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A channel evolution model for subtropical macrochannel systems

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ABSTRACT

A channel evolution model (CEM) represents stages of channel development in response to specific types of disturbance. In recent years, classic incised/disturbed CEMs have provided process-based understanding of channel adjustment and formed the cornerstone for river restoration and rehabilitation. While broadly applicable to alluvial systems in temperate and semi-arid regions, these models cannot be assumed to be universally applicable. Lockyer Creek in South East Queensland, Australia, has notable macrochannel morphology and is subject to high hydrological variability typical of many subtropical climates. The aim of this paper is to present a case study of channel adjustment and evolution in lower Lockyer Creek, to determine if existing CEMs adequately describe processes of channel adjustment and the associated trajectories of change typical of river systems in subtropical settings. Lockyer Creek has recently been subjected to a spate of flooding resulting in significant channel erosion. This offers an ideal opportunity to investigate the nature and rate of channel adjustment processes and place them in context of longer-term geomorphic adjustments in these systems. Specifically we address two questions. Firstly, do the classic incised/disturbed CEMs adequately represent the observed macrochannel adjustment? Secondly, if current CEMs are inadequate, what is the channel evolution model for these systems, of which lower Lockyer Creek is an example? Results show that these are non-incising systems where wet-flow bank mass failures (WBMFs) are the dominant process of channel adjustment. They occur within the channel bank top boundary resulting in no change to overall bank-top width. Furthermore, subsequent floods deposit sediment in the failure scars and failure headwalls generally do not retreat beyond channel bank-top. Channel adjustment has not followed the evolutionary stages for incised/disturbed channels and a new four stage macrochannel CEM is outlined for these subtropical systems. The proposed CEM illustrates a cyclical pattern of erosion by channel bank WBMF followed by re-aggradation, through deposition and oblique processes, contributing to bank rebuilding. This CEM provides sufficient information to determine the stage of macrochannel adjustment, enabling decisions to be made over whether intervention is required or will be successful.

1. Introduction

Natural rivers exhibit various channel forms based on their discharge and sediment loads which integrate the effects of climate, vegetation, soils, geology and basin physiography (Knighton, 1998). Change in any of these variables may, but not without exception, be expected to result in channel adjustment over time. As well as response to such allogenic factors, autogenic channel adjustment can occur due to internal adjustments such as meander migration leading to neck cut-offs, or levee aggradation leading to avulsion (Schumm et al., 1996). Evidence of past channels and their geometry are generally archived in adjacent floodplains and serve as reminders of such channel adjustment. Knowledge of these past adjustments or trajectories of change are important for predicting likely future trends and for setting realistic targets for river management that accommodate adjustments (Brierley and Fryirs, in press, 2005; Brierley et al., 2008), and move beyond application of steady-state equilibrium models derived from elsewhere that aim to produce 'stable channels'.

Phillips (2011) proposes that collectively the principles of gradient selection and threshold-mediated modulation can provide a thesis of why rivers have particular forms, or emergent properties, which may *mimic steady states*. Gradient selection implies that mass and energy fluxes in geomorphic systems occur along the steepest gradients and persist and grow. Here, the downslope flow of water is an example where concentrated pathways once initiated are preferred if external factors are maintained. Threshold-mediated modulation in geomorphic systems implies that there are upper and lower limits to system development governed by a process threshold. Exceeding a threshold limits the process and may switch it in the opposite (or different) direction (Phillips, 2011). For example, levee and floodplain aggradation may eventually limit the frequency of overbank deposition. The resulting

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flood confinement to the channel and greater depth of flows may then switch process from overbank deposition to channel bed erosion. The switch to erosional processes may prevail until some resistant basal material is reached limiting further bed erosion, or local base level reduces energy gradient and switches the process back to bed deposition. This threshold modulated switching between process modes has also been used to explain divergent and convergent landform evolution and switches between divergence and convergence (Phillips, 2014). Divergent evolution results in spatial heterogeneity, an increase in statistical variance of an indicator variable and has multiple possible end states. In contrast, convergent evolution results in spatial homogeneity, a decrease in statistical variance of an indicator variable and a single end or stable state. Convergence and a single end or stable state is often preferred in river management where stable river channel geometries can be used as templates for design (e.g. Rosgen, 2007). Divergence has been viewed as problematic by river managers who have set in place programs to maintain stable states without understanding that threshold-mediated modulation can limit divergence and switch to convergence. Hence, the principles of gradient selection and threshold-mediated modulation may be used to understand the magnitude, duration and direction of geomorphic adjustment.

Channel geometry describes the three-dimensional form of a channel and four degrees of freedom have been proposed to represent the planes of adjustment of this geometry through sediment erosion and deposition on channel banks and beds (Knighton, 1998). These four degrees of freedom are: cross-sectional form, bed configuration, planimetric geometry and channel bed slope. Schumm et al. (1984) developed a five stage channel evolution model (CEM) to explain the complex channel response to disturbance which incorporates all four planes. Stage I represents the perceived stable or initial channel form (Fig. 1). Stage II represents the initiation of channel bed degradation, whether direct and instantaneous due to channelization or indirect through alteration to water and sediment fluxes in a landscape. In Stage III degradation leads to exceedance of critical bank height, resulting in channel widening via bank mass failures. Stage IV sees a switch to bed aggradation and continued widening as the channel gradient decreases and knickpoints migrate upstream. Stage V marks the return to a quasi-equilibrium channel as bank slopes decrease, vegetation stabilizes the new inset floodplain and meander migration further reduces longitudinal slope. Simon (1989) describes a six stage CEM, slightly modified from Schumm et al. (1984), based around anthropogenic modification of West Tennessee channels. These CEM's have been developed and most commonly used to describe geomorphic adjustments that occur in fully alluvial rivers over timescales of 10^1–10^2 years in response to both natural and anthropogenic disturbances.

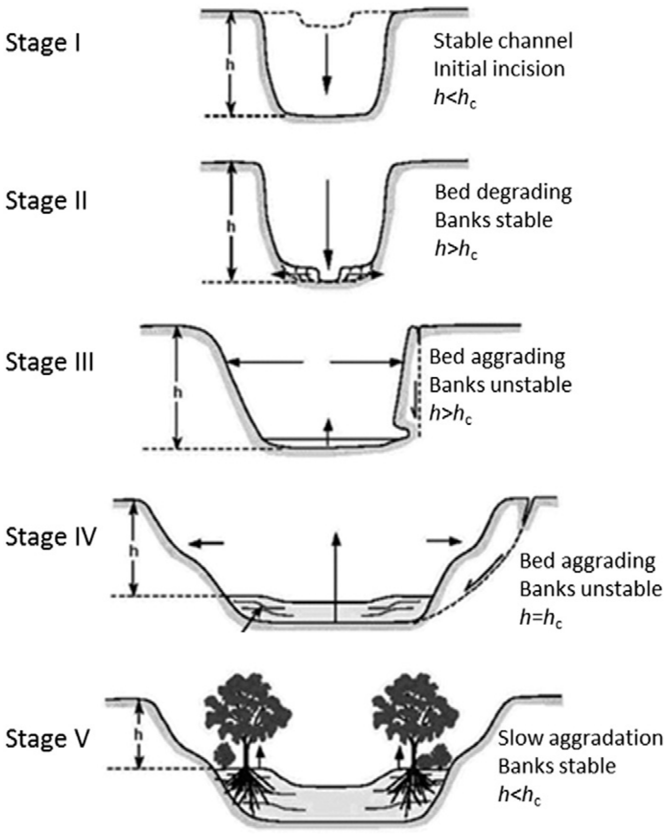

Fig. 1. Stages of classic channel evolution model of Schumm et al. (1984). *h* represents bank height and h_c is critical bank height.
Modified from http://www.austintexas.gov/faq/geomorphic-analysis.

Embedded within both the Schumm et al. (1984) and Simon (1989) models, the cycle of bank erosion explains how bed and bank (in)stability occurs at various stages (Brierley and Fryirs, 2005; Pizzuto, 1984; Thorne, 1982; Thorne and Lewin, 1979; Thorne and Tovey, 1981). As such, both CEMs have gained widespread acceptance and use in temperate and semi-arid North America, albeit with minor variations in sequencing owing to the type and scale of disturbance and the regional setting (e.g. Cluer and Thorne, 2014; Hawley et al., 2012; Heitmuller, 2014). The model has been evaluated for similar settings in Europe (e.g. Bollati et al., 2014) and temperate southeast Australia (e.g. Page and Carden, 1998). The effect of reafforestation in Europe has resulted in differing response trajectories following the initial stage of channel incision (Liebault and Piegay, 2001; Rinaldi and Simon, 1998). Given the similarity and widespread use of these CEMS, they will be referred to hereon as the classic CEMs.

The most common range of physical processes that can occur in a river system are represented by these classic CEMS. This results in their widespread use in channel restoration programs to determine the current morphological trajectory of a disturbed channel and to guide selection of the appropriate channel engineering works to return the system back to one of “stability” (i.e. Stage I) (e.g. Bledsoe et al., 2002; Hawley et al., 2012; Watson et al., 2002). However, these classic CEMs assume that: (1) rivers are fully alluvial; (2) there is no local bedrock control inhibiting incision; (3) the bed and banks are unconstrained and able to adjust; and (4) the system state preceding the initial disturbance stage represents a stable or steady state equilibrium. Given that all rivers do not fulfil these assumptions, the widespread use of these classic CEM's for interpreting geomorphic processes and identifying causes of channel degradation, particularly in river restoration practice, has been called into question (Hawley et al., 2012; Phillips, 2009).

Recently, South East Queensland (SEQ) has experienced a spate of floods causing significant channel erosion. A detailed description of the geomorphic processes which occurred during these floods is provided in Croke et al. (2013a), Grove et al. (2013), Thompson and Croke (2013) and Thompson et al. (2015). As part of the analysis into the recent SEQ floods Grove et al. (2013) determined that a significant proportion of the erosion could be accounted for as a result of wet-flow bank mass failure (WBMF). The more traditional bank erosion processes of slab, rotational or cantilever failures were not observed. Here, WBMF were caused predominantly by piping and sapping processes. Exfiltration from saturated or near-saturated banks on the falling limb of the flood hydrograph was sufficient for sediment removal from the bank and no significant volumes of sediment was left resting on the failure floor (Grove et al., 2013). Following the floods, major efforts have been underway to retard this erosion and return these channels to pre-flood conditions across the SEQ region on the assumption that this will improve the resilience of catchments to future floods. The template for restoration in SEQ has often been based on the assumption that channel response will follow the classic CEMs, and that engineered