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Effects of large wood on floodplain connectivity in a headwater Mid-Atlantic stream

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ABSTRACT

Large wood (LW) plays an essential role in aquatic ecosystem health and function. Traditionally, LW has been removed from streams to minimize localized flooding and increase conveyance efficiency. More recently, LW is often added to streams as a component of stream and river restoration activities. While much research has focused on the role of LW in habitat provisioning, geomorphic stability, and hydraulics at low to medium flows, we know little about the role of LW during storm events. To address this question, we investigated the role of LW on floodplain connectivity along a headwater stream in the Mid-Atlantic region of the United States. Specifically, we conducted two artificial floods, one with and one without LW, and then utilized field measurements in conjunction with hydrodynamic modeling to quantify floodplain connectivity during the experimental floods and to characterize potential management variables for optimized restoration activities. Experimental observations show that the addition of LW increased maximum floodplain inundation extent by 34%, increased floodplain inundation depth by 33%, and decreased maximum thalweg velocity by 10%. Model results demonstrated that different placement of LW along the reach has the potential to increase floodplain flow by up to 40%, with highest flooding potential at cross sections with high longitudinal velocity and shallow depth. Additionally, model simulations show that the effects of LW on floodplain discharge decrease as storm recurrence interval increases, with no measurable impact at a recurrence interval of more than 25 years.

1. Introduction

Large wood (LW) plays an important, yet undervalued role in river ecosystems. One of the most important functions of LW is its ability to increase floodplain connectivity, the lateral exchange of water and material between rivers or streams and their adjacent floodplains (Harvey and Gooseff, 2015; Covino, 2017). LW plays a crucial role in floodplain connectivity as it decreases longitudinal stream flow velocity (Davidson and Eaton, 2013), increases floodplain inundation (Collins and Montgomery, 2002), and increases transient storage (Mueller Price et al., 2016; Rana et al., 2017). This in turn can provide a variety of ecosystem services such as promoting geomorphic stability/instability (Montgomery et al., 2003), influencing the transport and storage of sediment (Parker et al., 2017), providing habitat for aquatic wildlife (Dolloff and Warren, 2003; Johnson et al., 2003), and enhancing water quality (Krause et al., 2014). While these ecological benefits are well acknowledged, LW can also be hazardous to infrastructure and people (Wohl et al., 2016). Historically, LW has been removed from streams for the purpose of limiting flood hazards (Wilford et al., 2004), lowering water tables to comply with Federal Emergency Management Agency (FEMA) regulations (Schmocker and Weitbrecht, 2013), and limiting damage to infrastructure such as culverts, roads, and bridges (Lagasse et al., 2012). Thus, management of LW is important and often requires a balance of ensuring infrastructure stability and protection of critical ecosystem services (Ruiz-Villanueva et al., 2016).

The importance of instream LW on fluvial processes has been widely acknowledged and extensively studied over the past 30 years (Abbe and Montgomery, 1996; Jeffries et al., 2003; Sear et al., 2010; Gurnell et al., 2002). LW is useful for restoring streams as it is relatively inexpensive and serves as a natural form of stream restoration and rehabilitation (Kail et al., 2007). As such, LW has widely been used in stream restoration, a multi-billion dollar industry in the U.S. and Europe (Bernhardt et al., 2005; Angelopoulos et al., 2017). Due to the widespread use of LW in stream restoration projects, there is a need to

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improve and optimize the use of LW.

There are currently several critical aspects of LW science that remain unexplored. First, the effects of LW in streams have been studied primarily at baseflow (Matheson et al., 2017). In contrast, little is known about the effects of LW during stormflow, when the majority of solute and sediment transport occurs (Ensign et al., 2006). However, directly measuring the impacts of LW during stormflow is challenging due to the stochastic nature of storm events and difficulty in capturing natural flood pulses. In addition, LW has been studied primarily in the Western U. S. (e.g., Bilby and Ward, 1991; May and Gresswell, 2003; Wohl and Goode, 2008). While these studies have provided valuable insight on LW dynamics, water resources management in this region differs greatly from that of humid regions of the world where water quality is of greater concern than water quantity (Karr and Dudley, 1981). Finally, studies have primarily focused on the transport and deposition of LW (e.g., Dixon and Sear, 2014; Ruiz-Villanueva et al., 2014), treating LW as dynamic system components as opposed to static instream structures. However, LW can also act as more permanent instream structures and affect critical ecological processes such as hyporheic exchange (Hester and Doyle, 2008), nitrate removal (Hester et al., 2016a,b), and habitat provisioning (Johnson et al., 2003). Due to these limitations, the effects of LW on stream flooding dynamics have been largely neglected. The shortage of and need for experimental research on these effects was the primary motivation for our research effort.

The overall goal of this study was to assess the impacts of LW on floodplain connectivity by utilizing experimental field observations and hydraulic modeling of a headwater stream in the US Mid-Atlantic region. Here, we hypothesized that the addition of LW increases floodplain connectivity while decreasing longitudinal velocity in the main channel. Specific research objectives included: 1) quantifying the impact of LW on floodplain inundation extent, depth, and velocity; 2) assessing the impact of LW at varying locations along the reach; and 3) quantifying the influence of LW on floodplain connectivity across a gradient of flood magnitudes. We addressed these objectives by conducting a series of experimental floods along a headwater stream, and then utilized hydrodynamic modeling combined with our field-scale measurements to characterize floodplain connectivity during the experimental floods and across a synthetic flow record. These results both improve our understanding of LW flood dynamics and provide further guidance for the restoration community in the use of LW.

2. Materials and methods

2.1. Study site

The study site is located in Blacksburg, Virginia at the Virginia Tech Stream Research, Education, and Management (StREAM) Lab (vtstreamlab.weebly.com/) in the Valley and Ridge physiographic province. We selected this location because it is representative of headwater streams. In addition, the StREAM Lab provided an advantageous location for flood experimentation as flood dynamics have been extensively studied there and there are several continuous flow monitoring stations (Jones et al., 2015; Azinheira et al., 2014; Hester et al., 2016a,b; Keys et al., 2016). Within the StREAM Lab, the study was conducted on a 50-m reach of Docs Branch (Fig. 1), a first-order tributary to Stroubles Creek with an average bankfull width of 0.93 m. This specific reach contains an H-flume with discharge measurements, which was used to set upstream boundary conditions. The stream is located at an altitude of 610 m above mean sea level and has an average slope of 0.01. The contributing watershed encompasses an area of 1 km^2 and is primarily composed of agricultural land use.

2.2. Flooding experiments

We conducted three experimental floods over a three-day period (e.g., one flood per day). During each flood, we dammed the stream channel upstream of the study reach by sealing two side-by-side 1.2 m diameter concrete culverts with a wooden sluice gate and plastic tarp. The experimental floods were then initiated by pulling the sluice gate and releasing the dammed water into the study reach. Prior to releasing the dammed water, ponded depth was measured to ensure that floods were similar in total volume. The initial flood was conducted to prime the system and ensure that floodplain soil moisture conditions were similar for the subsequent experimental floods. The second and third flood events (hereafter flood without LW and flood with LW, respectively) were used to examine the effects of LW on floodplain connectivity. Specifically, the flood without LW was released under normal conditions without wood in the stream, and the flood with LW was released after installing three pieces of LW in the reach (Fig. 1). We collected the three pieces of LW from a nearby upland and placed them horizontally in the stream with the rootwads facing upstream, based on the guidelines from previous research (Rafferty, 2013). All three pieces of LW spanned the stream channel width (Fig. 1b–d), as is generally the case in small streams (Gurnell et al., 2002). Floods were conducted from May 24-May 26, 2016. Using regional curves for non-urban streams in the ridge and Valley Province (Keaton et al., 2005), we found that the 1.5 year flood event for a 1 km^2 watershed would be 515 L/s. This is approximately 9 times greater than peak flows generated in both experimental floods, indicating that the experimental floods are representative of realistic floods that would occur multiple times per year.

At the upstream boundary of the reach, discharge was measured using a 0.9 m HL-type flume (Brakensiek et al., 1979) and an Onset HOBO Pressure Transducer (PT). Flow measurements from the flume were taken every minute and uploaded to a Campbell CR-1000 data logger. At the downstream end of the reach, flow measurements were taken using a SonTek Argonaut-SW Acoustic Doppler Velocimeter (ADV). Measurements from the ADV were also taken at 1-min intervals and directly uploaded to a field computer. Additionally, three Onset HOBO PTs were placed throughout the floodplain to measure flow depth (Fig. 1).

2.3. Hydrodynamic modeling

2.3.1. Model description

We used Hydrologic Engineering Center's River Analysis System (HEC-RAS) hydraulic modeling software to model 2-dimensional (2D) surface water hydrodynamics for the stream reach. HEC-RAS is commonly used for hydraulic modeling due to its strong computational abilities, quick processing time, and free availability through the U.S. Army Corps of Engineers. The recent addition of 2D modeling to HEC-RAS makes it an appealing option for floodplain modeling studies such as the one presented here. Specifically, HEC-RAS numerically solves the 2D Saint-Venant equations for conservation of mass (Eq. (1)), conservation of momentum in the x direction (Eq. (2)), and conservation of momentum in the y direction (Eq. (3)):

$$\frac{\partial H}{\partial t}+\frac{\partial (hv_x)}{\partial x}+\frac{\partial (hv_y)}{\partial y}=0 \quad (1)$$

$$\frac{\partial v_x}{\partial t}+v_x\frac{\partial v_x}{\partial x}+g\frac{\partial H}{\partial x}+g(S_f-S_0)=0 \quad (2)$$

$$\frac{\partial v_y}{\partial t}+v_y\frac{\partial v_y}{\partial y}+g\frac{\partial H}{\partial y}+g(S_f-S_0)=0 \quad (3)$$

where H is the water surface elevation, h is hydraulic head, v_x is velocity in the downstream direction, v_y is velocity in the transverse direction, g is acceleration due to gravity, S_f is the energy slope, and S_0 is the channel slope. The Saint Venant Equations (Eqs. (1)–(3)) are numerically solved using finite volume approximations discretized with respect to time and space. HEC-RAS can solve the full Saint-Venant equations or the diffusive wave approximation of the Saint-Venant