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Post-fire changes in sediment rating curves in a wet *Eucalyptus* forest in SE Australia

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SUMMARY

Empirical power law sediment rating curves of the form $C = aQ^b$ (where C is the sediment concentration, Q is the discharge rate, and the coefficient a and exponent b are fitted parameters), or the alternative form given by $\log(Q_s) = \log(a) + (b + 1)\log(Q)$ (where $Q_s = CQ$ is the sediment delivery rate, and the natural logarithm is used) are widely used for characterising sediment transport across a broad range of spatial and temporal scales. Fire frequently has a large effect on erosion rates and sediment delivery. We investigate the temporal changes in the coefficient a and exponent b for 3 years following a wildfire between February 2003 and April 2006, for two South Eastern Australian *Eucalyptus* forested catchments (136 and 244 ha) with mean annual rainfall of 1900 mm. Storm-event integrated sediment loads and discharges were calculated for each of 596 storm events using stage-discharge control structures and *in situ* turbidity measurements at 15 min intervals. Measurements were converted to sediment concentrations using regression relationships developed from storm activated water auto-samplers. The analysis identified: (i) strong negative linear relationships between the rating coefficient log(a), and the rating exponent b, reflecting sediment rating curves that "pivot" around a common fulcrum point in log–log space, (ii) a systematic shift in this linear relationship between log(a) and b as a function of time since fire, (iii) maximum values of b of ca. 2.5 (i.e. maximum non-linearity in the relationship between discharge and sediment delivery, and therefore maximum sensitivity to high peak-discharge events) immediately following the fire, which decline rapidly and monotonically by a factor of 10 to ca. 0.25 in the first 8 months, attributed to a dominance of hillslope erosion processes and declining rill and interill erodibility, (iv) irregular patterns in the value of b during the vegetation recovery period, probably reflecting a shift from hillslope dominated erosion processes to a greater contribution from channel processes (8–24 months after the fire) and (v) annual cycles in the value of b in the recovered state (24–38 months after the fire) ranging from a minimum of ca. 0.5 in the dry season to a maximum of ca. 1.5 in the wet season. The physical cause of these cycles could not be isolated in this study. The results provide a robust quantitative perspective on the magnitude and temporal variability of the sensitivity of catchments recovering from wildfire.

1. Introduction

The empirically observed power law rating curve relating sediment concentration C (M L^{-3}) to the discharge rate Q (L^3 T^{-1}) is given by;

$$C = aQ^b \quad (1)$$

where a and b are the sediment rating coefficient and exponent respectively, and M, L, and T are the dimensions mass, length, and time, respectively. Multiplying both sides of Eq. (1) by Q gives the sediment delivery rate Q_s (M T^{-1});

$$Q_s = aQ^{b+1} \quad (2)$$

And taking the natural logarithm of both sides gives,

$$\log(Q_s) = \log(a) + (b+1)\log(Q) \quad (3)$$

Which is the form often used to determine the values of the rating coefficient a and exponent b from empirical data using linear regression (e.g. Mimikou, 1982; Asselman, 2000; Syvitski et al., 2000; Desilets et al., 2007; Yang et al., 2007; Hu et al., 2009). The sediment rating parameter a contains information about converting discharge Q into sediment concentration C, and information about the offset of the rating line in log–log space. The rating exponent b is dimensionless, while the units of a depend on b;

$$\frac{\mathrm{M}}{\mathrm{L}^3}\left(\frac{\mathrm{T}}{\mathrm{L}^3}\right)^b \quad (4)$$

A value of b larger or smaller than unity (one) indicates the capacity of the stream to erode and transport sediment changes in a non-linear way with changing flow. For example, we could expect b to be greater than unity in a system where new sources of

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sediment become available as discharge increases. The rating exponent b typically varies from 0.5 to 1.5 and rarely exceeds 2, while the rating coefficient a varies over seven orders of magnitude (Syvitski et al., 2000).

Sediment rating curves as expressed in Eq. (3) quantify the empirical relationship between the discharge rate ($L^3 T^{-1}$) and the sediment delivery rate ($M T^{-1}$). Both these quantities vary continuously in time, and their physical measurement always involves some integration over time, which typically can vary from seconds to years. The duration of this integration determines the temporal resolution of changes that can be observed. For example, measurements integrated over minutes often reveal hysteresis patterns at the intra-storm event scale (Smith and Dragovich, 2009). These patterns or "hysteresis loops" are typically associated with strong differences between the sediment rating curve of the rising limb compared to the falling limb of the hydrograph (see Fig. 5). In contrast, measurements of discharge and sediment delivery rate integrated over an entire storm event will obscure intra-storm hysteresis, but may reveal seasonal hysteresis patterns in inter-event scale sediment rating parameters. Monthly variability can reflect a response to individual weather events, such as dry periods, or convective storms. Seasonal changes may reflect seasonal changes in the source of water and sediment, and have been known to result in hysteresis (Syvitski and Alcott, 1995). Inter-annual variability may result from climate trends, recovery from extreme events, or human induced changes (e.g. Hu et al., 2009), and the values of the rating parameters are also known to vary with spatial scale (Syvitski et al., 2000).

Several authors (Desilets et al., 2007; Moody and Martin, 2001; Ewing, 1996) have analysed the post-fire temporal changes in the parameters of sediment rating curves in western USA. Desilets et al. (2007) report $(b+1)$ values (derived mostly from falling limb samples) ranging from 1.29 immediately after the fire to 2.89 towards the end of the 16 month study period. Moody and Martin (2001) report a value for $(b+1)$ of 1.4 over 4 years post fire where the pre-fire value was reported as 3 (Williams and Rosgen, 1989).

An inverse exponential relationship between the rating coefficient a and exponent b exists over a wide range in timescales (Syvitski et al., 2000). Mathematically, this relationship derives from a set of rating curves given by Eq. (3) in log–log space pivoting about a common point, located in the first and forth quadrant in the Cartesian plane. This is illustrated schematically in Fig. 1. Note that log(a) is the y-intercept of the sediment rating curve, and $(b+1)$ is the slope of the sediment rating curve.

In January 2003 wildfire burnt two hydrologic research catchments (136 and 244 ha) in the East Kiewa Valley, Victoria, Australia. Previous publications have reported on various aspects of research following this fire, including annual sediment exports from the catchments (Lane et al., 2006), runoff and erosion processes (Sheridan et al., 2007) and in-stream nutrient exports (Lane et al., 2008; Noske et al., 2010). This paper reports on the temporal changes in sediment rating curve parameters from immediately after the fire (February 2003) until the catchments recovered to pre-fire sediment export rates and ground-layer vegetation cover levels in April 2006 (Lane et al., 2006).

2. Methods

2.1. Site description

The research catchments, Slippery Rock Creek (SRC, 136 ha) and Springs Creek (SC, 244 ha) are located in wet *Eucalyptus* forest within the East Kiewa Research Catchments in NE Victoria, Australia (Fig. 2), described by Leitch (1979), Laing (1981) Hough (1983), Papworth et al. (1990) and Lane et al. (2006). The geology consists of quartz diorite and Ordovician Gneiss (Laing, 1981). The topography is steep with the elevation ranging from 620 to 1520 m and slope gradients >24° on more than half the catchments (Leitch, 1979). The soils are friable brown gradational clay-loams and sandy clay-loams generally <1.5 m deep grading to coarse sand C horizons (Hough, 1983). There is decreasing pedalogical development with depth and stones and rocks are distributed throughout the profile. The surface soils have low susceptibility to slaking, dispersion, and erosion (Hough, 1983; McKenzie et al., 2004). The soils are classified in the Australian Soil Classification (Isbell, 1996) as Acidic Eutrophic Red Dermosols.

Mean annual rainfall is around 1800–2000 mm, with a winter/spring dominant distribution. Intense summer thunderstorms are common in the area. Snow falls intermittently at higher elevations. Mean daily maximum temperature is 17.2 °C and mean daily minimum is 5.4 °C. The vegetation is wet sclerophyll and has been described by Smith et al. (1981) and Papworth et al. (1990). At lower elevations (up to approximately 1100 m) vegetation is dominated by mixed eucalyptus, where principally mature Alpine Ash (*Eucalyptus delegatensis* RT Baker) exists in almost pure strands in the upper region of both catchments, often showing the effects of previous wildfires in 1919 and 1939. The East Kiewa Research Catchments were extensively burnt in January 2003 at a moderate-severe intensity, during widespread wildfires that burned more than 1.3 M ha of mostly forested land across the state of Victoria. A small (approx 1 ha) area in the upper part of the SRC catchment was not burnt. Severe crown scorch was apparent for most trees, and a high proportion of the Alpine Ash was killed. Details of burn severity in the research area are given by Lane et al. (2006).

2.2. Catchment instrumentation

Detailed descriptions of catchment instrumentation are provided in Lane et al. (2006), and are briefly described below. Discharge at Slippery Rock Creek was measured through a

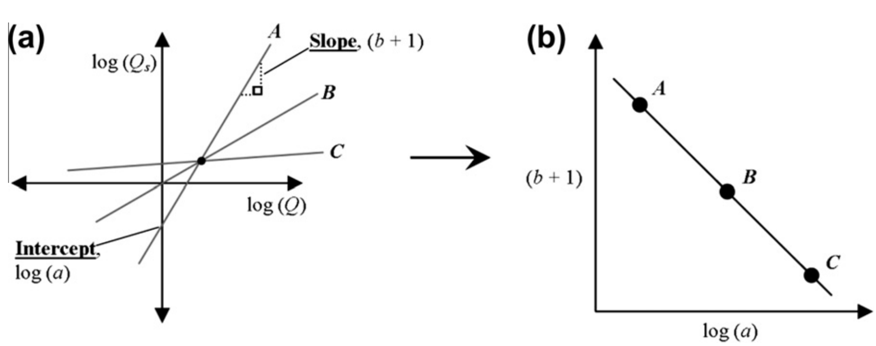

Fig. 1. An illustration of how a set of sediment rating curves (labelled A–C) based on Eq. (3) in log–log space, pivoting about a common point in the first quadrant of the Cartesian plane (a), will generate an inverse linear relationship between the rating coefficient a and the rating exponent $(b+1)$ (b).