JCHS TU Delft OPEN

JOURNAL OF COASTAL AND HYDRAULIC STRUCTURES

Vol. 3, 2023, 25

Driftwood Accumulation and Passage at V- and I-Rock Weirs in Mountain Streams

Kathryn Margetts[1], Belize Lane[2], Brian Mark Crookston[3]

Abstract

The transport and accumulation of driftwood, large wood, or large woody debris (LWD) in mountain streams is a natural part of catchment health and river connectivity. At hydraulic structures, the presence of driftwood has impacts on total discharge and upstream energy. Driftwood has been studied at a variety of spillways and weir types; however, little is known about its interaction at rock weirs. This study seeks to determine what factors affect the transport of driftwood and potential upstream impacts of driftwood accumulations at rock weirs through field-informed scaled model testing. Observations of driftwood at rock weirs located on the Blacksmith Fork River, a mountain stream located in Utah, USA, were used to replicate driftwood dynamics in V- and I-shaped rock weirs in a large flume. The river response to rock weirs on the corresponding section of the Blacksmith Fork River was also investigated using historic aerial imagery and field data. Approaches to driftwood management typically prioritize either natural processes or hydraulic structure safety and flow conveyance. A new hybrid approach should consider both aspects for rock weirs in mountain streams.

Keywords

Large woody debris, driftwood, river ecology, rock weirs

[1]kathryn.margetts@usu.edu, Utah State University, Utah Water Research Laboratory, Logan, Utah, USA
[2]belize.lane@usu.edu, Utah State University, Utah Water Research Laboratory, Logan, Utah, USA
[3]brian.crookston@usu.edu, corresponding author, Utah State University, Utah Water Research Laboratory, Logan, Utah, USA

This paper was submitted on 5 July 2022. It was accepted after double-blind review on 11 July 2023 and published online on 18 August 2023.

DOI: https://doi.org/10.48438/jchs.2023.0025

Cite as: "Margetts, Kathryn; Lane, Belize; Crookston, Brian Mark: Driftwood Accumulation and Passage at V- and I-Rock Weirs in Mountain Streams. Journal of Coastal and Hydraulic Structures, 3. https://doi.org/10.48438/jchs.2023.0025"

This paper is part of the **Thematic Series** of selected papers on large wood in fluvial ecosystems. The papers describe the (positive and negative) effects of large wood on aspects such as conveyance capacity and water depths, bed morphology, ecology and hydraulic structures. The series addresses novel approaches of large wood transport processes and management to develop a sustainable, safe and balanced approach to wood reintroduction. Series editors: Isabella Schalko & Elizabeth Follett.

1 Introduction

Driftwood or large woody debris (LWD) in rivers is integral to river morphology and ecology as the recruitment, transport, and accumulation or storage of woody materials through a catchment can influence river flow fields and sediment transport, provide habitat and cover, and introduce organics through leaching, accretion and decomposition (see Figure 1) (Gurnell et al., 2002; Ruiz-Villanueva et al., 2016; Wohl et al., 2016, 2019). The dynamics of driftwood in forested mountain catchments are illustrated in Figure 2, including four main stages: (1) input, (2) transport, (3) storage, and (4) output.

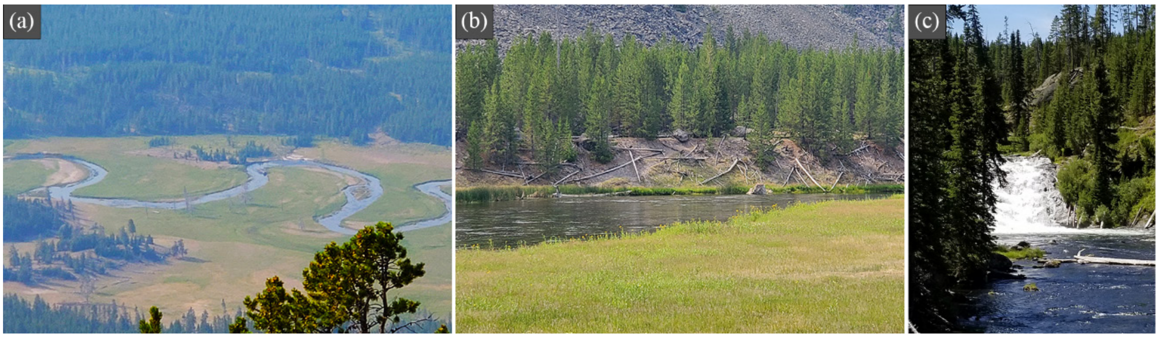

Figure 1: Forested catchments (a) with driftwood recruitment, (b) storage between high flow events, and (c) in Yellowstone National Park, Wyoming, USA (photos courtesy by Author).

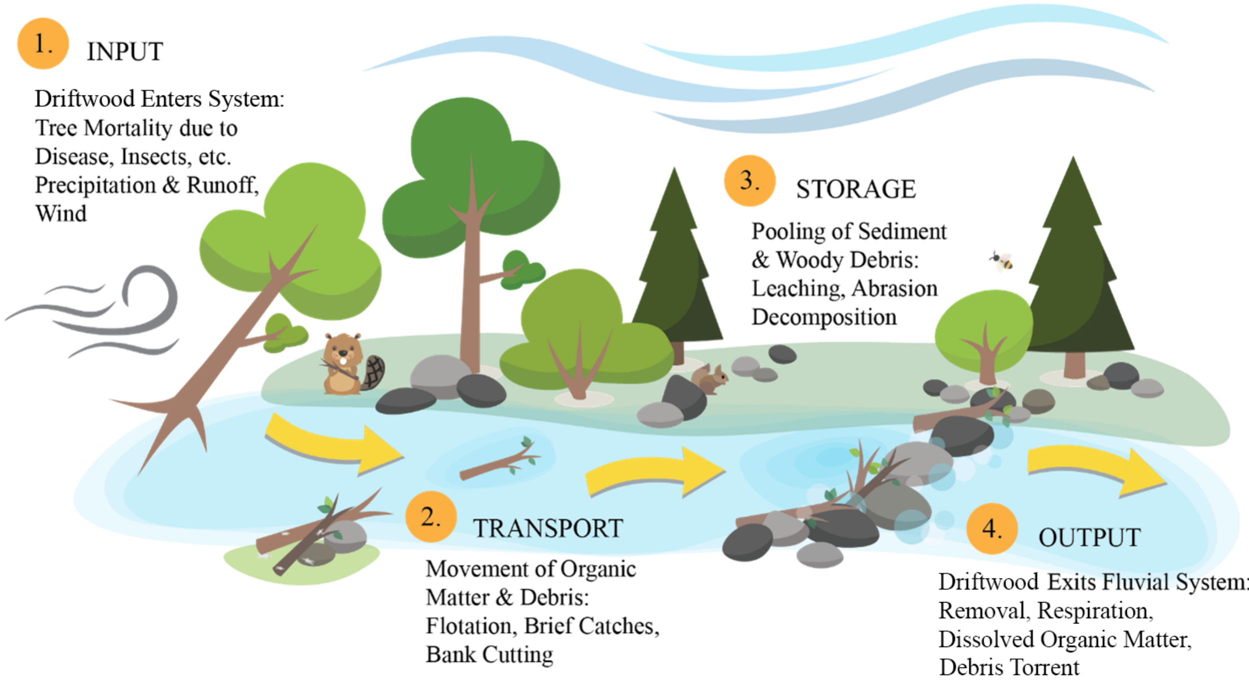

Figure 2: Driftwood recruitment, transport, storage, and output within a mountainous catchment.

Indeed, the value of driftwood has been recognized by scientists in recent decades with a focus on stream ecosystems (Gregory et al., 2003; Keller and Swanson, 1978; Le Lay et al., 2013; Wohl, 2020; Wohl and Scott, 2017). The presence of driftwood influences channel morphology and backwater rise with stored sediments creating fertile floodplains (Daniels and Rhoads, 2003; Gurnell et al., 2002; Keller and Swanson, 1978). For example, field investigations conducted in southeastern Australia indicate that the manual removal of driftwood and riparian vegetation from 1886–1995 had severe consequences for ecosystem health and channel stability that were reduced through careful driftwood reintroduction (Erskine and Webb, 2003; Webb and Erskine, 2003). Manual placement of driftwood and large wood structures that mimic natural conditions (i.e., nature-like structures) have been promoted within the river science community as a mitigation and restoration strategy to address local scour, bank erosion, and habitat loss due to urbanization, deforestation, or even wood removal or channel dredging, etc. (Cramer, 2012; Kail, et al., 2007; Lester et al., 2006; Roni et al., 2015; Rosgen, 2001; Wohl et al., 2016; Wohl and Scott, 2017). However, the success of such solutions is dependent upon hydraulic conditions and large wood location in combination with fluvial processes, as over time localized river conditions adjacent to a nature-like structure may shift.

Nature-like structures made of other materials have also increased in popularity, including many types of rock structures such as weirs, J-hooks, barbs, vanes, bendway weirs, and rock ramps (Puckett, 2008; Rosgen, 2001; Reclamation, 2016). These have been successfully implemented to aid in grade control, channel alignment and diversion, bank and flood protection, dam removal and river restoration, fish passage, and habitat formation (Puckett, 2008; Roni et al., 2006; Rosgen, 2001; USFWS, 2019). Of these structures, rock weirs are of particular interest to practitioners seeking an affordable and sustainable way to alter river hydraulics while considering local river conditions, natural processes and aquatic ecosystems (Abbe and Montgomery, 2003; Rosgen, 2001; Ruiz-Villanueva et al., 2016; 2016; USFWS, 2019).

Driftwood interactions with in-stream structures that influence water and sediment fluxes can be a transport barrier and thus introduce a potential safety hazard. For example, sediments and large volumes of driftwood may be recruited and transported through a river reach during infrequent flows or higher-magnitude floods (Badoux et al., 2015; Mao et al., 2013; Wohl et al., 2019) and get caught behind in-channel hydraulic structures such as spillways, weirs, and diversions. Specifically in wooded mountainous catchments, the interaction of large wood and hydraulic structures is inevitable, with potential concerns regarding driftwood blockage at the structure compromising hydraulic performance and structural stability along with backwater rise and flooding damage. This may be considered for all types of check dams, weirs, and grade structures regardless of construction material (Gippel, 1995; Puckett, 2008; Rosgen, 2001).

The combination of critical watershed functions and hydraulic hazards associated with driftwood has led to two distinct approaches (e.g., see Figure 3) to driftwood management as it related to hydraulic structures: (1) prioritizing natural processes and (2) prioritizing river conveyance and hydraulic structure safety. For instance, the Cape Fear rock ramp in North Carolina (Figure 3c) is an example of prioritizing natural processes as it sees some temporary driftwood accumulation (providing cover and habitat), which typically moves downstream during high flow periods. By contrast, efforts to prioritize river conveyance and structure safety are evident in field observations of the original gated Linville Dam in North Carolina (Figure 3a) and the newly rehabilitated labyrinth weir on the Brazos River in Texas (Figure 3b), which effectively block the natural transport of woody materials. At the boundary of these two approaches, a third hybrid or 'balanced' approach is possible which considers both priorities in river engineering.

Multiple scaled laboratory studies have focused on the interaction of driftwood with various in-channel structures. Specifically, studies have investigated wood passage probability and the potential for debris blockage or flooding at spillways (Furlan et al., 2018; Hartlieb, 2014; Johansson and Cederström, 1995; Schalko et al., 2018; Schmocker, 2017; Schmocker and Hager, 2013; Schmocker and Weitbrecht, 2013; Swiss Committee on Dams, 2017; U.S. Dept. of the Interior, 2020; Wallerstein et al., 1997), labyrinth weirs (Crookston et al., 2015; Vaughn, 2020), piano key weirs (Pfister et al., 2013; Venetz, 2014), ogee crest dams (Bénet et al., 2021; Furlan, 2019; Stocker et al., 2021), bridge decks (Schalko et al., 2020; Schmocker and Hager, 2011), and bridge piers (Schalko et al., 2020; Wyss et al., 2021).

Laboratory studies have also investigated the hydraulics of rock weirs and sediment transport (Pagliara et al., 2012, 2014, 2020; Pagliara and Chiavaccini, 2007), but the interaction of rock weirs and driftwood remains poorly studied. Observations of driftwood accumulation at both small and large rock weirs and rock ramps has been documented (see Figure 3); however, design guidance for engineers currently does not consider driftwood transport or accumulation and the corresponding hydraulic impacts in terms of flow conveyance, backwater rise, or structural stress. Improved in-stream cover is typically not a design objective of rock weir implementation in the civil engineering community (Reclamation, 2016).

Figure 3: Driftwood present at hydraulic structures (a) Linville Dam, NC, USA (b) Lake Brazos labyrinth weir, TX, USA (photo courtesy Freese & Nichols, Inc.) and (c) Cape Fear Lock and Rock Ramp, NC, USA (photo courtesy L. Aadland).

1.1 Research Objectives

This study was conducted to aid practitioners in determining the implications of driftwood as an element in the structural and hydraulic design of rock weirs. This study focuses on the influence of rock weir geometry, batch characteristics, and river hydraulics (steady and stepped hydrograph flows) on driftwood passage at rock weirs.

This was accomplished through scaled laboratory testing informed by a field study of the Blacksmith Fork (BSF) River, which is a mountain stream located within the Great Salt Lake Basin in UT, USA. Observations of the BSF included the response of the river reach to recent dredging, placement of rock weirs, and the post-construction transport of driftwood. The laboratory component focused on scaled models of flow and driftwood accumulations at I-shaped and V-shaped rock weirs, chosen to complement the rock weirs observed in the Blacksmith Fork River and rock weir geometries commonly implemented in rivers (Puckett, 2008; Rosgen, 2001). Traditionally, scaled hydraulic models are operated under steady-state conditions for a range of discharges (Novak et al., 2018; Task Committee on Hydraulic Modeling, Environmental and Water Resources Institute, ASCE 2000). However, this study included both steady (constant) and unsteady (i.e., change with time) flow conditions to observe any hysteresis and flux effects on driftwood movement.

Tests were designed to explore the effects of driftwood geometry and loading rate (i.e., batches) on passage or accumulation and corresponding hydraulic impacts. Key parameters measured in laboratory tests include effects of weir geometry, batch size, and steady vs. unsteady flows on driftwood passage. Use of organically shaped driftwood is similar to the approach used by Bénet et al. (2021), Pfister et al. (2013), Schalko et al. (2018) and Schmocker and Hager (2011), who studied naturally shaped driftwood at various hydraulic structures. The results of this composite study provide new insights regarding the interaction of rock weirs with driftwood and support the hybrid approach of balancing river heath and natural functioning with hydraulic structure performance.

1.2 Study Area: Rock weirs on the Blacksmith Fork River

The field study was conducted at the lower Blacksmith Fork (BSF) River, which is a mountain stream located in Cache County, Utah, USA within the Great Salt Lake Basin and adjacent to the towns of Hyrum and Logan (Figure 4). Geologic formations include dolostone, dolomitic limestone and brown sandstone intraformational breccia, with scattered springs and seeps (Williams and Taylor, 1964; Alger et al., 2021). The forested catchment is dominated by willow, mountain alder and red osier dogwood at higher elevation; at lower elevation the riparian vegetation includes box elder, cottonwood, and river birch, as well as invasive crack willow (Walker et al., 2020).

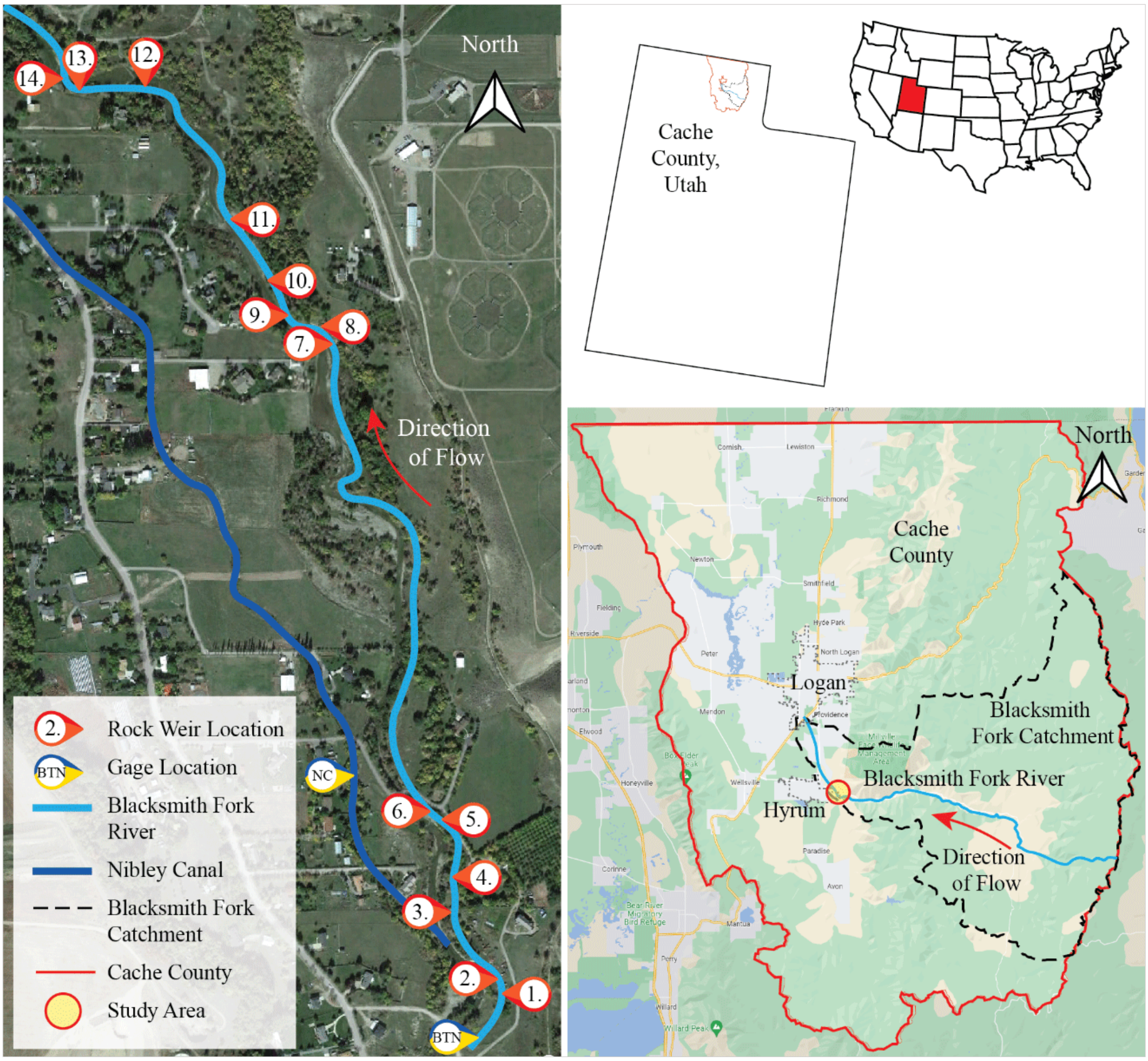

Figure 4: Study area of lower Blacksmith Fork River located in Nibley, Utah, USA. The BTN stream gage is located upstream of the rock weirs on the BSF, and diverted flow is measured via the NC gage. Rock weirs observed in the field are numbered for reference from upstream to downstream.

The BSF River at the USGS gaging station #10113500 (El. 1,520 m NGVD) has a drainage area of 681 km^2. This stream experiences periods of high and low flows corresponding with snowmelt, dry summer months, and water diversions for irrigation of local farmland (Alger et al., 2021).The USGS gaging station (not shown) period of record is from 1899–2022 and catalogs several major flood events of about 28 m^3/s or about seven times a typical baseflow (Jain and Lall, 2000). During high-flow periods, the stream also transports large volumes of woody debris and sediments (e.g., sand, gravels, and cobbles) (NRCS, 2013).

Peak spring runoff (primarily from snowmelt) in the BSF River is typically April–May followed by low summer flows (July–September), which are lowered further in the study reach due to several small irrigation diversions such as at the Nibley Canal Diversion immediately adjacent to Rock Weir 2 (see Figure 4). In addition to the USGS gaging station (not shown in Figure 4), a private stream gage (BTN) measures channel stage in the BSF River at 15-min intervals via an unvented pressure transducer (Level TROLL 400) located upstream of the study area (Figure 4) (Alger et al., 2021). Flow immediately downstream of the BTN gage is seasonally diverted to the Nibley Canal with gaging station (NC), which features a second unvented pressure transducer to gage channel stage. Rating curves relating channel stage to total discharge were developed by Alger et al. (2021) for the BTN and NC stream gages based on manual discharge measurements over a range of flow conditions. Discharge measurements used in this study were collected from January 2018 through November 2021 (Figure 5). BSF River streamflows through the study reach were estimated by taking the difference between the BTN gage and the NC gage. Daily average streamflows in the BSF River upstream and downstream from

Nibley Canal are plotted for 2018 to 2021 in Figure 5, including summer low flows exacerbated by streamflow diversion for irrigation (Alger et al., 2021). Note that streamflows or discharges are denoted by Q.

In the spring of 2011, extreme flooding, and debris blockage at bridges along the BSF River necessitated flood protection in the form of sandbags, pumping, and even evacuation of some residences (Anderson, 2011; Hisslop, 2013). In ensuing years, rising concerns of flooding led the Natural Resources Conservation Service, Cache County, and Logan City to determine the need for more permanent protection and erosion control in the form of rock weirs (i.e., prioritizing river conveyance and hydraulic structure safety). Subsequently, in 2013, a 2 km reach of the river (Figure 4) adjacent to moderate development was dredged of sediments and retrofitted with a series of 14 V-shaped or V-Notch rock weirs along with sections of bank armoring via riprap, with a primary focus on flow conveyance and structure safety (i.e., flood control, NRCS, 2013).

During dry years, the Nibley Canal diversion (Figure 4) can deplete stream flow almost entirely along the study reach containing rock weirs. This can lead to stress and mortality of fish (primarily brown and rainbow trout) associated with low dissolved oxygen and excessive stream temperature (Alger et al., 2021). Although periods with extremely low to no flow influence the natural transport of driftwood along the study reach, the field campaign was able to identify the type of woody debris recruited, transported, and stored in this forested mountain stream during dry conditions in the summer of 2021. In the following section, the field campaign is discussed along with how field observations informed the design of the Froude-scaled physical model, the rock weir types and stones, and the selection of driftwood and discharges for investigation in the laboratory.

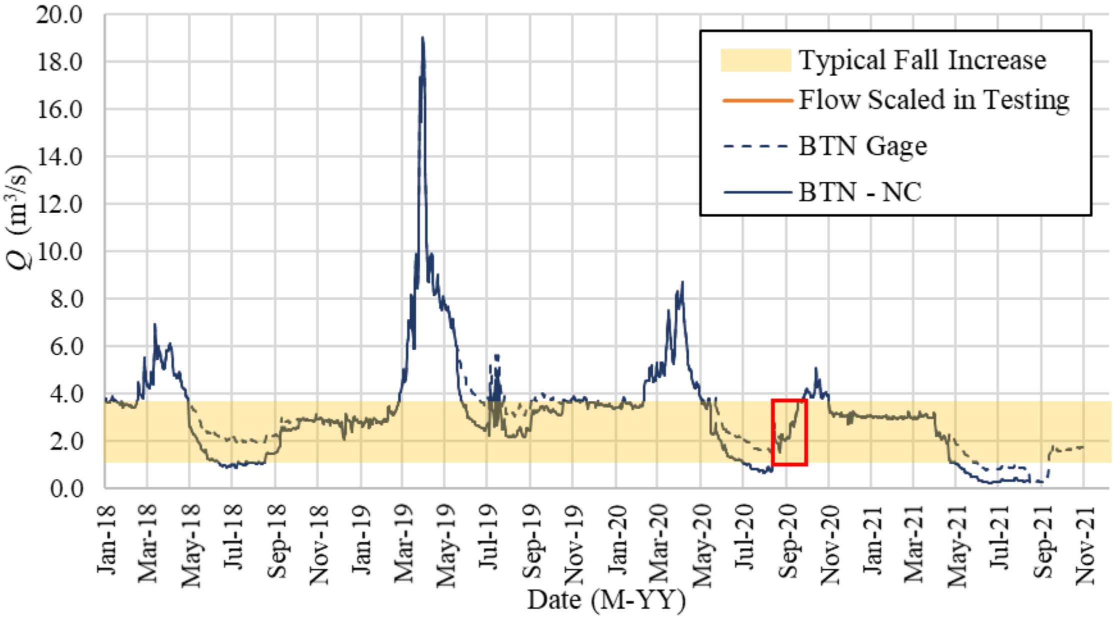

Figure 5: Daily average streamflow in BSF River Q (m^3/s) from 2018–2021. The yellow highlighted region identifies typical flow in the BSF between 1.25 m^3/s $\leq Q \leq$ 3.72 m^3/s, which covers the fall 2020 increase after low summer flows; flows scaled for use in the laboratory investigation are outlined in red, and specifically reflect gage data from the fall increase in discharge in 2020.

2 Methodology

This study included both field and laboratory components. The field investigation took place in the lower BSF River below Nibley Canal in northern Utah, USA (see Figure 4). The laboratory investigation was conducted in a large-scale flume located in the Utah Water Research Laboratory (UWRL) at Utah State University in Logan, Utah, USA. The primary purpose of the field campaign was to document the response of the BSF River reach in response to dredging and rock weir installations in 2013 and observe the interplay of rock weir, discharge, and movement of driftwood to inform the laboratory investigation. The primary purpose of the laboratory investigation was to consider, under controlled conditions, the passage and accumulation of natural woody debris elements and batches for two rock weir configurations

(V-shape and I-shape) for different debris loading conditions under steady and unsteady flow conditions. Factors studied that are influential in driftwood transport included driftwood element geometry, steady vs. unsteady (stepped hydrograph) flows, and rock weir geometry (I-or V-shaped).

2.1 Field campaign

Rock weirs and the presence of driftwood in the study reach of the BSF River were documented fall 2020 with returning field visits from summer to fall of 2021. Streamflow data for the reach was collected upstream of the rock weirs at the private BTN gage (Figure 4) with seasonal adjustments for flow diversions to the Nibley Canal (NC gage, see Figure 5). The BTN and NC gages provided daily average streamflow for the period available from 2018–2021 (Figure 5).

Field measurements taken at each rock weir included estimated bankfull width, b_{BSF}, an estimate of the original rock weir length following installation in 2014, L_{2014}, current rock weir length of the BSF River, L_{BSF}, and rock dimensions including diameter or width, d_{BSF}, and average rock weir height from the downstream side, P_{BSF} (see Table 1). Conditions of each rock weir and the adjacent river were also noted including any rock weir stone displacement, local scour, deposition of sediments, any lateral river migration and burial of rock weir sections, and the presence of driftwood.

The field campaign also included installation of trail cameras (H45 Trail Camera, 16 MP resolution with infrared LEDs for nighttime) at rock weirs #7 and #12 (Figure 4) to document general driftwood collection on weirs or movement not observed during field visits. Cameras captured images at two-hour intervals for approximately 30 days, giving insight as to how rising flow conditions following the irrigation season affect the transport of driftwood. Google Earth aerial imagery of the study reach pre- and post-rock weir installation was used to estimate the original configuration of each rock weir and the river response to dredging and rock weir installation.

Table 1: Rock Weir Geometry from select weirs in the lower BSF River study reach and Flume.

Weir #	Bank full Channel Width, b_{BSF} (m)	Current Length of Weir (2021), L_{BSF} (m)	Original Length of Weir (2014), L_{2014} (m)	Ave. Rock Width, d_{BSF} (m)	Ave. Downstream Weir Height, P_{BSF} (m)
7*	8	17	20	1.10	0.6
8	10	10	15	1.02	0.6
9	15	15	20	1.06	0.75
10	14.5	14.5	20	1.02	0.51
11	13	13	40	0.95	0.73
12*	14	14	30	1.13	0.73
Group Average	12.4	13.9	24	1.04	0.65

*Trail camera installation location

2.2 Laboratory investigation

Laboratory testing consisted of introducing predetermined driftwood accumulations (“batches”) across a flume by hand approximately 3 m upstream of a model rock weir. Batch elements were introduced all together or within a few seconds of each other; once a batch was entirely in the channel, time t began at $t = 0$ min. Following debris introduction, the total volume of driftwood passing and increase in upstream energy over time were monitored. Tests were conducted for both steady and stepped hydrograph flow at I- and V-shaped model rock weirs. All tests were repeated at least four times; however, further testing on the repeatability of driftwood passage at rock weirs may be necessary due to the variation in natural shape and structure of both the weir and debris elements (Furlan et al., 2017).

The flume used for the laboratory investigation portion of this study featured a headbox and baffle system to provide uniform tranquil flows to the rock weirs. Tranquil tailwater conditions were provided for a short reach downstream. The flume was trapezoidal in cross-section with a bottom width b = 1 m, 2:1 side slope, and a total length, l of 3.6 m (see Figure 6). The laboratory channel cross-section was a notably different from the BSF, which is much wider with natural banks and a movable bed; however, the laboratory setup allowed the study of woody debris at a rock weir abutment and along a center section of a rock weir. Due to differences between the actual river reach width and the laboratory flume, the study considered representing a section or portion of the river without distorting the horizontal or vertical geometric scaling. Although this is a limitation of the study the facility was of high value to this study for obtaining new insights into driftwood interaction at rock weirs.

Scaling was accomplished via Froude similitude and considered rock weir geometries observed in the field and an estimated critical flow depth, y_c, as the scaling length to maintain equivalent Froude numbers, F_r, between field and model. F_r for a trapezoidal channel may be computed via Eq. 1:

$$F_r = Q/\sqrt{g * A^3/T_w} \tag{1}$$

where Q is discharge, A refers to the cross-sectional area with a given flow depth, y, and T_w is the top width of flow at the cross-section. When F_r = 1, critical depth may be estimated. Flows considered (see Figure 5) in the BSF were 1.25 m^3/s ≤ Q ≤ 3.72 m^3/s. A channel width difference of 12 between the BSF River channel and the laboratory channel was also included in computing equivalent model discharges such that the laboratory flume represents a portion of the field channel width. The resulting geometric length ratio is L_r = 3. This L_r also allowed selection of stones with diameters for the model rock weirs, d_m, which were also 3 times smaller than stones from the BSF. This scale factor is large enough to cause minimal scale effects (Novak et al., 2018; Ettema, 2000).

2.2.1 Rock weirs

Field observations from the lower BSF River informed the scaling of model rock weirs situated in a large flume. Two rock weir configurations (I- and V-shaped) were chosen based on the original and current shapes of rock weirs observed in the BSF River. The weirs were placed in the flume with the annular space between stones grouted to maximize flow over the rock weirs as driftwood passage is sensitive to flow depths at the weir (Pfister et al. 2013; Vaughn et al. 2021). Large stones were donated by a homeowner on the BSF River and placed to approximate observed field conditions with a nonuniform crest elevation; the V- and I-shaped rock weirs had average heights P of 0.20 and 0.21 m and crest lengths L_c of 2.63 and 2.53 m, respectively; the V-shaped rock weir had an angle of approximately 60° to the side of the flume (see Figure 6).

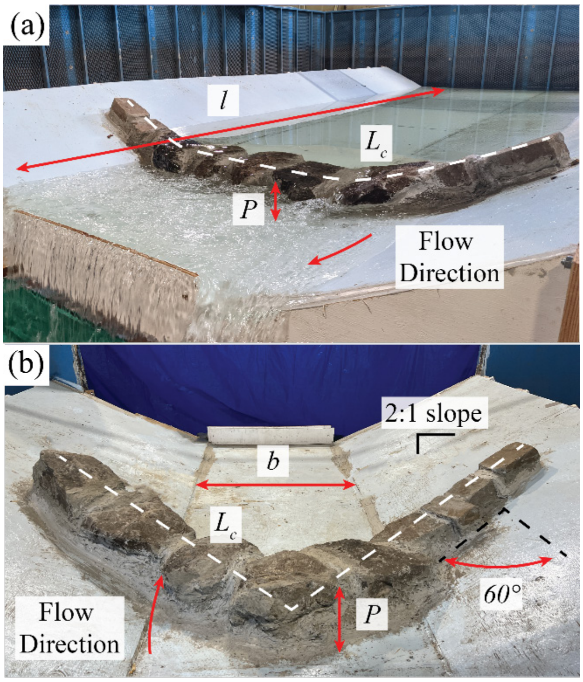

Figure 6: Experimental setup of (a) I-shaped rock weir and (b) V-shaped rock weir installed in laboratory flume (photos courtesy by Author).

Using Froude similitude and streamflow data from the lower BSF River (Figure 5), steady-state flows were selected for assessment in the flume, and a stepped hydrograph was developed (Table 2) representing an unsteady flow condition. Discharge was measured using a magnetic flowmeter (±0.25%) calibrated per ASTM standards. During testing of steady-state flows and the stepped hydrograph, measurement of upstream water elevation (i.e., flow depth y) was taken using a piezometer connected to a stilling well and point gage (± 0.15 mm). The upstream specific energy, E ($H + P = E$) was calculated using measurements for the weir height P, and total head above the weir crest, H along with a detailed survey (±1 mm) of the flume, rock weirs, and a scan of the rock weirs with an Intel® RealsenseTM D455 depth camera to estimate a representative weir height (Bung et al., 2021; Grunnet-Jepsen et al., 2019). Data comparison in terms of E was due to the organic shape of the crest on each model rock weir.

Table 2: Flow measurements at V- and I-shape model rock weirs from batch tests during steady discharge Q and average weir height and crest length.

	V-shape Weir			I-shape Weir		
Discharge (Q) L/s	Upstream Energy (E) m	Total Head (H) m	Top Width (T_W) m	Upstream Energy (E) m	Total Head (H) m	Top Width (T_W) m
20	0.226	0.026	1.891	0.234	0.0.024	1.942
30	0.261	0.059	2.022	0.265	0.0.055	2.067
40	0.275	0.075	2.089	0..275	0.0.065	2.106
Weir Height, P (m)	0.20			0.21		
Weir Length, L_c (m)	2.63			2.53		

2.2.2 Steady and unsteady flow conditions

To investigate any hysteresis and flux effect on driftwood movement, laboratory testing included fixed discharge or steady flows where a flow rate was set, the system was allowed to stabilize, and only then were driftwood experiments performed. However, as expected, flows in the BSF fluctuated temporally and thus this study explored if driftwood passage in the laboratory was also sensitive to changes in flow. Therefore, a gradually increasing and decreasing flow rate (i.e., flows that were changed with time or unsteady flows) was simulated by a stepped change in the supply piping, which at the weir is a gradual increase in discharge, not an abrupt or sharp increase or decrease in discharge (see Figure 7).

Specifically, the selection of flows for both steady flow and stepped hydrograph conditions was based on observed flows in the BSF that the model could provide (highlighted band in Figure 5), including the specific period where discharge increased beginning in September 2020 per the BTN stream gage data (noted within the red box in Figure 5 and detailed in Table 2, Table 3). From the selected data, scaled steady flows with width factor w = 12 and scaling ratio L_r = 3 were computed at 0.02, 0.03, 0.04, and 0.05 m^3/s corresponding to BSF flows of 0.90, 1.50, 2.10, and 3.03 m^3/s. The similarity in height and length between the V- and I-shaped weirs resulted in similar discharge characteristics at both weirs, which maintained total upstream energy E within 0.018 m of one another, as shown in Table 2.

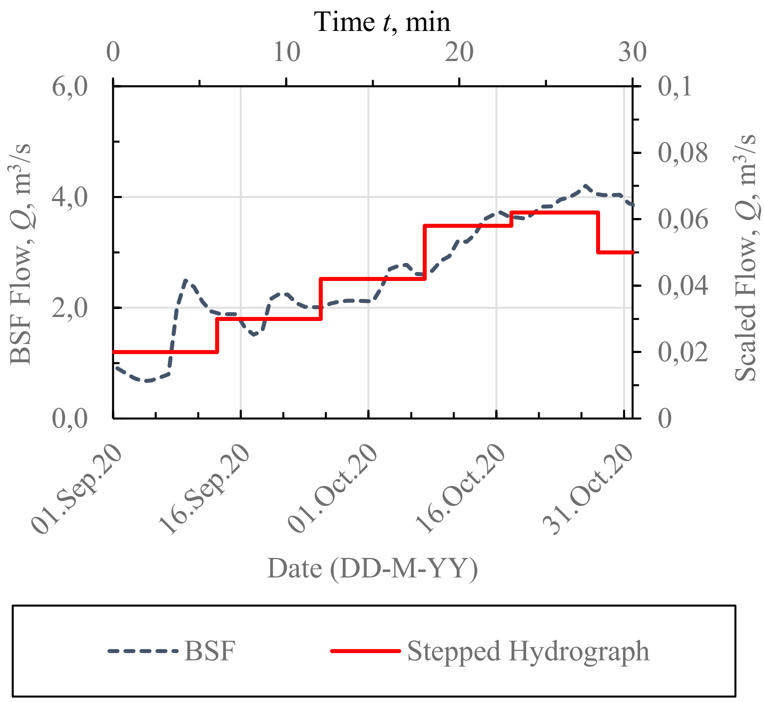

Figure 7: Average daily measured discharge on the BSF river during fall increase in discharge during September and October 2020 (see Figure 5) shown with the model stepped hydrograph scaled by F_r.

To develop the stepped hydrograph case, rounded statistical values (maximum, minimum, average, and one standard deviation) of average daily flows during September and October 2020 were used to create a synthetic hydrograph based on BSF flows. This hydrograph was subsequently scaled by F_r and divided into a stepped hydrograph (Figure 7) to facilitate manual flow changes during testing. Due to the variability in field data and the near-field size of the model rock weirs, time was not scaled or adjusted but specified based upon preliminary driftwood interaction with the I-rock weir. Note that the stepped hydrograph reflects discharge at the control valve in the supply piping and some attenuation and smoothing occurred in the headbox and rock weir channel and flow measurement at the rock weirs was not feasible (i.e., an immediate increase in discharge and depth did not occur at the rock weirs).

Model stepped hydrograph values are given in Table 3, which shows specific values of discharge, Q, and corresponding measurements of critical depth, y_c, area, A, and top width, T_w, at the BSF River and the flume for eight indices which correspond to points in the hydrographs shown in Figure 7. Scaling by F_r was intentional in preserving consistency in the critical depth between the BSF weirs and the model. Further confirmation of scale between the BSF and the laboratory portion of this study is given by the near linear relationship between y_c at the BSF weirs and the scaled model, which has an $R^2 = 0.97$ (Figure 8).

Table 3: Flow relationship between BSF River and Laboratory Model for Unsteady Simulations.

Index #	BSF River					Model Stepped Hydrograph				
	Q (m^3/s)	y_c (m)	A (m^2)	T_w (m)	F_r	Q (m^3/s)	y_c (m)	A (m^2)	T_w (m)	F_r
1	1.25	0.101	1.25	12.42	1.00	0.020	0.034	0.04	1.13	1.00
2	1.55	0.117	1.45	12.42	1.00	0.025	0.039	0.04	1.16	1.00
3	1.85	0.131	1.63	12.42	1.00	0.030	0.044	0.05	1.18	1.00
4	2.15	0.145	1.80	12.42	1.00	0.035	0.048	0.05	1.19	1.00
5	2.56	0.163	2.03	12.42	1.00	0.042	0.054	0.06	1.22	1.00
6	3.03	0.182	2.26	12.42	1.00	0.050	0.061	0.07	1.24	1.00
7	3.49	0.200	2.49	12.42	1.00	0.058	0.067	0.08	1.27	1.00
8	3.72	0.209	2.60	12.42	1.00	0.062	0.070	0.08	1.28	1.00

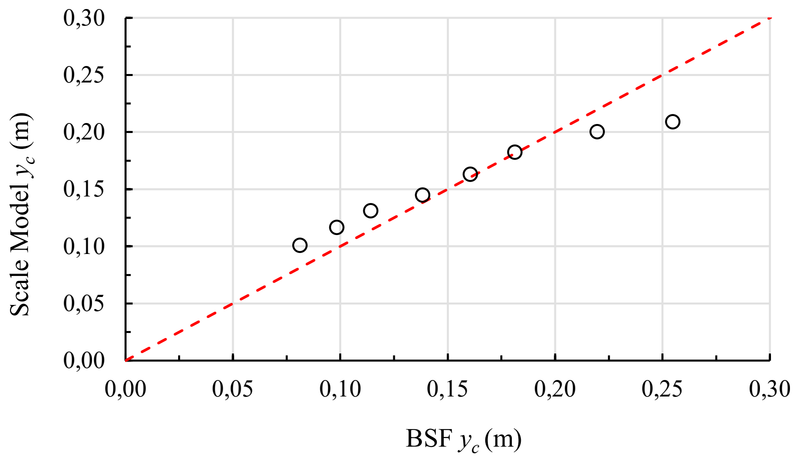

Figure 8: Comparison between y_c for scaled flow and at the BSF River, with $R^2 = 0.9724$.

2.2.3 Large woody debris

An important factor of the laboratory investigation was how driftwood batch geometry affected transport at V- and I-shaped rock weirs, including how the composition of a woody debris accumulation influences wood passage or entrapment. driftwood cataloged in the lower BSF study reach informed driftwood used in laboratory testing, which were selected as natural elements with branches, nobs, curves, etc. and gathered at the UWRL adjacent to the Logan River. Driftwood elements were similar in shape and size to logs or unbranched elements used in studies of driftwood blockage at bridge decks (Schmocker and Hager, 2011) and ogee crests (Bénet et al., 2021) and approximately five times larger than natural debris elements used in studies at labyrinth weirs (Vaughn et al., 2021) and piano-key weirs (Pfister et al., 2013). Excessive branching or irregularity in element shape, i.e., effective diameter (Pfister et al. 2013; Schmocker and Hager, 2011), was not considered in this study. Elements with multiple branches or rootstock configurations could potentially exhibit different impacts to upstream energy or flow conveyance (Schmocker and Hager, 2011).

Driftwood was measured and classified by length and diameter (see Table 4). Characteristic lengths L were measured (±1 mm) as the length along the longest part of the main branch. The diameter D of driftwood elements was calculated using digital calipers (±0.01 mm) to measure diameter at three places evenly spaced along the main branch. Due to the organic shape of the driftwood elements, D does not represent the diameter along the entire branch, rather, an average value is taken to be the characteristic diameter of the branch. Characteristic lengths ranged from 45–150 cm and characteristic diameters ranged from 1.5 to 6 cm. The density, ρ of each driftwood element was calculated by taking a presoaked weight divided by volume, Ꝟ. The weight scale accuracy was ± 0.001 kg. The volume of each element was measured by displacement of water (water surface difference accuracy ± 1 mm) in one of two large vertical measurement cylinders (d = 10.16, 15.24 cm).

Driftwood was grouped in length classes A–F and further grouped by element diameter; after initial testing and field observations, it was determined that elements from classes B, C, and D were best suited for use in accumulation passage tests. Measurements for these classes are given in Table 4.

Table 4: driftwood Elements by class with average volume, weight, and density.

Length Class and Characteristic Length, L (m)		Diameter Class, D (cm)	Volume, Ꝟ (m^3)	Weight, W (kg)	Density, ρ (kg/m^3)
B	0.5–0.74	1.5	1.09E-04	0.07	652.60
		2	2.03E-04	0.15	748.12
		4	5.15E-04	0.38	744.52
C	0.75–0.99	2	4.25E-04	0.20	465.20
		4	8.56E-04	0.45	527.53
		6	2.10E-03	1.27	605.09
D	1–1.49	2	4.49E-04	0.25	555.64
		4	1.39E-03	0.74	534.57
		6	2.64E-03	1.71	647.80

Driftwood was further grouped into three batches for laboratory testing: fine, medium, and coarse (Figure 9). Batch characteristics including element sizes were modeled based on observations of driftwood at the BSF rock weirs. The volume of each batch was consistent with driftwood loading observed in other mountain stream catchments and ranged from approximately 0.003–0.007 m^3/m^2 debris Ꝟ to unit channel area (Lester et al., 2006; Wohl and Scott, 2017). Total batch volume and median element volume increased from fine to coarse batches, with the fine batch having the smallest total volume Ꝟ = 6.4E-3 m^3 and the medium and coarse batches having Ꝟ = 8.4E-3 and 13.7E-3 m^3, respectively. Driftwood batches were formulated to include varying sizes of debris elements which could potentially act as “key, racked, or loose” within the accumulation structure (Abbe and Montgomery, 2003). Key elements are large enough to block smaller driftwood which would otherwise pass over the rock weir, while racked elements build up behind key elements and loose elements might pass or become dislodged from the total driftwood accumulation (Abbe and Montgomery, 2003).

Figure 9: Model driftwood sourced from the Logan River, including (a) fine, (b) medium, and (c) coarse batches with elements labeled by class as detailed in Table 4 (photos courtesy by Author).

3 Results

Observations from the lower BSF River, including measurements of rock weirs and driftwood in the fall of 2020 and summer to fall of 2021, provided insight into the impacts of in-stream structures in a mountain stream environment and the natural transport of driftwood. Field observations informed laboratory testing on the passage of driftwood accumulations, which considered the potential for driftwood transport as a function of rock weir geometry, driftwood characteristics, and river hydraulics.

3.1 Field Observations – BSF River

Following dredging and installation of rock weirs in 2013, a significant change in the studied section of the BSF was observed. River response included lateral channel migration, appreciable bedload during annual high flow periods, a decrease in channel slope with upstream deposition and partial burial of rock weirs. Local scour downstream of rock weirs and some instances of displaced rock weir stones was also observed. It is uncertain the exact mechanism that destabilized the rock weir stones, but observations support movement due to drag forces and local scour at the downstream base of the rock weir. The role of driftwood accumulation was not conclusive, but any driftwood accumulation would have increased drag forces on the structure.

BSF rock weirs #5 (similarly for weir #6) at one year after installation Figure 10a) and five years after installation (Figure 10b) make it is clear that for this section of the BSF the channel migrated to the north and east, cutting off the right abutment of the rock weir where it originally tied into the left bank. A significant sediment deposit on the left side of the channel completely blocks the left side of weir #5, so that it functions more as an I-shaped rock weir than the original V-shaped rock weir. As of field observations in 2020, weirs #1–6 are entirely toppled and no longer functioning in their intended capacity, and weirs #7–12 are filled with sediment deposits; historic aerial imagery supports that rock weirs have not been resilient to changes in the BSF since around 2017.

The BSF River rock weirs were observed during field excursions in the fall of 2020 and summer of 2021. All rock weirs had been affected by heavy upstream sedimentation, many of which had native riparian grasses and shrubs present (see Figure 10, Figure 11a) from periods of very low flows due to drought and upstream flow diversion for irrigation. Sediment deposits were considered general channel aggradation with the bedload including cobbles with d = 5–20 cm along with small gravels and sands. Upstream deposition at weir #9 (Figure 11b) filled in gaps between rock weir stones and decreased the slope of the channel. Downstream local scour was evident at weir #10, exacerbated by a man-made hole at the left side of the channel (Figure 11c). Rock toppling and sliding were evident at rock weirs #1–6, and 10–12 (weirs #10 and #12 in Figure 11c, d respectively). Thus, from the field investigation the stability of rock weir stones in the BSF was compromised from typical annual flows.

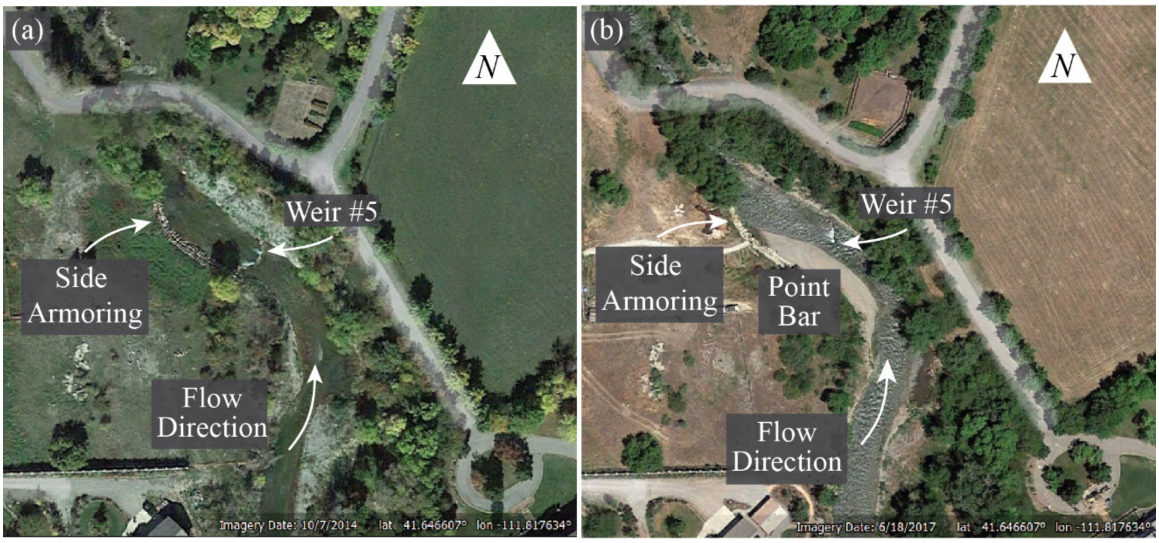

Figure 10: Lower BSF River rock weir #5 and side channel armoring in (a) 2014 and (b) 2017.

Figure 11: Lower BSF River rock weirs (a) weir #5 with vegetated sediment deposits on the left bank and cut-off of a tie-in on the right bank; toppled rocks downstream (b) weir #9 shows deposition upstream and between rocks (c) weir #10 displays local scour exacerbated by a man-made hole and sliding rocks (d) weir #12 has large gaps between rocks (photos courtesy of Author).

Driftwood observed in the lower BSF River reflected recruitment due to windstorms, bank erosion, and beaver activity (Figure 2). Low or no-flow conditions during drought conditions in the extremely dry summer of 2021 caused driftwood to become stranded mid-channel or at rock weirs where it had accumulated due to insufficient flow depths at the weirs relative to debris dimensions (Figure 12). Driftwood elements in the field ranged from 100–250 cm in length and 3.5–18 cm in diameter.

During flow monitoring at weirs #7 and #12 (Figure 12), cameras captured the increase of flow and subsequent transport of driftwood along the study reach from September to late October of 2021. It is estimated that flow increased at these weirs to approximately 1.6 m^3/s (Author 2021) and flow depths to approximately 0.15 m, mobilizing some driftwood from channel banks. An accumulation of branches with $d \approx 1–2$ cm and $L \approx 50–100$ cm was retained at the right of weir #12 on 27 October 2021 (Figure 12b). Weir #7 retained previously stored driftwood along the left side of the channel, including a large tree and several smaller branches caught beneath it (see Figure 12c).

Weir #12, which was located approximately 30 meters downstream of a unique beaver dam, had the most year-round clogging of driftwood at the weir itself (Figure 12a, b). Most of this driftwood was assumed to be recruited from the beaver dam itself, which was composed primarily of channel cobbles with small volumes of woody debris (Figure 13).

Figure 12: driftwood present at the BSF River rock weirs. (a) driftwood captured upstream of weir #12 before flow increased in September 2021, (b) driftwood caught at weir #12 driftwood during flow increase in fall 2021, (c) driftwood caught at the left side of weir #7 exposed during summer 2021, with a 0.6 m long pile driver for scale (photos courtesy by Author).

Figure 13. A rock-dominated beaver dam located approximately 30 m upstream of weir #12.

3.2 Scale model results

Laboratory testing of driftwood focused on the influence of batch composition, weir geometry, and total discharge on passage probabilities at the V- and I-shaped rock weirs. The relationship between driftwood accumulation from batches and backwater rise was studied through flow characteristics (E and F_r) for steady discharge and stepped hydrograph tests. For steady and unsteady flows, the difference in percent volume passing, $\cancel{V}\%$, was measured with time and as an average for each weir configuration and flow type. Effects of weir geometry and total discharge on driftwood passage were also considered for steady and unsteady flows.

3.2.1 General observations

Driftwood batches introduced upstream of weirs in the test flume typically consolidated into one or two main accumulations with interlocked branches with driftwood accumulations collapsing further when reaching the rock weir and as time elapsed, as illustrated in Figure 14. Passage or clogging of driftwood accumulations was largely dependent upon the location of a few key driftwood elements, often of the larger size in batch classes, which is similar to field observations. More key elements were dislodged as discharge increased and thus more total volume passed. This was true in general for increasing steady flows as well as unsteady flow testing.

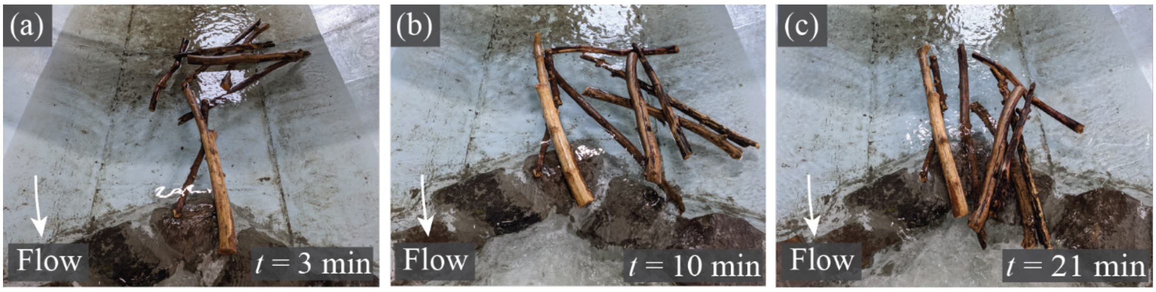

Figure 14: Collapse of coarse batch driftwood structure over time during a stepped hydrograph test at (a) t = 3 min, 20 L/s, (b) t = 10 min, 30 L/s and (c) t = 21 min, 58 L/s.

The majority of driftwood elements re-oriented to be parallel with flow as they moved down the channel (Figure 14). Batches tended toward the notches between stones, which were lower than the average weir crest and thus had slightly increased discharge. Debris batches would often catch at the diameter, on nubs or small knots on the upstream side of the rock weir and collapse as individual elements either passed or became further entrapped at the rock weir.

Accumulations of driftwood caused backwater rise and corresponding increase of E upstream of the model rock weirs. Backwater rise was considered in terms of upstream F_r compared to specific energy normalized by critical depth

$E\ /\ y_c$ and relative change in upstream energy $\Delta E/E_r$, where E_r is the reference specific energy prior to any driftwood clogging on the weir and $\Delta E = E - E_r$. The effects of driftwood accumulation on backwater rise for both steady and unsteady flows was described by polynomial functions shown in Figure 15 and given in Equations 2 and 3 for I- and V-shaped rock weirs, respectively. Note that the R^2 for both Eqs. 2 and 3 is 0.99.

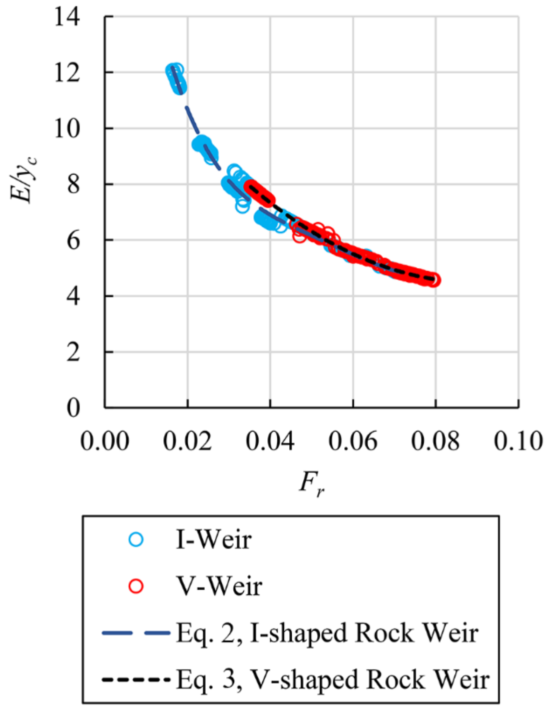

Figure 15: Relationship between energy to critical depth and F_r during unsteady tests for Fine, Med, and Coarse volume batches at I-shaped and V-shaped rock weirs.

$$\frac{E}{y_c} = 1{,}854{,}500Fr^4 - 402{,}212Fr^3 + 32{,}658.4Fr^2 - 1{,}244Fr + 25.41 \quad \text{I} - \text{shaped Rock Weir} \tag{2}$$

$$\frac{E}{y_c} = 1152.4Fr^2 - 206.91Fr + 13.769 \quad \text{V} - \text{shaped Rock Weir} \tag{3}$$

The range of upstream F_r is narrow and the increase in backwater was about 15% or less for the driftwood batches tested. The effects of driftwood on relative energy $\Delta E/E_r$ during both steady state and hydrograph testing are presented in Figure 16 for $F_r < 0.10$. Note that during hydrograph testing E was measured at t=1 min intervals. For rock weirs, backwater rise as measured by relative energy, was generally below 0.08 and lower for V-shaped rock weirs than for I-shaped rock weirs. Relative energy is consistent with data collected at other hydraulic structures of interest, including labyrinth weirs (Vaughn, 2020; Vaughn et al., 2021).

Total driftwood volume passage is interdependent as driftwood accumulation typically reduces hydraulic efficiency, generating backwater rise and an increase in relative energy as illustrated in Figure 17 that shows retained volume is generally increasing with increasing relative energy; note that there is some scatter during hydrograph testing (Figure 17a) as the debris-rock weir interaction was dynamic, causing a dynamic hydraulic response. Specifically, a wood element would catch on the weir, cause backwater, then the element may respond and shift slightly location, etc. (unsteady conditions). However, increasing volume with increasing relative energy is clearly illustrated for the steady-state testing (see Figure 17b) where the interaction of wood and weir were observed until stable and then measurements were taken. It was also observed that fine debris batches passed more percent volume ($\forall$%) during flows with lower relative energy $\Delta E/E_r < 0.015$, while coarse and medium debris required higher relative energy $\Delta E/E_r > 0.02$ to pass more than 60% of total volume (Figure 17b).

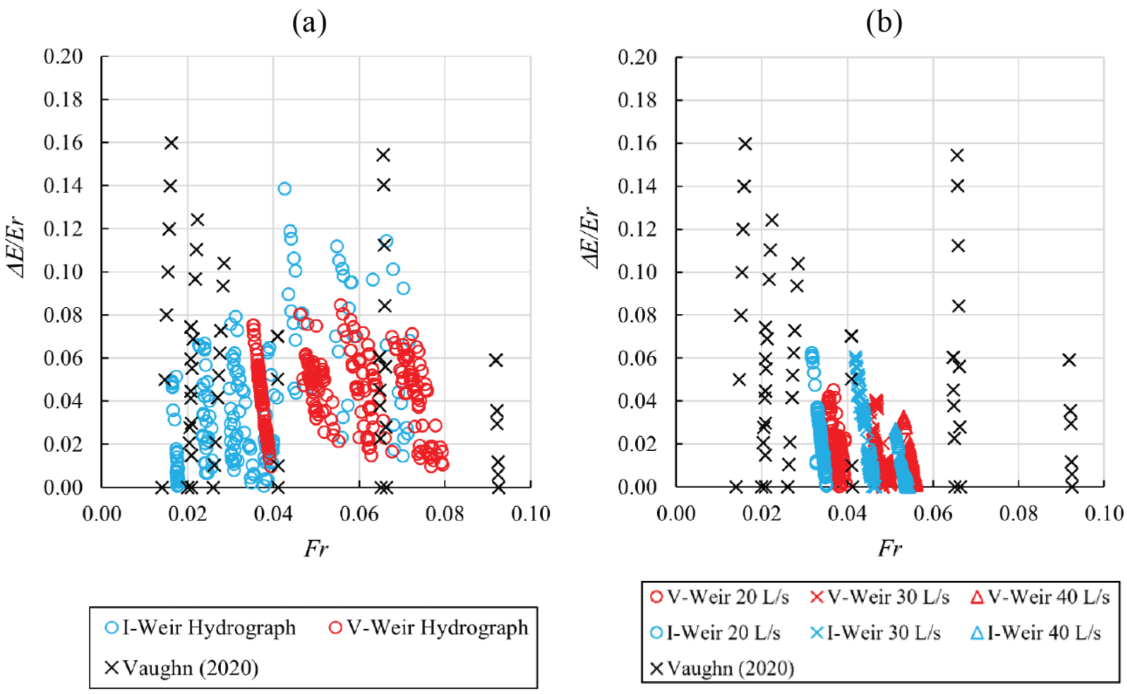

Figure 16: Relationship between relative energy and F_r during (a) unsteady flow tests and (b) steady flows for Fine, Med, and Coarse volume batches at I-shaped and V-shaped rock weirs.

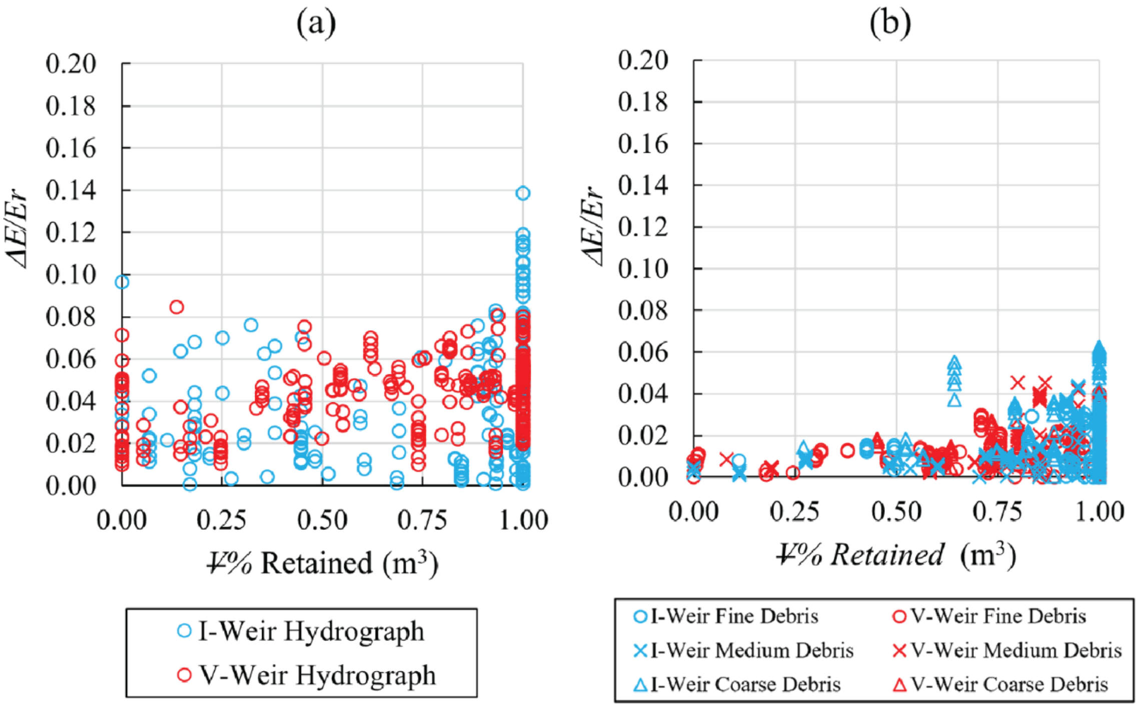

Figure 17: Relationship between relative energy and F_r during (a) unsteady flow tests and (b) steady flows for Fine, Med, and Coarse volume batches at I-shaped and V-shaped rock weirs.

3.2.2 Steady vs. unsteady flows

Both weir configurations passed a finite volume of driftwood during steady discharge and stepped hydrograph tests, with no volume passing after 26 minutes during a 30-minute test. Figure 18 shows results of Ꝟ% retained the I- and V-shaped rock weirs over time during steady state and stepped hydrograph testing. For steady-state tests, the duration of driftwood that would temporarily catch on the rock weir and then pass were similar and it is important to note that when testing natural debris elements an observation period is beneficial as some elements may not immediately pass over the weir but with time will be transported downstream. The role of weir geometry in plan also is evidenced for larger driftwood elements; more time elapsed for medium and coarse driftwood passage at the I-shaped rock weir compared to the V-shaped weir.

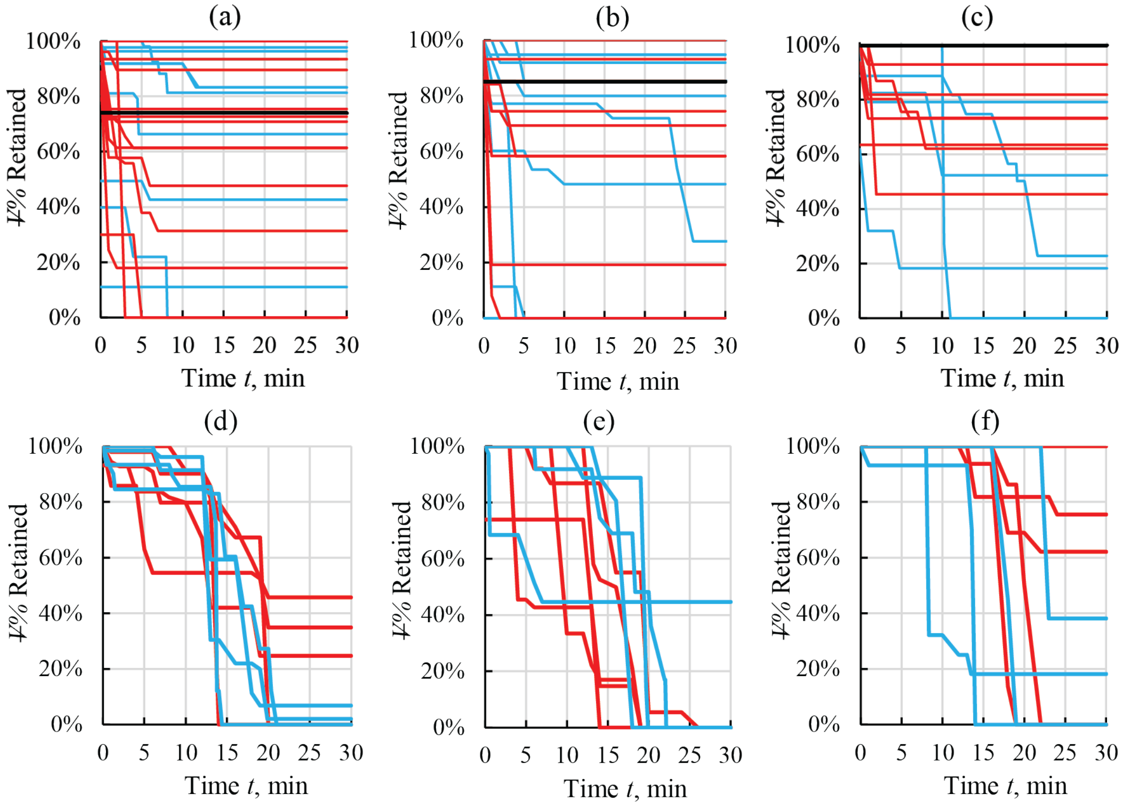

Figure 18: The percent volume (Ꝟ%) of driftwood retained at I- and V-shaped rock weirs shown in blue and red, respectively, for (a) fine, (b) medium, and (c) coarse batches during steady flows with a black dashed line indicating median Ꝟ% retained and (d) fine, (e) medium, and (f) coarse batches during unsteady flows.

During steady flow testing, the majority of driftwood passed over I- and V-shaped rock weirs within 10 minutes (Figure 18). As total discharge was increased in both steady state and stepped hydrograph testing, there was an increase in total Ꝟ% passing. Steady-state tests showed a significant increase in Ꝟ% passing between 30 and 40 L/s, averaging 34.5%. These flows are reflected in the hydrograph tests between 6 and 15 minutes, when the majority of driftwood passes at either weir type (Figure 18d, e, f).

Batch composition had a significant effect on driftwood passage evidenced in the increasing median values of Ꝟ% retained for fine, medium, and coarse batches of 74%, 85%, and 100%, respectively. Additionally, the timing of driftwood passage was most consistent in the fine batch for both steady and unsteady flows (Figure 18a, d), even between I- and V-shaped rock weirs. Time to passage became increasingly variable in medium and coarse batches, with some coarse debris entrapped for the entirety of steady flow and hydrograph tests.

Results of average Ꝟ% passing for each batch are given in Figure 19, which shows the same trend of increased passage from fine to coarse batch types under a given flow. In general, the fine and medium batches passed a similar total Ꝟ%, with a difference ranging from 0.9–12.1% between V- and I-shaped rock weirs during steady state testing. Two outliers of this trend for the fine and coarse driftwood batches were observed at the I-weir for flows of 20 and 40 L/s, respectively (Figure 19a). Specifically, very similar average Ꝟ% were passed for the fine batches at 20 L/s, and less Ꝟ% passed for the coarse batch at 40 L/s than for the Fine and Med batches. This can be explained due the interaction of individual wood elements as the batches interacted with the rock weirs.

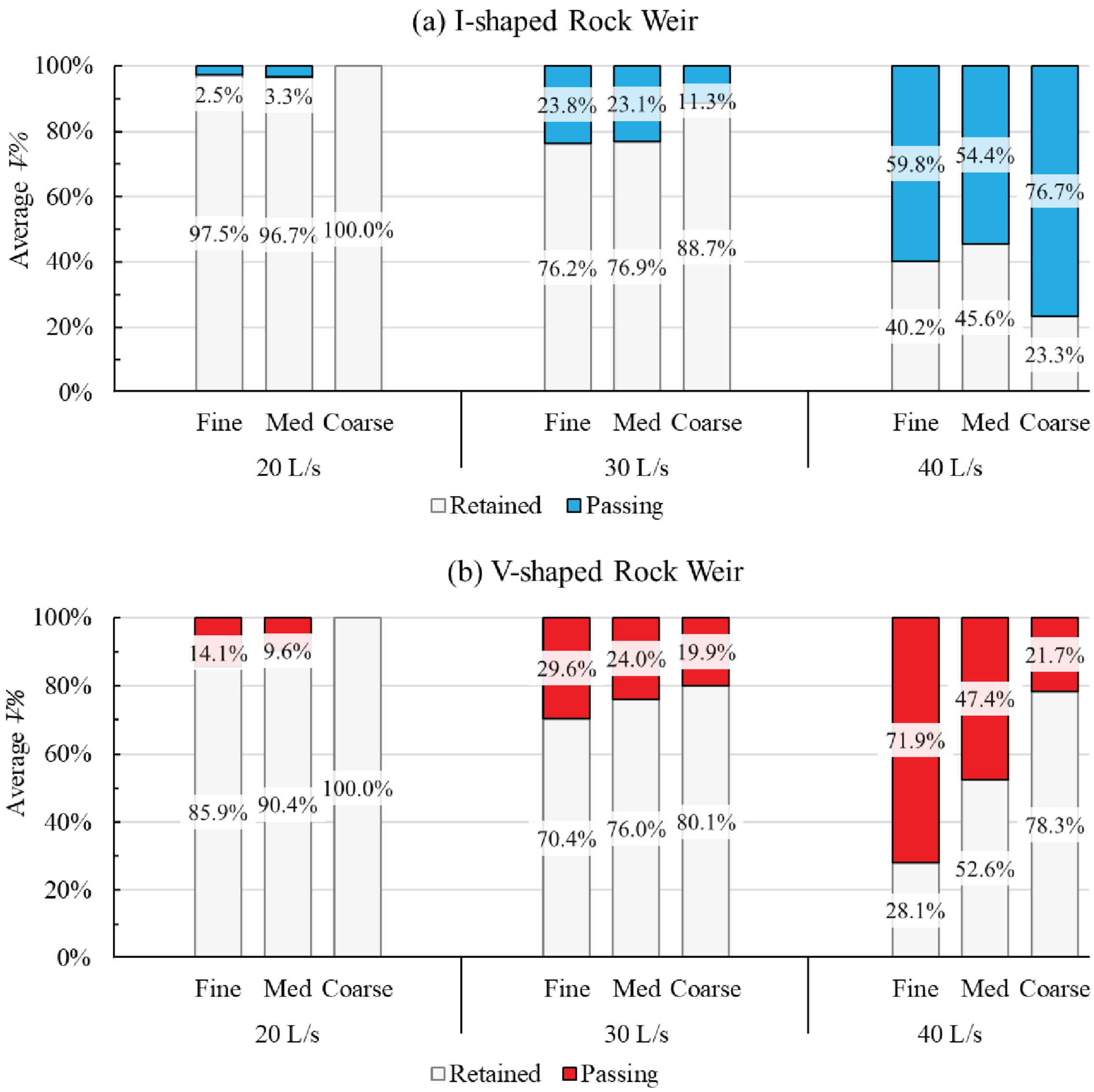

Figure 19: Average Ꝟ% passing and retained at (a) I-shaped and (b) V-shaped rock weirs at constant flow rates of 20, 30, and 40 L/s.

During unsteady flow tests, average Ꝟ% passing at the I-weir decreased consistently from fine to coarse batch types, similar to trends observed in steady state testing (Figure 20a). However, unlike average results from steady flows, the V-weir passed a lower average Ꝟ% than the I-shaped weir for fine and coarse batches. Another inconsistency in the V-weir results for unsteady flow was a 100% average volume passage for the medium debris batch (Figure 20b). Additional testing of volume passage may be necessary for quantifying average effects of batch composition and steady vs. unsteady flows for I- and V-shaped rock weirs.

Weir configuration did not lead to a significant change in the final Ꝟ% of driftwood passing, likely due to the similarity in total weir length and height between the V- and I-shaped rock weirs (L_c = 2.63, 2.53 m, P = 0.20, 0.21 m, respectively), which in turn cause similar total E and H for specific discharges (Table 2).

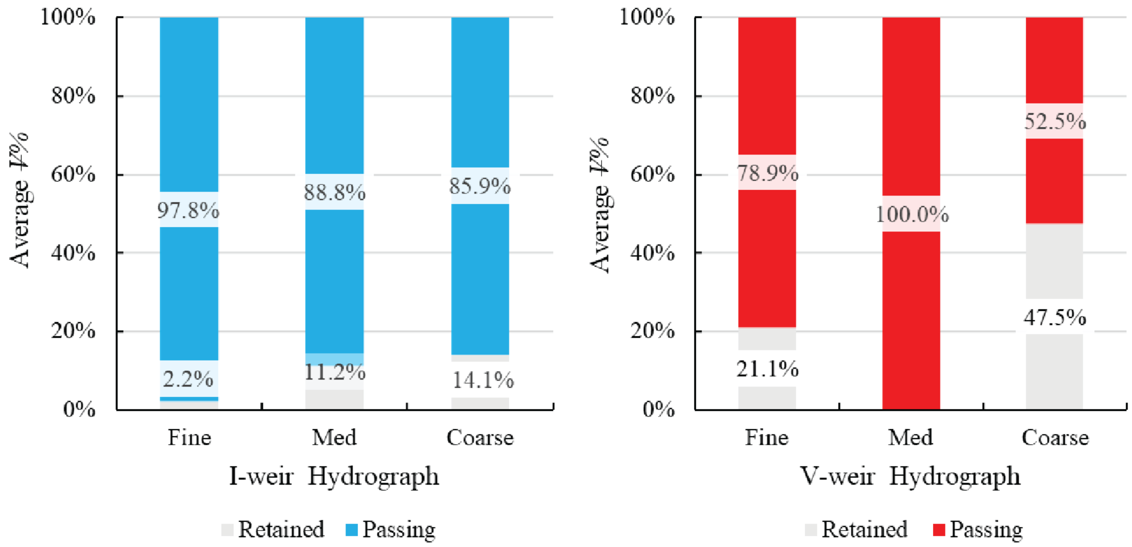

Figure 20: Average V% passing and retained at (a) I-shaped and (b) V-shaped rock weirs during hydrograph testing.

4 Discussion

This study focused on the interaction of driftwood at rock weirs in the BSF River (a mountain stream) and testing driftwood accumulations and passage in a laboratory setting. Rock weirs in the BSF River were in poor condition, with many buried in sediment and displaying toppled or sliding rocks. Discharge in the BSF is primarily driven by spring snowmelt, leading to extreme discharge and mobilization of sediment beyond the normal bedload during certain times of the year (Figure 5). High spring flows are the most likely cause for rock toppling and sedimentation of the BSF rock weirs within a few short years of installation (Figure 10). The rock weirs overall lacked resilience to the extreme flows and bedload movement present in the BSF River.

Driftwood observed in the BSF was largely caught upstream or on top of rock weirs (Figure 12). The presence of driftwood likely increased drag forces at the weirs; however, it was more likely spring runoff that caused most rock toppling at the BSF rock weirs. Debris movement is of greatest concern during drought and dry periods, specifically during the summer when flow is primarily diverted to the Nibley Canal. During these times, the BSF rock weirs see little to no flow making the movement of woody debris highly improbable. The lack of conveyance in the BSF also affects wildlife including fish which are typically killed due to insufficient DO available with higher flow conditions.

Failed rock weirs such as those observed in the BSF River show signs of downstream scour that destabilized stones connected with preferential flow paths in the form of stone gaps or thalwegs in the river where rocks have toppled or slid. Sediment and debris are transported primarily through these flow paths, and it is less likely for driftwood to be stored or provide cover at rock weirs with large gaps between rocks. Conversely, designing rock weirs with a variable crest elevation may be useful in river systems where there is a need to transport large amounts of driftwood and sediment, such as the BSF River where such crest geometries are also considered for fish passage and seasonal flows.

Testing natural driftwood accumulations at I- and V-shaped rock weirs was undertaken in a laboratory setting to observe driftwood passage. Sediment storage and transport was not considered in laboratory tests. A smooth flume allowed results to focus on flow characteristics upstream of the rock weir and at the weir crest without the effects of a mobile bedload, as observed in the BSF River. The I- and V-shaped rock weirs installed at the flume were composed of rocks and scaled by F_r to maintain critical flow depths. Driftwood batch composition (fine, medium, and coarse) remained unchanged between tests.

Batch characteristics (total volumes) were based on debris observed in other mountain streams (Lester et al., 2006; Wohl and Scott, 2017). Diameter was the main controlling factor in driftwood passage, and elements with $D \geq 4$ cm had the greatest effect on total batch passage for steady and unsteady flows. Time also played a role in debris passage, and most driftwood elements passed within 10–15 minutes for a given steady flow. In unsteady flow tests, the majority of driftwood passed between 6 and 15 minutes or during flows of 30 and 40 L/s. In comparing data from testing steady and unsteady discharge scenarios, it is apparent that weir configuration has less of an effect on driftwood passage than total discharge.

Practitioners are encouraged to focus on a balanced approach to prioritizing structural safety and river conveyance while considering the natural processes of a given river or watershed. The management of driftwood is crucial to this balanced approach (Wohl et al., 2016). Understanding the interaction between driftwood and rock weirs in mountain streams is a valuable tool for practitioners considering implementation of nature-like structures. Flume tests conducted for steady and unsteady flows may have additional application to various catchments with rock weirs or other organic channel spanning weirs, such as logs (Wohl et al., 2016).

Data presented on driftwood retention for steady flows and stepped hydrographs may be used in determining passage rates for driftwood with characteristics similar to the fine, medium, or coarse debris batches for similar flow depths. Additionally, equations presented for two rock weir configurations (I-weirs and V-notch weirs) are intended to aid practitioners in determining effects of driftwood accumulation to backwater rise via total upstream energy E via F_r for sub-critical flows.

5 Conclusions

This study examined the interaction of driftwood at rock weirs in mountain streams through field observations on the lower BSF River and a laboratory investigation of driftwood entrapment at of V- and I-shaped rock weirs. Specifically, the study aimed to answer questions relating the passage of driftwood at rock weirs to batch characteristics in terms of element geometry and size, variation in flow between steady discharge and stepped hydrographs, and I- and V-shaped weir configurations. Results of driftwood impacts to backwater rise were cataloged via upstream energy E and average head H at the rock weirs.

Findings at the BSF rock weirs include observations of heavy sedimentation and rock toppling, likely caused by high spring flows; driftwood did not appear to be a factor in the toppling or sliding of the rock weirs. Scaled rock weirs and driftwood used in laboratory testing were modeled after those observed in the BSF River. The use of natural driftwood together with rocks sourced from the BSF River for model weirs is novel in its application in large flume testing.

The passage of driftwood at model rock weirs was monitored based on driftwood batch characteristics, steady and stepped hydrograph flows, and rock weir geometry. Driftwood batch composition (fine, medium, coarse) correlated with the total volume of driftwood passing, where passage decreased as median element size increased. Elements with $D \geq 4$ cm had the greatest effect on total batch passage and coarse debris was typically retained at either rock weir configuration longer than medium and fine batches. Total *Ꝟ%* driftwood passing increased with discharge, and the most passage occurred during stepped hydrograph testing. Rock weir geometry did not appear to have a large effect on total *Ꝟ%* driftwood passing in steady discharge tests, likely due to a similarity in discharge rates between the V- and I-shaped rock weirs. However, during stepped hydrograph tests, a higher *Ꝟ%* driftwood passed the V- than the I-shaped weir.

Acknowledgements

This study was supported by a private donation by D. Campbell and by the State of Utah through Utah State University.

Author contributions (CRediT)

KM[1]: Data curation, Formal Analysis, Investigation, Methodology, Writing – original draft. BL[2]: Investigation, Methodology, Resources, Writing – review & editing. BC[3]: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

References

Abbe, T. B.; Montgomery, D. R. 2003. “Patterns and processes of wood debris accumulation in the Queets river basin, Washington.” *Geomorphology*, 51 (1–3): 81–107. https://doi.org/10.1016/S0169-555X(02)00326-4.

Alger, M., B. A. Lane, and B. T. Neilson. 2021. “Combined influences of irrigation diversions and associated subsurface return flows on river temperature in a semi-arid region.” *Hydrological Processes*, 35 (8). https://doi.org/10.1002/hyp.14283.

Anderson, M. 2011. “Cache County residents prepare as Blacksmith Fork nears flood stage.” *KSL.com*, May 11, 2011.

Badoux, A., M. Böckli, D. Rickenmann, C. Rickli, V. Ruiz-Villanueva, S. Zurbrügg, and M. Stoffel. 2015. “Large wood transported during the exceptional flood event of 24 July 2014 in the Emme catchment (Switzerland).” 3. Padova, Italy.

Bénet, L., G. De Cesare, and M. Pfister. 2021. “Reservoir Level Rise under Extreme Driftwood Blockage at Ogee Crest.” *J. Hydraul. Eng.*, 147 (1): 04020086. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001818.

Bung, D. B., B. M. Crookston, and D. Valero. 2021. “Turbulent free-surface monitoring with an RGB-D sensor: the hydraulic jump case.” *Journal of Hydraulic Research*, 59 (5): 779–790. https://doi.org/10.1080/00221686.2020.1844810.

Cramer, M. L. 2012. *Stream Habitat Restoration Guidelines*. Olympia, Washington: Co-published by the Washington Departments of Fish and Wildlife, Natural Resources, Transportation and Ecology, Washington State Recreation and Conservation Office, Puget Sound Partnership, and U.S. Fish and Wildlife Service.

Crookston, B. M., D. Mortensen, T. Stanard, B. P. Tullis, and V. M. Vasquez. 2015. "Debris and Maintenance of Labyrinth Spillways." in *Proc., USSD 2015 Annual Conf.* Denver, United States Society on Dams.

Daniels, M. D., and B. L. Rhoads. 2003. “Influence of a large woody debris obstruction on three-dimensional flow structure in a meander bend.” *Geomorphology*, 51 (1–3): 159–173. https://doi.org/10.1016/S0169-555X(02)00334-3.

Erskine, W. D., and A. A. Webb. 2003. “Desnagging to resnagging: new directions in river rehabilitation in southeastern Australia.” *River Res. Applic.*, 19 (3): 233–249. https://doi.org/10.1002/rra.750.

Furlan, P. 2019. “Blocking probability of large wood and resulting head increase at ogee crest spillways.” Lausanne, EPFL. https://doi.org/10.5075/EPFL-THESIS-9040.

Furlan, P., M. Pfister, J. Matos, and A. J. Schleiss. 2017. “Blocking Probability of Driftwood at Ogee Crest Spillways with Piers: Influence of Woody Debris Characteristics.” 8.

Furlan, P., M. Pfister, J. Matos, and A. J. Schleiss. 2018. “Influence of density of large stems on the blocking probability at spillways.” *International Symposium on Hydraulic Structures*, 3.

Gippel, C. J. 1995. “Environmental Hydraulics of Large Woody Debris in Streams and Rivers.” *Journal of Environmental Engineering*, 121 (5): 388–395. https://doi.org/10.1061/(ASCE)0733-9372(1995)121:5(388).

Gregory, S. V., K. L. Boyer, and A. M. Gurnell. 2003. “Ecology and Management of Wood in World Rivers.” *Ecology and Management of Wood in World Rivers*, 37. https://doi.org/10.1002/esp.1546.

Grunnet-Jepsen, A., J. N. Sweetser, P. Winer, A. Takagi, and J. Woodfill. 2019. “Projectors for Intel® RealSense™ Depth Cameras D4xx.” Accessed February 1, 2020. https://dev.intelrealsense.com/docs/projectors.

Gurnell, A. M., H. Piégay, F. J. Swanson, and S. V. Gregory. 2002. “Large Wood and Fluvial Processes.” *Freshwater Biology*, 47 (4): 601–619. https://doi.org/10.1046/j.1365-2427.2002.00916.x.

Hartlieb, A. 2014. *Vorsorgender und nachsorgender Hochwasserschutz: ausgewählte Beiträge aus der Fachzeitschrift WasserWirtschaft*. (S. Heimerl and H. Meyer, eds.). Wiesbaden: Springer Vieweg.

Hisslop, C. 2013. “Cache Valley communities still dealing with aftermath of 2011 floods.” *Cache Valley Daily*, February 22, 2013.

Jain, S., and U. Lall. 2000. “Magnitude and timing of annual maximum floods: Trends and large-scale climatic associations for the Blacksmith Fork River, Utah.” *Water Resour. Res.*, 36 (12): 3641–3651. https://doi.org/10.1029/2000WR900183.

Johansson, N., and M. Cederström. 1995. *Floating Debris and Spillways*. International Conference on Hydropower. New York: ASCE.

Kail, J., D. Hering, S. Muhar, M. Gerhard, and S. Preis. 2007. "The use of large wood in stream restoration: experiences from 50 projects in Germany and Austria: Large wood in stream restoration." *Journal of Applied Ecology*, 44 (6): 1145–1155. https://doi.org/10.1111/j.1365-2664.2007.01401.x.

Keller, E. A., and F. J. Swanson. 1978. "Effects of Large Organic Material on Channel Form and Fluvial Processes." 20.

KSL.com. 2011. "Morgan, Cache county residents fighting flood waters." *ksl.com*, April 18, 2011.

Le Lay, Y.-F., H. Piégay, and B. Moulin. 2013. "12.3 Wood Entrance, Deposition, Transfer and Effects on Fluvial Forms and Processes: Problem Statements and Challenging Issues." *Treatise on Geomorphology*, 20–36. Elsevier.

Lester, R., W. Wright, and M. Jones-Lennon. 2006. "Determining target loads of large and small wood for stream rehabilitation in high-rainfall agricultural regions of Victoria, Australia." *Ecological Engineering*, 28 (1): 71–78. https://doi.org/10.1016/j.ecoleng.2006.04.010.

Mao, L., A. Andreoli, A. Iroumé, F. Comiti, and M. A. Lenzi. 2013. "Dynamics and management alternatives of in-channel large wood in mountain basins of the southern Andes." *Bosque (Valdivia)*, 34 (3): 15–16. https://doi.org/10.4067/S0717-92002013000300008.

Novak, P., V. Guinot, A. Jeffrey, and D. E. Reeve. 2018. *Hydraulic Modelling – an Introduction: Principles, methods and applications*. CRC Press.

NRCS. 2013. *Emergency Watershed Protection: Blacksmith Fork River Floodplain Restoration*. Cache County, Utah: NRCS, Cache County, Logan City.

Pagliara, S., and P. Chiavaccini. 2007. "Failure mechanisms of base and reinforced block ramps." *Journal of Hydraulic Research*, 45 (3): 407–420. https://doi.org/10.1080/00221686.2007.9521774.

Pagliara, S., S. M. Kurdistani, and L. Cammarata. 2014. "Scour of Clear Water Rock W-Weirs in Straight Rivers." *J. Hydraul. Eng.*, 140 (4): 06014002. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000842.

Pagliara, S., M. Palermo, and I. Carnacina. 2012. "Live-bed scour downstream of block ramps for low densimetric Froude numbers." *International Journal of Sediment Research*, 27 (3): 337–350. https://doi.org/10.1016/S1001-6279(12)60039-0.

Pagliara, S., M. Palermo, and D. Roy. 2020. "Experimental investigation of erosion processes downstream of block ramps in mild curved channels." *Environ Fluid Mech*, 20 (2): 339–356. https://doi.org/10.1007/s10652-019-09681-1.

Pfister, M., D. Capobianco, B. Tullis, and A. J. Schleiss. 2013. "Debris-Blocking Sensitivity of Piano Key Weirs under Reservoir-Type Approach Flow." *J. Hydraul. Eng.*, 139 (11): 1134–1141. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000780.

Puckett, P. R. 2008. "The Rock Cross Vane: A Comprehensive Study of an In-Stream Structure." Dissertation. North Carolina State University.

Roni, P., T. Beechie, G. Pess, and K. Hanson. 2015. "Wood placement in river restoration: fact, fiction, and future direction." *Can. J. Fish. Aquat. Sci.*, (B. Jonsson, ed.), 72 (3): 466–478. https://doi.org/10.1139/cjfas-2014-0344.

Roni, P., T. Bennett, S. Morley, G. R. Pess, K. Hanson, D. V. Slyke, and P. Olmstead. 2006. "Rehabilitation of bedrock stream channels: the effects of boulder weir placement on aquatic habitat and biota." *River Res. Applic.*, 22 (9): 967–980. https://doi.org/10.1002/rra.954.

Rosgen, D. L. 2001. "The Cross-Vane, W-Weir and J-Hook Vane Structures...Their Description, Design and Application for Stream Stabilization and River Restoration." *Wetlands Engineering & River Restoration 2001*, 1–22. Reno, Nevada, United States: American Society of Civil Engineers.

Ruiz-Villanueva, V., H. Piégay, A. M. Gurnell, R. A. Marston, and M. Stoffel. 2016. "Recent advances quantifying the large wood dynamics in river basins: New methods and remaining challenges: Large Wood Dynamics." *Rev. Geophys.*, 54 (3): 611–652. https://doi.org/10.1002/2015RG000514.

Schalko, I., L. Schmocker, V. Weitbrecht, and R. M. Boes. 2018. "Backwater Rise due to Large Wood Accumulations." *J. Hydraul. Eng.*, 144 (9): 04018056. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001501.

Schalko, I., L. Schmocker, V. Weitbrecht, and R. M. Boes. 2020. "Laboratory study on wood accumulation probability at bridge piers." *Journal of Hydraulic Research*, 58 (4): 566–581. https://doi.org/10.1080/00221686.2019.1625820.

Schmocker, L. 2017. *Floating Debris Retention Racks at Dam Spillways*. 37th IAHR World Congress. Beijing: China Three Gorges Corporation.

Schmocker, L., and W. H. Hager. 2011. “Probability of Drift Blockage at Bridge Decks.” *J. Hydraul. Eng.*, 137 (4): 470–479. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000319.

Schmocker, L., and W. H. Hager. 2013. “Scale Modeling of Wooden Debris Accumulation at a Debris Rack.” *J. Hydraul. Eng.*, 139 (8): 827–836. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000714.

Schmocker, L., and V. Weitbrecht. 2013. “Driftwood: Risk Analysis and Engineering Measures.” *J. Hydraul. Eng.*, 139 (7): 683–695. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000728.

Stocker, B., I. Schalko, A. Lais, and R. M. Boes. 2021. “Discussion of ‘Reservoir Level Rise under Extreme Driftwood Blockage at Ogee Crest’ by Loïc Bénet, Giovanni De Cesare, and Michael Pfister.” *J. Hydraul. Eng.*, 147 (12): 07021012. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001945.

Swiss Committee on Dams. 2017. *Floating Debris at Reservoir Dam Spillways*. Luzern, Switzerland: Swiss Committee on Dams.

Task Committee on Hydraulic Modeling, Environmental and Water Resources Institute, ASCE, R. 2000. *Hydraulic Modeling: Concepts and Practice*. (R. Ettema, ed.). Reston, VA: American Society of Civil Engineers.

U.S. Bureau of Reclamation (Reclamation), E. H. Gordon, K. Collins, C. Holmquist-Johnson, and M. Scurlock. 2016. “Rock Weir Design Guidance.” 197.

U.S. Dept. of the Interior. 2020. *Spillway Debris Physical Model Study Morning glory Spillway Structure*. 40. Hydraulic Laboratory Report. Department of the Interior, Bureau of Reclamation.

U.S. Fish and Wildlife Service (USFWS). 2019. “Fish Passage Engineering Design Criteria.” USFWS, Northeast Region R5, Hadley, Massachusetts.

Vaughn, T. 2020. “Submerged and Floating Woody Debris-Blocking Sensitivity of Labyrinth Weirs.” Logan, Utah: Utah State University.

Vaughn, T., M. Pfister, and B. M. Crookston, and. 2021. “Floating Woody Debris: Blocking Sensitivity of Labyrinth Weirs in Channel and Reservoir Applications.” *J. Hydraul. Eng.*, 147 (11): 06021016. https://doi.org/10.1061/(ASCE)HY.1943-7900.0001937.

Venetz, P. 2014. “Sensitivity of Piano Key Weirs Regarding Drift Wood Blockage under Channel-Type Approach Flow.” M.Sc. thesis. Ecole Polytechnique Fédérale de Lausanne.

Walker, R. H., M. C. Orr, and S. W. Miller. 2020. “Factors contributing to leaf decomposition vary with temperature in two montane rivers of the Intermountain West, Utah.” *Aquat Sci*, 82 (3): 49. https://doi.org/10.1007/s00027-020-00723-1.

Wallerstein, N., C. R. Thorne, and S. R. Abt. 1997. *Debris Control at Hydraulic Structures in Selected Areas of the United States and Europe*. Waterways Experiment Station. U.S. Army Corps of Engineers.

Webb, A. A., and W. D. Erskine. 2003. “Distribution, recruitment, and geomorphic significance of large woody debris in an alluvial forest stream: Tonghi Creek, southeastern Australia.” *Geomorphology*, 51 (1–3): 109–126. https://doi.org/10.1016/S0169-555X(02)00327-6.

Williams, J. S., and M. E. Taylor. 1964. “The Lower Devonian Water Canyon Formation of Northern Utah.” 16.

Wohl, E. 2020. “Wood process domains and wood loads on floodplains.” *Earth Surf. Process. Landforms*, 45 (1): 144–156. https://doi.org/10.1002/esp.4771.

Wohl, E., B. P. Bledsoe, K. D. Fausch, N. Kramer, K. R. Bestgen, and M. N. Gooseff. 2016. “Management of Large Wood in Streams: An Overview and Proposed Framework for Hazard Evaluation.” *J Am Water Resour Assoc*, 52 (2): 315–335. https://doi.org/10.1111/1752-1688.12388.

Wohl, E., N. Kramer, V. Ruiz-Villanueva, D. N. Scott, F. Comiti, A. M. Gurnell, H. Piegay, K. B. Lininger, K. L. Jaeger, D. M. Walters, and K. D. Fausch. 2019. “The Natural Wood Regime in Rivers.” *BioScience*, 69 (4): 259–273. https://doi.org/10.1093/biosci/biz013.

Wohl, E., and D. N. Scott. 2017. “Wood and sediment storage and dynamics in river corridors.” *Earth Surf. Process. Landforms*, 42 (1): 5–23. https://doi.org/10.1002/esp.3909.

Wyss, A., I. Schalko, and V. Weitbrecht. 2021. “Field Study on Wood Accumulation at a Bridge Pier.” *Water*, 13 (18): 2475. https://doi.org/10.3390/w13182475.