Evaluating fish passage effectiveness through a sequence of modified vortex rock weirs

Josie Mielhausen[1], Jaclyn Cockburn[1], Paul Villard[2], and André-Marcel Baril[2]

[1]University of Guelph
[2]Stantec Toronto

May 20, 2022

Abstract

Vortex rock weirs (VRW) are often used in natural channel design applications to maintain channel form and function, provide physical channel stability, and contribute to habitat enhancement. A balanced approach is required to achieve conflicting goals of VRWs, which include providing erosion protection while allowing fish passage under various water level conditions. This research evaluated a sequence of asymmetrical rock weirs with 3-dimensional flow. Field assessments completed between June and September 2018 monitored water level, water temperature, and surveyed channel features at 10 rock weirs and 11 adjacent pools under different water level conditions. The structural dimensions and local velocity at each rock weir were compared to the swimming characteristics of local fish species to determine fish 'passability' and suggest best practices for rock weir design and construction. Results concluded fish passage occurs through gap and over-weir flow pathways and was most effective under low water level conditions. Further, appropriate design considerations based on rock weir gradient, rock weir width, keystone size, and pool length contributed to 100% fish passage effectiveness under all water level conditions. To address conflicting goals and the impact on fish passage for small-bodied fish species, methodology is provided for predicting local velocity and fish passage effectiveness through rock weir systems, inform best practices for rock weir design and construction while balancing the requirements for channel stability and fish passage, and contribute to fish population management strategies.

Evaluating fish passage effectiveness through a sequence of modified vortex rock weirs

Authors

Josie Mielhausen[1, 2]

Jaclyn Cockburn*[1]

Paul Villard[3]

André-Marcel Baril[3. 4]

[1]Department of Geography, Environment & Geomatics, University of Guelph, Guelph ON, Canada

[2]Present address: GeoProcess Research Associates, Ottawa ON, Canada

[3]GEO Morphix Ltd, Campbellville ON, Canada

[4]Present address: Minnow Aquatic Environmental Services, Toronto ON, Canada

*Corresponding author: Jaclyn Cockburn (email) jaclyn.cockburn@uoguelph.ca, (phone) 1-519-824-4120 ext 53498, (fax) 1-519-837-2940

Significance Statement

This field study evaluated fish passage through a series of vortex rock weirs that were built to address channel migration and erosion alongside a road. The fish that use this channel are relatively small minnows and need the water moving over and through the rock weirs to be slow enough that they can swim through or situated such that they can leap over the rock weirs. The significant findings from this study show that key design stage elements (e.g., material size, material placement) ensured fish passage was possible under low, intermediate and higher water levels throughout the study period.

Acknowledgements

University of Guelph for graduate research funding to JM, Canadian Foundation for Innovation (JC, #31341) for infrastructure funding that supported this research. GEO Morphix Ltd. provided resources for field data collection and analysis. The Regional Municipality of York and Gerard Sullivan for providing access to Weslie Creek, background materials, and support for this research.

Abstract

Vortex rock weirs (VRW) are often used in natural channel design applications to maintain channel form and function, provide physical channel stability, and contribute to habitat enhancement. A balanced approach is required to achieve conflicting goals of VRWs, which include providing erosion protection while allowing fish passage under various water level conditions. This research evaluated a sequence of asymmetrical rock weirs with 3-dimensional flow. Field assessments completed between June and September 2018 monitored water level, water temperature, and surveyed channel features at 10 rock weirs and 11 adjacent pools under different water level conditions. The structural dimensions and local velocity at each rock weir were compared to the swimming characteristics of local fish species to determine fish 'passability' and suggest best practices for rock weir design and construction. Results concluded fish passage occurs through gap and over-weir flow pathways and was most effective under low water level conditions. Further, appropriate design considerations based on rock weir gradient, rock weir width, keystone size, and pool length contributed to 100% fish passage effectiveness under all water level conditions. To address conflicting goals and the impact on fish passage for small-bodied fish species, methodology is provided for predicting local velocity and fish passage effectiveness through rock weir systems, inform best practices for rock weir design and construction while balancing the requirements for channel stability and fish passage, and contribute to fish population management strategies.

Keywords

River restoration, fish passage, vortex rock weir, ecohydrology

Introduction

Surrounding land use heavily influences river systems (Hawley et al., 2013; Navratil et al., 2013; Vietz et al., 2014). Specifically, pressures from urban development contribute to changes in water and sediment delivery. This effectively alters the flow mechanics and sediment dynamics of river systems. To maintain fluvial geomorphological connectivity and aquatic ecological function (i.e., fish passage) in ecosystems impacted by urban development, river restoration is required (Ward and Standford, 1995; Clarke et al., 2003; and Jasson et al., 2007). River restoration practices, including in-stream vortex rock weir (VRW) construction, are implemented as a design component to maintain overall channel form and function (Gilvear, 1999; Clarke et al., 2003; Klingeman et al., 2004). Rock weirs are increasingly preferred because they provide physical channel stability, habitat enhancement, and the hydromechanics to allow upstream fish passage for local fish species (Corwin et al., 2007). Rock weirs have conflicting goals, where they are installed as a high flow feature to maintain channel stability but provide conditions for low flow processes such as fish passage (Thomas et al., 2000).

Rock weirs vary in gradient, structure, and geometry, and are uniquely tailored to site-specific conditions depending on the local channel morphology, hydrologic regime, and target fish communities. Many studies evaluate fish passage effectiveness through conventional fishways (Bice et al., 2017; Romao et al., 2018; Zhang and Chanson, 2018), however, few experiments consider the irregularity of natural materials and the unique design of rock weirs for fish passage effectiveness (Dodd et al., 2017). Further, many conventional fishways are designed for large-bodied fish species on large-scale river systems, and as such, few studies evaluate fish passage effectiveness for small-bodied fish species on small-scale systems. According to Hatry et al. (2013), only 9% of all documented fishways in Canada (211) are evaluated using appropriate methods to understand geomorphological and ecological effectiveness. It is important to note that of the 211 documented fishways in Canada, most are applied on large-scale systems and target large-bodied fish species.

The purpose of this research was to evaluate the effectiveness of rock weirs for small-bodied fish passage in Weslie Creek. Field assessment was completed under varying water level conditions to observe rock weir structural geometry and flow. Rock weir structural geometry and flow characteristics were applied to identify fish passage effectiveness based on providing appropriate velocities through gap and over-weir flow pathways. The structural dimensions of the rock weirs were assessed to understand how design and construction influences fish passability and opportunities for fish refuge. Determining the critical design and construction components to facilitate fish passage through rock weirs, while also ensuring channel stability, will inform future river restoration works. This work will also provide recommendations for balancing opposing goals, such as fish passage and channel stability on a small-scale, in natural channel design.

Study Site

The research was conducted at Weslie Creek, one of four major tributaries of the East Holland River, located in Aurora, Ontario, Canada. The East Holland River subwatershed (247 km^2) originates on the north slope of the Oak Ridges Moraine and extends to the confluence with the West Holland River and Lake Simcoe's Cook's Bay. Surficial geology is characterized by glaciolacustrine deposits, and soils dominated by silt and clay-sized material (LSRCA, 2010). The average annual temperature is approximately 6°C, and the average annual precipitation is approximately 815 mm (LSRCA, 2010). Peak discharge events are associated with snowmelt and spring rainfall, which typically occur from March-April and April-May, respectively. According to the Ontario Flow Assessment Tool (OFAT), mean annual flow for the 9.5 km^2 drainage basin including the Weslie Creek reach is 0.09 m^3/s.

Following realignment to accommodate road improvements in support of a dam removal upstream, Weslie Creek was restored using natural channel design practices. A sequence of rock weirs was installed downstream of the decommissioned dam site to enhance channel and bank stability and facilitate fish passage for local species. The rock weirs are designed with various keystones and keystone sizes allowing 3-dimensional flow. Additionally, the rock weirs are asymmetrical, with alternating high and low points to enhance longitudinal connectivity through the system.

Methods

In spring 2018, 10 rock weirs and 11 adjacent pool features were established as cross-sections for monitoring at Weslie Creek. Using real-time kinematic (RTK) GPS, a topographical survey was completed through the reach, at each cross-section, and at each rock weir keystone. Reach profile and cross-section elevation data were collected by taking bed and water surface elevation points with the RTK GPS every 20 cm systematically. The rock weir keystone elevation data were collected by taking elevation points with the RTK GPS on the surface of the keystone and around the exposed circumference. RTK GPS produced elevation data accurate to +/- 0.02 m. From the topographical survey, channel and rock weir geometries, and bed and water level elevation differences were determined.

Physical habitat conditions, including water depth and water temperature, were monitored continuously throughout the field season using Onset HOBO pressure transducers. One sensor was installed in a stilling well at pool 7, and another on the adjacent right bank to collect atmospheric pressure data, once per hour. The data were retrieved from each sensor every two weeks to ensure data quality and assess equipment productivity, particularly following large rainfall events. Wolman (1954) pebble counts were completed (measuring 20 pebbles at each pool feature) and monumented photographs were taken on a bi-weekly basis to identify bed substrate composition at each pool, and record changes at each pool during the field season.

Velocity measurements were collected using a three-dimensional acoustic Doppler velocimeter (ADV) (+/- 0.01 m/s). At each pool, the ADV was positioned in the flow at 60% depth. Velocity measurements were collected every 10 cm from left bank to right bank (Newson and Newson, 2000; Carollo et al., 2002). At each rock weir, velocity measurements were collected at active gap and/or over-weir flow pathways. Under intermediate and high-water level conditions, where the gap and/or over-weir flow pathways were larger in width, multiple velocity measurements were collected across the pathway, and an average "cross-section" velocity was identified for the associated pathway.

To evaluate fish passage effectiveness through the rock weirs, the swimming characteristics of local fish species were compared to the velocities through rock weir gap and over-weir flow pathways. The target fish species were identified by reviewing local conservation authority watershed and sub-watershed reports, and the swimming characteristics for each fish species were identified by reviewing relevant literature.

Results

Water level ranged from 0.27 m to 0.61 m during the field season (Figure 1). Minimum water level was recorded on June 23, 2018, and the maximum water level was recorded on November 3, 2018. Three general water level conditions (low, intermediate, and high) were identified over the field season based on time of assessment. Average daily water temperature ranged from -0.1°C to 23.5°C (Figure 1). Minimum water temperature was recorded on November 14, 2018, and the maximum water temperature was recorded on July 1, 2018. During field visits, several small fish species were observed in the pools and moving upstream through the rock weir features. These species were identified as Blacknose Dace (*Rhinichthys atralutus*), Creek Chub (*Semotilus atroma-culatus*), and Mottled Sculpin (*Cottus bairdi*).

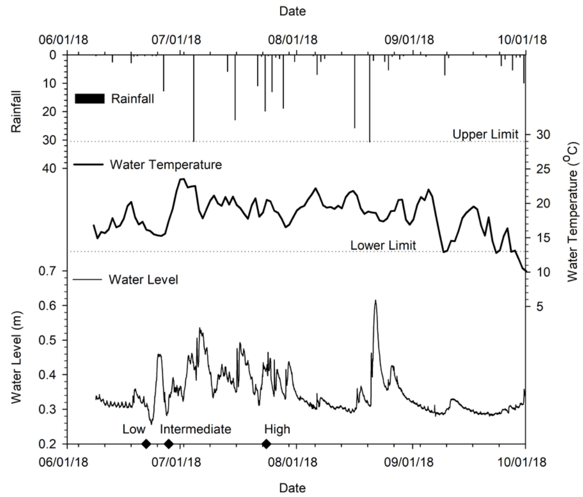

Figure 1. Daily rainfall, daily water temperature, and hourly water level along the study reach. Upper and lower temperature limits for fish species local to Weslie Creek are labeled on the water temperature graph (LSRCA, 2000; Eakins, 2018). Field assessment days are shown with diamonds along the lower x-axis.

The channel profile has a slope of 0.02 (2%) and the low flow channel had a sinuosity of 1.32 (Figure 2). All cross-sections were identified as asymmetrical, with varying channel bank slopes and different keystone shapes and sizes (Figure 2). Further, rock weir asymmetry alternates between cross-sections (Figure 2). Bed substrate distribution curves were developed for each pool feature to reflect the Wolman (1954) pebble count results for the six sampling days throughout the field season. The results of each bed substrate sampling day were merged and organized by pool feature to identify changes in bed substrate composition through the field season. Given the similarity in the bed substrate distribution curves for June 22, 2018, June 28, 2018, July 13, 2018, July 25, 2018, August 14, 2018, and September 7, 2018, it was determined that bed substrate composition did not change during this field season.

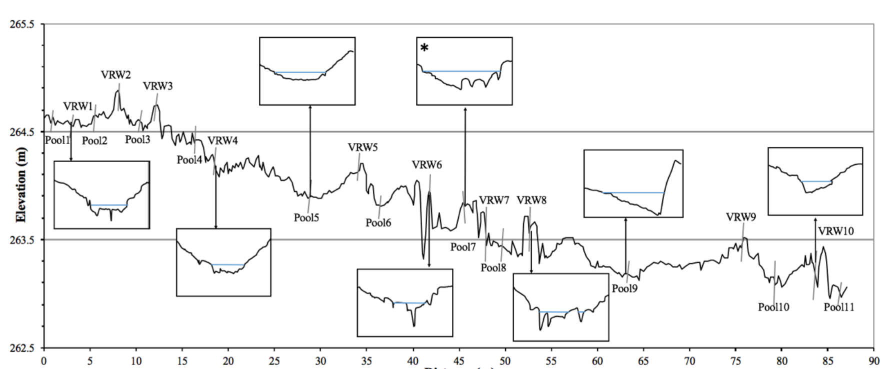

Figure 2. Reach profile from upstream (left) to downstream (right) with representative pool (above profile) and rock weir (below profile) cross-sections. The asterisk in the Pool 7 cross-section indicates the stilling welling location. Vertical exaggeration is 0.08 m.

Over 530 velocity measurements were collected to identify a range of velocities at each pool feature. Collectively, under all water level conditions, the cross-section velocity in pool features ranged from -0.14 m/s to 0.83 m/s. Recirculation zones were located near the channel banks in 6/11, 7/11, and 10/11 pool features under low, intermediate, and high-water levels, respectively. Recirculation zones are recognized as locations where the velocity measurement is a negative value, indicating flow moving in an upstream direction (Kimura and Hosoda, 1997).

Over 70 velocity measurements were collected in gap and over-weir flow pathways to identify flow through rock weir structures under different water level conditions. Velocities in gap pathways ranged from -0.14 m/s to 1.10 m/s. Additionally, velocities in over-weir pathways ranged from 0.10 m/s to 0.18 m/s. Depending on the water level condition (low, intermediate, high), the ratio of gap to over-weir flow pathways, and the total number of flow pathways differs. Under low water level conditions, there were a greater number of gap flow pathways. As water level increases to intermediate water level conditions, individual gap flow pathways merge to form one large gap, and/or over-weir flow pathways begin to form. Further, as water level increases to high water level conditions, the number of gap flow pathways minimizes, while flow over the keystones (over-weir flow) becomes more common. The ratio of gap to over-weir flow pathways was 17:1, 18:5, and 11:10 under low, intermediate, and high-water level conditions, respectively.

Swimming characteristics for local fish species within Weslie Creek were identified. The local fish community was comprised of small-bodied fish species with specific swim speeds, which were considered in the VRW design. A comparison between velocity through pool features, rock weirs, and burst swim speeds (m/s) was completed to identify where fish passage opportunities exist or do not exist under different water level conditions. Additionally, the preferred water temperature range for all local fish species was compared to the measured water temperature collected at pool 7 to estimate habitat suitability in pool features. Finally, the vertical distance between weir crest and the downstream pool at each rock weir was measured to determine if upstream movement is possible through leaping under both suitable and unsuitable flow conditions.

Based on fish passability, reach longitudinal connectivity was analyzed under low, intermediate, and high-water level conditions (Figure 3). Under low water level conditions (June 22, 2018), 100% fish passability (passable for all fish species) was achieved through all pool features and through 9/10 rock weirs (Figure 3 - Low). Under low water level conditions, there is no gap or over-weir flow through VRW2, which restricts fish passage (Figure 3 - Low). Under intermediate water level conditions (June 28, 2018), 100% fish passability was achieved through all pool features and through 6/10 rock weirs (Figure 3 - Intermediate). Under intermediate water level conditions, gap and over-weir flow at VRW2, VRW3, VRW6, and VRW10 exceeded burst swim speeds of one or more local fish species. However, 1 to 3 pathways were available for faster swimming species through these weirs (Figure 3 - Intermediate). Under high water level conditions (July 25, 2018), 100% fish passability was achieved through all pool features, and through 6/10 rock weirs (Figure 3 - High). Under high water level conditions, gap and over-weir flow at VRW1, VRW2, VRW3, and VRW9 exceeds burst swim speeds of one or more local fish species. However, 1 to 2 pathways were available for faster swimming species through these weirs (Figure 3 - High). It is important to note that velocity measurements were collected at 60% water depth, which provides an average velocity for the pathway. Fish are more likely to pass through the pathway near the channel bed where velocities are lowest. As such, these velocity values are conservative to inform fish passage effectiveness. Depending on the water level and rock weir design, different flow pathways are available for fish passage. At VRW2, under low water level conditions, the only possible flow pathways were through orifices. This is true for other low gradient rock weirs (Figure 4a). Further, at a high gradient rock weir (Figure 4b), the vertical distance between upstream water level and weir crest is minimal, and therefore connectivity is maintained between upstream and downstream flows. Figure 4b demonstrates that at a high gradient rock weir, it is likely that orifice, gap, and over-weir flow pathways are active. An analysis was conducted to determine if weir gradient at Weslie Creek influenced fish passability through the reach under different water level conditions (Table 1).

Table 1. Total fish passability based on rock weir gradient.

Weir	Gradient	% Passability Low Water Level	% Passability Intermediate Water Level	% Passability High Water Le
1	-0.01	100	100	100 for </= 4 species
2	-0.02	0*	100 for </= 4 species	100 for </= 4 species
3	-0.02	100	100 for </= 4 species	100 for </= 4 species
4	-0.05	100	100 for </= 4 species	100
5	-0.10	100	100	100
6	-0.08	100	for </= 4 species	100
7	-0.14	100	100	100
8	-0.09	100	100	100
9	-0.05	100	100	100 for </= 4 species
10	-0.06	100	100 for </= 4 species	100

* Fish passage opportunities exist through leaping or orifice flow pathways, based on the presence of fish species upstream.

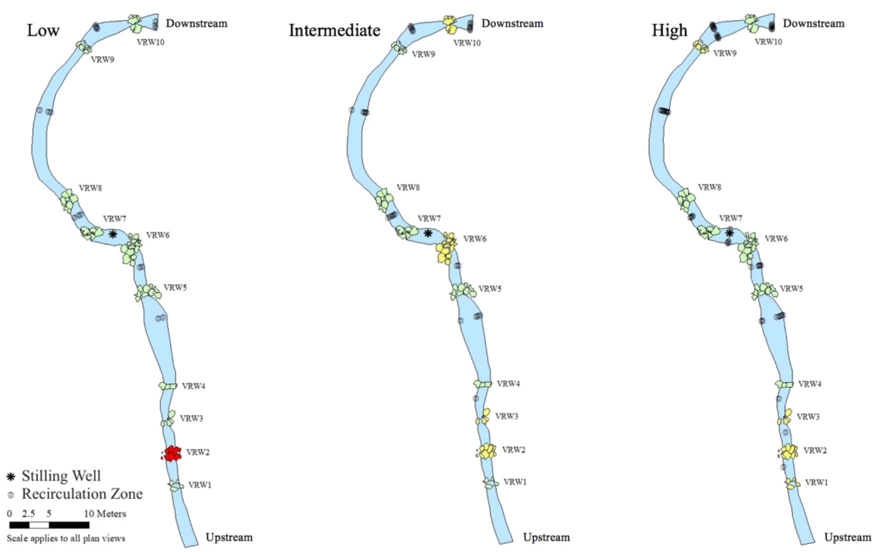

Figure 3. Fish passability in low (a), intermediate (b), and high (c) water level conditions. Rock weirs that provide 100% fish passability are represented by green keystones, rock weirs that provide fish passage for 4 or fewer fish species are represented by yellow keystones, and rock weirs that do not provide gap or over-weir flow pathways are represented by red keystones. Note that red keystones allow orifice flow and leaping opportunities for fish passage. Further, recirculation zones indicate potential locations for fish refuge during unsuitable swimming conditions.

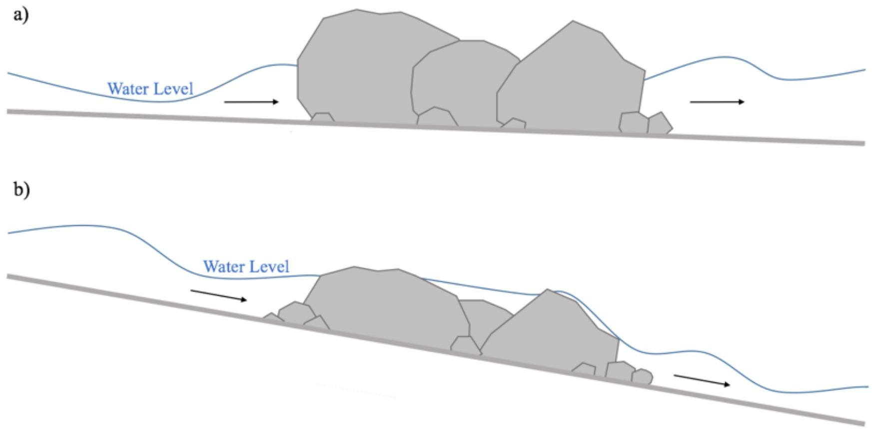

Figure 4. Profile schematics of a low gradient rock weir (a) and high gradient rock weir (b). The difference in gradient depicts how embeddedness changes depending on how gentle or steep the channel bed is. A greater level of embeddedness provides upstream and downstream connectivity without obstructions to the flow path (b).

Depending on water level condition and gradient, rock weir keystones are either exposed or experience 'drowned conditions'. Under low water level conditions, low gradient rock weir keystones are exposed, where the keystone surfaces are above water level, and water moves downstream through orifice flow pathways. Under intermediate water level conditions, low gradient rock weir keystones begin experiencing 'drowned conditions', where approximately 50% of the keystone surfaces are submerged, and water moves downstream through orifice and gap flow pathways. Under high water level conditions, low gradient rock weir keystones experience fully 'drowned conditions', where keystone surfaces are submerged, and water moves downstream through orifice, gap, and over-weir flow pathways. Particularly in locations where low water level conditions are dominant (i.e., Weslie Creek), low gradient rock weirs may impede fish passage by limiting gap and over-weir flow pathways for upstream movement. High gradient rock weirs, and the connectivity between upstream and downstream flow that is already established (Figure 4a), experience more 'drowned conditions' than exposed conditions, and therefore, provide greater opportunities for local fish species to maneuver through gap and over-weir flow pathways.

When velocities for upstream or downstream movement are not favourable, habitat conditions within the pool features need to serve as refuge with respect to flow velocities and thermal conditions. The range of preferred water temperatures for all local fish species was identified and compared to the average daily water temperature collected in Weslie Creek. The average daily water temperature was consistently within the preferred water temperature range for local fish species from June 6, 2018 until September 24, 2018. The water level logger was placed in pool 7 (Figure 2), which is deeper than the other pool features within the reach, thus it is important to note that the water temperature is likely cooler than in other, more shallow pools (i.e., Pool 5 – Figure 2).

To assess pool features in terms of both fish passability and suitability to serve as refuge with respect to flow velocities, the length of each pool feature in Weslie Creek was identified and compared to downstream fish passage effectiveness and the number of refuge opportunities available at the sampling cross-sections, respectively (Table 2). These results indicate that longer pool features facilitate increased fish passability downstream, and 10/11 pool features in Weslie Creek provide opportunities for fish habitat and/or refuge under all water level conditions.

Table 2. Pool length influences fish passability through the downstream VRW and available locations for fish refuge.

Pool #	Length (m)	Pool Depth (m) *	Total # Locations for Fish Refuge Under all Water Level Conditions
1	7.40	0.14	0
2	2.30	0.10	1
3	2.40	0.11	1
4	3.60	0.11	1
5	11.20	0.17	34
6	3.90	0.13	15
7	3.80	0.20	5
8	2.50	0.16	20
9	20.70	0.25	23
10	5.90	0.20	26
11	2.40	0.25	19

* Measured in the thalweg during low water level conditions to provide a conservative value for fish habitat suitability.

Another easily identifiable rock weir dimension related to fish passage is the ratio of rock weir size to channel width. The width of a channel, and subsequently the width of a constructed rock weir, influences the number and size of keystones used. For example, a larger cross-section requires more keystones, footer stones, and river stones to construct the rock weir between channel banks. Fish passability under different water level conditions was examined as a function of rock weir width to determine if this design consideration can inform fish passage effectiveness (Table 3).

Table 3. Total fish passability based on rock weir width, number of keystones, and sizes of keystones.

Weir	Weir Crest Width (m)	# of keystones	Range of Keystone Sizes (m)	% Fish Passability (Low Water Level)	%
1	1.9	5	0.2 – 0.8	100	1
2	3.1	8	0.4 – 1.1	0*	1
3	2.2	4	0.6 – 0.8	100	1
4	2.4	3	0.6 – 1.3	100	1
5	3.6	9	0.5 – 1.0	100	1
6	3.5	9	0.6 – 1.1	100	1
7	3.3	8	0.2 – 1.1	100	1
8	3.5	9	0.2 – 1.3	100	1
9	2.7	6	0.3 – 0.7	100	1
10	2.5	7	0.2 – 1.0	100	1

* Fish passage opportunities through leaping or orifice flow pathways, based on the presence of fish species.

Discussion

Critical Design Components for Effective Fish Passage

Critical design components for effective fish passage include channel gradient, keystone characteristics, and weir geometry. In nature-like fishways features are used to ensure three-dimensional circulation (downstream, across the stream, and within the water column). This is achieved by their asymmetrical position using various keystone shapes and sizes. The asymmetrical nature of the rock weirs assessed introduces a secondary gradient and sinuosity through the cross-section, and maintains channel stability under different water level conditions (Figure 2). An asymmetrical rock weir design enhances fish passage effectiveness by activating gap, and over-weir flow pathways – either independently or simultaneously – depending on the water level condition (Figure 3). One of the main objectives of rock weirs is to reduce overall channel gradient in restored systems (Williams et al., 2012). In creating smaller drops to reduce channel slope, a secondary gradient is introduced at each rock weir structure, which is an important design consideration for fish passage. Where gradient is gentle, keystones appear to protrude from the channel bed, and where gradient is steeper, keystones appear more embedded within the channel bed (Figure 4). Furthermore, protruding keystones obstruct connectivity between upstream and downstream flows. For example, at a low gradient rock weir (Figure 4), the vertical distance between water level and weir crest is large enough to reduce connectivity between upstream and downstream flows.

The three rock weirs that allow 100% fish passability under all water level conditions were associated with the highest rock weir gradient levels through the reach (-0.086 – -0.144; Figure 3). A higher rock weir gradient decreases the vertical distance between upstream water level and weir crest, enhances keystone embeddedness, provides adequate gap and over-weir flow pathways for movement, and ultimately maintains longitudinal connectivity through the restored system. Although steep slopes are considered a flaw in conventional fishway designs (Katopodis and Williams, 2012; Williams et al., 2012), nature-like fishways provide a naturally gradual slope through the reach (Roscoe and Hinch, 2010), and as such, higher secondary gradients at the rock weirs are acceptable. Additionally, the gradient of each rock weir structure within a restored reach is easily identifiable and is appropriate for use as a method to preliminarily monitor fish passability without conducting extensive in-field data collection.

Keystone Characteristics

All rock weirs that provided 100% fish passability have a weir crest width greater than 3.0 m (Table 3). Further, all rock weirs that allow 100% fish passability have a greater than average number of keystones, and range of keystone sizes (Table 3). The 100% fish passage effectiveness is likely attributed to the number of flow pathways that are available given a greater number of keystones, as well as a range of keystone sizes, to fill the cross-section. Rock weir throat width is a parameter used to inform failure rates for in-stream structures, with results suggesting that the larger the rock weir throat width, the less common failure is (Varyu et al., 2009). However, studies evaluating the relationship between rock weir throat width (or crest width for modified rock weir designs) and fish passage are not available. Further research is required to identify a robust relationship between rock weir width and fish passage effectiveness. It is important to note that rock weir keystones are selected based on hydraulic sizing to withstand high flow events through a reach (Thomas et al., 2000). Additionally, a factor of safety is applied to ensure conservative keystone sizing. Large keystones are used for channel stability, which reduces the required number of keystones in a rock weir structure, and further reduces potential pathways for fish passage. Based on this research, and to address the conflicting goals between channel stability and fish passage in river restoration, it is recommended that keystones be sized to enhance gap flow pathways for fish passage, but not undermine channel stability, particularly during high flow events. This design consideration can be incorporated to ensure resilience, fish passability for the local fish community, and complete qualitative monitoring of fish passage effectiveness following construction.

Embeddedness

As previously mentioned, the rock weirs in Weslie Creek are asymmetrical (Figure 2) which provides a secondary gradient for fish passage to enhance longitudinal connectivity depending on water level. However, the rock weir that restricts gap and over-weir flow under low water level conditions (VRW2) (Figure 3) has a low gradient, and is less embedded near the weir crest than other rock weir structures (Table 1). As such, the keystones protrude further out of the channel bed, reducing longitudinal connectivity (Figure 4). This effectively decreases the opportunity for upstream water to pass through gap or over-weir flow pathways. Rather, the water moves as orifice flow and enters the downstream pool through available gaps beneath the keystones. According to Keller et al. (2012) many rock weir designs require 'drowned conditions' to facilitate fish passage. This idea is consistent with necessary conditions to enhance fish passage effectiveness at VRW2, where opportunities for gap and over-weir flow pathways are only available under intermediate and high-water level conditions ('drowned conditions') (Figure 5). Depending on water level characteristics at the rock weir system, design considerations should be applied to construct rock weirs with a high degree of embeddedness, or opportunities for 'drowned conditions' to enhance fish passage. For example, Weslie Creek experiences low water level conditions for the majority of the field season and as such, rock weirs should be constructed with a high degree of embeddedness for maintaining longitudinal connectivity. However, in systems characterized by high water level conditions, constructing rock weirs that can experience 'drowned conditions' is likely more important than embeddedness. As such, if 'drowned conditions' are more common in these systems, longitudinal connectivity and fish passage effectiveness would increase through the reach. It terms of embeddedness, it is important that the material size used for constructing rock weirs is large enough to maintain structure stability and resilience to failure, but small enough to remain embedded. These dimensions are based on site-specific characteristics, as well as requirements for the target fish community, to ensure passage is possible at critical times (i.e., spawning periods).

Figure 5. Looking upstream at VRW2 (a low gradient rock weir) under low (top photo), intermediate (middle photo), and high (bottom photo) water level conditions. It is evident that orifice flow is the only active flow regime under low water level conditions, while orifice, gap, and over-weir flow are active simultaneously

under intermediate and high-water level conditions. VRW2 under low water level conditions demonstrates the importance of embeddedness for enhancing fish passage effectiveness, while VRW2 under high water level conditions demonstrates the effect of 'drowned conditions'.

Orifices

Orifices are challenging to survey in the field post-construction, and were assumed to be minor with regards to facilitating fish passage in the present study. In various river restoration projects, impermeable geotextile layers are installed at the stream bed and upstream of the weir crest to prevent orifice flow. However, this was not the case in Weslie Creek, where geotextile layers were not used in the rock weir design. Rather, smaller keystones and river stones were used to control flow. Although the design concepts for Weslie Creek indicate that keystones and footer stones are compacted with a mixture of 90 mm – 225 mm river stone, orifice flow is present based on field observations (i.e., VRW2). It is possible that the river stone placed in the orifices were transported downstream during large rain events, and consequently provided opportunities for orifice flow. Based on observations in the field, it is likely that orifices throughout the Weslie Creek rock weir system are < 0.05 m in width and depth. Literature recognizes rock weir designs that are purposely constructed with orifices as the preferred pathways for fish passage (e.g., Ead et al., 2004). Further, orifice design may enhance fish passage effectiveness via associated turbulent structures (Silva et al., 2012), or by providing space for energy dissipation through the structure.

Under low water level conditions, gap and over-weir flow may not be activated over or through rock weirs. During these times, orifice flow provides the only pathway for local fish species to travel upstream or downstream, depending on their life stage and behavioural characteristics. According to Kupferschmidt and Zhu (2017), velocity through orifices must be less than the maximum burst speed of the local fish species. This is also true for gap and over-weir flow. The difficulty associated with evaluating the effectiveness of orifices for fish passage, particularly during in-field analysis, is the inaccessibility for sampling equipment. Although orifice flow is considered non-negligible in Weslie Creek, sampling the required geometries and flow beneath keystones was not possible. Silva et al. (2012) analyzed fish passage effectiveness through orifices, however the research was conducted in a flume setting with the appropriate equipment for measuring velocity in such confined spaces.

Distance Between Rock Weirs

The characteristics of pool features surrounding rock weirs upstream and downstream are an important consideration for fish passability. According to Martens and Connolly (2010), suitable pool features provide refuge opportunities, habitat for rearing, and leaping pools for local fish species. The distance between rock weirs (i.e., the length of the pool feature) also influences flow through/over the downstream rock weir by dissipating energy and maximizing flow resistance (Wang et al., 2009). Pool features at Weslie Creek that were less than 4.0 m in length were more likely to produce flows that exceed local fish species' burst swim speeds (m/s) and therefore reduce fish passability (Table 2). In contrast, the pool features that were greater than 4.0 m in length provide 100% fish passability under all water level conditions (Table 2). This is supported by literature that suggests pool length is the primary geometric dimension that influences flow through both conventional and nature-like fishways (Wang et al., 2009; Bermudez et al., 2010).

It was determined that as pool length increases, the total number of opportunities for fish habitat and/or refuge also increases, with few outlying instances. In terms of fish habitat and/or refuge, it is important to note that although recirculation zones were not identified in all pools under all water level conditions (Figure 3), the measured velocities were below fish species' critical swim speeds. To recognize all possible locations for fish habitat and/or refuge in the Weslie Creek reach, further analysis is required to identify the sustained swim speeds for local fish species. For example, low cross-sectional velocity values (i.e., 0.02 m/s) were measured at pool features in Weslie Creek and most likely facilitate fish habitat and refuge, however the sustained swim speeds appropriate for local fish species are unknown. As such, only locations with stagnant or recirculation zones were used as indicators for fish habitat and/or refuge in Weslie Creek. Since sustained swim speeds are less than burst swim speeds, it is likely that such low cross-sectional velocity values do support local fish habitat and/or refuge conditions (Beamish, 1978).

In terms of pool length, there are conflicting goals between channel stability and fish passage (Thomas et al., 2000). With a greater pool length, the distance between rock weirs increases, and creates a greater drop height between rock weirs. Fewer rock weirs throughout the reach is problematic for channel stability due to a larger gradient. Additionally, fewer rock weirs throughout the reach is problematic for fish passage due to the greater drop heights local fish species are required to maneuver. It is recommended that pool lengths (the distance between rock weirs) be large enough to provide suitable conditions for passage, habitat, and refuge, but not undermine channel stability. The conclusion from this analysis should be applied in future natural channel design projects to ensure pool features are measured to an appropriate length to provide maximum opportunities for 100% fish passability and channel stability.

Evaluating Effective Rock Weir Design and Construction

According to Lucas and Baras (2008), river restoration efforts (such as fishways) should provide 90% overall passage efficiency for diadromous and potamodromous fish species to be considered functional. Fish passability through a reach is a function of three components: appropriate water depth, velocity, and gradient for leaping (Williams et al., 2012). It is important that such components are suitable for the target fish species within the system, both at the rock weir structures and pool features (Williams et al., 2012). The results of this research suggest that fish passability through the reach is most effective and longitudinal connectivity is most complete under low flow conditions (Figure 3). This is likely attributed to the number of active gaps available for fish passage. Although not all gaps facilitated the appropriate velocity for local fish passage, 9/10 rock weirs have at least one suitable pathway. With 90% overall passage efficiency based on local velocity measurements, the rock weirs at Weslie Creek are considered functional under low water level conditions. Excessive velocities through flow pathways that inhibit fish passage upstream is recognized as the most likely cause of passage failure and non-functionality through rock weir systems (Knaepkens et al., 2006). The mark-recapture of non-salmonid species through a pool-weir system in Belgium yielded 0%, 8%, and 29% fish passage effectiveness for bullhead (*Cottus gobio*), perch (*Perca fluviatilis*), and common roach (*Rutilus rutilus*), respectively. These fish species are larger and have stronger swimming capabilities than species local to Weslie Creek. This demonstrates that despite the size of the fish species and their swimming and/or leaping capabilities, where velocities exceed burst swim speeds, the rock weir system is not functional.

The general consensus concerning rock weirs and fish passage is that there is a lack of standardized monitoring protocols for evaluating effectiveness or fish passability (Silva et al., 2018). Further, fish passage analyses are common in the literature, however their measure of effectiveness differs. The structural differences between rock weirs and other nature-like fishways also contributes to challenges for comparing fish passage results. For example, PIT-tagging is common for fish passage monitoring in larger species (e.g., Tummers at al 2016; Martens and Connolly, 2010). However, in small-bodied fish, such as those in Weslie Creek, a different approach is needed. Rather than observing where the fish go, the hydrodynamics and geometries of the system were used to evaluate fish passage feasibility given physiological abilities of the expected local fish populations. In addition to the different methods and the different measures of fish passage effectiveness, it is likely that rock weir structure and design differences contribute to differences in fish passability results. Target fish species with different burst swim speeds will require different conditions (i.e., rock weir design and water level) to facilitate fish passage. As such, a relationship may exist between the size/swimming characteristics of fish species and appropriate conditions for fish passage effectiveness. Large-bodied fish species require greater water depth and can employ stronger burst swim speeds to maneuver rock weirs, while small-bodied fish species require smaller water depth and require lower velocities through rock weirs for passage. Such relationships must be considered in rock weir designs for effective fish passage for the target fish community.

Conclusion

As the use of rock weirs as a component of natural channel design in small-scale watercourses (i.e., $< 2 - 10$ m channel width, low gradient) becomes more common, it is necessary that appropriate monitoring techniques are established to evaluate fish passage effectiveness. Additionally, where rock weirs are constructed, determining the critical design and structural components, including placement, materials and geometry, that enhance fish passage effectiveness is important for informing future designs. The modified rock weir system at Weslie Creek was assessed for fish passage effectiveness based on gap and over-weir flow under different water level conditions. Fish passability was most effective (100% fish passability through 9/10 rock weirs) under low water level conditions, which was representative of the system during the majority of the field season. Further, fish passability was least effective under intermediate and high-water level conditions, likely due to the asymmetrical nature of the rock weir structures and the low ratio of over-weir flow pathways to gap flow pathways with more water in the system. These conditions typically lasted for approximately three days, and observations from adjacent pools suggest adequate refuge habitat while passage through the weirs were limited.

The structural components of the rock weirs were compared to fish passage effectiveness and critical design components were identified based on gradient, keystone characteristics (i.e., number and size), distance between rock weirs, embeddedness, and orifices. Critical design components for effective fish passage include:

- Steep secondary gradients at rock weirs to enhance longitudinal connectivity and active orifice, gap, and over-weir flow pathways
- A greater number of keystones and larger range of keystone diameters at each rock weir to provide opportunities for energy dissipation and various pathways (in terms of shape and size) for fish passage
- Greater keystone embeddedness to enhancing longitudinal connectivity under all water level conditions
- A greater distance between rock weirs (greater pool length) to provide opportunities for recirculation zones to form, and provide locations for fish refuge

Design considerations for effective fish passage should not undermine the conditions required to provide channel stability through the reach. These findings should be applied in future river restoration works, where natural channel design is used to address fish passage and stability. Incorporating critical design components for rock weirs will enhance fish passage efficiency, provide bed and bank stability, and limit the requirements for post-construction monitoring.

References

Bice, C. M., Zampatti, B. P., & Mallen-Cooper, M. (2017). Paired hydraulically distinct vertical-slot fishways provide complementary fish passage at an estuarine barrier. *EcologicalEngineering* , *98* , 246-256.

Carollo, F. G., Ferro, V. I. T. O., & Termini, D. (2002). Flow velocity measurements in vegetated channels. Journal of Hydraulic Engineering, 128(7), 664-673.

Clarke, S. J., Bruce-Burgess, L., & Wharton, G. (2003). Linking form and function: towards an eco-hydromorphic approach to sustainable river restoration. Aquatic Conservation: Marine and Freshwater Ecosystems,13(5), 439-450.

Corwin, E., Jagt, K., & Neary, L. (2007). Evaluating the Effects of Vortex Rock Weir Stability on Physical Complexity: Penitencia and Wildcat Creeks.

Dodd, J. R., Cowx, I. G., & Bolland, J. D. (2017). Efficiency of a nature-like bypass channel for restoring longitudinal connectivity for a river-resident population of brown trout. Journal of Environmental Management, 204, 318-326.

Gilvear, D. J. (1999). Fluvial geomorphology and river engineering: future roles utilizing a fluvial hydrosystems framework. Geomorphology, 31(1-4), 229-245.

Hatry, C., Binder, T. R., Thiem, J. D., Hasler, C. T., Smokorowski, K. E., Clarke, K. D., ... & Cooke, S. J. (2013). The status of fishways in Canada: trends identified using the national CanFishPass database. Reviews in Fish Biology and Fisheries, 23(3), 271-281.

Hawley, R. J., MacMannis, K. R., & Wooten, M. S. (2013). Bed coarsening, riffle shortening, and channel enlargement in urbanizing watersheds, northern Kentucky, USA. Geomorphology, 201, 111-126.

Jansson, R., Nilsson, C., & Malmqvist, B. (2007). Restoring freshwater ecosystems in riverine landscapes: the roles of connectivity and recovery processes. Freshwater Biology, 52(4),589-596.

Katopodis, C., & Williams, J. G. (2012). The development of fish passage research in a historical context. Ecological Engineering, 48, 8-18.

Kimura, I., & Hosoda, T. (1997). Fundamental properties of flows in open channels with dead zone. Journal of Hydraulic Engineering, 123(2), 98-107.

Klingeman, P., Martz, M., Walla, H., Castro, J., & Groznik, F. (2004). Ecosystem goals, river dynamics, and river restoration design. In Proceedings of the 2004 world water and environmental resources congress: critical transitions in water and environmental resources management, June.

Knaepkens, G., Baekelandt, K., & Eens, M. (2006). Fish pass effectiveness for bullhead (Cottus gobio), perch (Perca fluviatilis) and roach (Rutilus rutilus) in a regulated lowland river. Ecology of Freshwater Fish, 15(1), 20-29.

Kupferschmidt, C., & Zhu, D. Z. (2017). Physical modelling of pool and weir fishways with rock weirs. River Research and Applications, 33(7), 1130-1142.

LSRCA (2010). East Holland River Subwatershed Plan. Retrieved March 12, 2018, from https://www.lsrca.on.ca/Shared%20Documents/reports/east-holland- subwatershed- plan.pdf

Lucas, M., & Baras, E. (2008). Migration of freshwater fishes. John Wiley & Sons.

Martens, K. D., & Connolly, P. J. (2010). Effectiveness of a redesigned water diversion using rock vortex weirs to enhance longitudinal connectivity for small salmonids. North American Journal of Fisheries Management, 30(6), 1544-1552.

Navratil, O., Breil, P., Schmitt, L., Grosprêtre, L., & Albert, M. B. (2013). Hydrogeomorphic adjustments of stream channels disturbed by urban runoff (Yzeron River basin, France). Journal of Hydrology, 485, 24-36.

Newson, M. D., & Newson, C. L. (2000). Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. Progress in Physical Geography, 24(2),195-217.

Romão, F., Branco, P., Quaresma, A. L., Amaral, S. D., & Pinheiro, A. N. (2018). Effectiveness of a multi-slot vertical slot fishway versus a standard vertical slot fishway for potamodromous cyprinids. Hydrobiologia, 816(1), 153-163.

Roscoe, D. W., & Hinch, S. G. (2010). Effectiveness monitoring of fish passage facilities: historical trends, geographic patterns and future directions. Fish and Fisheries, 11(1), 12-33.

Silva, A. T., Lucas, M. C., Castro-Santos, T., Katopodis, C., Baumgartner, L. J., Thiem, J. D., ... & Burnett, N. J. (2018). The future of fish passage science, engineering, and practice. Fish and Fisheries, 19(2), 340-362.

Thomas, D. B., Abt, S. R., Mussetter, R. A., & Harvey, M. D. (2000). A design procedure for sizing step-pool structures. In Building Partnerships (pp. 1-10).

Tummers, J. S., Hudson, S., & Lucas, M. C. (2016). Evaluating the effectiveness of restoring longitudinal connectivity for stream fish communities: towards a more holistic approach. Science of the Total Environment, 569, 850-860.

Varyu, D., Russell, K., & Holburn, E. (2009). Quantitative Evaluation of Rock Weir Field Performance. World Environmental and Water Resources Congress 2009. doi:10.1061/41036(342)329

Vietz, G. J., Sammonds, M. J., Walsh, C. J., Fletcher, T. D., Rutherfurd, I. D., & Stewardson, M.J. (2014). Ecologically relevant geomorphic attributes of streams are impaired by even low levels of watershed effective imperviousness. Geomorphology, 206, 67-78.

Ward, J. V., & Stanford, J. A. (1995). Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. River Research and Applications, 11(1), 105-119.

Williams, J. G., Armstrong, G., Katopodis, C., Larinier, M., & Travade, F. (2012). Thinking like a fish: a key ingredient for development of effective fish passage facilities at river obstructions. River Research and Applications, 28(4), 407-417.

Wolman, M. G. (1954). A method of sampling coarse river-bed material. EOS, Transactions American Geophysical Union, 35(6), 951-956.

Zhang, G., & Chanson, H. (2018). Three-dimensional numerical simulations of smooth, asymmetrically roughened, and baffled culverts for upstream passage of small- bodied fish. River Research and Applications, 34(8), 957-964

Tables:

Table 1. Total fish passability based on rock weir gradient.

Weir	Gradient	% Passability Low Water Level	% Passability Intermediate Water Level	% Passability High Water Le
1	-0.01	100	100	100 for </= 4 species
2	-0.02	0*	100 for </= 4 species	100 for </= 4 species
3	-0.02	100	100 for </= 4 species	100 for </= 4 species
4	-0.05	100	100 for </= 4 species	100
5	-0.10	100	100	100
6	-0.08	100	for </= 4 species	100
7	-0.14	100	100	100
8	-0.09	100	100	100
9	-0.05	100	100	100 for </= 4 species
10	-0.06	100	100 for </= 4 species	100

* Fish passage opportunities exist through leaping or orifice flow pathways, based on the presence of fish species upstream.

Table 2. Pool length influences fish passability through the downstream VRW and available locations for fish refuge.

Pool #	Length (m)	Pool Depth (m) *	Total # Locations for Fish Refuge Under all Water Level Conditions
1	7.40	0.14	0
2	2.30	0.10	1
3	2.40	0.11	1
4	3.60	0.11	1
5	11.20	0.17	34
6	3.90	0.13	15
7	3.80	0.20	5
8	2.50	0.16	20
9	20.70	0.25	23

Pool #	Length (m)	Pool Depth (m) *	Total # Locations for Fish Refuge Under all Water Level Conditions
10	5.90	0.20	26
11	2.40	0.25	19

* Measured in the thalweg during low water level conditions to provide a conservative value for fish habitat suitability.

Table 3. Total fish passability based on rock weir width, number of keystones, and sizes of keystones.

Weir	Weir Crest Width (m)	# of keystones	Range of Keystone Sizes (m)	% Fish Passability (Low Water Level)	%
1	1.9	5	0.2 – 0.8	100	1
2	3.1	8	0.4 – 1.1	0*	1
3	2.2	4	0.6 – 0.8	100	1
4	2.4	3	0.6 – 1.3	100	1
5	3.6	9	0.5 – 1.0	100	1
6	3.5	9	0.6 – 1.1	100	1
7	3.3	8	0.2 – 1.1	100	1
8	3.5	9	0.2 – 1.3	100	1
9	2.7	6	0.3 – 0.7	100	1
10	2.5	7	0.2 – 1.0	100	1

* Fish passage opportunities through leaping or orifice flow pathways, based on the presence of fish species.

Figure Captions

Figure 1. Daily rainfall, daily water temperature, and hourly water level along the study reach. Upper and lower temperature limits for fish species local to Weslie Creek are labeled on the water temperature graph (LSRCA, 2000; Eakins, 2018). Field assessment days are shown with diamonds along the lower x-axis.

Figure 2. Reach profile from upstream (left) to downstream (right) with representative pool (above profile) and rock weir (below profile) cross-sections. The asterisk in the Pool 7 cross-section indicates the stilling welling location. Vertical exaggeration is 0.08 m.

Figure 3. Fish passability in low (left), intermediate (middle), and high (right) water level conditions. Rock weirs that provide 100% fish passability are represented by green keystones, rock weirs that provide fish passage for 4 or fewer fish species are represented by yellow keystones, and rock weirs that do not provide gap or over-weir flow pathways are represented by red keystones. Note that red keystones allow orifice flow and leaping opportunities for fish passage. Further, recirculation zones indicate potential locations for fish refuge during unsuitable swimming conditions.

Figure 4. Profile schematics of a low gradient rock weir (a) and high gradient rock weir (b). The difference in gradient depicts how embeddedness changes depending on how gentle or steep the channel bed is. A greater level of embeddedness provides upstream and downstream connectivity without obstructions to the flow path (b).

Figure 5. Looking upstream at VRW2 (a low gradient rock weir) under low (top photo), intermediate (middle photo), and high (bottom photo) water level conditions. It is evident that orifice flow is the only active flow regime under low water level conditions, while orifice, gap, and over-weir flow are active simultaneously under intermediate and high-water level conditions. VRW2 under low water level conditions demonstrates the importance of embeddedness for enhancing fish passage effectiveness, while VRW2 under high water level conditions demonstrates the effect of ‘drowned conditions’.