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Ecological functions of restored gravel bars, the Trinity River, California

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ABSTRACT

Gravel augmentation has been increasingly used in sediment-limited systems in regulated channels as a means of creating morphological changes that beneficially affect the functioning of downstream ecosystems. Despite this trend, there have been few empirical studies to quantify these effects in relation to the morphology of gravel bars, especially in terms of riverine material exchanges such as heat and organic matter. We conducted field-based hydro-geomorphological observation of different mechanisms of gravel bar restoration in the downstream of Trinity Dam, California: a medial and a point bar deposited fluvially during high-flow gravel injection, an additional point bar created by direct placement of gravel, and an island created by side channel excavation. We measured water temperature, suspended particulate organic matter (S-POM) concentration, hydraulic gradients and shallow water width under base flow conditions along the perimeter of the gravel features. We then assessed water temperature modulation derived from hyporheic exchanges and S-POM retention of the gravel features, comparing the functions of the dynamically-constructed medial and point bars to those of the mechanically-constructed island and point bar. Diurnal water temperature fluctuations showed a notable thermal heterogeneity including cooling (1.5–3.1 °C) during summer peak temperatures, buffering in amplitude (1.2–4.0 °C) and lagging in phase (0.3–14.5 h), especially in the bar-tails and alcoves of the gravel bars. All of the gravel features reduced S-POM concentration at baseflow, showing the highest retention efficiency in the medial bar. In addition, the fluvially formed the medial and point bars had higher hydraulic gradients and wider shallow waters than the constructed features. Our results indicate that gravel bar restoration can increase hyporheic exchange and S-POM retention by increasing hydraulic gradients at baseflow, refreshing bed materials to enhance substrate permeability, and elongating the wetted boundary length in shallow waters. Our study results suggest that mechanically created in-channel geomorphic features combined with coarse sediment augmentation can increase channel complexity, driving hyporheic flows and increasing S-POM retention, thus ultimately resulting in thermal heterogeneity and food availability along gravel bed channels.

1. Introduction

In-channel gravel features (e.g., riffles and bars) play important ecological roles in rivers, such as providing diverse habitats for adult and juvenile fish (Beschta and Platts, 1986; Geist and Dauble, 1998; Beechie et al., 2005), retaining organic matter filtered from surface waters thus making it available for utilization by stream biota as energy resources (Speaker et al., 1984; Aspetsberger et al., 2002; Hunken and Mutz, 2007), and enhancing nutrient cycling (Newbold et al., 1982; Tockner et al., 1999) with consequent benefits to stream ecosystem metabolism (Triska et al., 1989). In particular, downstream of dams, retention of reservoir-derived plankton and contaminants contributes to restoration of the downstream foodweb and self-purification along channels (Walks and Cyr, 2004; Doi et al., 2008; Ock and Takemon, 2014). In addition, hyporheic exchange (water exchange between surface and subsurface along the riverbed) serves to increase hydrologic and thermal heterogeneity through vertical continuity (Tonina and Buffington, 2007; Poole et al., 2008) in gravel river channels. Moreover, hyporheic exchange favors biogeochemical transformation, acting as an important sink for anthropogenic nitrogen (Fernald et al., 2006; Kasahara and Hill, 2007) and phosphorous (Hendricks and White, 2000; Vervier et al., 2009), improving water quality to much greater degree than observed in surface water or deeper groundwater (Hester and Gooseff, 2011).

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Trapping of sediment within reservoirs typically creates sediment deficit in the downstream channel, which can trigger a chain of riverine geomorphic changes, such as riverbed degradation, channel incision, bank erosion, and loss of in-channel geomorphic features like riffle-pool sequences and various types of gravel bars (Kondolf, 1997; Petts and Gurnell, 2005), resulting in loss of physical habitat complexity (Graf, 2006) and in decreased biodiversity of stream biota (Power et al., 1996; Osmundson et al., 2002). In particular, loss of gravel bars and riffles leads to loss of hyporheic exchange and consequent loss of thermal heterogeneity critically important for salmonids (Burkholder et al., 2008; Hanrahan, 2008).

Therefore, coarse sediment can be viewed as a resource needed to support habitat complexity and ecological functions in regulated channel reaches below dams. Restoration programs in rivers below dams increasingly involve addition of coarse sediment to the channel with the aim of mitigating sediment starvation, reestablishing normative rates and magnitudes of physicochemical and biological processes (Beechie et al., 2010), and rebuilding geomorphic structures required for restoration of ecological functions (Wheaton et al., 2004a; Brown and Pasternack, 2008). Among these efforts, gravel augmentation for enhancing spawning riffles has been undertaken downstream from at least 18 dams in California (Kondolf and Matthews, 1993; Bunte, 2004; Kondolf et al., 2014). For example, a well-documented program for creating spawning habitat for Chinook salmon (*Oncorhynchus tshawytscha*) known as the "spawning habitat integrated rehabilitation approach" (SHIRA) has been implemented in the Mokelumne River below Camanche Dam (Merz et al., 2004; Pasternack et al., 2004; Wheaton et al., 2004b; Merz et al., 2006; Brown and Pasternack, 2009). The gravel riffles created for salmon spawning also support a rich assemblage of benthic macroinvertebrates (Merz and Chan, 2005).

Compared to the riffle features created mainly for spawning habitats, gravel bars restored in regulated channels can provide more complex habitats for anadromous salmon, including pools for adult holding and backwaters for juvenile rearing habitat near the bar edge, along with riffles for spawning. Gravel bar features have been mechanically created mainly by excavation of side channels and shaping of channel margins, sometimes in concert with gravel placement (Roni et al., 2002; Morley et al., 2005). A more recent approach to restore gravel bars below dams is to actively add gravel during high-flow releases from dam. The high-flow gravel injection can induce sediment transport and deposition downstream, creating gravel bars through fluvial geomorphologic processes, termed *dynamic construction* (Gaeuman, 2014).

While the roles of restored gravel bars in contributing to riverine material exchange (e.g., organic matter, nutrients and heat, as well as water) across lateral and vertical interfaces have been increasingly recognized (i.e., Triska et al., 1993; Kasahara and Hill, 2007; Hester and Doyle, 2008; Lewandowski and Nützmann, 2010), and some recent river restoration projects have had objectives of promoting both hyporheic exchange and organic matter retention (Boulton, 2007; Schiemer and Hein, 2007; Hester and Gooseff, 2011), there have been few empirical studies to quantify these ecological effects, especially in relation to the morphology of the gravel features.

The Trinity River in Northern California is the focus of one of the most comprehensive programs to restore salmonid habitat by a combination of ecological flow restoration, coarse sediment supply augmentation and mechanical construction of complex habitat features (USDOI, 2000; Brown and Pasternack, 2008; Gaeuman, 2012). By virtue of its combination of approaches, the Trinity River Restoration Program (TRRP) provides an opportunity to *contrast mechanical* vs. *dynamic construction*. We studied the Lowden Ranch Rehabilitation project, where an island and a point bar were mechanically constructed, and a medial bar and point bar newly were formed by high-flow gravel injection directly upstream.

Hydrological and geomorphic aspects of increased channel complexity resulting from physical restoration below dams and fish usage of resulting habitats have been well documented (Quinn and Peterson, 1996; Roni et al., 2002; Rosenfeld et al., 2008; Palmer et al., 2010; Harrison et al., 2011; Chase et al., 2013). In the Trinity River, for example, salmon habitat assessment studies of spawning redds (Goodman et al., 2010; Chamberlain et al., 2012) as well as fry and premolt rearing conditions (Beechie et al., 2012; Alvarez et al., 2013) have been mainly undertaken. More recently, spatial distribution of freshwater mussel beds has been investigated in relation to hydrologic disturbance (May and Pryor, 2015). However, there has been a "missing link" in our understanding of how this increased habitat complexity (e.g., by restoration of gravel bars) influences riverine ecological functions (Kondolf et al., 2006), as well as the physical habitat requirement assessment. For instance, to assess thermal diversity due to hyporheic flow in a reach scale, we need to know how the two types of gravel bars, dynamically-constructed vs. mechanically-constructed, influence hydraulic gradient and substrate permeability, which in turn largely determine hyporheic flow rate (Tonina and Buffington, 2007). Likewise, the feasible link between S-POM retention and its related geomorphic characteristics such as shallow zone and perimeter complexity (Minshall et al., 2000) should be elucidated. In this study, to provide a comprehensive picture of the ecological function of restored gravel bars with diverse geomorphic characteristics, and permit assessment of their roles in ecosystem recovery in regulated channels (Fig. 1), we conducted field-based hydro-geomorphic observation of in-channel gravel features created by these different mechanisms of gravel bar and island restoration, and then investigated their subsequent influences on hyporheic flow and S-POM retention along the gravel bar channels.

2. Material and methods

2.1. Study area

The Trinity River, a large gravel-bed river located in northwest California, was impounded by Trinity Dam (164 m high and 3020 million m^3 storage) and the smaller Lewiston Dam (28 m high and 18 million m^3 storage) downstream in 1964. In the early years of operation, about 90% of the Trinity River's flow was diverted to the Sacramento River for hydroelectric generation en route and then diversion for agriculture from the Sacramento River (Fig. 2). The reduced flow and sediment load downstream of Lewiston Dam altered channel morphology, including armoring the bed, channel narrowing and stabilization, and encroachment of riparian vegetation into the formerly active channel, changes that resulted in loss of salmonid habitat (Milhous, 1982). Recognition of dramatic decreases in salmon and steelhead population (by 53–96%, depending on the species) led to initial restoration efforts in 1970s, which have continued to the present. In 2000, the US Department of the Interior established the Trinity River Restoration Program (TRRP), a multi-agency partnership that seeks to restore the river's fishery by implementing annual high flow releases, gravel augmentation, and mechanical rehabilitation projects (USDOI, 2000). Gravel augmentations to the Trinity River below Lewiston Dam were first undertaken in 1976 in the form of direct construction of spawning riffles; augmentations have continued over the decades since, but the implementation techniques have evolved to the current emphasis on restoring dynamic channel processes by injecting large quantities for redistribution by flows (Gaeuman, 2012).