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Technical note

Evaluation of passage and sorting of adult Pacific salmonids through a novel fish passage technology

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ABSTRACT

Throughout their life cycle, salmonids migrate between different habitats. During their journey, they often encounter barriers, such as hydropower dams, which may impede their migration and therefore decrease habitat connectivity. Fish passage systems have been developed to enable the migration of fish around barriers but their design is rarely adaptable to a wide range of species and hydraulic conditions. The Whooshh Fish Transport System (WFTS) is a fish passage technology that was designed to move fish around barriers through a flexible tube using differential air pressure. In this study, we evaluated the combination of the WFTS with the Whooshh Ellips Scanning Sorting system (WESS). This combined system allows autonomous and volitional entry, and subsequent selective upstream passage for fish of different sizes. The sorting by size and the passage efficiency of Chinook salmon (*Oncorhynchus tshawytscha*) and steelhead (*O. mykiss*) through the WESS-WFTS was assessed. We found that the WESS-WFTS was able to sort the fish by size, few fish had external injuries, and few unexpected events (e.g. backward transport, discontinuous transport) occurred. Our results support the use of the WESS-WFTS as an effective transport system for adult salmonids when used in conjunction with a volitional fishway entrance.

1. Introduction

Due to increasing demand for renewable energy, hydropower has become an important source of electricity production in countries where river water resources are abundant such as Brazil, China, Canada, and United States (Pineau et al., 2017). Hydropower dams generate inexpensive and efficient electricity, but also provide flood control, water for municipal, industrial, and agricultural use, and opportunities for recreation (Bednarek, 2001). However, hydropower dams also negatively impact fish populations inhabiting rivers by acting as barriers to migration and decreasing habitat connectivity (Montgomery et al., 1999; Sheer and Steel, 2006; Pelicice et al., 2015).

To mitigate the impacts of hydropower barriers on fish populations, conventional methods such as fish ladders and trap-and-haul have been routinely used to facilitate fish passage. Fish ladders, for example, of which there are four general designs (i.e. pool and weir, vertical slot, denil and nature-like), have been constructed to pass more than 25 species of fish, but the performance of these structures with respect to attraction and passage efficiency (i.e., number of fish that exit relative to number that enter) has varied considerably (Castro-Santos and Letcher, 2010; Bunt et al., 2011; Brown et al., 2013; Agostinho et al., 2016). On average, attraction rates among designs have ranged from 48% (nature-like) to 77% (pool-and-weir). Mean passage efficiency has also varied among structures, from 40% for pool-and-weir to 70% for nature-like designs. More specifically, Brown et al. (2013) reported that system-wide passage efficiency for fishways used by American shad (*Alosa sapidissima*) in the Connecticut, Merrimack, and Susquehanna Rivers were < 3% in recent years (2005–2010), and that passage between the first and second dams for these rivers was as low as 4% (Connecticut River).

Major limitations of developing fish passage systems are behavior and swimming abilities that differ widely among species. Few passage systems have been designed that can accommodate the range of hydraulic conditions needed to meet these requirements for a variety of species. As a result, fish assemblages upstream of hydropower barriers can be altered dramatically because successful passage tends to be dominated by a few species, those best suited to the fish passage system in place, particularly in tropical rivers where species can number in the hundreds (Pompeu et al., 2012; Agostinho et al., 2016). Passage delays also impart high energetic costs to migrating fish that potentially

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decrease survival, iteroparity, and recruitment (Castro-Santos and Letcher, 2010). Moreover, active passage methods, such as trap-and-haul, require the direct handling of fish, which can lead to added stress and mortality (Keefer et al., 2010). These observations suggest more efficient and adaptable fishway technologies may help improve passage, thereby reducing the impacts that hydropower barriers have on migratory species and aiding efforts to conserve fish communities.

The Whooshh Fish Transport System (WFTS) is a fish passage technology designed to move fish around barriers through a flexible tube using differential air pressure. It has been developed as an alternative to conventional fish passage systems. Because it is scalable and not limited by hydraulic conditions, it can be effectively deployed at in-river barrier sites where other methods (e.g., fish ladders, trap-and-haul) are prohibitive due to accessibility and (or) operating costs. The ultimate long-term goal of this system is to be able to sort fish of different sizes and species through multiple tubes.

Recent studies that assessed the influence of the WFTS on physiological responses in adult Rainbow Trout (*Oncorhynchus mykiss*) and adult Chinook Salmon (*O. tshawytscha*) showed no significant differences in injury, stress, immune system response, or reproductive function when the WFTS was compared to transport methods involving direct handling (Mesa et al., 2013; Geist et al., 2016). However, in these studies, the fish entered the WFTS by netting and hand loading them into the system. Also, the transport tubes used in these studies were sized to accommodate trout and salmon within specific ranges of girth to ensure proper functioning of the system. These constraints present challenges to previously studied versions of the WFTS to pass large numbers of adult fish during spawning migrations because multiple species often migrate at similar times within river systems, and individuals can exhibit a wide range of sizes.

In this study, we evaluated a new water to water version of the WFTS that was designed to allow volitional entry and selective upstream passage for fish of different sizes. In this new version, the WFTS was combined to an imaging and sorting system, the Whooshh Ellips Scanning Sorting system (WESS). Our study focused on Chinook Salmon and steelhead (*O. mykiss*) which are typically distinct in respect to size, potentially enabling the identification of each species based upon size sorting. The objectives of this study were to (1) evaluate the feasibility of the combined system WESS-WFTS to transport Chinook Salmon and steelhead and sort them between two sizes groups and (2) assess its effects on fish during their passage through the system. To address these objectives, we quantified sorting, passage efficiency, and the number of unexpected transport events, and monitored short-term survival and fish condition.

2. Material and methods

2.1. Study site

The study was conducted using hatchery adult fall Chinook Salmon and steelhead returning to the hatchery (Ringold Springs Rearing Facility) operated by the Washington Department of Fish and Wildlife (WDFW). The site is located on the eastern shore of the Columbia River at river kilometer 567 from the Pacific Ocean. The juvenile rearing and adult return facilities at the hatchery are supplied with water from springs that flow from the nearby upland plateau (2 m^3/s at 14–15 °C). Returning adult Chinook Salmon and steelhead are captured in a holding pool after swimming through a V-trap weir located approximately 200 m upstream from the confluence of Spring Creek and the Columbia River (Fig. 1). The fish are then hand-sorted and transferred to broodstock holding ponds or released back to the river to support the recreational fishery (steelhead only). The trap is operated to enumerate adult returns of both species from September through December.

2.2. Testing apparatus

The test system in this study was configured to allow volitional entry and subsequent passage of fish, and sort them by size. The combined fish passage system included three main components (Figs. 2 and 3):

1 Alaska Steeppass fishway, flow box, and false weir: The Alaska Steeppass (Ziemer, 1962; height 1.0 m, width 0.6 m, length 10.0 m, slope 20%) extended from the adjacent shore into the adult Spring Creek holding pool and was used to enable volitional entry of fish. The flow box (height 1.0 m, width 0.6 m, length 3.0 m) supplied water (~0.3–0.4 m^3/s) to the steeppass and connected it to the false weir, the point of entry into the WESS. The false weir was supplied with supplemental spring water (~0.03 m^3/s) and operated manually or automatically to control the water flow and attract fish to the WESS entry.

2 WESS: The WESS consisted of an aluminum enclosure tapered along the bottom to guide fish to the sorting chute entry at a speed of approximately 2 m/s. Six machine vision cameras (3 infrared and 3 visible spectrum) were positioned at defined angle locations within the WESS to image the fish. A sensor at the entry of the WESS activated the cameras and sent the resulting images for processing through a computational and a decision algorithm to sort the fish, which was computed on a local server. The decision algorithm was used to sort fish by size, using fish girth (circumference) as the decision criterion. Pictures of a fish were taken from 3 different angles and were used to estimate width and length. The girth was then computationally derived based on a length-weight-girth relationship function that was derived from previously collected data on Chinook salmon and steelhead (J. Bryan, personal communication).

3 WFTS: Following the sorting decision algorithm in the WESS, fish were either bypassed or transported to a tube. A sorting gate located at the entrance of the bypass and transport tube allowed the passage of the fish into either tube. If a fish was sorted to be transported by the tube, it was sent towards a sorting chute connecting the WESS to an accelerator chamber (height 0.43 m, width 0.34 m, length 2.78 m). The accelerator chamber was directly connected to the transport tube. The transport tube (length 30 m, diameter 0.15 m) was composed of an extruded flexible polymer manufactured as a single continuous tube and was used to move fish misted with water by application of differential air pressure. It was sized for salmon approximately 7–14 kg in mass (maximum girth 480–600 mm). The outside of the tube was covered with thermal and solar insulation to reduce temperature fluctuations during operation. Polyethylene lines (diameter 6 mm) running along the top of the tube provided lubrication by supplying water to spray ports at 5-minute intervals. If a fish was sorted to be bypassed, it was sent towards the bypass tube at the sorting gate. The bypass tube was a 0.5 m long and 0.3 m diameter PVC pipe.

2.3. System operation

Adult Chinook Salmon and steelhead entered the collection pool upstream of the hatchery V-trap weir from September through November 2017. Fish sorting and passage through the system were evaluated on 8 days, from October 2 to November 7, 2017, from approximately 0700 to 1500. At the start of each testing day, the fish were crowded to the lower end of the pool using a beach seine (1.5 m high × 10 m long) to confine them downstream of the steeppass entrance.

A schematic representation of the Chinook Salmon and steelhead passage through the fish passage system is shown in Fig. 3. From the collection pool, the fish volitionally ascended the steeppass, passed over the false weir where they were partially dewatered, then entered the WESS and began a downward, ten-degree angle slide through the

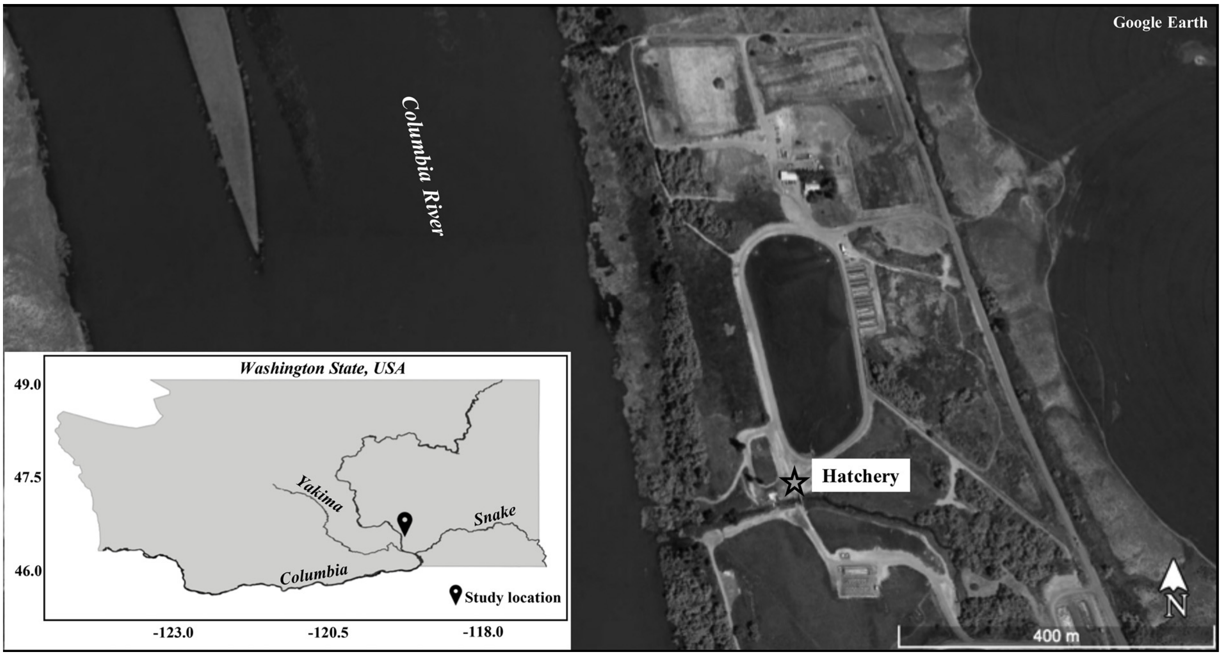

Fig. 1. Map of the study location in Washington State (USA). Three rivers are indicated on the Washington State map: Columbia, Snake, and Yakima.

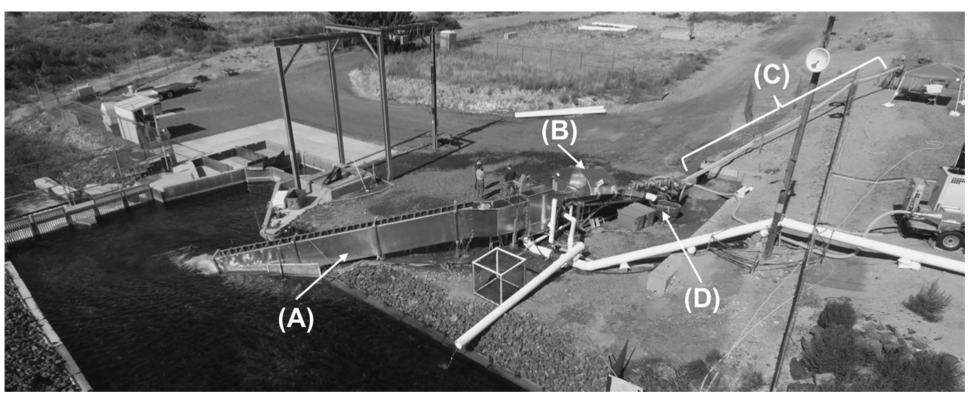

Fig. 2. Aerial photo of the fish passage system set-up. The letters identify the main components of the system: (A) Steeppass fishway; (B) Whooshh Ellips Scanning Sorting system (WESS); (C) transport tube; (D) bypass tube. The transport tube and bypass tube are part of the Whooshh Fish Transportation System (WFTS).

system assisted by a small stream of water less than 5 mm deep. Multiple images were captured for each fish that entered the WESS which were simultaneously uploaded to the computational processing and sorting decision algorithm to identify individual fish and route them towards the transport tube or the bypass tube.

In the WESS, if fish were too close together (less than 0.5 s apart) and could not be individually identified to accurately determine measurements and (or) ensure safe separation through the sorting gates, they were directed to the bypass, regardless of their size.

Fish routed for transport passed through the sorting gate where additional sensors monitored their movement through the open accelerator door toward the transport tube. Once inside the accelerator chamber, surplus water flow was drained off while the upper door closed. The chamber pressure was equalized to the tube pressure established by the blower, after which the lower chamber door opened. Once fish were in contact with the tube, a pressure differential was created and the fish were subsequently pushed by air pressure through the transport tube.

The time of fish passage from cresting the false weir to the transport tube entry was 1.5 to 2 s. Upon exit from the transport tube or the bypass, the fish landed in a pool (1 m deep, 2.5 m wide, 5 m long for transport; 0.8 m deep, 1.3 m long, 0.6 m wide for bypass) where they were caught with a dip net, anesthetized and examined (see *Fish assessment*). Total passage time from the false weir through the transport tube was typically 4 to 8 s.

2.4. Fish assessment

After entry into their respective landing pools, transported and bypassed Chinook Salmon were individually placed into an oxygenated tank filled with 100 L of spring water (within 2 °C of the holding pool temperature) and 15 ppm Aqui-S 20E (Aqui-S New Zealand LTD, New Zealand) for approximately 2 min. Once Chinook Salmon were sedated, they were measured for length and girth, weighed for mass, then assessed for overall external body condition, fungus cover, and their sex identified. Steelhead were similarly measured for girth (estimate only because fish were not anesthetized as required by WDFW protocol) and assessed for external condition and sex identification. The assessment of external condition for both Chinook Salmon and steelhead was based on recent macroscopic injuries only. The condition evaluation was ranked on a scale ranging from 1 to 5, with 1 being the worst condition (Table 1; J. Fryer, personal communication). The time of sampling and the sorting outcome (i.e., transport or bypass) were also noted. Unexpected operating events such as two fish passing over the false weir or

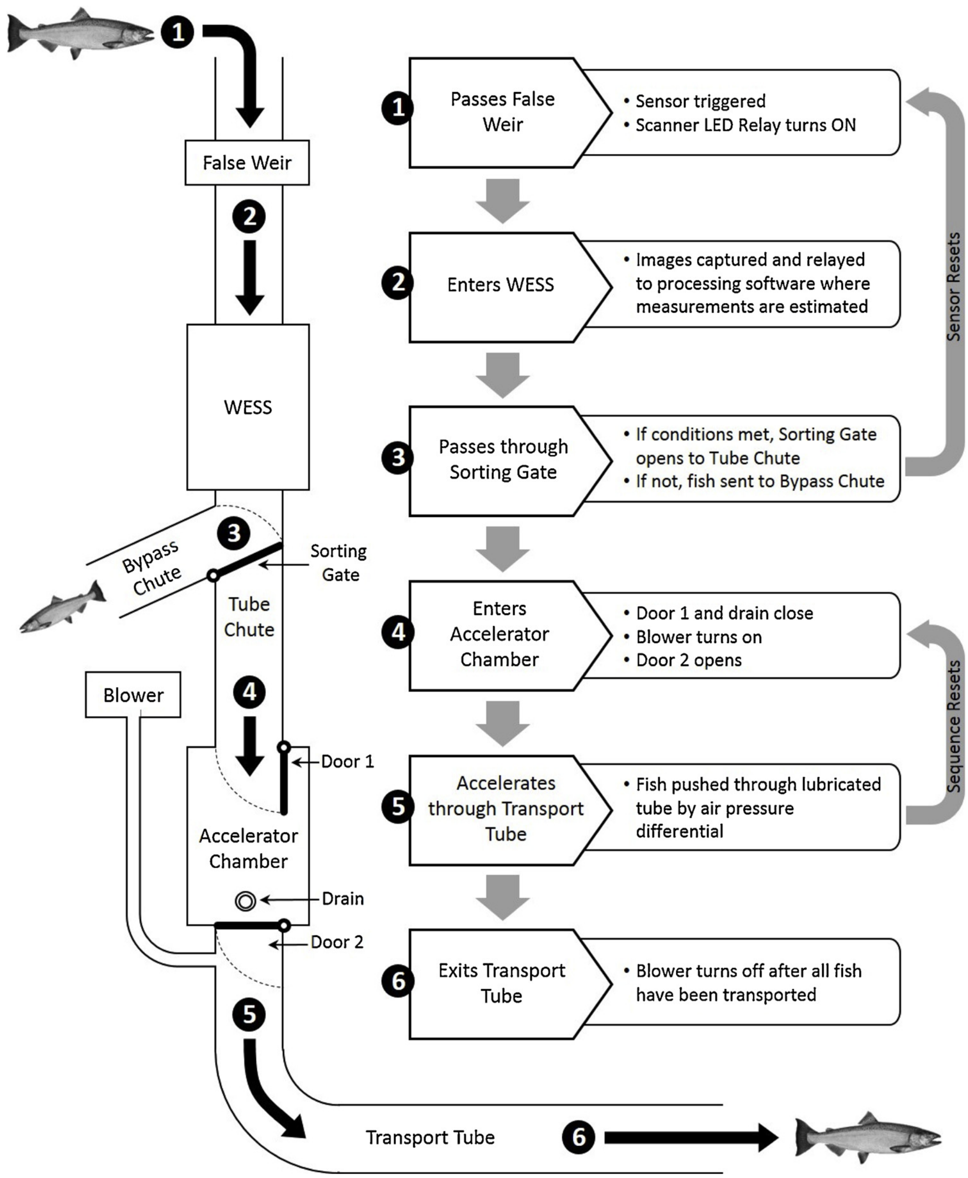

Fig. 3. Schematic representation of Chinook Salmon and steelhead passage through the fish passage system after climbing the steeppass.

Table 1
Description of the fish condition scale used in this study.

Condition scale	Evaluation of recent macroscopic injuries
5	No injuries on the fish, or injuries on fish do not break skin
4	Injuries break the skin but do not penetrate the muscle
3	Injury penetrates the muscle
2	Injury penetrates a body cavity (includes brain case and spine visible)
1	Fish is missing a large portion of body or appendages

through the WESS system at the same time, backward entry into the transport tube or bypass, and impingement or collision with the mechanical sorting gate were recorded. After measurement and assessment, the fish were transferred by net into a WDFW transport truck for transfer to a hatchery raceway (Chinook Salmon) or placed in a separate holding pen within the original collection pool (steelhead) for eventual release back into the Columbia River. Each day, Chinook Salmon were dip netted directly from the holding pool as a non-passage control group and assessed in a manner identical to the fish that volitionally entered the system. Water and air temperatures were recorded daily throughout the period of the study. Water temperature and dissolved oxygen levels in the transport truck were also monitored throughout the study.

2.5. Analysis

In the WFTS, to allow the differential pressure needed for an effective and efficient passage, it was assumed that the transport tube should be at least 85% occluded by the fish. The transport tube was 85% occluded when a fish had a girth of 400 mm. Consequently, our criteria to evaluate the sorting was based on a 400 mm girth limit with fish having a minimum girth of 400 mm being transported to the tube and fish having a maximum girth of 400 mm being bypassed.

Differences in girth, length, and weight among tube transported, bypassed, and control fish were assessed using the Kruskal-Wallis analysis of variance by ranks test because the data were not normally distributed and this assumption could not be met by transformation ($\log_{10}$). The Dwass-Steel-Critchlow-Fligner test was used for pairwise comparison with the level of significance of all analyses set at $p = 0.05$.

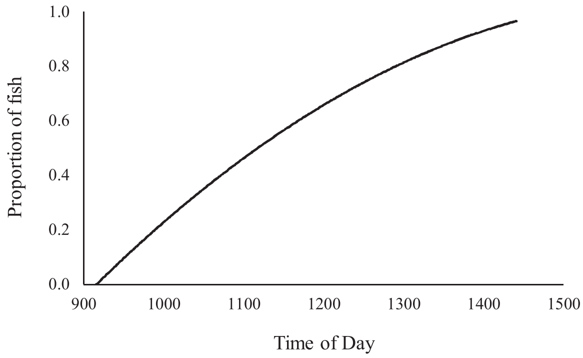

Fig. 4. Proportion of Chinook Salmon and steelhead that were transported through the fish passage system in relation to the time of day.

3. Results

3.1. Sorting by size

During the study period, 367 Chinook Salmon and 85 steelhead passed through the false weir and the combined system WESS-WFTS. Most fish (60%) moved in pulses through the combined system in the morning (Fig. 4) and movement ceased by early to mid-afternoon. The frequency distribution of girth among transported, bypassed, and control Chinook Salmon and steelhead is shown in Fig. 5. Girth ranged from 285 mm to 490 mm, 205 mm to 480 mm, and 210 mm to 472 mm for transported, bypassed and control fish, respectively. The corresponding median (± median absolute deviation MAD; the median of the variable comprising the absolute values of the differences between the median and each data point) measurements of girth, length, and mass for Chinook Salmon and steelhead are shown in Tables 2 and 3, along with the number of both species that were transported, bypassed, or used as control fish. Most of the Chinook Salmon (~75%, $n = 225$; Table 2) were transported, whereas the majority of the steelhead (~93%, $n = 79$; Table 3) were bypassed. Girth, length, and mass were all significantly greater for transported than bypassed ($W \geq 60.8$, $p < 0.001$) and control Chinook Salmon ($W \geq 58.2$, $p < 0.001$). Length and mass also differed significantly between bypassed and control Chinook Salmon ($W \geq 6.7$, $p < 0.001$), whereas girth did not ($W = 1.3$, $p = 0.62$). For steelhead, girth was measured only for fish routed to the bypass, and it was significantly less than the girth of bypassed Chinook Salmon (Mann-Whitney $U = 2{,}924.5$, $p < 0.001$).

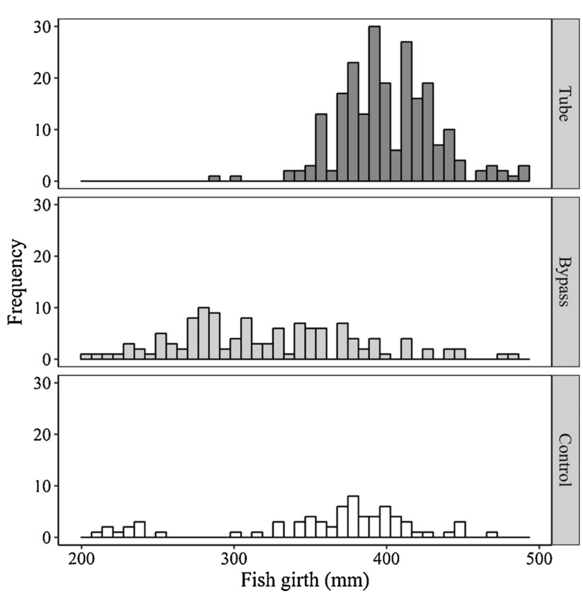

Fig. 5. Frequency of fish girth for transported into tube (Tube; dark grey), bypassed (Bypass; light grey), and control (Control; white) Chinook Salmon and steelhead.

Of all Chinook Salmon and steelhead that entered the WESS, 47.3% ($n = 107$) of transported fish had a girth less than 400 mm, whereas 10.6% ($n = 13$) of bypassed fish had a girth greater than 400 mm (Fig. 6). The majority of these events were for Chinook Salmon with only one fish being a steelhead. Most of the fish that were transported and had a girth less than 400 mm (82.5%) had a girth ranging between 360 mm and 400 mm and were Chinook Salmon.

3.2. Fish injury and unexpected events

Among all the Chinook Salmon examined for recent macroscopic injuries, hemorrhaging was the only injury observed, typically in the fins and eyes, and it occurred in 3.0% ($n = 11$) of the Chinook Salmon that entered the WESS (Table 4). Hemorrhaging was observed in 6 of 225 transported fish (2.7%), 4 of 69 control fish (5.8%), and 1 of 73 bypassed fish (1.4%). One Chinook Salmon died during transport through the tube due to a human error during the system setup on the study site that affected the fish exit guidance system.

A combined $n = 47$ Chinook Salmon and steelhead experienced unexpected events during the study (Table 5). The majority of the fish that experienced an unexpected event (97.9%) were transported, and the most common unexpected events were backwards transport (74.5%) and getting temporarily stalled in the transport tube (17.0%). Of the total number of fish experiencing an unexpected event, hemorrhages were observed in 5 of them (10.6%).

4. Discussion

The evaluation of the passage of adult Chinook Salmon and steelhead through the combined WESS-WFTS showed that the fish were successfully transported towards the tubes, the external injuries were minor and below the level of the non-passage fish control group, and the number of unexpected events experienced by both species were low. This study demonstrates that the WESS-WFTS has the potential to sort and transport migratory adult salmonids around in-stream barriers.

The length and girth of transported fish were significantly larger than those that were bypassed. The algorithm used in the WESS to distinguish differently sized fish with minimal error was successful at 73.5%. Overall, we observed more fish with a girth less than 400 mm being transported compared to fish with a girth greater than 400 mm being bypassed. However, fish with a girth size higher than 400 mm and diverted to the bypass may also have been deliberately diverted as a result of the default rule. If there were two or more fish in close proximity such that the WESS could not distinguish between or among them, or because their proximity in time did not allow the sorting gate to be safely opened and closed before the next fish encountered it, the fish were automatically bypassed.

Among the fish less than 400 mm in measured girth sorted to the transport tube, only 16.7% experienced an unexpected event. This suggests that the transport tube used in this study may have been able to accommodate fish over a wider range of girth than initially assumed, which could have practical implications for field deployment, particularly for fish such as Pacific salmon because most of these species have age structured populations that vary widely in size. However, it is important to note that the number of unexpected events observed in our study were likely underestimated. We retrospectively reviewed a subsample of video records made of fish passage through the WESS and sorting gate and observed that more fish traveled backwards through those points than were recorded to have been transported backward through the tube during the study. Our video analysis also revealed the fish recorded to have been transported backwards through the tube were generally oriented in that position soon after passing the false weir.

Table 2
Median girth (mm), length (mm), mass (kg), overall physical condition, percent fungus cover, and sex for transported, bypassed, and control Chinook Salmon. The total number of Chinook Salmon in each treatment is also noted. MAD = median absolute deviation; SD = standard deviation.

Treatment	Girth (mm) ± MAD	Length (mm) ± MAD	Mass (kg) ± MAD	Condition ± SD	Fungus Cover (%) ± SD	Male	Female	Total Fish
Control	360.3 ± 37.1	710.0 ± 59.3	3.9 ± 1.2	4.8 ± 0.4	1.1 ± 3.7	39	30	69
Transport Tube	401.1 ± 29.7	750.0 ± 44.5	4.6 ± 0.9	4.4 ± 0.6	0.8 ± 2.3	88	137	225
Bypass	350.0 ± 51.9	736.5 ± 95.6	3.3 ± 1.1	4.7 ± 0.5	0.1 ± 0.7	43	30	73

Overall, the percentage of Chinook Salmon and steelhead that had injuries following passage was low (1.9%). These results are comparable to those reported by Mesa et al. (2013). They observed no injury or mortality for adult Rainbow Trout that were hand loaded and transported through an earlier developmental version of the WFTS with a 15 m tube. By contrast, the injury and mortality rates reported by Geist et al. (2016) were higher than the ones observed in our study, but their fish were also more reproductively mature. High mortality of mature fish during spawning migrations has been shown to be related to poor physiological condition in sockeye salmon (Young et al., 2006), and the fish transported by Geist et al. (2016) were within days of spawning and generally in a weakened condition. In addition, the mortality rates reported by Geist et al. (2016) included observations for several days after passage, whereas we evaluated only immediate mortality. Injuries assessment allow us to provide information on short term effects of the system on the fish. However, further studies are needed to assess potential long-term effects of the system to the individual or population such as the transfer of disease between fish being transported into the system.

Anecdotally, we observed a higher rate of unexpected events when two or more fish entered the system within several seconds of each other. This occurrence could have been related to insufficient time for the sorting gate to be reset after passage of the lead fish. Controlling the rate of fish entry into the sorting system with a gate or on-off cycling of the water flow at the false weir might help reduce the number of unexpected events, but at a potential cost to volitional entry. Multiple numbers of Chinook Salmon and steelhead frequently held position either in the flow box and (or) immediately below the false weir for tens of minutes before attempting to pass over the false weir and enter the WESS. Whether this reflected a design-related issue or a behavioral inhibition to move into the WESS is unclear, but visible activity such as human movement or shutting off the water flow to the false weir often resulted in the fall back of these fish down the steeppass into the holding pool. Such responses not only lower the rate of entry into the system, but they also impose additional energetic cost to re-ascend the steeppass and an increase of injury risk during descent. Time controlled, sequential entry into the WESS may require further modifications of the flow box to include a chute or channel that guides fish into a single file as they approach the false weir.

The evaluation of fish passage through a system combining the components of both active (WFTS) and passive (Alaska Steeppass) fishways allowed us to discuss short-term passage performance for both components. An advantage of the WFTS over conventional passive fishways is that passage efficiency after entry can approximate 100%,

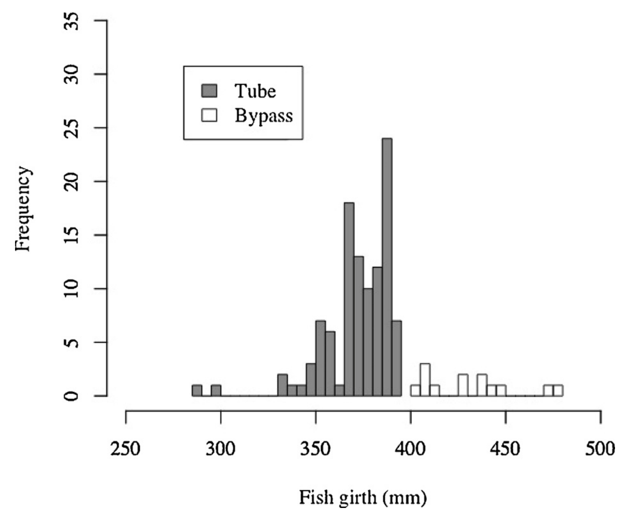

Fig. 6. Frequency of fish less than 400 mm girth being sorted to the transport tube (dark grey) and fish greater than 400 mm girth being sorted to the bypass (white).

Table 4
The type and number of injuries for transported, bypassed, and control Chinook Salmon examined in the study (n = 367).

Injury Type	Control *n = 69*	Transported *n = 225*	Bypassed *n = 73*
Hemorrhage	4	6	1
Exophthalmia	0	0	0
Mortality	0	1	0

Table 5
Number of unexpected events for Chinook Salmon and Steelhead combined.

Unexpected events	Number of fish
Transported backwards	35
Error setup of transport tube	1
Temporarily stalled in transport tube	8
Temporarily stalled in transport tube and transported backwards	3
Total number of fish	47

Table 3
Median girth (mm), mean overall physical condition, and sex for transported and bypassed Steelhead. Data could not be collected on each fish for all of these metrics, so the total number of Steelhead in each sorting decision is also noted. MAD = median absolute deviation; SD = standard deviation.

Treatment	Girth (mm) ± MAD	Condition ± SD	Male	Female	Total Fish
Transport Tube	NA	5.0	1	NA	6
Bypass	290.0 ± 22.2	5.0	2	14	79

obviating problems associated with potential delays in migration. Passage delays in conventional fishways can increase energetic costs, levels of stress, and rates of injury and disease (Castro-Santos et al., 2009). Bypass-associated delays with the WFTS have the potential to adversely impact actively migrating fish. Also, the percentage of bypassed fish in our study (13%) was comparable to fall back rates (i.e. the proportion of fish that ascend ladders into the forebay of hydropower dams only to pass back through the dam to the tailrace) of conventional fishways. Chinook Salmon fall back rates were estimated at between 1 and 31% in the Snake and Columbia rivers (Washington, USA; Mueller et al., 2012) and at 19% in the upper Cowlitz River Basin (Washington, USA; Kock et al., 2016).

The results of our study also illustrate the current limitations of the combined WESS-WFTS system for a real-world application to pass large numbers of fish with varying motivation, size and migratory duration. First, volitional entry of fish into the system was facilitated by the addition of a steeppass. Passive fishways such as the Alaska Steeppass require that a series of behavioral events including detection, entry, and ascent take place even before they encounter the WESS-WFTS. In our study, the fish swimming behavior was episodic and temporally variable; it is important to note that our system was not operating 24 h per day. We also found that the size of Chinook Salmon was significantly greater for transported than control Chinook Salmon. A study led by Mallen-Cooper and Stuart (2007) in Australia showed that 88% of both small and big fishes successfully ascended a denil fishway with 8.3% slope compared to 31% at the 20% slope. Improving the design of the fishway could increase the attraction into the steeppass (or similar volitional fishways) and the ascension of a wide size range of fish. This will be critical for effective deployment of the WESS-WFTS in river systems.

Secondly, a bypass option was included in our study because the WTFS was limited to a single transport tube that constrained the size of fish that could be transported. In an actual WFTS deployment, multiple transport tubes would be configured to accommodate passage for the full range of sizes and species of fish encountered in the waterway, removing the potential adverse impacts that could result from migration delay. Finally, comprehensive calibration of the WESS to the range of girths and lengths likely to be encountered within the spawning migration would also help optimize the sorting decision process. Some fish with girth less than 400 mm that were sorted to the transport tube ($n = 7$) became temporarily delayed during transport and study protocol required intervention such that they were moved with the aid of a sponge manually placed behind them in the tube to produce an effective air seal. This manipulation required a shutdown and restart of the WESS-WFTS system and the false weir. Whether such interruptions affected the motivation of fish holding in the flow box to subsequently move through the false weir and into the WESS is unknown. However, removing the supplemental water from the false weir (~10% of the total flow) likely altered the hydraulic conditions within the flow box and the Alaska Steeppass, and possibly the volitional movement of fish in this part of the system. Eliminating or at least reducing system shutdowns resulting from sorting errors will also be important for applications involving high abundance populations. A future study evaluation of the effectiveness of the WFTS to sense a temporary stall and to autonomously adjust the blower settings to address the stall would potentially provide valuable insight into increasing system efficiencies and the ability of the system to operate autonomously.

Future studies should be performed to demonstrate the comparative performance of the system in terms of attraction, entry, and passage to a conventional fishway at a hydropower dam or similar barrier. Ideally, such a test should include some form of telemetry (e.g., Radio or acoustic telemetry and Passive Integrated Transponder tags) to accurately quantify movement into and passage through the respective fishway systems. Telemetry methods have provided highly detailed quantification of passage processes and have been most effective for evaluating structure and species-specific performance (Wagner et al., 2012; Thiem et al., 2013). In terms of the WESS-WFTS, we observed an increase in unexpected events when multiple fish passed over the false weir successively or at the same time. This points to the need to measure passage time through the WESS. Estimating the passage time and concurrent fish entry numbers could allow an eventual correlation with unexpected events and their potential correction. Also, the sorting algorithm that is currently based on fish size (the relation between width, length, and girth) could be combined with other physical criteria such as species-specific external appearance to refine the sorting functionality and expand the application of the system to rivers where hydropower barriers impede or alter the migratory patterns of multiple species.

5. Conclusions

In summary, our results support the view that the combined WESS-WFTS has the potential to sort and transport migratory adult salmonids when used in conjunction with a volitional fishway entrance. The main advantage of the combined system is that once fish enter the WESS-WFTS, the potential passage rate can approach 100%. This could eliminate the need and capital expense to fully construct conventional, permanent fishways around large-scale hydropower projects, which can vary widely in passage performance. Rather, the WESS-WFTS could be combined with small-scale volitional fishways that need to serve only as a point of attraction and entry.

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