Geomorphology 126 (2011) 314–332

Contents lists available at ScienceDirect

Geomorphology

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

Ecogeomorphic feedbacks in regrowth of travertine step-pool morphology after dam decommissioning, Fossil Creek, Arizona

Brian M. Fuller [a], Leonard S. Sklar [a,*], Zacchaeus G. Compson [b], Kenneth J. Adams [b], Jane C. Marks [b], Andrew C. Wilcox [c]

[a] Department of Geosciences, San Francisco State University, United States
[b] Department of Biological Sciences, Northern Arizona University, United States
[c] Department of Geosciences, University of Montana, United States

ARTICLE INFO

Article history:
Received 21 September 2009
Received in revised form 15 May 2010
Accepted 18 May 2010
Available online 25 May 2010

Keywords:
Travertine
Step-pools
River restoration
Algae
Erosion
Aquatic ecosystems

ABSTRACT

The linkages between fluvial geomorphology and aquatic ecosystems are commonly conceptualized as a one-way causal chain in which geomorphic processes create the physical template for ecological dynamics. In streams with a travertine step-pool morphology, however, biotic processes strongly influence the formation and growth of travertine dams, creating the potential for numerous feedbacks. Here we take advantage of the decommissioning of a hydroelectric project on Fossil Creek, Arizona, where restoration of $CaCO_3$-rich baseflow has triggered rapid regrowth of travertine dams, to explore the interactions between biotic and abiotic factors in travertine morphodynamics. We consider three conceptual frameworks, where biotic factors independently modulate the rate of physical and chemical processes that produce travertine dams; combine with abiotic factors in a set of feedback loops; and work in opposition to abiotic processes, such that the travertine step-pool morphology reflects a dynamic balance between dominantly-biotic constructive processes and dominantly-abiotic destructive processes. We consider separately three phases of an idealized life cycle of travertine dams: dam formation, growth, and destruction by erosive floods. Dam formation is catalyzed by abiotic factors (e.g. channel constrictions, and bedrock steps) and biotic factors (e.g. woody debris, and emergent vegetation). From measurements of changes over time in travertine thickness on a bedrock step, we find evidence for a positive feedback between flow hydraulics and travertine accrual. Measurements of organic content in travertine samples from this step show that algal growth contributes substantially to travertine accumulation and suggest that growth is most rapid during seasonal algal blooms. To document vertical growth of travertine dams, we embedded 252 magnets into nascent travertine dams, along a 10 km stretch of river. Growth rates are calculated from changes over time in the magnetic field intensity at the dam surface. At each magnet we record a range of hydraulic and travertine composition variables to characterize the dominant mechanism of growth: abiotic precipitation, algal growth, trapping of organic material, or *in situ* plant growth. We find: (1) rapid growth of travertine dams following flow restoration, averaging more than 2 cm/year; (2) growth rates decline downstream, consistent with loss of dissolved constituents because of upstream travertine deposition, but also parallel to a decline in organic content in dam surface material and a downstream shift in dominant biotic mechanism; (3) biotic mechanisms are associated with faster growth rates; and (4) correlations between hydraulic attributes and growth rates are more consistent with biotic than abiotic controls. We conclude that the strong influence of living organisms on rates of travertine growth, coupled with the beneficial effects of travertine on ecosystem dynamics, demonstrate a positive feedback between biology and geomorphology. During our two-year study period, erosive flood flows occurred causing widespread removal of travertine. The temporal distribution of travertine growth and erosion over the study period is consistent with a bimodal magnitude–frequency relation in which growth dominates except when large, infrequent storms occur. This model may be useful in other systems where biology exerts strong controls on geomorphic processes.

1. Introduction

At a planetary scale, Earth surface morphodynamics are influenced by the interaction of living organisms with abiotic physical and chemical processes and materials. Life exists on Earth in part because abundant water is present in the liquid phase (Schwartzman, 2002). The course of the proliferation of life and its evolution has been profoundly influenced by geologic events, from the slow shifting of continents (Brown and Lomolino, 1998) to sudden extraterrestrial impacts (Benton and Twitchett, 2003). Living organisms in turn affect the surface in myriad ways, from the creation of free oxygen in the atmosphere in the Archean to the ubiquitous and transformative effects of human activities today (Vitousek et al., 1997; Hooke, 2000).

* Corresponding author.
E-mail address: leonard@sfsu.edu (L.S. Sklar).

0169-555X/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2010.05.010

Do the strong interactions of life and its abiotic environment extend down to the scale of individual river channels? Although an emerging literature focuses on dynamic interactions between life and landscape morphodynamics (e.g. Corinblit et al., 2007; Reinhardt et al., 2010), most previous work on the linkages between life and fluvial geomorphology has focused primarily on the role of the physiochemical processes in setting the template for biological processes (Vannote et al., 1980; Minshall et al., 1983; Doyle et al., 2003). In the field of river restoration, a useful conceptual model for a five-component chain of causality (Fig. 1; Stillwater Sciences, 2001) begins with (1) the supply of materials (e.g. water, sediment, and nutrients), which drive (2) the geomorphic processes (e.g. erosion, and transport and deposition of sediment), which lead to (3) formation of characteristic landforms (e.g. bars, pools, and floodplains). These morphologic units provide (4) habitat for various life cycle stages of species of concern (e.g. spawning, rearing, and over-wintering for salmonids), the quality of which helps determine (5) the population and community responses (e.g. species abundance, diversity, and trophic complexity). Although this systems perspective provides a framework for understanding how biota respond to the abiotic environment, the assumed one-way direction of influence does not incorporate the possibility of feedbacks between biotic and abiotic processes in driving fluvial morphodynamics, for example the effect of riparian vegetation on bank strength, channel width and rates of bank erosion (e.g., Gurnell, 1995; Micheli and Kirchner, 2002) (Fig. 1).

Dietrich and Perron (2006) posed the question of whether a topographic signature to life exists and concluded that although living organisms often play essential roles in shaping landforms, life may impart only a statistical tendency favoring certain topographic outcomes over others; however, the full range of possible topographic outcomes could arise without the participation of life. For example, the contribution of riparian vegetation to bank strength may make channels narrower (Hey and Thorne, 1986), but narrow channels with strong banks also occur because of clay-rich or bedrock bank material. Consideration of the potential for feedbacks between biotic and abiotic processes suggests that the role of life may be most clearly discerned in the dynamics of fluvial systems, rather than in a static measure of channel form.

Travertine streams, where active $CaCO_3$ precipitation from supersaturated spring-fed baseflow creates a characteristic step-pool morphology, provide an excellent model system to investigate complex interactions between biology and geomorphology. Travertine streams occur in a wide variety of climatic and geomorphic settings; in his comprehensive monograph on travertine, Pentecost (2005) identifies more than 100 studied travertine streams, distributed across six continents. Biological processes affect travertine growth across a wide range of scales (e.g. Emeis et al., 1989; Pedley, 1992; Pentecost, 2003, 2005). At the channel scale, log jams and other large woody debris (LWD) catalyze travertine dam formation by causing high-velocity overflow, which accelerates CO_2 outgassing and calcite deposition (Viles and Pentecost, 1999). On the crests of travertine dams, surface area for travertine precipitation is provided by the trapping of floating algal mats and leaf litter, and by *in situ* growth of algae and emergent macrophytes (Merz-Preis and Riding, 1999). At the scale of individual mineral crystals, microbial respiration lowers local pH, enhancing precipitation rates (Takashima and Kano, 2008). Travertine step-pool morphology, in turn, can have a strong positive influence on ecosystem processes. Recent work in Fossil Creek, Arizona, has shown that significantly higher rates of primary production, respiration, and nutrient retention occur within travertine reaches, compared to the non-travertine riffle-pool morphology along the same stream (Marks et al., 2006; Carter and Marks, 2007; Compson et al., 2009).

In this study we take advantage of the recent decommissioning of a hydroelectric diversion dam on Fossil Creek, and the restoration of perennial $CaCO_3$-rich baseflow, to explore the biotic and abiotic influences on the rapid formation and growth of travertine dams. Using two years of measurements of travertine growth and erosion, combined with measures of morphologic and biologic conditions, at more than 250 locations, we find evidence for a set of positive feedbacks driving rapid geomorphic change.

In this paper we have used a somewhat unconventional structure. We begin by introducing the Fossil Creek field site, so that we can then use the dynamics of this particular river system to motivate three distinct frameworks for conceptualizing feedbacks and other interactions between biotic and abiotic processes. In the following three sections, we apply those three conceptual frameworks to an idealized life cycle of a travertine dam: first dam formation, then dam growth, and finally dam destruction by erosive floods. In each of these three sections we report the relevant field and analytic methods followed directly by the corresponding results and interpretations. In the discussion section we focus on the implications of our findings for understanding ecogeomorphic feedbacks in fluvial morphodynamics, including applications to river restoration.

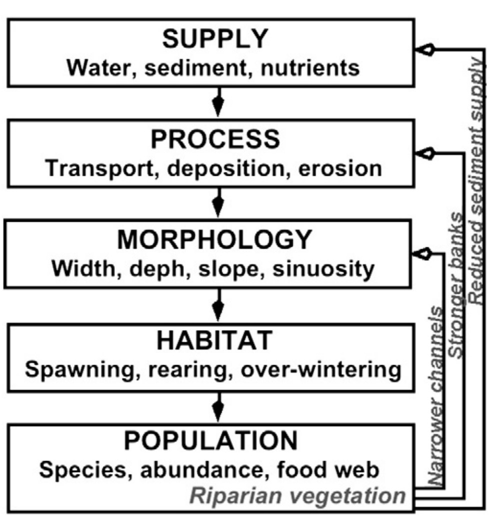

Fig. 1. Conceptual chain of causality linking abiotic watershed and channel conditions to biological responses. One-way linear model does not account for feedbacks, such as effect of riparian vegetation on bank erosion and channel width (modified from Stillwater Sciences, 2001).

2. Fossil creek study site

Fossil Creek is a tributary to the Verde River in central Arizona (Fig. 2A), and has cut a deep canyon into the Mogollon Rim, the southwestern edge of the Colorado plateau. Perennial and steady baseflow of ~1200 l/s (Feth and Hem, 1962; Malusa et al., 2003) discharges from seven springs located ~22 km upstream of the confluence with the Verde (Fig. 2B). Upstream of the springs, the channel is dry except during monsoonal and winter storms and a brief spring snow-melt. Downstream of the springs, the baseflow supports a lush corridor of riparian vegetation, bounded by steep and arid hillslopes. The spring-fed baseflow has high concentrations of dissolved calcium and bicarbonate ions, which precipitate as calcite as outgassing of dissolved CO_2 creates high levels of super-saturation (Malusa et al., 2003). The Martin formation below the Redwall limestone is a major source of the calcium carbonate-bearing groundwater (Feth and Hem, 1962), with dissolution driven in part by mantle-derived CO_2 (Crossey et al., 2006). Bedrock exposed in the channel bed and canyon walls includes Paleozoic sedimentary rocks of the Supai group and Coconino sandstone, and Cenozoic volcanic rocks, including basaltic lava and tuff from repeated flows into the pre-existing Fossil Creek canyon (Twenter, 1962; Feth and Hem, 1962; Blakey, 1990).