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Kathryn A. Margetts
Utah State University, kathryn.margetts@usu.edu

B. M. Crookston
Utah State University

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K.A. Margetts[1] and B.M. Crookston, Ph.D., P.E.[1]
[1]Civil & Environmental Engineering Dept., Utah Water Research Laboratory
Utah State University
Logan UT 84321
UNITED STATES
E-mail: kathryn.margetts@usu.edu

Abstract: *Often, large woody debris (LWD) at hydraulic structures is considered hazardous from a performance and public safety perspective. However, the sustainable management of rivers requires the consideration of ecological impacts of LWD such as cover for aquatics and the natural movement of LWD through a catchment. Therefore, this study explores the interaction of natural (nonuniform) LWD with rock weirs through field observations in the Blacksmith Fork River in Utah, USA and laboratory testing at the Utah Water Research Laboratory. The passage probability of individual LWD at rock weirs is observed and tested in an effort to describe the balance between hydraulic structure performance and river ecology via the natural transport of LWD by the river at rock weirs. Results demonstrate that LWD entrapment is a function of rock weir geometry, hydraulic conditions at the weir, and LWD element length and representative diameter. Orientation of LWD elements approaching the rock weir also contributes to entrapment probability. For lesser flow depths, minor accumulations of LWD at rock weirs do not negatively impact the hydraulic performance as evidenced by the head-discharge rating curve.*

Keywords: *rock weir, large woody debris, natural debris elements, physical modelling.*

1. INTRODUCTION

The natural transport and accumulation of driftwood or large woody debris (LWD) in a river reach is beneficial for watersheds as it helps to maintain or restore natural river functions that promote self-sustaining river ecology and river processes (Aadland, 2010; Reclamation, 2016). As a result, the physical benefits of LWD in streams has been of high interest in the river science community over the past decade (Gurnell *et al*., 1995; Wohl *et al*., 2016, 2019). In fact, manual placement of LWD and engineered woody structures are now common mitigation or restoration strategies used to address habitat loss due to extensive wood removal, channel dredging, etc. (Cramer, 2012; Roni *et al*., 2015; Rosgen, 2001; Wohl *et al*., 2016, 2019).

However, it is not uncommon for streams and rivers to include hydraulic structures for management efforts. It is common for LWD to accumulate at various structure types such as spillway crests (Crookston *et al.*, 2015; Furlan *et al.*, 2018; Pfister *et al.*, 2013), gates (Bénet *et al.*, 2021), bridge piers (Schalko *et al.*, 2020) or culverts (Larinier, 2002). Often, transport of debris is linked to catchment geomorphology, landcover, and hydrology; for example, increased river flows resulting from precipitation events or seasonal cycles (e.g., snow melt). As a result, LWD may be an engineering safety concern as accumulation on a structure may inhibit hydraulic performance, such as performance of a fish ladder, passage of a large storm event through a spillway, or overtopping and failure of a road crossing.

Natural functions associated with LWD accumulation include provision of habitat for aquatic species, particularly cover for fish, increased habitat complexity, and increased nutrient and sediment storage in the watershed (Gurnell *et al.,* 1995, 2002). Juvenile and rearing trout in particular seek cover in pools near boulders and LWD (Andonaegui, 2000). Natural processes also include large-scale fluxes in LWD, via transfer processes of input and output along a stream reach. Although improvement of natural processes is not typically the primary project objective for implementing hydraulic structures such as rock weirs, those weirs where LWD has accumulated have proven to be ecologically beneficial (Andonaegui, 2000; Rosgen, 2001). Rock weirs are intended to mimic nature in design (i.e., grade control structures, diversions, fish passage), and it is becoming a common practice in the USA to design rock weirs to include large, woody elements (Rosgen, 2001; Reclamation, 2016).

Alternatively, structures may cause LWD to accumulate, which can potentially block the entire crest or channel. This poses a risk both hydraulically and ecologically as significant debris blockage can inhibit existing river processes, reduce the hydraulic efficiency of a structure, and for rock weirs, potentially cause structural instability of the stones (Larinier, 2002; USFWS, 2019). The effects of LWD accumulation have been studied for large concrete structures such as spillways (Furlan *et al.,* 2018; Vaughn, 2020; Crookston *et al.,* 2015) and bridge piers (Schmocker & Hager, 2011, 2013; Schalko *et al.,* 2020). However, to the authors' knowledge no studies pertaining to LWD affecting the hydraulic performance of rock weirs has been conducted. Thus, a key remaining research challenge for rock weirs is to assess the relative benefits and potential concerns of LWD accumulation (Wohl *et al.,* 2016) and to provide design guidance that promotes balance between conveyance/hydraulic performance objectives, river morphology, and environmental objectives for more sustainable rock weir designs.

1.1 Rock Weirs

Rock weirs consist of a row of boulders or stones placed in a channel and thus have an uneven crest elevation (Figure 1a). They are built for a variety of purposes such as stream rehabilitation, fish passage, channel alignment or grade control, and improved sediment processes (Rosgen, 2001). These weirs have a variety of geometries (Kupferschmidt & Zhu, 2017) and weirs may be placed in series to form a rock ramp (i.e., block ramp) as a natural passage for fish (Figure 1b). Rosgen (2001) has cataloged a selection of generally accepted methods used in the design of rock weirs. Furthermore, there are multiple USA government-issued design manuals on rock weir and natural fish passage design (e.g., Aadland, 2010; Reclamation, 2016; USFWS, 2019).

Figure 1 – Examples of rock weirs including a) a V-Notch rock weir located in Blacksmith Fork River, Hyrum, Utah, USA (photo courtesy of K. Margetts) and b) a rock ramp acting as a natural fish ladder in Rock Creek, Montana, USA (photo courtesy G. Jordan). https://www.flickr.com/photos/usfwsmtnprairie/8960106516

The design of a rock weir considers hydraulic performance, rock element stability, foundation scour, and sedimentation. Examples of hydraulic studies on individual stone stability and foundation scour include Pagliara and Palermo (2013a,b), which provide improved methods for the design and construction of rock weirs. Guidelines for predicting sedimentation and incipient bedload motion at rock weirs have also been standardized by Reclamation (2016). However, as with many in-stream hydraulic structures, the successful implementation of a rock weir not only requires proper field installation but also requires a detailed understanding of the river reach, river morphology, and corresponding catchment while anticipating future growth and change in the system. This includes river ecology and biological processes supported by the natural transport of woody debris (Gurnell *et al*., 1995; Wohl *et al*., 2016, 2019).

Although literature includes numerous noteworthy studies on large woody debris (LWD) at other in-stream structures (Pfister *et al*., 2013; Ruiz-Villanueva *et al*., 2014; Schalko *et al*., 2020; Schmocker & Hager, 2011, 2013), rock weir design guidance provides limited information regarding passage or blockage probabilities of debris elements and consideration for debris accumulation and corresponding hydraulic effects (e.g., Reclamation, 2016; USFWS, 2019; Aadland, 2010; Rosgen, 2001). Indeed, as with the aforementioned considerations the accumulation of LWD should also be anticipated in design and to achieve sustainability goals, which support natural processes such as the creation of habitat cover and storage of organic material and sediment (Wohl *et al.,* 2019). Overlooking LWD accumulation at rock weirs may result in failure to achieve hydraulic performance goals, unforeseen maintenance such as debris removal or relocating boulders after a storm event, or unsatisfactory river connectivity and channel response. Therefore, there is a clear need to understand first the blockage or passage probabilities for natural debris elements and additionally, the effects of LWD accumulation at rock weirs for appropriate design consideration.

2. RESEARCH METHODS

In this study, investigating the interaction of LWD at rock weirs included two components: field observations along the Blacksmith Fork (BSF) River located in Hyrum, Utah, USA and large-scale laboratory testing at the Utah Water Research Laboratory at Utah State University in Logan, Utah, USA. In the Blacksmith River, field observations provided insights as to construction and behavior of typical rock weirs in a mountainous catchment. In the laboratory, LWD was modeled using non-uniform branches collected at the Logan River and classified by geometries including average element diameter and total length. A model rock weir (see section 2.2) was constructed in a large flume to assess the passage probability of natural woody debris elements. Additional testing will include debris accumulation scenarios, modeled on actual stream debris loadings (Roni *et al.,* 2015).

2.1 Large Woody Debris

LWD has been modeled using both uniform and nonuniform elements. Vaughn (2020) and Schmocker and Hager (2013)) used smooth dowels or sticks to represent trees stripped of branches as transported to and by the river. The focus of this study, however, is on modeling LWD using more complex debris elements with twists, knots, and branches similar to those found in nature and what was observed in the Blacksmith Fork River. This approach expands upon prior studies which have utilized trunks with multiple branches or root wads (trunks with branches at one end) (Bénet *et al.,* 2021; Pfister *et al.,* 2013; Schmocker & Hager, 2011). LWD elements are defined herein as singular trunks with up to one branch (extending >2 cm) along with natural variations (knots, etc.). Branches were sourced locally and divided into size classes based on length and diameter for flume testing (see Table 1 and Figure 2). For example, class D4 represents 100 cm ≤ L ≤ 149 cm and an average element diameter D =4 cm.

Table 1 – Length and Diameter classes with corresponding flow rates tested for individual debris element passage probability.

		Experimental Discharge ***Q***		
Length Class, *L* (cm)		**Diameter Class, *D* (cm)**		
		2	**4**	**6**
B	50-74	20, 30 l/s		
C	75-99	20, 30, 40, 50 l/s	20, 30, 40, 50 l/s	
D	100-149	20, 30, 40, 50 l/s	20, 30, 40, 50 l/s	30, 40, 50 l/s
E	150-169	20, 30, 40, 50 l/s	20, 30, 40, 50 l/s	40, 50 l/s
F	170-185	30, 40, 50 l/s	30, 40, 50 l/s	50 l/s
			40, 50 l/s	50 l/s

Figure 2 – Selection of LWD size classes pictured with a 45.7 cm (18 in.) ruler.

2.2 Laboratory Testing: Passage Probability

The laboratory study was conducted in a large (trapezoidal) flume with a base of 1 m, length of 6 m, and 2H:1V side slopes. Rough-cut flat-topped rocks obtained with permission from the Blacksmith River were placed at the downstream end of the channel to form a cross-vane rock weir (i.e., an I-weir; see Rosgen (2001), Figure 3) with a width of 0.25 m, length of 2.53 m, and height of 0.21 m. Mortar was used to ensure rock stability and eliminate seepage between rocks and between the weir and channel. The top of the rock weir was specifically designed with a nonuniform crest elevation, including several lower areas such as might be seen in typical rock weirs.

Instrumentation in the flume included a piezometer connected to a stilling well and point gage (±0.15 mm) for measurement of water elevation upstream of weir. Total head above the weir (*H*) was calculated from point gage elevation and a survey of the flume bottom (0.0016 m accuracy). Discharge was measured with a magnetic flow meter (±0.25%) calibrated per ASTM standards. Debris characteristic diameters and lengths were measured within ±1 mm.

Passage probability tests were patterned after Vaughn (2020), who studied the probability of individual LWD entrapment at labyrinth weirs. Testing was carried out by introducing individual woody debris elements approximately 3 meters upstream of the laboratory rock weir at discharges of: 20 l/s, 30 l/s, 40 l/s, and 50 l/s (see Table 1). Passing probabilities Π were recorded along with individual element characteristics, approach orientation of the woody element to the rock weir (stream-wise or channel-spanning) and the element location in the channel (center, right, left looking downstream). Passage probability tests for each size class of LWD were repeated at least 30 times to ensure 90% confidence passage probability (Furlan *et al.,* 2018).

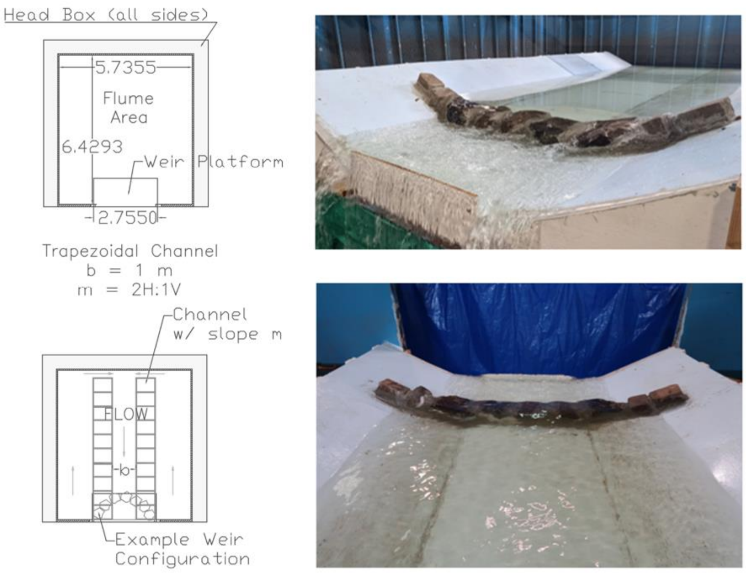

Figure 3 – Flume plans (lengths in m) and laboratory setup with flows of 30 L/s (top right) and 50 L/s (bottom right), photos courtesy K. Margetts.

3. RESULTS

Passing probability Π tests were conducted at four flow rates, *Q* (see Table 1). Each class of LWD was categorized by *L* and *D*, and initial results show that these dimensions are the most influential in determining element passage or entrapment at the rock weir. Despite LWD orientation or the presence of some small branching, the overall controlling factors for entrapment remained the characteristic *L* and *D* of the given element. In general, passage probabilty, the inverse of entrapment probability, increased with flow rate, particularly as class size decreased.

This is evident in results of passing probability as a function of the dimensionless diameter-to-total head ratio (*D/H*) and dimensionless length-to-total head ratio (*L/H*) shown in Figure 4b. Of these parameters, *D/H* appears to play a slightly larger role than *L/H* in passage probability, as evidenced by a slightly steeper downward trend in passing probability (Figure 4a). Note that the variability in Π is in part due to the twists, knots, and branches of the elements and the irregular surface of the rock weir. Another controlling factor in the variability of Π is the flow rate Q. As Q increases, the probability LWD will pass also increases. Higher flow rates (40, 50 L/s) and corresponding greater flow depths have more ability to pass debris than lower flow rates (20,30 L/s), particularly for the more natural debris shapes. As shown in Figure 4, higher discharges also have a greater Π to pass the same size of debris.

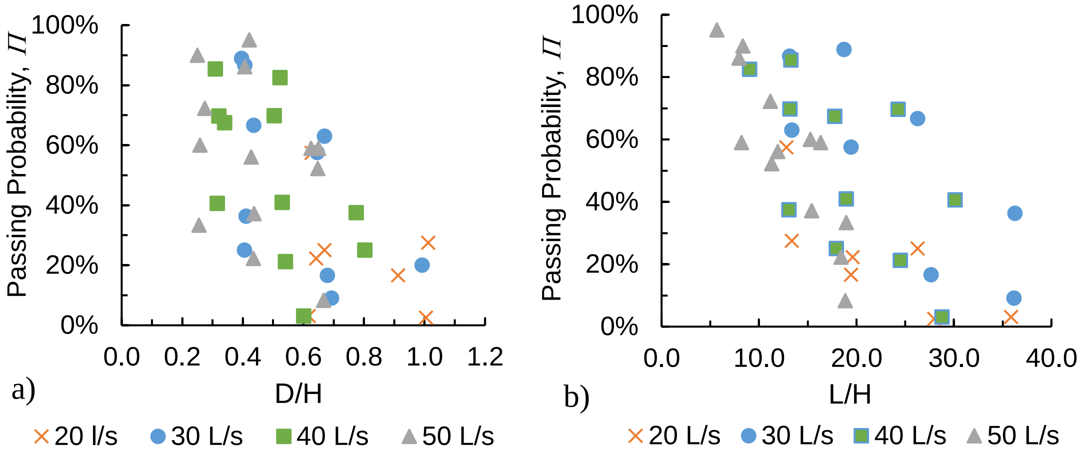

Figure 4 – Passing Probability versus (a) *D/H*) and (b) *L/H* at *Q*= 20 L/s, 30 L/s, 40 L/s, and 50 L/s.

Laboratory tests also showed evidence that LWD elements aligned perpendicular to the channel (channel-spanning) were slightly more likely to become entrapped than those oriented parallel to the channel (stream-wise). The probability of LWD entrapment was higher for channel-spanning elements than for streamwise LWD that approached the weir.

4. FIELD OBSERVATIONS: BLACKSMITH FORK RIVER

Field observations also indicated the likelihood of LWD entrapment at rock weirs. Rock weirs in the Blacksmith Fork River (BSF River) were investigated regarding general conditions between date of installation or construction and current conditions, with a focus on LWD accumulation. The rock weirs shown in Figure 1a are a v-shaped rock weir and are part of a series of 14 rock weirs implemented along a 2 km reach of the BSF River in 2013 to aid in flood protection (NRCS, 2013). Construction of the weirs included significant dredging and removal of sediments in this river reach (personal communication B. Neilson, Nov. 3, 2020). By 2017, the river's response had compromised the majority of the rock weirs, which had become filled with sediment, single rock toppling, etc. Figure 5 shows how the channel meandered to the north (right if looking downstream) and scoured the rock weir abutment or channel tie-in. It is unsurprising to see the large sediment deposit on the left bank.

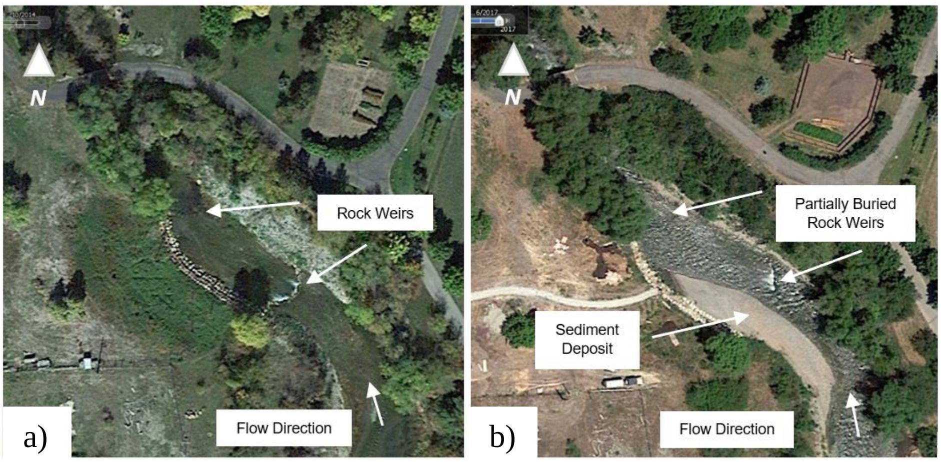

Figure 5 – Blacksmith Fork River Rock Weirs in (a) 2014 and (b) 2017 (Google, n.d.).

During field observations conducted on November 3, 2020, researchers observed current conditions at 7 V-notch rock weirs in the BSF River. At the time of observation, USGS stream gage 10113500 (9 km upstream of the weirs) gave a discharge of 2100 l/s (USGS, 2020). The active channel was 9 to 15 m in width and approximately 0.5 to 1 m in depth with some deeper pools.

It was observed that areas of sedimentation at several weirs had become heavily vegetated with riparian grasses and small shrubs. Weirs located farther downstream displayed toppled or mis-aligned rocks, likely due to insufficient stone foundation preparation (stones not well seated for seasonal flow fluctuations), excessive loading from sedimentation, and/or the passage of woody debris through the channel. Two of the observed weirs had accumulated a very small amount of woody debris (<25% m^3 LWD/m^2 channel area).

Additional field observations were carried out on October 29, 2021 under similar conditions. Figure 6 shows accumulations of LWD at a rock weir, which was entirely buried with non-cohesive gravels and sands on the left portion. LWD covered approximately 25% of the weir, oriented both parallel and perpendicular to the weir.

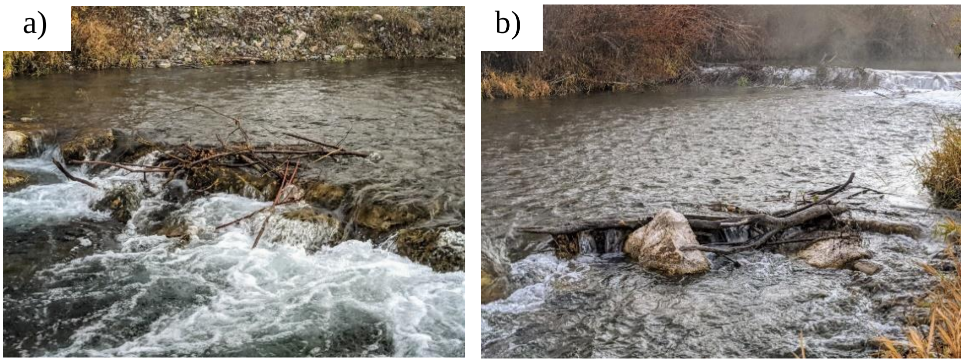

Figure 6 – Stream-wise and channel-spanning LWD entrapped at a BSF River rock weir October 29, 2021 (photo courtesy of K. Margetts).

It was concluded that sediment buildup at the BSF rock weirs led to a decrease in channel slope, altering river morphology. Such changes in river morphology and corresponding habitat may have undesirable ecological impacts such as temperature changes, higher flow velocities, insufficient flow depths, etc. In contrast, the presence of small LWD accumulations caught at the rock weirs provided some cover (Figure 5). Based on the amount of LWD observed, it is unlikely that LWD accumulation was the primary cause of a structural failure to the weirs (i.e., stone displacement).

Although this study does not focus on rock weirs and sedimentation, field observations indicate that the river in only 2 years had a significant response to the weirs in terms of sedimentation. It is unknown if this response was intended, but likely the design of the rock weirs and dredging the river of gravels and sands did not sufficiently consider river morphology and annual bedload cycles and sediment sources in the BSF upstream of the rock weirs. It is also unknown if any future maintenance will be performed on the rock weirs.

5. CONCLUSION

Healthy incorporation of large woody debris (LWD) at rock weirs includes understanding the balance between hydraulic and ecologic performances necessary for a sustainable river system. Field observations and laboratory testing provided useful insights on the interaction of LWD with straight and v-shaped rock weirs.

V-shaped rock weirs observed at the BSF River demonstrated the potential negative impacts of a rock weir channel stabilization project. Heavy sedimentation and toppled rocks due to high flows resulted in poor performance of the weirs. Ecologically, the river response and change in habitat raise concerns for local aquatics including trout. The BSF River is an example of how the objectives of channel stabilization projects do not always align with habitat improvement (Ball *et al.,* 2007) and the challenges of considering river morphology and catchment hydrology in the design of rock weirs.

Although the BSF rock weirs were not functioning properly, LWD accumulations were representative of the likelihood for organic material to become caught at this type of in-stream structure. LWD trapped at the rock weirs provided a minimal amount of cover and organic matter to the channel, while not appearing to disrupt the structure or hydraulics of the weir.

Laboratory testing provided further evidence of the potential for LWD to become entrapped at rock weirs. Element length *L* and diameter *D* were the most significant factors in the probability of LWD passage. The *D/H* ratio had more of an impact on passage probability than the length-head ratio. LWD elements aligned perpendicular to the channel were slightly more likely to become entrapped at the rock weir than those oriented streamwise (parallel).

Due to the potential for LWD to become entrapped at rock weirs, further testing of entrapment probability is necessary for identifying the hydraulic thresholds that balance LWD conveyance objectives with natural benefits. Data collected on the impacts of LWD passage, entrapment and accumulation will help improve future design of rock weirs. Data from the physical model may be used in future research or CFD modeling of rock weirs. Rock weirs may be the perfect in-stream structure for accumulating LWD in moderate, environmentally beneficial amounts while not putting critical infrastructure at risk.

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