001; Wilford et al., 2004; Welsh and Davies, 2011; Santangelo et al., 2012).

* Corresponding author.
E-mail address: claire.kain@stategrowth.tas.gov.au (C.L. Kain).

https://doi.org/10.1016/j.sedgeo.2017.10.005

By definition, debris flows have sediment concentrations above 60% by volume and behave in a plastic manner (Pierson, 2005a). However, the boundaries between flow types are not static and depend ultimately on flow behaviour rather than absolute sediment concentration (Pierson and Costa, 1987; Davies et al., 1992; Takahashi, 2007). Debris flows transport sediment as a massive, unsorted network of clasts, which can allow boulders to be suspended in a matrix of finer sediment and carried farther than would be possible by water flow alone (Pierson and Costa, 1987). Hyperconcentrated flows contain approximately 20–60% sediment by volume, and behave in a manner that is intermediate between debris flows (Bingham fluid) and Newtonian stream flows (Pierson and Costa, 1987; Pierson, 2005b). Like debris flows, they are capable of transporting boulders as well as fine material, although, in contrast to debris flows, boulders are generally transported as bedload (Pierson, 2005b) and sediment is commonly deposited from suspension in the same manner as stream flows (Pierson and Costa, 1987). Hyperconcentrated flows may be extremely erosive in steeper channels and tend to cause large-scale aggradation in lower gradient channels. Ouellet and Germain (2014) show that alluvial fans can be dominated by hyperconcentrated flow, which may leave sediment deposits that show characteristics of both debris flow and fluvial processes. River floods transport less sediment by volume and flood-related sediment deposition on alluvial fans may occur from channelised flow, complex channel flow (braided) or sheet flow (Bull, 1972).

Fans that are fed by both debris flows and flooding are termed 'composite fans' (NRC, 1996; Blair and McPherson, 2009; Scheinert et al., 2012). These fans are commonly dominated by lobes and levees in the steeper reaches (debris flow morphology) and divergent flow channels with an apron of finer sediment down-fan (consistent with streamflow deposition). When quantifying the flooding hazard on composite alluvial fans, it can be useful to consider debris flow and stream flood probabilities separately. NRC (1996) point out that a debris flow is not a 'random' event such as a rainfall driven runoff flood, but rather relies on the availability of accumulated debris in conjunction with a triggering event. As such, the average occurrence frequency of debris flows on a fan may not be the same as that of stream floods, and the risk from debris flow events can essentially reset to near zero following a major event that strips the source sediment in the catchment (NRC, 1996). Consequently, there are significant challenges involved in determining magnitude-frequency relationships for debris flows that have implications for hazard management and remediation solutions, as shown by the comprehensive study by Stoffel (2010) in the Swiss Alps. The triggering events for slope failure and/or flooding are generally explored in terms of rainfall frequency, intensity and duration (e.g., Caine, 1980; Rigby et al., 2005; Guzzetti et al., 2008; Chen et al., 2017).

Accurate identification of the dominant environmental processes is necessary to predict future risk on a given alluvial fan. Previous studies have explored differences in the morphometry of fluvially dominated alluvial fans versus those primarily formed by debris flows (Kostaschuk et al., 1986; de Scally et al., 2001, 2010; Crosta and Frattini, 2004; de Scally and Owens, 2004; Chen and Yu, 2011; Santangelo et al., 2012). In general, debris flow-dominated systems occur in conjunction with small high-relief basins and flood dominated systems are associated with larger, less rugged watersheds. Other factors that control the basin morphometry and affect the occurrence of debris flows versus fluvial flows include lithology, vegetation type and cover, and land use (Calvache et al., 1997; Sorriso-Valvo et al., 1998; Lorente et al., 2002; Wilford et al., 2004; Santangelo et al., 2012). Fan deposits left after a debris flow are generally poorly sorted with matrix-supported boulders, and may be reverse graded (Costa, 1984). The toe of a debris flow deposit is often lobate in shape and levees are commonly present at the sides of the transport path (Costa, 1988; Pierson, 2005a). In contrast, deposits left by hyperconcentrated flows and floods are more commonly normally graded, better sorted, imbricated and may include features such as bars and splays (Pierson, 2005b).

Fans have long been classified based on field surveys and analysis of their sediment deposits and stratigraphy (e.g., Allen, 1965; Bull, 1972; Blair and McPherson, 1994). More recent advances in topographic methods, remote sensing technology such as LiDAR, and GIS have provided new ways to understand alluvial fan functioning and evolution (e.g., He et al., 2003; Rowbotham et al., 2005; Cavalli and Marchi, 2008; Hashimoto et al., 2008; Chen and Yu, 2011; Santo et al., 2015; Chou et al., 2017). Hydraulic modelling has also been employed to explore flooding hazard and sediment movement patterns (e.g., O'Brien et al., 1993; Nakatani et al., 2016), and sometimes used alongside remote sensing and/or field methods for this purpose (e.g., Pelletier et al., 2005; Toyos et al., 2007, 2008).

Alluvial fan systems are well studied globally, but little research has been undertaken in Australia. Additionally, few studies have combined geomorphological investigations with hydraulic modelling to understand alluvial fan flooding hazard. An understanding of debris flow and flooding hazard on alluvial fans is of particular interest in Tasmania, Australia, where such systems are common. Moreover, two major regional flooding events have occurred within a 5 year period, which had serious impacts on some alluvial systems and raised questions of future recurrence and risk for landowners. As such, the aim of this research is to understand the dominant processes involved in the 2011 and 2016 alluvial fan floods at Caveside, Tasmania, using a combined landscape analysis and modelling approach to ascertain whether these specific events were related to debris flows or floods. Additionally, we aim to classify the dominant processes occurring within this system to better understand the hazard potential from future events in Caveside and in similar systems around Tasmania.

1.1. Study area

The Caveside area lies at the base of the Great Western Tiers (GWT) in Tasmania, Australia (Fig. 1) and includes the Westmorland Stream alluvial system. The GWT form an elevated plateau capped by Jurassic age dolerite underlain by sandstone and mudstone dominated lithologies (Parmeener Supergroup). The Parmeener Supergroup unconformably overlies strongly folded Ordovician limestone (Gordon Group) present near the base of the escarpment (Jennings and Burns, 1958; Corbett et al., 2014). Slopes formed on Parmeener rocks are generally much gentler than dolerite slopes, but are steepest where underlain by resistant units such as the Ross Sandstone, which occurs in the upper part of the escarpment (Fig. 1). The Gordon Group limestone has a strongly developed karst landscape containing numerous dolines and cave systems (Jennings and Burns, 1958; Corbett et al., 2014).

The mountain slopes above Caveside are part of the Great Western Tiers National Heritage Area and Tasmanian Wilderness World Heritage Area (TWWHA), which is forested land (Eucalyptus, scrub and temperate rainforest species) that operates largely as a natural system. The escarpment is dissected by a number of incised streams, including Westmorland Stream, the focus of this study. Where these streams exit the escarpment they form alluvial fans that transition downstream into low gradient alluvial flood plains. The formation age of the alluvial lowlands is unknown, although these processes are likely to extend back through Quaternary glacial periods, as previously described in Tasmania (e.g., Wasson, 1977; McIntosh et al., 2012). The slope deposits of talus and colluvium (derived mainly from Parmeener rocks) are susceptible to landslides, including both shallow failures and larger deep-seated features.

Westmorland Stream forms a constrained alluvial fan (Fig. 1) that has been cleared and farmed since the mid to late 1800s. The Westmorland Stream catchment headwaters are near the top of the dolerite escarpment (Fig. 1) and drop from an elevation of over 1200 m to about 300 m AHD (Australian Height Datum) at the base of the alluvial fan. The overall stream length is approximately 7 km, reflecting a relatively steep average stream gradient of about 130 m km^{-1}.