Journal of Environmental Management 202 (2017) 412–423

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Arrested geomorphic trajectories and the long-term hidden potential for change

L. Allan James

University South Carolina, USA

ARTICLE INFO

Article history:
Received 19 April 2016
Received in revised form
1 February 2017
Accepted 6 February 2017
Available online 14 February 2017

Keywords:
Potential geomorphic change
Evolutionary trajectory
Inhibitors
River management

ABSTRACT

Geomorphic systems often experience morphological changes that define a trajectory over decadal time periods. These trends can be halted by natural inhibitors such as vegetation, knickpoints, bed armor, or bank cohesion, or by anthropogenic inhibitors such as revetment, levees, or dams. Details about where and how channels and floodplains are stabilized are often poorly understood, which poses a risk that modern projects could unwittingly remove critical stabilizing elements (inhibitors) and unleash an episode of rapid change. The potential for destabilization is particularly keen for rivers that were severely altered by human activities but were stabilized by an inhibitor before readjustment was complete. This study uses aerial photographs to examine two cases of arrested geomorphic trajectories in the lower Yuba and Feather Rivers of northern California after 150 years of severe human disturbance. Channel adjustments were inhibited in distinctly different ways. First, channelization of the Feather River across a high-amplitude meander bend ~4 km below the Yuba-Feather River confluence resulted in a knickpoint at Shanghai Shoals that retreated upstream at an average rate of 3.67 m/yr from 1963 to 2013 with two episodes of rapid retreat. Shanghai Shoals was breached in 2013. Second, numerous wing dams on the Yuba River constructed in the early nineteenth century limit floodplain widening and prevent return to an anastomosing channel planform. Their stabilizing role is important to preventing mobilization of mining sediment with high concentrations of mercury. These rivers exemplify how arrested geomorphic trajectories may impact sustainable river management, and how recognition of fluvial evolution is essential to sustainable river management.

1. Introduction

1.1. Geomorphic trajectories

Conventional river management focuses on identifying and designing channels to equilibrium conditions, which are relatively stable. The long-prevailing concept of dynamic equilibrium envisions alluvial channel systems in which morphological changes are self-regulated and governed by negative feedbacks that dampen change (Gilbert, 1877; Hack, 1960; Lane, 1955; Mackin, 1948). This focus on stability underestimates the importance of change and the recognition that change and instability include a variety of potential theoretical outcomes (Brierley et al., 2008; Graf, 1979; Phillips, 1999). When anthropogenic alterations are considered, instability and transformation may be the rule, rather than the exception. Equilibrium is often disrupted by abrupt changes in tectonics, climate change, or human disturbance. Under these circumstances, adjustments may occur in channel size, shape, plan form, gradient, or boundary materials that are not easily accommodated by equilibrium or regime theory or the tools that they employ such as hydraulic geometry or other linear models. Modern river science and management seek to expand their conceptual and methodological basis from stable systems in equilibrium to dynamic systems prone to change. This can be seen in a growing emphasis on morphological change in classification systems (Downs, 1995) and river management (Brierley and Fryirs, 2015; Thorne, 1997). Concepts of change also call for the consideration of historical perspectives. For example, Macklin and Lewin (1997) stress the need for a greater understanding of river history at a variety of time scales. Alternative conceptualizations and methodologies have emerged, such as complex non-linear dynamics (Phillips, 2003, 1999) and evolutionary trajectories of channel systems (Brierley et al., 2008) that are more broadly applicable to river management. Although these approaches may be associated with greater

---

E-mail address: ajames@sc.edu.

http://dx.doi.org/10.1016/j.jenvman.2017.02.011
0301-4797/

uncertainties, they can be applied to a broad array of conditions changing over decades, including non-linear responses and anthropogenic activities for which governing conditions may change substantially (Brierley and Fryirs, 2015).

Research referring to trajectories has grown rapidly in recent years. Trajectories in geomorphic and ecological systems represent a tendency for systematic adjustments in rates, processes, or form over a period of time. Brierley and Fryirs (2005) note that knowledge of geomorphic trajectories is essential to predicting future change. Their River Styles Framework uses the trajectory of future river conditions to assess the potential for river recovery. Hughes et al. (2005) note that riparian restoration trajectories provide a more realistic assessment of variability and uncertainties in projecting habitats than assessments based on the use of reference conditions. The more specific concept of 'evolutionary trajectories' has been advanced in Australian and European river research that acknowledges complexities introduced by multivariate, nonlinear, or indeterminate evolutionary behavior that may govern fluvial change over decadal time scales (Brierley et al., 2008). Evolutionary trajectories recognize the importance of historical and anthropogenic changes, as well as process-based trajectories that can be used to assess the likelihood of future river behavior (Brierley and Fryirs, 2015). Surian et al. (2009) describe 'evolutionary trends' by studying changes in width and incision in five gravel-bed rivers in northeastern Italy, and relate these trends to human activities and river management issues such as bank protection maintenance. Ziliani and Surian (2012) describe three distinct multi-decadal 'evolutionary trajectories' in the morphological evolution of the Tagliamento River, Italy and attribute them primarily to reach-scale human activities. David et al. (2016) examine four time periods over 160 years in analyzing the evolutionary trajectory of the Garonne River, France. Lespez et al. (2015) use trajectory analysis with an historical and anthropogenic emphasis and contrast this approach with conventional principles based on preservation of natural geodynamic processes. They point out that restoration projects should not regard watershed controlling conditions as intransient, but should be developed from a regulated river perspective (Brierley and Fryirs, 2005; Downs and Gregory, 2004). Analysis of trajectories instills the recognition of complex non-linear dynamics and may reveal invalid assumptions that channels will necessarily recover to equilibrium conditions, (Piégay, 2016).

1.2. Arrested trajectories and boundary inhibitors

Alteration of a trajectory represents a non-linear response with respect to time. A shift in rates or directions of change may be caused by changes in thresholds, storage of mass or energy, feedbacks, and competitive relationships (such as channels in a braid bar vying for flow), which are all earmarks of non-linear dynamics (Phillips, 2003). Human manipulations of watersheds and river systems often change evolutionary trajectories and—especially where channel stabilization is engineered—may arrest trajectories. Arrested trajectories may represent the potential for substantial geomorphic change and tendencies for channel adjustments that could release large amounts of mass and energy if they are removed. This paper is concerned with changes in trajectories generated by resistant features that arrest or inhibit on-going processes at the boundary layer of fluvial systems. Inhibitors are essentially agents that impose a high threshold for change in boundary conditions. They are not uncommon, although they may be subtle or hidden and not recognized as such. Many anthropic structural changes to rivers, such as dams, levees, and bed or bank protection, represent arrested trajectories, but inhibitors may also be non-anthropogenic (Table 1). For example, the trajectory of an aggrading channel may be inhibited by a landslide or engineered dam that reduces sediment downstream. Similarly, a degradational trajectory may be inhibited by bed armor resulting from exposure of channel lag material or introduction of coarse cobbles.

The reaction to removal of inhibitors is often the same as the response to threshold exceedance, which has been extensively studied in geomorphology (Schumm, 1973, 1977; 1980). Threshold exceedance describes a process in which the application of forces results in little response until a critical resistance is exceeded, at which time a step-functional increase in response occurs. For example, in bedload transport, a *threshold of critical power* occurs when stream power exceeds resistive forces (Bull, 1979, 1980):

$$\text{Stream Power}/\text{critical power} > 1.0 \tag{1}$$

Extrinsic threshold exceedance occurs when external forces have little response until they exceed the resisting forces. In contrast, *intrinsic threshold exceedance* may occur by internal, progressive weakening of the inhibiting factor (Schumm, 1973). In the case of arrested geomorphic trajectories, the emphasis is on recognizing factors that inhibit geomorphic response and can release potential energy if removed. Threshold exceedance is not necessary if the inhibitor is removed by human activities.

1.3. Anthropogenic disturbance as a common precursor or cause of arrested trajectories

Although local stabilizing features occur naturally, human disturbances and structures are commonly associated with inhibitors that arrest trajectories. Anthropogenic change may encourage arrested trajectories in two ways. First, channels may be stabilized directly by human structures, such as by bank or bed protection, dams, or levees. Second, human disturbance may generate a new geomorphic trajectory that is halted by natural or artificial means. Channel instability, erosion, sedimentation, and increased flood risks often result from disturbances and are locally engineered to halt the trajectory. Two case studies are presented here to provide diverse examples of arrested trajectories: a knickpoint that has protected a channel bed and wing dams that protect channel banks. Both impose inhibitors that govern channel and floodplain morphological evolution in systems in which recovery from a disturbed, aggraded condition has been temporarily arrested.

When trajectories are arrested, the stabilizing element becomes a potential trigger and its removal may instigate a period of rapid change. Recognition of disturbed conditions, arrested trajectories,

Table 1
Examples of inhibitors that arrest fluvial trajectories.

A. Factors that alter water and sediment deliveries
1. Reduced loads: natural or engineered dams, detention and retention structures, terracing, land conservation, reforestation
2. Increased loads: dam breaching or removal, urbanization, abandonment of conservation measures, deforestation
B. Factors that protect against erosion or flooding
1. Bank protection: rip-rap, root wads, revetment, gabions, ramparts, wing dams, flood walls, vegetation, etc.
2. Bed armoring
3. Levees, floodwalls, or dykes that laterally constrain channels