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Simulating stream response to floodplain connectivity and revegetation from reach to watershed scales: Implications for stream management

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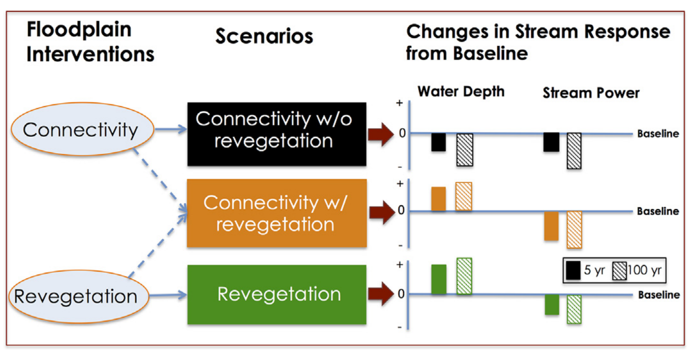
HIGHLIGHTS

- Influence of floodplain connectivity and revegetation on ecosystem services provided by stream was quantified
- Interventions influenced different aspects of stream response in diverse ways and varied widely along reaches
- Landscape and morphology of reaches may determine the effectiveness of interventions
- Individual interventions have their own benefits and shortcomings between target and non-targeted areas
- Careful evaluation is needed to compare benefits and costs among interventions

GRAPHICAL ABSTRACT



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ABSTRACT

Natural-infrastructures (e.g., floodplains) can offer multiple ecosystem services (ES), including flood-resilience and water quality improvement. In order to maintain these ES, state and non-profit organizations consider various stream interventions, including increased floodplain connectivity and revegetation. However, the effect of these interventions is rarely quantified. We build a hydraulic model to simulate the influence of above-mentioned interventions on stream power and water depth during 5 yr and 100 yr flood return-intervals for two watersheds in Vermont, USA. Simulated revegetation of floodplains increased water depth and decreased stream power, whereas increasing connectivity resulted in decline of both responses. Combination of increased connectivity and floodplain revegetation showed greatest reduction in stream-power suggesting that interventions may influence stream response in diverse ways. Across all three interventions, 14% and 48% of altered reaches showed increase in stream power and water depth over baseline, indicating that interventions may lead to undesirable outcomes and their apparent effectiveness can vary with the measure chosen for evaluation. Interventions also influenced up to 16% of unaltered reaches (i.e., in which no interventions were implemented), indicating the consequences of interventions can spread both up and downstream. Multivariate analysis showed that up to 50% of variance in stream response to interventions is attributable to characteristics of reaches, indicating that these characteristics could mediate the effectiveness of interventions. This study offers a framework to evaluate the potential ES provided by natural infrastructure. All stream interventions involve tradeoffs among responses and between target and non-target areas, so careful evaluation is therefore needed to compare benefits and costs among interventions. Such assessments can lead to more effective management of stream-floodplain ecosystems both in Vermont and elsewhere.

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1. Introduction

Stream-floodplain ecosystems (hereafter stream-floodplain) are some of the most productive on the earth (Tockner and Stanford, 2002) and offer a range of ecosystem services (ES), including supporting unique habitat and biodiversity, improving water quality, reducing flooding and providing recreation value (Costanza et al., 1997; Brauman et al., 2014; Hanna et al., 2017). Simultaneously, stream-floodplain systems are also one of the most threatened and heavily managed, mostly to further exploit the services provided by these unique ecosystems (Tockner et al., 2010; Bhattacharya et al., 2016). Subsequently, these activities have resulted in modification of >95% of streams in the Northern Hemisphere (Vitousek et al., 1997).

To address the continuing degradation of stream-floodplains over the past several decades, restoration managers have been using geomorphic form and structure based interventions, such as straightening of streams, altering flow patterns via flow deflectors and boulders and removing dams and levees to minimize ecological impact (c.f., Bernhardt et al., 2005). Over time these restoration practices have become a billion-dollar enterprise in the United States (Bernhardt et al., 2005) and are also widely used worldwide (Arthington and Pusey, 2003; Nakamura et al., 2006; Jeong et al., 2011; Rinaldi et al., 2011). Most of these restoration activities are done under the assumption of restoring streams to the pre-disturbance condition or a certain reference that is rarely known (Palmer et al., 2005, 2014a). Due to limitations of restoring streams to an unknown reference, restoration ecologists have been looking at other alternatives that can integrate river function and processes with socioeconomic benefits that rivers may provide (Dufour and Piegay, 2009). In order to attain these objectives, restoration ecologists have started to support nature-based solutions that can simply maintain ecosystem services provided by these floodplains (Costanza et al., 1997), while preserving the overall health of streams (Gilvear et al., 2013; Palmer et al., 2014b; Hanna et al., 2017).

Conservation organizations, like The Nature Conservancy, have also incorporated these nature-based solutions into their conservation activities to maintain healthy habitat for biodiversity and to minimize flooding and water quality issues downstream (TNC, 2017). Nature-based solutions are also being implemented in streams and floodplains across the European Union to increase their resilience to flooding (Baptist et al., 2004; Leyer et al., 2012). Given the rise in recognition of nature-based solutions for increasing flood protection and mitigating water quality issues, there is a need to understand how these nature based solutions affect ecosystem services provided by floodplains. In particular, the influence of nature-based solutions on hydrologic and geomorphic behavior of floodplains in ways that affect their ES remains unclear.

Many natural floodplain-based interventions include revegetation and increasing stream-floodplain connectivity. Revegetating floodplains has played a role in many restoration activities focusing on stabilizing stream banks, reducing sediment and nutrient loads, and mitigating flooding (Bernhardt et al., 2005). Studies have shown how vegetation biomechanics (e.g., roughness) can reduce the stream velocity resulting in flood reduction downstream (c.f., Hupp and Osterkamp, 1996). However, some studies suggest that revegetating floodplains, by reducing local velocities, can also lead to rise in water depth upstream (Wang and Wang, 2007). In addition to reducing floods, floodplain vegetation can minimize sediment and nutrient loading by taking up and processing nutrients and trapping sediments (Dosskey et al., 2010). Through its effect on velocity of overbank flows, floodplain re-vegetation also has the ability to reduce stream power (i.e., the rate of energy expenditure along stream; Bagnold, 1966) locally and in downstream reaches. Reduction of stream power in downstream reaches may minimize stream incision and bank collapse (Beschta and Platts, 1986). This in-turn may lead to decrease in delivery of sediment bound nutrients (e.g., phosphorus) downstream (Sekely et al., 2002). Recently, Dixon et al. (2016), using a heuristic hydrological modeling approach at a large spatial scale (>10 km^2), showed that landscape-based reforestation can significantly reduce flood peaks at a watershed scale. However, our understanding of how floodplain re-vegetation may influence flood depth and stream power has been limited to idiosyncrasies of a few reaches, and it remains unclear how the influence of revegetation on hydro-geomorphic response of streams may vary along multiple reaches at large spatial scales.

Increasing stream-floodplain connectivity is another critical stream intervention. In this context, connectivity refers to the exchange of water, nutrients, organic matter and biota between streams and floodplains (Opperman et al., 2010). Stream-floodplain connectivity can be increased by removing berms and dykes (Gergel et al., 2002), or by lowering the floodplain (Baptist et al., 2004). In general, greater accessibility of floodplains to streams during flooding can result in dissipation of energy, reduction in velocity, and changes in water depth locally and downstream (Rijke et al., 2012; Jacobson et al., 2015). Further, greater connectivity can also provide more opportunities for settling of sediments and particulate bound nutrients (e.g., phosphorous) on floodplains (Noe and Hupp, 2005). A number of studies have simulated the influence of floodplain reconnection on flood peak attenuation (Woltemade and Potter, 1994; c.f., Sholtes and Doyle, 2011), and have collectively emphasized the sensitivity of stream-floodplain properties (e.g., width, slope, and length) on flood peaks. Many of these previous studies however, either involve watershed-wide interventions or a narrow focus on responses along a few reaches. Thus, there remains a need for more nuanced understanding of how changes in stream connectivity can influence hydro-geomorphic responses along several reaches at a large spatial scale.

The effectiveness of stream interventions in attaining a desired outcome (e.g., reduction in flooding) depends on understanding the underlying processes and drivers mediating hydrological, ecological and geomorphic responses of floodplains (Ward et al., 2001;Palmer et al., 2005;Beechie et al., 2010). Interventions are likely to alter the fundamental forms and functions of floodplains, so knowing the driving processes may help in sustaining those basic properties of the ecosystem. In particular, investigating the influences of stream intervention along multiple reaches can provide us opportunities to relate these stream responses to their corresponding geomorphic characteristics within a watershed. Understanding these interactions may assist practitioners and policy makers to target interventions where they are mostly likely to make a positive difference.

To address these research gaps, we used scenario-based modeling to identify potential flooding and water quality benefits of revegetating floodplains and increasing floodplain connectivity in two watersheds of Vermont. We studied a suite of stream responses, including water depth and stream power, to compare their sensitivities to interventions. This work advances our understanding of how nature-based solutions could affect ES provided by stream-floodplain systems. It develops a novel framework that integrates stream restoration with ES, and it provides a simple screening approach to guide natural resource managers in targeting interventions to maximize intended outcomes.

Specifically, two primary questions guide this study: a) How may stream responses (water depth and stream power) vary with floodplain lowering and revegetation? and b) How do geomorphic and topographic characteristics of reaches mediate these responses? We hypothesized that the revegetation intervention would lead to local increase in water depth and variable effects on stream power due to the interaction of reduction in velocity and increase in shear stress associated with a rise in water depth. We expect the connectivity intervention to lead to decline in both water depth and stream power over baseline due to greater accessibility of floodplains to stream. The combination of connectivity and revegetation scenarios may have variable effects on water depth and stream power depending upon how interventions interact and influence the stream response.