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Research papers

Effects of in-stream structures and channel flow rate variation on transient storage

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ABSTRACT

In-stream structures can potentially enhance surface and subsurface solute retention. They form naturally in small streams and their installation has gained popularity in stream restoration for multiple purposes, including improved water quality. Yet few studies have quantified the cumulative effect of multiple structures on solute transport at the reach scale, nor how this varies with changing stream flow. We built a series of weirs in a small stream to simulate channel spanning structures such as natural debris dams and stream restoration log dams and boulder weirs. We conducted constant rate conservative (NaCl) tracer injections to quantify the effect of the weirs on solute transport at the reach scale. We used a one dimensional solute transport model with transient storage to quantify the change of solute transport parameters with increasing number of weirs. Results indicate that adding weirs significantly increased the cross-sectional area of the surface stream (A) and transient storage zones (A_s) while exchange with transient storage (α) decreased. The increase in A and A_s is due to backwater behind weirs and increased hydrostatically driven hyporheic exchange induced by the weirs, while we surmise that the reduction in α is due at least in part to reduced hydrodynamically driven hyporheic exchange in bed ripples drowned by the weir backwater. In order for weir installation to achieve net improvement in solute retention and thus water quality, cumulative reactions in weir backwater and enhanced hydrostatically driven hyporheic exchange would have to overcome the reduced hydrodynamically driven exchange. Analysis of channel flow variation over the course of the experiments indicated that weirs change the relationship between transient storage parameters and flow, for example the trend of increasing α with flow without weirs was reversed in the presence of weirs. Effects of flow variation were substantial, indicating that transient storage measurements at a single point in time typically cannot be extrapolated to estimate net annual effects. Thus, rigorous evaluation of water quality effects of stream restoration structures requires measurements at multiple channel flow rates.

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1. Introduction

Human development such as agriculture and urbanization strongly affects streams (Wenger et al., 2009), including loss of ecosystem function (FISRWG, 1998; USEPA, 2006) due to excess nitrogen and phosphorus, riparian disturbance, higher peak flow, and mobilized sediments (Howarth et al., 2002). Excess nutrient delivery in turn causes eutrophication in downstream waters such as the Chesapeake Bay, Gulf of Mexico, and Long Island Sound (Breitburg et al., 1999; Houde et al., 1999; Kemp et al., 2005; Scavia and Bricker, 2006; USEPA, 2010). Streams receive, assimilate, and transport nutrients (Bernhardt et al., 2003, 2005), and can be a hotspot for excess nutrient removal (Seitzinger et al., 2002).

The practice of stream restoration can improve habitat in degraded streams and benefit water quality by removing dissolved nutrients such as nitrogen (Baron et al., 2002; van Driel et al., 2006; Bukaveckas, 2007; Craig et al., 2008; Lawrence et al., 2013; Mueller et al., 2014; Scott et al., 2014; Veraart et al., 2014; Johnson et al., 2015). Stream restoration often entails stream channel modifications that reduce surface velocities and promote exchange with the subsurface (hyporheic exchange). Common structures used for this purpose include cross-vanes, J-hooks, channel spanning logs, boulder weirs, and root wads (Doll et al., 1999; Roni et al., 2006; Daniluk et al., 2013; Miller and Kochel, 2013; Palmer et al., 2014). These structures can also potentially improve water quality by regulating temperature (Arrigoni et al., 2008; Hester et al.,

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2009; Menichino and Hester, 2014), removing toxins (Bencala and Walters, 1983; Harvey and Fuller, 1998; Fuller and Harvey, 2000), and retaining excess dissolved and suspended nutrients (Craig et al., 2008; Hester et al., 2016). Regulatory bodies, such as the Chesapeake Bay Program (CBP) and the Western Oregon Stream Restoration Program, provide support and guidelines for restoring water quality in regional water bodies. For example, the Chesapeake Bay program, which was formed to lead the restoration of water quality in the Chesapeake Bay region encourages structures like debris dams and brush sills for nutrient removal (Berg et al., 2014).

Velocity reducing stream restoration structures can potentially modify transient storage, which has been defined as the temporary retention of flow and solute from the main channel (Bencala and Walters, 1983) that ultimately returns to the main channel. Transient storage can occur on the surface (exchange with off-channel dead zones – surface transient storage) and in the shallow subsurface (hyporheic transient storage). The latter, generally having more reactive surface area and longer residence time, is considered more conducive to chemical or biogeochemical reactions beneficial to water quality (Hester and Gooseff, 2010; Hester et al., 2013). The transient storage model describes solute transport in a stream using the one dimensional advection dispersion equation augmented with terms representing exchange with immobile transient storage zones along the reach (Bencala and Walters, 1983). The size of the overall transient storage zone and exchange rate between main channel and transient storage zone can be estimated by fitting measured tracer breakthrough data, and provide a convenient way of measuring the "potential" of the stream to retain and process solutes (Bencala et al., 1990; Workshop, 1990; D'Angelo et al., 1993; Hall et al., 2002; Ensign and Doyle, 2005; Lautz and Siegel, 2007; Gordon et al., 2013; Zarnetske et al., 2015).

Studies have shown that in-stream structures drive hyporheic exchange (Lautz and Siegel, 2006; Hester and Doyle, 2008; Daniluk et al., 2013), yet fewer studies have evaluated transport of nutrients that impair water quality. Studies of individual structures such as log dams have shown that they increase biogeochemical or thermal heterogeneity in the subsurface thereby creating biogeochemical hotspots (Kasahara and Hill, 2006; Lautz and Fanelli, 2008; Menichino and Hester, 2014), but fewer studies have evaluated cumulative reach scale effects. Briggs et al. (2013) found that hyporheic zones induced by beaver dams can create localized hotspots for nutrient processing but their net effect on nutrient removal at the reach scale was minimal. Gordon et al. (2013) studied cross-vanes and similarly concluded insignificant reach scale impact. Hines and Hershey (2011) did not find significant difference in ammonium uptake across completed restoration structures like cross-vanes. In modeling studies, Azinheira et al. (2014) and Hester et al. (2016) found insignificant impact of hyporheic exchange induced by two in-stream weirs in a 90 m reach. Zimmer and Lautz (2015) studied the addition of a single cross vane and concluded that if head gradient across the structure is too large, it may induce hyporheic exchange with residence times that are too short to promote significant nutrient processing.

The cumulative effect of a series of structures has shown greater potential than single structures to increase transient storage. Jin et al. (2009) found that transient storage area increased with the number of beaver dams. Ensign and Doyle (2005) observed higher ammonium and phosphate uptake velocity after adding a series of flow baffles in a stream. Roberts et al. (2007) observed that adding a series of flow-obstructing logs enhanced transient storage and ammonia uptake. Transient storage parameter estimation is strongly dependent on channel flow, as shown by multiple studies (Valett et al., 1996; Hall et al., 2002; Ward et al., 2013a, 2013b). Yet, to the best of our knowledge, no studies so far have systematically related the presence or number of instream structures to transient storage parameters (e.g., cross-sectional area, transient storage size) while simultaneously evaluating the effects of varying channel flow rate. Yet, such relations are key to understanding the impact of stream restoration structures on solute transport and may allow better prediction of their effects on water quality.

The overall aim of this study was to measure the effect of multiple small channel spanning structures (representing typical restoration structures such as log dams and boulder weirs) on solute transport and transient storage characteristics of a stream. Our main objective was to test the effect of increasing number of in-stream structures on transient storage. Specific expectations were that: 1) weir construction would increase surface transient storage by creating pools and zones of slow moving water; 2) weir construction would enhance hyporheic transient storage zone size and exchange by creating hydrostatic head gradient across the weirs; and 3) increasing the number of weirs would correspondingly enhance transient storage parameters. A secondary objective was to quantify the hydrologic transport effects of structures across a range of channel flow rates.

2. Methods

2.1. Study site and background hydrologic monitoring

The field site is a second order (field observation and USGS topo maps) stream dominated by riffle-pool and step-pool (log dam) features located in the Jefferson National Forest in southwestern Virginia (37°20′N 80°21′W). The stream drains a catchment of about 1 km^2 (Fig. 1) and eventually flows to the James River and the Chesapeake Bay. Stream flow at the project reach is highest during the winter and sometimes becomes intermittent during late summer and early autumn. Background specific electrical conductance increases with decreasing flow and ranges between 15 and 25 uS/cm. Experiments were conducted during the late spring baseflow recessions between May 11 and June 9, 2015 with flow declining from 14 to 4 L/s.

Our experiments utilized a control reach (MS1 to MS2) and a treatment reach (MS2 to MS3) downstream of the control reach (Fig. 1). The two reaches were both 80 m in length (measured along the thalweg) and are contiguous with very similar geomorphology and bed material. The primary purpose of the control reach was to help interpret changes in the treatment reach, allowing us to better distinguish effects of experimental manipulation from those due to natural channel flow variability. The control reach has an average slope of 0.056 m/m and the treatment reach has an average slope of 0.066 m/m (both have a measurement error of ±0.001 m). The upper half of the control reach lies adjacent to the end of a steep hill slope, while the remaining portion of the control reach and the entire treatment reach had comparatively flat floodplains on both banks. The channel is typically about 2 m wide and 0.5 m deep with near vertical banks. Based on visual observation, winter high flows were generally contained within the channel.

We also installed a stilling well in the stream channel at the upstream end of the treatment reach. We measured absolute pressures in the stilling well (surface water), and in the air with HOBO pressure transducer sensor-loggers (Onset, Bourne, MA). Water depths were calculated by subtracting atmospheric pressure from the absolute pressures and dividing by the specific weight of water. The HOBOs logged pressure continuously in the stream at 15 min intervals starting in July 2014.

2.2. Stream tracer injection and weir construction

We performed six experiments (E1 through E6) that differed in terms of number of in-stream structures and/or flow rate in the channel (Table 1). We installed a series of structures (weirs) in

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