Earth Surf. Dynam. Discuss., 2, 1093–1128, 2014
www.earth-surf-dynam-discuss.net/2/1093/2014/
doi:10.5194/esurfd-2-1093-2014

Earth Surface Dynamics
Discussions
Open Access

Hitting rock bottom: morphological responses of bedrock-confined streams to a catastrophic flood

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Received: 16 October 2014 – Accepted: 10 November 2014 – Published: 9 December 2014

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The role of extreme events in shaping the earth's surface is one that has held the interests of Earth scientists for centuries. A catastrophic flood in a tectonically quiescent setting in eastern Australia in 2011 provides valuable insight into how bedrock channels respond to such events. Field survey data (3 reaches) and desktop analyses (10 reaches) with catchment areas ranging from 0.5 to 169 km^2 show that the predicted discharge for the 2011 event ranged from 400 to 900 $\text{m}^3\,\text{s}^{-1}$, with unit stream power estimates of up to 1000 $\text{W}\,\text{m}^{-2}$. Estimated entrainment relationships predict the mobility of the entire grain size population and field data suggests the localised mobility of boulders up to 4.8 m in diameter. Analysis of repeat LiDAR data demonstrates that all reaches (field and desktop) were areas of net degradation via extensive scouring of mantled alluvium with a strong positive relationship between catchment area and normalised erosion ($R^2 = 0.8$). The extensive scouring in the 2011 flood decreased thalweg variance significantly with the exposure of planar bedrock surfaces, marginal bedrock straths and bedrock steps, along with the formation of a plane-bed cobble morphology. Post-flood field data suggests a slight increase in thalweg variance as a result of the smaller 2013 flood, however the current nature and distribution of channel morphological units does not conform to previous classifications of upland river systems. This suggests that extreme events are significant for re-setting the morphology of in-channel units in such bedrock systems. As important, is the exposure of the underlying lithology to ongoing erosion.

1 Introduction

1.1 Importance of bedrock channel morphology and processes

Upland channels, often referred to as bedrock channels due to the strong control of bedrock over process and thus morphology, received scarce attention in the literature throughout the 20th century due to the concentration of human interests in lowland alluvial valleys (Halwas and Church, 2002; Toone et al., 2014). The relatively recent recognition of steep headwater channels as critical habitats and sediment sources, as well as their role in landscape evolution has encouraged research in recent decades, with a particular focus on process-based morphology (Montgomery and Buffington, 1997) and the nature and rates of bedrock incision (Sklar and Dietrich, 1998; Tinkler and Wohl, 1998). Such river channels often comprise a mixture of alluvial and non-alluvial features, but are delineated by the high sediment transport capacity of flows relative to sediment supply (Howard et al., 1994). The morphology of most fluvial channels is the result of hierarchical arrangements of alluvial material into bedforms or channel units which form sequences which characterise the reach-scale morphology (Shields, 1936). This morphology is the function of physical processes resulting from a suite of variables, foremost; geology, climate and land use, which drive the topography, discharge, sediment characteristics and the potential influence of vegetation (Buffington et al., 2003).

Recent interest in the process-based morphology of bedrock channels has led to the creation of a number of morphological classification models for steep mountain streams (Wohl and Merritt, 2001). An important contribution by Montgomery and Buffington (1997) outlined a framework for reach-scale classification of upland streams into visually identifiable and physically distinct categories which has been applied and adapted by a number of subsequent researchers to describe bedrock channels in specific catchments (Halwas and Church, 2002; Golden and Springer, 2006; Thompson et al., 2006; Wohl and Merritt, 2008). The Montgomery and Buffington (1997) classification includes six classes in an idealised downstream progression; colluvial, bedrock, cascade, step pool, plane bed, pool riffle and dune ripple (Fig. 1). The most robust predictors of bedrock channel morphology are the relationship between slope and drainage area, sediment supply and sediment transport capacity ratios and channel geometry (Montgomery and Buffington, 1997; Thompson et al., 2006; Wohl and Merritt, 2008). The state of a channel at any given time is strongly influenced by the dis-

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turbance regime and the lag-time since the most recent disturbance (Montgomery and Buffington, 1997). This highlights the need to investigate the channel morphology of stream networks which have recently undergone a significant disturbance and determine if a change in process domain has occurred and the nature or trajectory of such change. As such, the specific objectives of this study are: (1) quantify the morphological response of bedrock channels to an extreme event, (2) determine if a directional change in process domain occurred, (3) assess the degree of mantle removal and potential bedrock erosion and present an evolutionary model for upland bedrock-confined channels that are subject to such extreme events. In post-orogenic terrain where bedrock is rarely exposed in the channel network the frequency of such rare events and their effectiveness is likely to be a key factor in determining long-term bedrock incision rates.

1.2 Response of bedrock channels to disturbance

The geomorphic effectiveness of floods describes the ability of an event to affect the shape or form of the channel morphology or the landscape (Wolman and Gerson, 1978). In fluvial systems, this change primarily occurs through the transportation of sediment and subsequent rearrangement, destruction or creation of channel units. This can result in wholesale channel reorganisation or minor changes to channel dimensions which do not affect overall processes (Thompson et al., 2006). Geomorphic effectiveness is a function of the size and duration of the disturbance and the inherent resistance of the system in terms of boundary conditions (Wohl, 2007). Bedrock channels in small catchments have highly variable flow regimes and resistant boundary conditions. Low frequency, high discharge floods are the “geomorphically effective” floods, as larger flows are required to mobilise sediment and propagate bedrock erosion and incision (Wolman and Miller, 1960; Costa and O’Connor, 1995; Milan, 2012). Due to the fact that individual settings exhibit vastly different characteristics in terms of boundary resistance, the frequency of effective processes and rates of recuperative processes, the magnitude of a discharge is only one factor in determining the extent of changes caused by an event (Costa, 1974). The literature regarding geomorphic responses to disturbance indicates that floods of similar scale and frequency can produce vastly different changes to channel morphology (Costa and O'Connor, 1995) due to antecedent conditions such as flood ordering and timing, and internal factors such as condition of riparian vegetation and/or presence of large wood or log jams.

Baker (1977) highlights the role of flood variability in determining morphological channel response to flooding. The range of flood magnitudes experienced by a stream is a strong predictor of the degree of geomorphic impact of floods between different settings. The high variability of discharges typical of upland drainage networks creates a system which maintains relatively uniform structure during normal flow periods and responds catastrophically to large, infrequent events (i.e. > 100 yr ARI) (Miller, 1995; Jansen, 2006; Wohl, 2007). The response of upland channels to geomorphically effective floods is critical to a robust understanding of both process-based morphology in bedrock channels, and catchment-wide effects of flooding, as the morphology of upland drainage networks has a significant impact on the nature of downstream disturbance propagation.

1.3 Role of large floods in channel evolution

As rare, large magnitude events operate as the geomorphically effective discharges in steep montane drainage networks, they inherently play a major role in the long-term morphology and evolution of channels in such settings. Large flood events can fundamentally alter the sediment supply and transport capacity of such systems, which ultimately dictates channel form and stability. As such, large floods can cause instability through either aggradation or erosion of coarse-grained alluvium (Turowski et al., 2013). This is particularly relevant in an eastern Australian context where extreme hydrological variability (see Finlayson and McMahon, 1988) may influence this ratio and thus the morphological stability and evolution of such systems (Nanson, 1986; Thompson et al., 2006). This may suggest that in some settings river channels can adjust to conditions set by major floods and subsequently maintain a flood-dominated

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morphology (Fuller, 2008; Hickin, 2009). The high spatial resolution of modern LiDAR imaging allows the analysis of such morphological changes through the mapping of in-channel features, creation of digital elevation models (DEMs) and change assessment through rendering of multi-temporal DEMs of difference (DODs) (Croke et al., 2013). Recent studies highlight the range of applications for LiDAR analysis at different scales, from reach-scale to catchment wide processes (Charlton et al., 2003; Croke et al., 2013; Grove et al., 2013). Catchments for which LiDAR data records pre- and post-disturbance morphology present a unique opportunity to assess changes to processes and morphology as a result of disturbance on a range of scales, from discrete channel units to basin-wide trends. The presence of pre and post 2011 flood LiDAR in the Lockyer valley, Queensland allows for such an assessment. Previous studies in the region have focussed on the alluvial reaches (or variations in responses between confined and unconfined reaches and bank erosion within agricultural and semi-agricultural settings (Croke et al., 2013; Grove et al., 2013; Thompson and Croke, 2013). In contrast, the main aim of this study is to assess the channel response in forested bedrock-confined settings to an extreme event and examine the current channel based on existing morphological classification systems by utilising multi-temporal LiDAR-DEMs and field surveys.

2 Regional setting

2.1 Southeast Queensland

Southeast Queensland has a highly variable climate and the long-term precipitation patterns of eastern Australia are influenced by global systems including the El-Niño-Southern Oscillation (ENSO), the Sub-Tropical Ridge (STR) and the Indian Ocean sea surface temperature patterns (Kirkup et al., 1998). These systems lead to highly variable multi-year rainfall and discharge regimes and decadal trends of above- and below-average rainfall across eastern Australia and have been described in the literature as

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flood and drought dominated regimes (Erskine and Warner, 1988). Hydrologically, this manifests in high streamflow variability in many parts of eastern Australia, particularly northern NSW and Southern Queensland (Rustomji et al., 2009).

2.2 Upper Lockyer Catchment

The Lockyer Valley lies east of Toowoomba and west of Brisbane in South East Queensland, Australia (Fig. 2) and the catchment has a drainage area of 2600 km^2, comprising approximately a quarter of the Brisbane River catchment (Croke et al., 2013). The alluvial lowlands of the Lockyer Valley are one of the most productive agricultural regions of Australia, being intensively cultivated for horticulture whilst the upper Lockyer region is dominated by grazing for livestock, with the southern and western extents of the catchment being steep and forested, reaching elevations of up to 700 m a.s.l. (Australian Height Datum; AHD). The climate of the Lockyer Valley is sub-humid, subtropical and strongly seasonal, with 65–70 % of total rainfall occurring between October and March, in part due to higher precipitation intensities associated with summer storms generated by sub-tropical lows. Average annual rainfall in the upper Lockyer region is ~ 800 mm (at Helidon; Fig. 2). The study area is a post-orogenic upland region located on the eastern side of the Great Dividing Range. The lithology of the region is dominated by sedimentary and metamorphosed sedimentary rocks of Jurassic-Triassic and Permian origin respectively (Geological Survey of Queensland, 2011). The streams of the upland region are steep, narrow bedrock-confined channels with discontinuous mantling of the bedrock by coarse-grained alluvium or colluvium.

2.3 Flooding in the Lockyer Catchment

On 10 and 11 January 2011, catastrophic flooding occurred in the Lockyer Catchment resulting in extensive geomorphic change and damage to infrastructure and the loss of human life. The flooding was preceded by months of record-breaking rainfall across south-east Queensland (National Climate Centre, 2011). The extended and consistent nature of this rainfall resulted in the saturation of the Lockyer catchment, effectively creating run-off conditions where rainfall could not infiltrate the soil column and was transmitted directly to streams. On the 10 January, a low pressure system moved inland over the catchment, colliding with upper level and monsoon troughs (BMT WBM Pty. Ltd., 2011) and intensifying under orographic uplift in the north and west of the basin. This resulted in extreme rain intensities of up to ~ 150 mm in 2 h in the upland bedrock-confined tributaries of Fifteen Mile Creek and Alice Creek sub-catchments (Fig. 2) with an annual exceedance probability (AEP) for rainfall of greater than 2000 years at Helidon (SEQ Water, 2011). This heavy precipitation played a disproportionate role in the flooding due to the high intensity of localised rainfall in a very short period and the steep-confined nature of the upland channels which rapidly transmitted this water downstream. A second heavy rainfall event occurred in the summer of 2013 across coastal Queensland which resulted in flooding in the Lockyer and Brisbane catchments, with the highest 1 day rainfall between 22 and 28 January being the sixth-highest on record since 1900 (Bureau of Meteorology, 2013). While flooding throughout the Lockyer Valley was extensive, geomorphic change and infrastructure damage were less catastrophic than 2011. The characteristics of the 2011 flood and flood frequency calculations for the upper Lockyer are presented in Table 1. Log Pearson III analysis returned an average recurrence interval (ARI) for the 2011 flood of ~ 60 years at Spring Bluff and 45 yr at Helidon which is much less than previous estimates, highlighting that the estimated return intervals are heavily dependent on whether data up to 2013 is included in the analysis. In contrast the 2013 flood represented an ARI frequency of 8–5 years for Spring Bluff and Helidon respectively.

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3 Methods

3.1 Site selection and field survey

Selection of potential study reaches was carried out using a Geographical Information System (GIS). Using a 1 m Digital Elevation Model (DEM), aerial photography and a 1 : 100 000 digital surface geology map, three reaches of similar lithology and varying contributing drainage area and slope were selected for field survey which were accessible by road. An additional ten reaches were selected for spatial analysis based on the same criteria. Channel "reaches" are sections of channel reaches of at least 10 channel widths in length, which represent sections of a stream containing a sequence of channel units throughout which morphology and gradient are relatively constant (Montgomery and Buffington, 1997; Wohl and Merritt, 2011). The average reach length surveyed was ~ 1200 m.

Study reaches were surveyed along the low-flow channel using differential GPS survey equipment (Trimble R7 and R8 GNSS System) in April 2013. A lack of base station static data for each of the surveys prevented post-processing, requiring the 2013 field data to be normalised to the LiDAR data sets (see Sect. 3.3). To measure thalweg variance a thalweg longitudinal profile was measured in each of three representative field reaches with in-channel units mapped along with the presence, location and height of flood marks from the 2011 flood, including tree scarring and flood debris on the channel boundary. Cross-sections were surveyed at the upstream and downstream extent of the study reaches and grain-size data was collected using a modified Wolman (1954) method with grainsize determined by the measurement of 100 clasts per bar.

3.2 Entrainment threshold calculations

Due to the lack of stream gauges in the study area the magnitude of the 2011 flood in the three field reaches has been estimated using the Manning equation, based on cross-sectional surveys including water surface elevation and reach-averaged water

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surface slope. A range of roughness estimates were used to calculate values for predicted discharge, shear stress and stream power with values of discharge constrained in the most downstream reach by previous basin-scale modelling (see Thompson and Croke, 2013).

The estimation of Manning's n for hydrological calculations characterising the 2011 flood event was carried out using the Meyer-Peter and Müller (1948) equation, which accounts for the increased turbulence of deep-water flow associated with large flood events in mountain channels.

$$n = \left((D_{90})^{1/6}\right)/26 \tag{1}$$

where D_{90} = particle size representing the 90th percentile of bedload

Calculation of predicted entrainment thresholds for the sediment fractions of the three study reaches was made using a range of flume- and field-based equations in order to test their applicability in catastrophic floods in such settings. The Shields Parameter (Shields, 1936) is a flume-based calculation which describes a "universal" threshold for the initiation of movement of bedload according to shear stress and grain size.

$$\tau_* = \frac{\tau_c}{(\gamma_s - \gamma)D} \tag{2}$$

where τ_c = critical shear stress; γ_s = specific weight of bed material; γ = specific weight of water; D = bed material particle diameter and τ_* = dimensionless Shields parameter.

Komar and Carling (1991) propose a modified shear-stress equation based on the use of reference particles to predict the entrainment of bed material in steep natural channels with poorly sorted, coarse bedloads.

$$\tau_{ci} = \tau^*_{c50}(\gamma_s - \gamma)D_i^{0.3}D_{50}^{0.7} \tag{3}$$

where τ_{ci} = crictical shear stress for particle of interest to move; τ^*_{c50} = dimensionless Shields parameter for D_{50}; D_i = diameter of particle size of interest and D_{50} = diameter of the median particle size of the channel bed.

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The Bathurst (1987) equation uses a unit discharge approach to predict entrainment thresholds in steep mountain channels with coarse bed materials, accounting for the effects of exposure and protection in mixed-size sediment stores.

$$q_c = 0.15 g^{0.5} D^{1.5} S^{-1.12} \tag{4}$$

where q_c = critical water discharge per unit width; g = acceleration due to gravity; D = diameter of particle size of interest and S = slope

$$q_{ci} = q_{cr} \left(\frac{D_i}{D_r} \right)^b \tag{5}$$

where q_{ci} = critical unit discharge for the movement of particles of size D_i; q_{cr} = critical unit discharge for the reference particle size D_r and b = an exponent (derived from Eq. 5)

$$b = 1.5 \left(\frac{D_{84}}{D_{16}} \right)^{-1}. \tag{6}$$

3.3 Spatial analysis

Spatial analysis was undertaken using georeferenced field survey data and LiDAR-derived DEMs flown in 2010 (pre-flood) and 2011 (post-flood). DEMs of difference (DoD) were created based on the subtraction of one DEM from the other and the subtraction of an error surface. The error surface was created from residuals of the height difference derived from digitised sealed roads along the valley bottom. Finally, a single SD error value of ±0.23 m, based on the propagated error from each of the DEMs, was applied for the entire DoD (see Croke et al., 2013 for error quantification methods). In order to integrate the 2013 field data with the 2010 and 2011 LiDAR it was necessary to normalise the 2013 field survey point data to the 2011 LiDAR-derived DEM. This was done by calculating the vertical displacement of 20 % of the field survey points per reach, which were assumed not to have changed between 2011 and

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2013, such as prominent bedrock ledges on the channel margin. The mean displacement was then applied to all field-derived point data. Multi-temporal longprofiles and cross-sections of the study reaches were derived from the 2010 and 2011 DEMs and plotted with field survey points from 2013. Vertical variability was quantified for each data set by applying a linear regression to the longitudinal profile data and calculating residuals. Cross-sectional area values were calculated by determining the maximum height of channel-marginal sedimentary units in the pre-flood data (2010) and calculating area below this height for pre- and post-flood data. To determine the mass flux of sediment in these bedrock settings a volumetric analysis was undertaken between the pre-flood and post-flood DEMs for the additional ten desktop reaches (~ 1 km in length) in the same lithology with catchment areas ranging from 0.5 to 169 km^2. We present normalised erosion indices where net volumetric change per reach is divided by total reach area ($m^3\,m^{-2}$).

4 Results

4.1 Sediment entrainment in an extreme event

Peak discharge for the 2011 flood, based on flood scarring and estimated Manning's n values equivalent to those used by Thompson and Croke (2013) in their catchment-wide modelling for the same event, yields discharge values ranging from 415 to 933 $m^3\,s^{-1}$, shear stress values up to 388 $N\,m^{-2}$ and cross-sectional averaged unit stream power of 1077 $W\,m^{-2}$ (Table 2) for an event that was 6–8 m flow depth. All three entrainment approaches predict the mobilisation of the D_{50} in each of the reaches in the 2011 flood, but with the Shields parameter predicting insufficient competence to transport the D_{max} (Table 3). Field observations and aerial imagery show that the entire bedload fraction was mobilised during the 2011 flood in each of the three reaches, indicated by the extensive channel stripping and removal of extensive coarse-grained mantle with the transport of boulders of at least 1.67 m in diameter (D_{max} at Murphys

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Creek). Anecdotal evidence and field observations suggest that clasts up to 4.82 m were transported during the 2011 flood (Fig. 3). The Komar and Carling (1991) approach and the Bathurst (1987) equation both successfully predict the mobilisation of the entire sediment fraction during the 2011 flood (Table 3). Magnitudes of the 2013 flood in three field reaches could not be estimated due to insufficient depth control (e.g. lack of flood debris).

4.2 Morphological response of the 2011 and 2013 floods

Repeat photographs (Fig. 4), aerial imagery and LiDAR indicate a channel mantled in coarse-grained alluvium in the study reaches prior to the 2011 flood, with narrow, stable low-flow channels and densely vegetated coarse-grained bars. Longitudinal profiles from pre-flood LiDAR show a high degree of longitudinal variability, with alternating sequences of riffles/steps and pools in the three reaches and deep, narrow low-flow channels (Figs. 4 and 5). LiDAR-generated pre-flood cross-sectional morphology also demonstrates the presence of channel marginal features, presumed to be vegetated coarse-grained bars or benches.

The 2011 flood resulted in catastrophic channel stripping with the total destruction of channel units and the removal of in-channel and riparian vegetation (Fig. 4b). The post-flood LiDAR demonstrates large decreases in longitudinal variance with the stripping of coarse alluvium through to channel widening via the removal of in-channel or channel marginal sediment stores (Fig. 4b). The channel floor was lowered to bedrock along segments of the three reaches exhuming bedrock steps, filling in existing pools and producing longitudinal profiles in which the bedrock steps represent the major areas of significant channel bed variability (Fig. 5a–c). Significant erosion of alluvium is evident throughout the three reaches with post-flood cross-sections taking on a uniformly wide trapezoidal shape (Fig. 6) with channel cross-sectional area expanding by 66 and 123 % (Table 4).

The 2013 flood represents an event with a much smaller ARI than the 2011 flood with an estimated recurrence interval in the upper catchment of < 10 years ARI. Separating

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the morphological impacts of the 2013 vs. the 2011 floods is difficult. Nevertheless, field survey data following this smaller event demonstrates increased variability of the longitudinal profiles since 2011 with small accumulations of sediment forming cobble-gravel riffles and the excavation and scour of a number of shallow pools (Fig. 5a–c). The 2013 flood event represented a discharge which resulted in considerable sediment distribution throughout the upper Lockyer catchment, evident in the re-formation of in-channel bars and riffles, however flow depths where most likely < 3 m in contrast to twice that in the 2011 flood. Cross-sections from the field survey in 2013 show small amounts of sediment accretion adjacent to the low flow channel with the establishment of primary colonisers and what appears to be a recovery towards a more variable and stable morphology.

4.3 Spatial analysis of reach-scale volumetric change

To determine the mass flux of sediment in these headwater settings a volumetric analysis was undertaken for an additional ten reaches (~ 1 km in length) in the same lithology with catchment areas ranging from 0.5 to 168 km^2. Analysis of volumetric change across the reaches, which vary in slope and contributing area, show a number of clear trends in the degree and location of erosion and deposition in bedrock-confined reaches of the upper Lockyer during the 2011 flood. Figure 6 demonstrates the nature of erosion and deposition within one of the three field reaches; Murphys Creek. The relatively straight nature of this reach resulted in a uniform pattern of channel stripping concentrated through the centre of the bedrock channel, with deposition along the channel margins in discontinuous pockets. All of the reaches (field and desktop), exhibit net erosion as a result of the 2011 flood, with an average loss of 0.4 $m^3 m^{-2}$ across the 13 reaches A clear correlation between catchment area and normalised erosion in the 2011 flood suggests that increasing discharge and total stream power (with contributing area) has played a key role in the area–erosion relationship (Fig. 6b; $R^2 = 0.80$).

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4.4 A morphological classification in an erosional landscape

The three field reaches exhibit poorly organised channel morphologies which are the direct result of the major flood in 2011. Generally, the reaches show a similar morphology despite the significant differences in contributing area and gradient. The Murphys Creek reach (largest catchment area) has the greatest degree of vertical variability with Paradise Creek (smallest catchment area) exhibiting very little vertical (bed) variability. The three reaches have morphologies of alternating sequences of pools, riffles and bedrock steps but with significant planebed sections. The channel floor is mantled with cobble to boulder sized material, with stretches of each reach flowing over bedrock steps where 1–2 m of coarse bed material has been removed. Sediment sorting of individual channel units is very poor with grain sizes ranging from sand to large boulders. Throughout the three reaches, the low-flow channels have high width to depth ratios and abut exposed bedrock straths or the bedrock valley margin along the majority of the reaches surveyed. The morphology of Murphys Creek and Fifteen Mile Creek do not fit within the visually identifiable morphologies and physical characteristics of the Montgomery and Buffington (1997) and Thompson et al. (2006) classifications. All three of these reaches lie within the physical parameters of pool-riffle morphologies according to the classification of eastern Australian bedrock channels outlined by Thompson et al. (2006), yet they exhibit morphological characteristics generally found in steeper channels including bedrock steps and extensive planebed channel stretches. Whilst we cannot accurately constrain the nature of in-channel assemblages in the three reaches prior to the 2011 flood, the photographs and pre and post-LiDAR data points to significant re-organisation of the morphological units in this large magnitude event (Figs. 4 and 5). In the following section we discuss the implications for such wide-spread re-arrangement on both the evolution of such channels and their potential shift in process domains associated with extreme events.

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5 Discussion

Confined bedrock rivers can only erode and incise the lithological substrate when the exposed bedrock (e.g. knickpoints) are subject to the mechanical abrasion and plucking processes in the modern hydrological regime. In tectonically active settings it has been shown that incision rates decrease, associated with earthquake-produced sediment that mantles the bedrock channels (Yanites et al., 2011). Yet, in tectonically passive settings with little to no earthquake-derived sediment and moderate to low relief it is worthy to ask the question; what magnitude events remove the sediment mantle and how often? Whilst the nature of such erosional events are stochastic (Snyder et al., 2003) their occurrence in settings such as the Great Dividing Range, where long-term erosion rates are very low, would be pivotal in providing the opportunity to erode the bedrock. It would appear that channels in these settings are often mantled with coarse bed material – "an alluvial overprint" (Carling, 2009). This cover effect has been the focus of much research over the last two decades (Seidl and Dietrich, 1992; Sklar and Dietrich, 2001) and essentially demonstrates the role of an alluvial mantle in limiting bedrock erosion (see Finnegan et al., 2014). Whilst we are not able to absolutely determine the pre-flood channel morphology for the upper Lockyer study area the LiDAR derived longitudinal profiles, cross-sections and photographs all indicate much narrower channel geometries and pronounced vertical variability in the longitudinal profile. Both of these suggest a significantly mantled channel with stable coarse-grained bedforms. The 2011 flood was of sufficient magnitude and exceeded critical thresholds such that in all field and desktop reaches the effect was a net loss of sediment. Such a loss in all reaches would suggest that such settings are flushed or are "flood-cleaned" (using the classification scheme of Turowski et al., 2012) in such extreme events. Interestingly however, the exposed or exhumed bedrock steps in the three field reaches all represent no more than 15 % of the length of the current channel floor, within any given reach, inferring that most of the reach is still effectively mantled by coarse-grained alluvium. In summary, we emphasize that the 2011 flood was an extreme event that ini-

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tiated widespread loss of the alluvial mantle and exposed bedrock steps that can now be attacked by abrasion and plucking processes.

5.1 Morphological channel response to the January 2011 flood and subsequent channel recovery

The catastrophic 2011 flood resulted in extensive channel stripping, with the wholesale transport of sediment, removal of mature riparian vegetation and significant reductions in longitudinal and cross-sectional variability. This event constituted the largest flood on record for the catchment and one of the largest on record in Australia in terms of specific peak discharge (Thompson and Croke, 2013), overcoming entrainment thresholds for the entire grain-size population. The morphological response of the study reaches is consistent with a number of previous studies in which steep, confined channels experience decreases in morphological variability, channel widening and scour to form "U" shaped channels (Nanson and Hean, 1985; Reinfelds and Nanson, 2001; Milan, 2012).

The degree of confinement evident in the study reaches also holds implications for the nature of sediment transport during the 2011 flood. The entrainment threshold calculations carried out in this study predicted the entrainment of the entire grain-size population. However, anecdotal evidence and recent deposits of extremely large boulders up to 4.82 m in diameter (Fig. 3) suggest that these empirical equations underestimate the effectiveness of catastrophic floods in such settings. The entrainment of unusually large clasts and comparatively voluminous bedload deposits during large floods is not unique, having been observed in other upland drainage basins (Milan, 2012) and may be a function of the non-Newtonian conditions of flow due to high concentrations of debris. The study reaches of the upper Lockyer possess significantly lower gradients than channels typically associated with the hyper-concentrated flows (Costa, 1974). Nonetheless, the rapid onset of the 2011 flood and intensity of run-off resulted in extreme transmission speeds downstream, which may have contributed to debris-type flows (Thompson and Croke, 2013).

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5.2 Modern channel morphology and classification

The scale of catastrophic channel stripping during the 2011 flood and deposition of flood debris in a discontinuous mantle along the narrow valley floor of the upper Lockyer has resulted in a wider more uniform channel morphology for all three field reaches. The stripping of alluvium down to bedrock in a number of locations has produced regular planated rock surfaces and rock steps along the channel floor which now dominate vertical variations in morphology and drops in channel gradient. These morphologies do not adhere well to the existing classifications for upland streams outlined by Montgomery and Buffington (1997) and in the Australian context, as outlined by Thompson et al. (2006). The three study reaches are not particularly steep in terms of mountain streams, falling within the pool-riffle domain of the Thompson et al. (2006) morphological classification but which display long sections of featureless planebed morphology (e.g. Fifteen Mile and Paradise Creek, Fig. 5). The extent of erosion of the alluvial mantle during the 2011 flood has resulted in significant bedrock control in the modern morphology, with bedrock abutting the low-flow channel of large stretches of the three reaches and bedrock steps forming the major vertical variability. This degree of bedrock control over channel morphology is often attributed to steeper gradient reaches, highlighting the geomorphic effectiveness of the 2011 flood in changing the sediment supply and sediment transport capacity characteristics of the upper Lockyer.

Golden and Springer (2006) highlight the fact that the wholesale mobilisation of alluvium during large floods causes mixed alluvial-bedrock reaches to operate as bedrock reaches in the immediate aftermath of mantle removal. The current morphologies observed in the upper Lockyer indicate that the time for morphological recovery in terms of organisation of in-channel units has not yet been sufficient. The slight increase in long profile variability (e.g. re-scouring of pools) and greater arrangement of sedimentary stores within the study reaches during the smaller 2013 event suggests that the stream network has the capability in re-shaping its erosional form potentially towards a more stable morphology. These changes, which will occur according to the physical setting

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of individual reaches and available sediment and energy inputs, can be assumed to form more stable morphologies which reflect their physical setting and will be more closely aligned with existing frameworks of upland stream classification Constraining the recovery time for such channels will form an important step in understanding the time required for such hydrologically variable systems to return to a stable state.

5.3 An evolution model for upland bedrock confined channels

A conceptual model of bedrock channel evolution in the Lockyer (Fig. 7) illustrates the change from a more stable channel morphology (pre 2011 flood form), to a cleaned and reset channel (post 2011 extreme flood), and redeveloping channel bedforms (2013 and subsequent smaller floods). The model parallels the 3 phases of bed transport of Warburton (1992), but illustrates the mechanisms and timing of bedrock incision.

Alluvial cover controls bedrock incision through armouring the channel bed from the forces of water, saltation and suspended sediment (Seidl et al., 1994; Sklar and Dietrich, 2001). Bedrock channel evolution models have focused on bed average vertical incision when quantifying the effects of tools and cover (e.g. Sklar and Dietrich, 1998). Finnegan et al. (2007) differentiated between slot-averaged incision and bed-averaged incision so as to account for cross section variation in incision rates and therefore interaction between sediment supply and channel shape. This was further enforced by Nelson and Seminara's (2011) bedrock evolution model showing that for vertically incising bedrock channels, the cross section shape is strongly controlled by the history of sediment supply. While data from this study cannot convey information on the sediment supply history, it does show the effect of the extreme flood on cleaning the channel of bars and benches, unearthing the bedrock straths before leaving a lag of cobbles and boulders (cobble planebed) interspersed by planar and stepped bedrock sections. Further, as depicted in Fig. 4, the active channel bed has been laterally relocated within the larger valley floor. This may have implications for models such as Finnegan et al. (2007) in which a single focus point (slot) in the channel was em-

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phasised for vertical incision compared to data presented here which shows the active channel or slot being moved across the valley bottom.

6 Conclusions

Field survey data and desktop-based analyses for 13 reaches with catchment areas ranging from 0.5 to 169 km^2 show that the predicted discharge for the 2011 event ranged from 400 to 900 $m^3 s^{-1}$, with unit stream power estimates of up 1000 $W m^{-2}$. The absolute return interval for these small catchments is difficult to constrain but the nearby gauge records and anecodotal evidence suggests the 2011 flood was a rare and an extreme event. Estimated entrainment relationships predict the mobility of the entire grain size population and field data suggests the localised mobility of boulders up to 4.82 m in diameter. Morphological change has been quantified with repeat LiDAR data that showed all 13 reaches were areas of net erosion via extensive scouring of mantled alluvium with a strong positive relationship between catchment area and normalised erosion. The extensive scouring in the 2011 flood decreased bed level variance significantly with the exposure of planar bedrock surfaces, marginal bedrock straths and bedrock steps, along with the formation of plane-bed cobble morphology. The current nature and distribution of channel morphological units does not conform to previous classifications of upland river systems, but illustrates a change in process domain due to changes in the sediment supply and sediment transport capacity relationship induced by the 2011 flood. Post-flood field data suggests a slight recovery in bed level variance, hence bedform (re)development as a result of the smaller 2013 flood. This highlights the significance of the extreme events like the January 2011 flood for re-setting the morphology of such bedrock systems. Long-term rates of landscape lowering/bedrock incision must be sensitive to the frequency and magnitude of such mantle-removing events and the 2011 flood has now exposed bedrock steps within these settings, providing an opportunity for bedrock erosion.

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Acknowledgements. This project was funded through an Australian Research Council funded linkage project (LP120200093). We would like to thank the industry partners in this project, landholders in the upper Lockyer catchment and James Daley for assistance in the field.

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Table 1. Flood characteristics of the 2011 flood, showing calculated Flash Flood Magnitude Index (FFMI; SD of the $\log s_{10}$ of the annual maximum series) and the average recurrence interval (ARI) for the 2011 event for data up to 2010 and 2013 inclusive; 2010 values from Thompson and Croke (2012). Q_p = maximum recorded flow; MAF = mean annual flow. See Fig. 1 for gauge locations.

	2010 Data		2013 Data	
	Spring Bluff (143 219A)	Helidon (143 203C)	Spring Bluff (143 219A)	Helidon (143 203C)
Length of record (y)	31	24	34	27
Catchment area (km^2)	18	357	18	357
FFMI	0.88	0.7	0.95	1.40
Q_p gauged ($m^3 s^{-1}$)	361.5	3642	361.5	3642
Specific peak discharge ($m^3 s^{-1} km^{-2}$)	20.08	11.76	20.08	11.76
Q_p/MAF	15.1	10.9	15.1	10.9
Recurrence interval (y)	~ 2000	100	59	45

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Table 2. Reach characteristics and calculated discharge, stream power and shear stress for the 2011 flood in each of the three field reaches.

	Area (km^2)	Slope ($m\,m^{-1}$)	Channelwidth (m)	D_{50} (mm)	D_{95} (mm)	Manning's n	Q ($m^3\,s^{-1}$)	ω ($W\,m^{-2}$)	τ ($N\,m^{-2}$)
Murphys Creek	168	0.005	70	85	500	0.1	897	690	286
Fifteen Mile Creek	89	0.008	70	85	505	0.1	933	1077	388
Paradise Creek	26	0.011	76	67	236	0.09	415	616	277

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Table 3. Results of flow competence equations for the 2011 flood, greyed out cells indicate that sediment entrainment is not predicted. τ_c = critical shear stress ($N\,m^{-2}$); q_{ci} = critical unit discharge for the movement of particles of size d.

	Shields (1936)			Komar and Carling (1991)			Bathurst (1987)		
	τ_c (d_{50})	τ_c (d_{95})	τ_c (d_{MAX})	τ_c (d_{50})	τ_c (d_{95})	τ_c (d_{MAX})	q_{ci} (d_{50})	q_{ci} (d_{95})	q_{ci} (d_{MAX})
Murphys Creek	68.79	**404.91**	**1351.57**	71.54	114.62	174.81	3.95	5.07	6.01
Fifteen Mile Creek	68.79	408.83	**880.55**	71.54	111.51	153.72	2.49	3.03	3.29
Paradise Creek	54.22	191.32	**398.19**	56.39	77.15	102.56	1.22	1.63	1.92

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Table 4. Cross-sectional area changes due to the 2011 flood at each of the three study reaches. Cross-sections were extracted ~ every channel width from the pre and post-LiDAR in the three reaches.

	Cross-sectional Area 2010 (m^2)	Cross-sectional Area 2011 (m^2)	Change (%)
Murphys Creek	42	91	123
Fifteen Mile Creek	39	67	66
Paradise Creek	22	37	68

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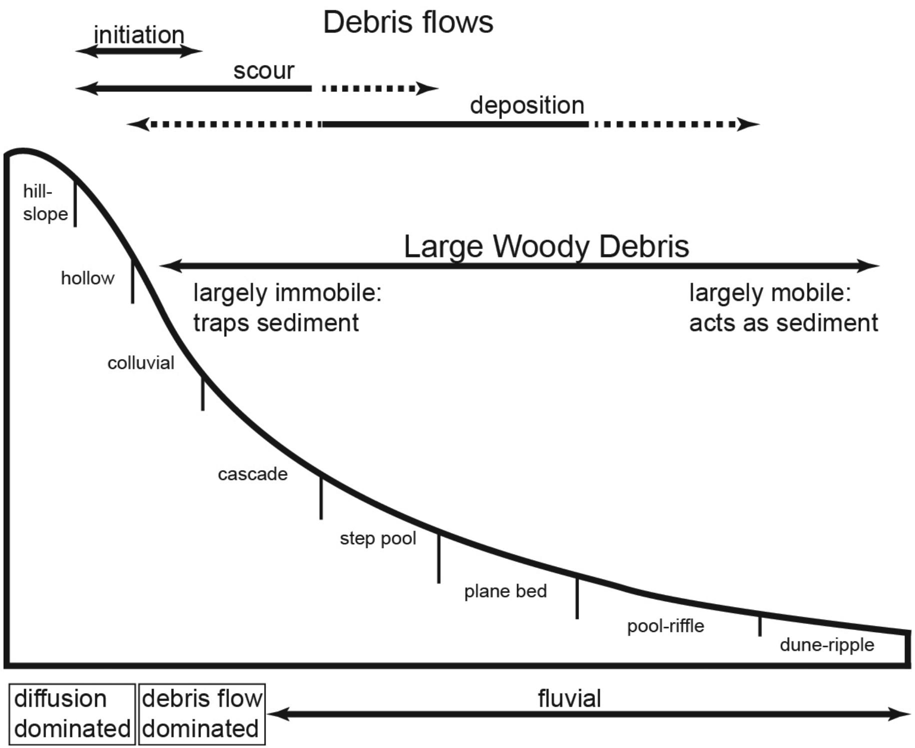

Figure 1. Idealised long profile downslope through the channel network showing distribution of channel types and controls on channel processes (from Montgomery and Buffington, 1997).

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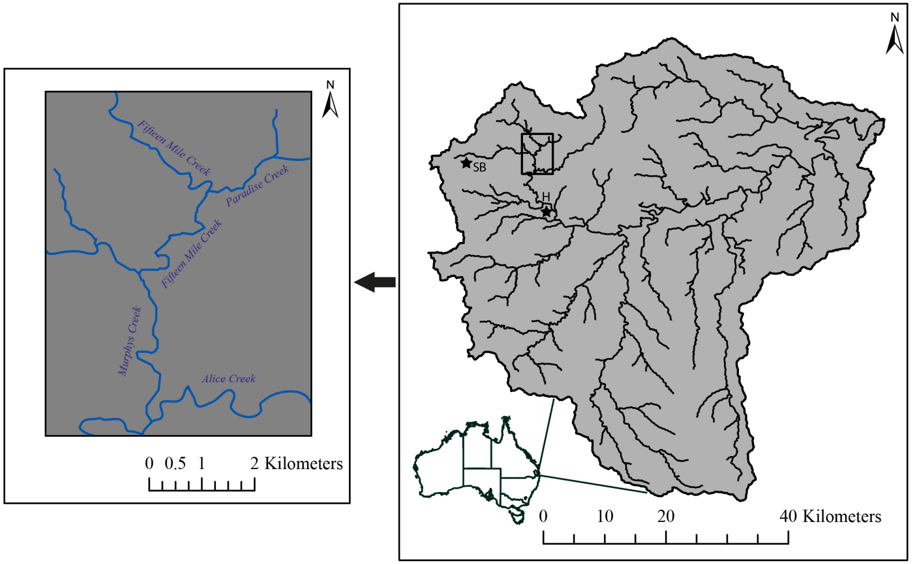

Figure 2. Location of the Lockyer Valley in southeast Queensland, Australia, including location of the study area in the upper valley.

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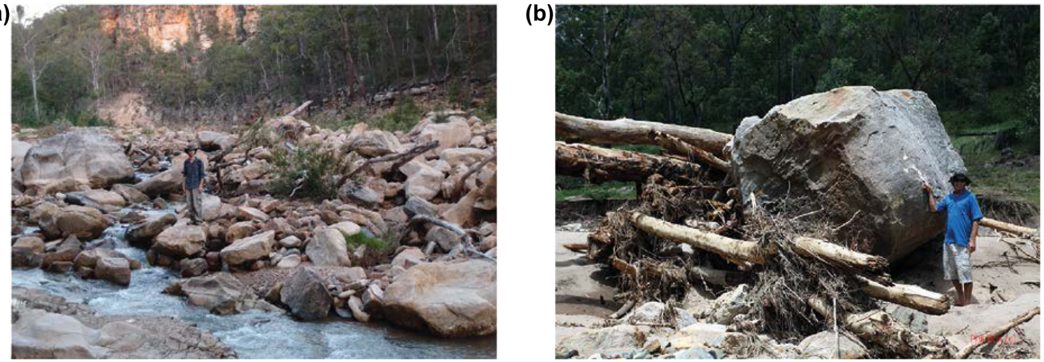

Figure 3. Photographs of large particles mobilised in the 2011 flood event: **(a)** boulder bar at Fifteen Mile Creek with D_{50} of 2325 mm and: **(b)** large boulder with b-axis of 4820 mm at Paradise Creek.

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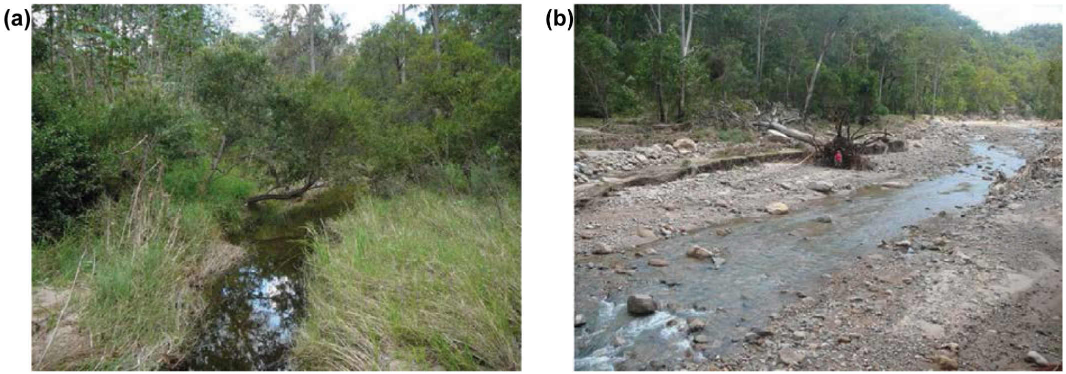

Figure 4. (a) Pre-flood (2010) and, **(b)** post-flood (2011) photography of Paradise Creek in the upper Lockyer Valley, showing catastrophic channel stripping and widening.

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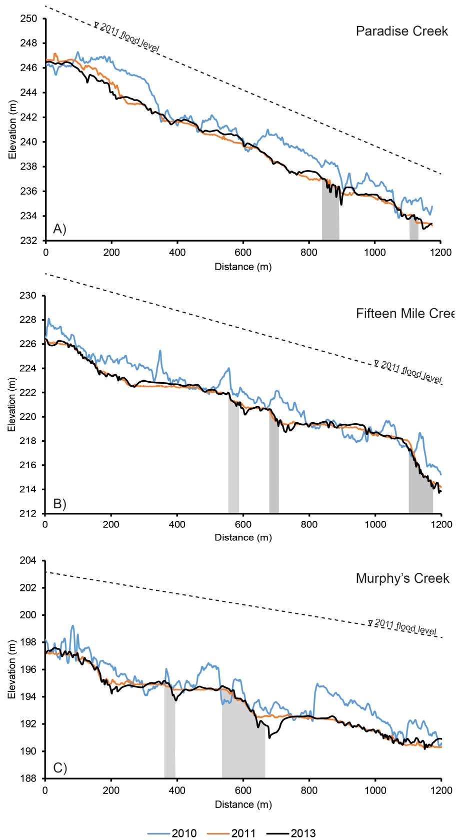

Figure 5. Longitudinal profiles of the three field sites; **(a)** Paradise Creek; **(b)** Fifteen Mile Creek; **(c)** Murphys Creek. Derived from 2010 and 2011 LiDAR (pre and post-2011 flood) and 2013 normalised DGPS thalweg profile (post-2013 flood). Dashed black line represents average water surface profile for the January 2011 flood based on DGPS elevations of flood marks. Grey shaded bars in each profile highlights exhumation of bedrock step in the 2011 flood.

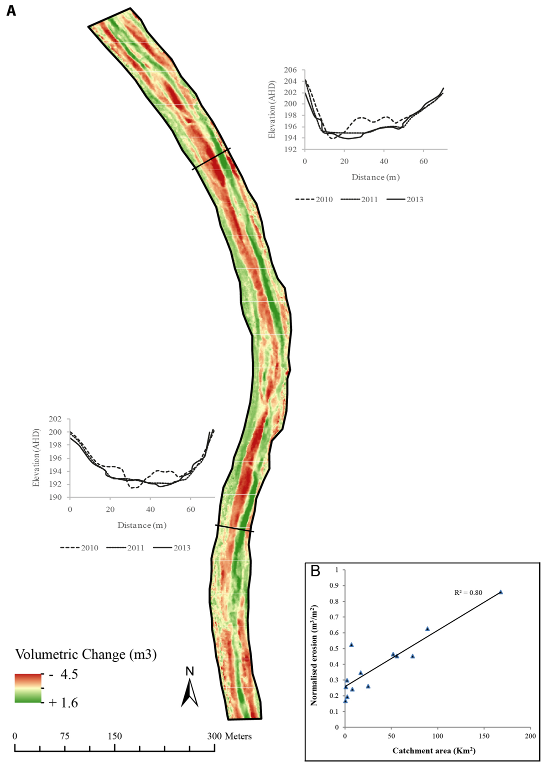

Figure 6. (a) Map of volumetric change at Murphys Creek due to the 2011 flood. Negative values indicate erosion, units in $m^3\,m^{-2}$. Insets are temporal cross sections derived from 2010 and 2011 LiDAR (pre and post-2011 flood) and 2013 DGPS survey data (post-2013 flood) showing the effects of the 2011 flood on channel cross-sectional area; **(b)** relationship between catchment area and normalised erosion for three field and ten desktop reaches in the upper Lockyer Valley. Derived from DoDs between the 2010 and 2011 LiDAR data.

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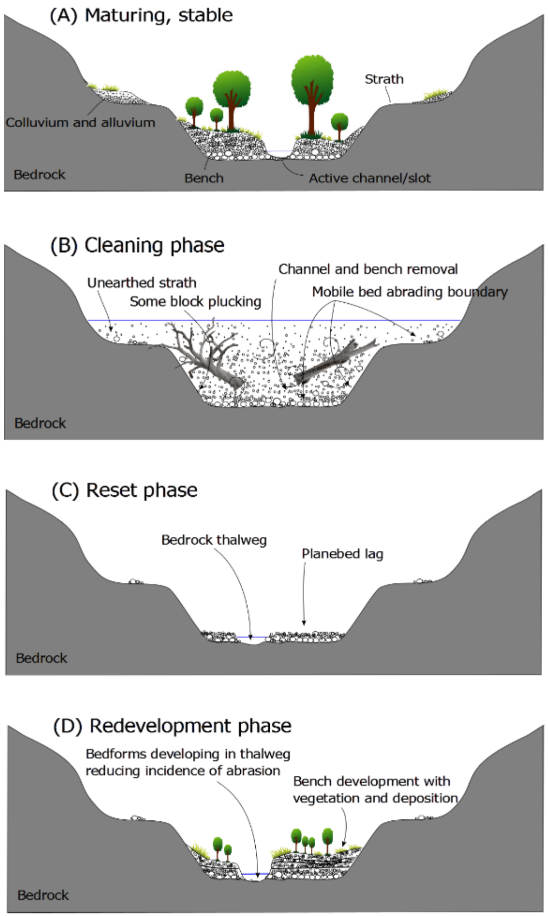

Figure 7. Schematic model for the evolution of mantled bedrock channels in an extreme event.

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