Guide to Waterfall Fish Barrier Assessment

Jason Blackburn, Brad Hurkett, and Logan Redman
Alberta Conservation Association
101 – 9 Chippewa Road
Sherwood Park, Alberta, Canada
T8A 6J7

EXECUTIVE SUMMARY

Invasive species are a significant threat to native trout populations, and potentially the greatest threat to Westslope cutthroat trout (WSCT) in Alberta, through hybridization and competition. To effectively safeguard against extirpation, it is essential that existing pure populations remain protected from invasive species, and new pure populations are established. Several sub-populations of native trout remain genetically pure because of waterfall barriers that impede upstream migration of invasive fish. Similarly, habitats above barriers represent opportunities to expand the ranges of native trout and their total habitat areas through introduction/re-introduction of pure stocks. To date there is no single assessment method to identify and rank barriers in the context of invasion risk. Our objective was to develop a standard method for assessing natural fish passage barriers. After evaluating approximately 100 known barrier locations and approximately 200 barrier features, we developed a waterfall barrier assessment methodology to identify, measure, classify, and rank a complex range of natural waterfall barriers to upstream fish invasion. We developed methods to quantify and characterize four primary variables that affect upstream invasion potential at waterfall barriers: leaping obstacles, stream velocity, swimming depth, and turbulence. We generated feasible swimming and leaping performance charts to determine theoretical barrier passage by fish size category, and a barrier scoring framework that ranks passage difficulty. Updates to this manual are planned as opportunities for improving the assessment methodology are identified.

ACKNOWLEDGEMENTS

Funding for this manual was provided by Alberta Conservation Association (ACA) and Environment and Climate Change Canada (ECCC). Thank you to the core ACA field crew, Jessy Dubnyk and Kacey Barrett, and to ACA support staff, Scott Seward, Sarah Paterson, and Mark Storey, for your hard work and positive attitudes. We are grateful to Dave Hagedorn (AEP) for providing field camp accommodations at Racehorse Creek Provincial Campground, and to Matthew Coombs and Kenton Neufeld (AEP) for exchange of barrier information and data. Special thanks to Mike Rodtka (ACA) and Peter Aku (ACA) for reviewing this report. Chris Katopodis of Katopodis Ecohydraulics Ltd. provided a comprehensive review and useful suggestions which improved this manual.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

1.0 INTRODUCTION

To effectively safeguard against extirpation of imperiled native trout, it is essential to protect and expand the range of existing populations, as well as to increase the number of new populations. In Alberta, invasive species are a serious threat to westslope cutthroat trout (WSCT; *Oncorhynchus clarkii lewisi)* (COSEWIC 2016), bull trout (*Salvelinus confluentus*) (COSEWIC 2012), and Athabasca rainbow trout (*Oncorhynchus mykiss)* (COSEWIC 2014) populations through hybridization and competition. Although habitat fragmentation is also a major threat to many of Alberta's native trout populations (e.g., road crossing barriers), several subpopulations of WSCT remain genetically pure primarily because of the natural waterfall barriers that impede upstream invasions by non-native species such as rainbow trout (The Alberta Westslope Cutthroat Trout Recovery Team 2013). Maintaining and isolating headwater populations from invasion is critical to the protection and persistence of genetically pure trout (Bingham et al. 2016), which may serve as stocks for restorations and recovery (Fausch et al. 2006). Habitats upstream of barriers also represent opportunities for expanding the range and total critical habitat area of native trout species through introduction or re-introduction of pure stocks (Fausch et al. 2006).

Identification, inventory, and assessment of barriers isolating genetically pure populations of trout and their habitats is necessary to prioritize recovery and build strategies for range expansions on a stream-by-stream basis. Before restoration activities are considered, it is essential to assess waterfall barriers for their potential to protect reintroduced upstream populations from invasive species. To date there is no single recognized assessment methodology to identify and rank natural waterfalls in the context of invasion risk. After evaluating approximately 100 known barrier locations and approximately 200 barrier features, we have developed a barrier assessment methodology to identify, measure, classify, and rank a complex range of waterfall barriers to upstream invasion. This manual outlines detailed methods for measuring and recording data during barrier assessments to ensure datasets are consistent, comparable, and correctable across the native trout species range. The information presented here follows the same order of events required to complete a waterfall fish barrier assessment, as they appear on the Barrier Assessment data form. This manual will be updated as opportunities for improving the barrier assessment methodology are identified.

1.1 Eligible Barriers

In Alberta both natural and anthropogenic obstacles impede fish movements and constrain populations, defining their distributions and upstream limits (COSEWIC 2012, 2014, 2016). Similarly, both forms of obstacles impact population genetics (Wofford et al. 2005; Carpenter 2016; Davis et al. 2018). A standard assessment protocol specific to anthropogenic culvert barriers has already been established (McCleary et al. 2007; Alberta Environment and Parks 2015). Impermanent natural barriers, such as logjams, log waterfalls, land slumps, and beaver dams, temporarily fragment populations (Davis et al. 2018) but are unreliable to secure upstream populations from long term invasion threats. This manual is intended for assessing natural permanent geologic barriers to upstream migrating fish, in the context of invasion risk, and for selecting anthropogenic barriers such as dams and weirs that share more permanent isolation properties that facilitate native trout conservation.

1.2 Barrier Descriptions

1.2.1 Barrier Types

Waterfall is a generic term broadly applied by a casual observer to a wide variety of natural landforms that involve descending water. Powers and Orsborn (1985) were the first to formally categorize waterfalls in the context of barriers to migrating fish into three main groups: waterfalls, chutes, and cascades. We have refined the definitions of these three barrier types based on Reiser et al. (2006) and field observations of natural barriers across the WSCT range in Alberta (key modifications to previous definitions are presented in italics):

- **Waterfall** – an abrupt change in water velocity where water passing over the brink of the crest separates from the streambed *at some point. It does not require total free-fall and may remain or come into contact with the bedrock/precipice face at various points throughout. Usually exceeds a 23-degree angle.*

- **Chute** – a steep gradient where the water stays *mainly* in contact with the streambed throughout the course of the feature. *Usually less than a 23-degree angle.*

- **Cascade** – stream reach where a series of waterfalls and/or chutes of varying intensities *are characterized by turbulence and white-water* resulting from complex and/or chaotic roughness elements. *Broadly encompasses anything that is multi-featured, with turbulence and white-water present.*

1.2.2 Barrier Modes

Barrier modes are the elements that impede fish from ascending instream obstacles, subject to the fish's required mode of travel (swimming or leaping) to successfully navigate past it. We conceived the following four key barrier modes and the requirements for a complete upstream barrier to fish migration, based on common physical instream impediments.

- **Leaping barriers** – the height and/or distance of the barrier exceeds the fish's leaping ability at burst speed.

- **Swimming velocity barriers** – stream velocity exceeds the fish's burst swimming speed performance over a given time and distance.

- **Swimming depth barriers** – flow depth over the obstacle is insufficient for the fish to effectively propel itself over the barrier while swimming.

- **Swimming turbulence barriers** – White-water turbulence presents fish with fluctuating water velocity and orientation difficulties, and/or decreased fluid density of swimming medium, reducing effective swimming power.

Leaping Barriers

Determining whether a barrier can prevent fish from ascending it by leaping depends on the physical dimensions of the barrier, the swimming capabilities of the fish species, and the biomechanics involved in fish leaping (Figure 1).

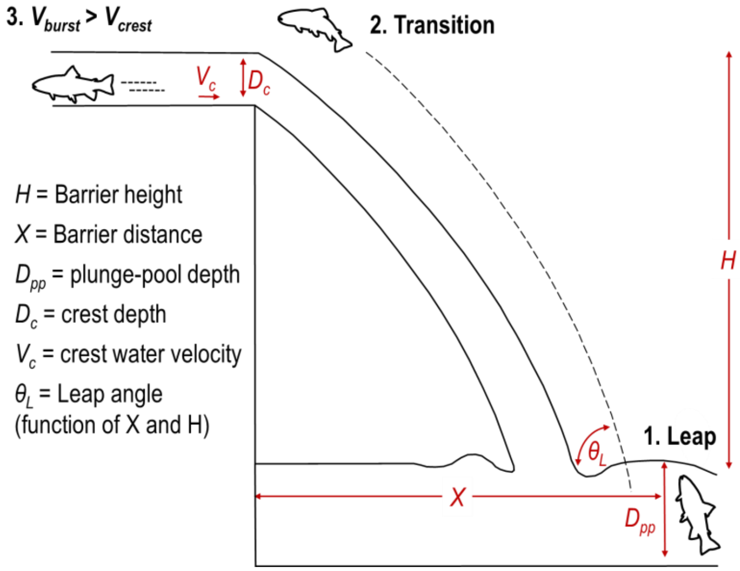


Figure 1. Schematic of the conditions required for successful ascension over a leaping barrier, modified from Powers and Orsborn (1985).

Fish passage over a leaping barrier is determined by comparing the maximum jump height of the fish to the length and height dimensions of the barrier being ascended. Therefore, leaping barriers that prevent fish passage are those that subvert one or more of the conditions required for a successful leap over the barrier. The following are the three conditions required for a successful leap over a barrier (Powers and Orsborn 1985) and the subsequent local variables that could impede fish passage via leaping:

1. Suitable plunge pool depth (D_{pp}) greater than or equal to the fish's length is required for a fish to achieve the appropriate leap angle and gain enough momentum to achieve its maximum jump height. Therefore, D_{PP} less than the length of the fish will result in an unsuccessful leap due to insufficient water depth and subsequently prevent fish passage.

2. Suitable crest water depth (D_c) for swimming is required for a fish to transition from a jump to a swim, upon reaching the barrier crest. A shallow D_c that does not immerse the fish and allow for full swimming propulsion will result in an unsuccessful transition to swimming and subsequently prevent fish passage. Although not typically a limiting factor to fish passage, D_c can be a deciding variable where barriers occur in close succession to one another, where insufficient depth prevents adequate approach, or when staging for the next immediate barrier attempt.

3. To proceed beyond the barrier crest, a fish must have swimming ability greater than the stream velocity at the crest (V_c). Therefore, a V_c greater than the ability of the fish to overcome it would prevent fish passage due to stream velocity. Due to the anatomy of most barriers, V_c is not likely to be a limiting factor to fish passage except where features occur in close succession to one another and when fish approach or stage for the next immediate barrier.

Swimming Velocity Barriers

To determine whether a velocity barrier can prevent fish from ascending it by swimming depends on the fish's maximum swimming speed and the average water velocity within the chute (V_{ch}), from the crest to the pool surface. According to Reiser et al. (2006), passage at velocity barriers is determined by comparing the distance (X) a fish can travel at maximum swimming speed for 15 seconds to the chute length (X_m) (i.e., slope distance) (Figure 2). A simplified theoretical assertion is that if barrier length exceeds the distance a fish can travel in 15 seconds at burst speed, and/or the velocity exceeds the fish's swimming ability, fish passage will be prevented. Not yet accounting for correlation between swim speed and time (i.e., fatigue), the theory is explained in the following simplified calculation and schematic:

$$X_m < V_{burst}\,(15\text{sec}) - V_{ch}(15\text{sec})$$

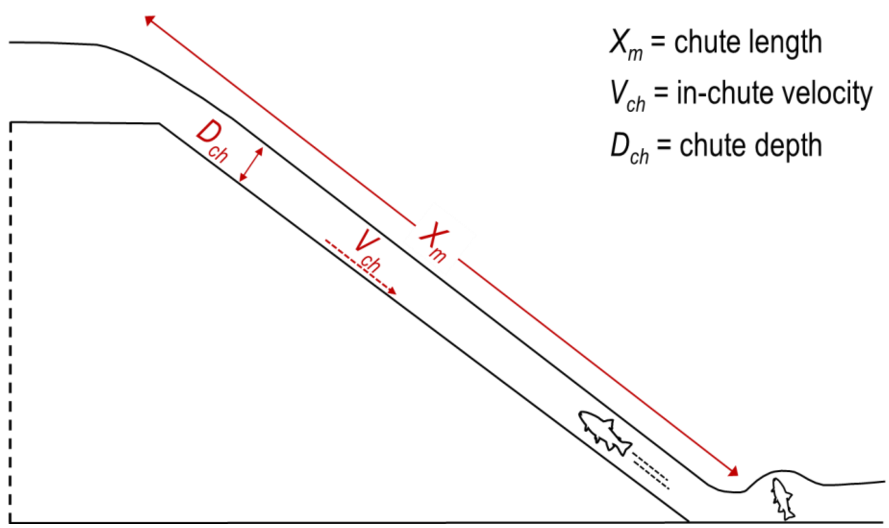


Figure 2. Schematic of the conditions required for successful ascension over a swimming velocity barrier, modified from Powers and Orsborn (1985) and Yeomans-Routledge et al. (2012).

Swimming Depth Barriers

Adequate swimming depth is required for a fish to use its full swimming power (Webb 1975). Water depths that fail to fully submerge the fish impair its ability to generate sufficient thrust. Swimming depth barriers have been recorded as significant impediments to fish movement and in many instances act as greater obstacles than stream velocity (Fox et al. 2016; Stephens et al. 2015). Though larger fish can overcome higher water velocities than smaller fish (Katopodis and Gervais 2016), swimming depths may preclude the passage of larger fish while permitting smaller ones, provided their swimming capabilities can overcome stream velocity (Fox et al. 2016; Stephens et al. 2015) (Figure 3). Consequently, in-chute depth may produce selective barriers (Stephens et al. 2015) where smaller individuals are the potential vectors of hybridization.

Literature-based minimum swimming depth requirements have typically been developed for successful passage through road culverts (Kilgore et al. 2010), to facilitate fish passage with minimal difficulty. The resulting minimum depth recommendations for non-anadromous salmonids from various government agencies are therefore often conservative (e.g., ranging from 12–24 cm) (Hotchkiss and Frei 2007; Kilgore et al. 2010). The Maine Department of Transportation (2004) recommends species-specific critical depths based on 1.5x fish body depth (BD), enabling full immersion of all fins and subsequently maximum thrust potential. We have elected to use 1.5x BD as the minimum swimming depth invading fish would require to ascend chute barriers. Consequently, barriers where average chute depths are less than 1.5x that of an invading fish's BD will prevent fish passage and subsequently upstream invasions.

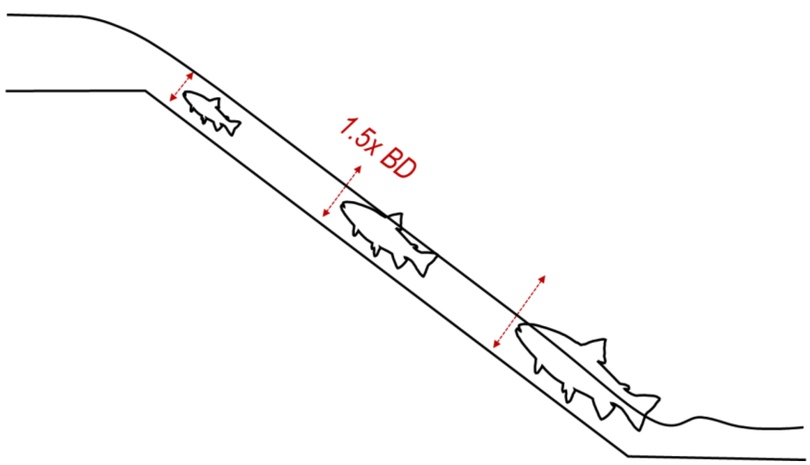


Figure 3. Example of in-chute depth that accommodates passage of smaller fish that are fully submerged, while restricting passage of fish with larger body depths that are unable to make full use of swimming power.

Swimming Turbulence Barriers

Instream turbulence is a major factor restricting fish movements (Fox et al. 2016; Puzdrowska and Heese 2019), and one of the most common obstacles encountered at natural barriers across native trout ranges in Alberta. Typically suppressing fish movement (Lacey et al. 2012), turbulence may either increase or decrease swimming performance (Cotel and Webb 2012; Lacey et al. 2012; Liao 2007). Experts in the fields of fluid mechanics and hydrodynamics have been researching indices to quantify turbulence itself, such as turbulence intensity (Odeh et al. 2002) and turbulence kinetic energy (Puzdrowska and Heese 2019) as meaningful measures limiting fish mobility (Stephens et al. 2015). However, to date, measurement of stream turbulence has yet to become formalized (Franca and Brocchini 2015), and no broadly applicable field assessment application has been developed. Therefore, quantifying this highly complex and unpredictable variable remains largely impractical for broad scale barrier assessments for the time being.

Nonetheless, turbulence remains a key factor governing the efficacy of barriers to prevent invasion and requires a means of assessment. Powers and Orsborn (1985) qualitatively assessed turbulence visually from a perspective of habitat fragmentation—as it limits access to potential spawning habitat by anadromous salmon—and assumed that barriers steep enough to accelerate flows into turbulent white-water were total fish passage barriers (unless a clear leap over it could be attained). Although Powers and Orsborn's (1985) turbulence assessment was not done in the context of invasion threat, we have adopted a similar qualitative approach by incorporating a visual assessment of the white-water turbulence. In addition, we have included key principles stemming from recent laboratory studies that measured fish passage success over barriers, and the relationships between turbulence and fish swimming behaviours and ability (Silva et al. 2012; Amaral et al. 2016, 2018, 2019). The following is a synthesis of those key principles:

1. **Eddie Size and Distribution -** The size and distribution of eddies within a turbulence barrier is thought to be a primary driver of fish swimming behaviour and ability to ascend through this type of barrier (Silva et al. 2012; Amaral et al. 2019). Fish typically overcome turbulence where the diameter of eddies is smaller or larger than fish body length; turbulence with eddies about the same size as fish body length, can cause increased disorientation and/or displacement out of the swimming pathway (Silva et al. 2012). Therefore, turbulence where eddy size is uniform throughout will impede passage of fish that are similar in size to the eddy diameter but allow passage to fish that are smaller or larger than the eddy diameter. Conversely, frequent and abrupt transitions between eddies of different sizes will impede a broader range of fish sizes from ascending the barrier.

2. **Behaviour -** In general fish avoid unexpected fluctuations in water velocity (Amaral et al. 2019) and show a preference for resting areas without turbulence (Amaral et al. 2018). Yet turbulence (and potentially air entrainment) increases fish attraction (Amaral et al. 2016), stimulates upstream ascent (Amaral et al. 2016, 2019), and potentially aids fish in detecting functional pathways through the turbulence barrier (Amaral et al. 2019). The eddies that provide resting areas along a chute barrier may also inhibit fish passage by: causing disorientation and displacement from the pathway (Silva et al. 2012), limiting swimming ability (Amaral et al. 2019), or cueing changes in swimming behaviour (Amaral et al. 2018) that adversely affects successful passage, such as a switch from an ascent to a holding swimming behaviour which may be inadequate to overcome the remaining water velocity along the barrier pathway.

3. **Pathways –** The following are generalizations pertaining to swimming pathways through turbulent flows based on evidence and observations in the above laboratory studies:
   a) Barriers with the most direct swimming pathway up the barrier (i.e., the straightest, shortest route with the fewest obstacles or course corrections) had the highest fish passage rates.

b) Continuous arrangement of roughness elements along the pathway (i.e., substrates) resulted in continuous dissipation of energy, more uniform turbulence, and higher fish passage rates.
c) Barriers with the most uniform turbulence had the highest rate of fish passage despite higher overall velocities because of reduced energy dissipation/flow obstruction.
d) Barriers where velocity, turbulence, and/or air entrainment interacted moderately to heavily with downstream plunge pools attracted and stimulated fish ascent the most.

Consequently, the most passable turbulence barriers to fish are those that are straight with a continuous arrangement of roughness elements, have uniform turbulence and eddy size, and have a downstream plunge pool influenced by turbulent stream flows. Therefore, the most effective turbulence barriers to prevent fish passage are those that require convoluted swimming pathways with directional changes, have transitions between eddies of various sizes, and have downstream plunge pool arrangements that obscure or inhibit detection of functional swimming pathways, and/or misdirect fish in a non-functional travel direction.

Like other barrier modes, turbulence alone may not constitute a complete barrier to fish; however, passage difficulty is likely increased (Puzdrowska and Heese 2019) and compounded with other passage variables and modes acting upon swimming fish. As such, we have chosen to use a categorical methodology to visually assess white-water turbulence intensity and arrangement with the assumption that increased white-water *reduces* the swimming ability of fish attempting to ascend barriers, and that relative visual estimations of air entrainment (i.e., white-water intensity) are indicative of the underlying turbulence.

1.3 Methodology Background – Quantification and Characterization of Barrier Modes

1.3.1 Swimming Theory and Potential

The main factor that determines the ability of fish to ascend a barrier is swimming capability and performance. Fish swimming speeds are generally classified into the following three categories based on endurance and energy consumption; burst, prolonged, and sustained swim speeds (Katopodis and Gervais 2016). Burst speed is the fastest used for capturing prey, avoiding danger, and navigating high velocity flows. It is an anaerobic sprint which uses white glycolic muscle fibres and has the shortest endurance time of <20 seconds. Conversely, sustained swim speed is used for cruising and foraging and consists of slower aerobic swimming (using red muscle fibres) that can be maintained indefinitely without fatigue. An intermediate category is prolonged swim speed involving both aerobic and anaerobic processes with endurances ranging from >20 seconds up to approximately 30 minutes (Katopodis and Gervais 2016). For assessing fish passage barriers, we used burst speed as it relates best to ascending and navigating high velocities.

Maximum burst speeds reported in the literature have typically been measured in body lengths per second (BL/s) and range from 10–15 BL/s (brown and brook trout [*Salmo trutta and Salvelinus fontinalis*, respectively]) in critical and fixed velocity tests (Katopodis and Gervais 2016) to >25 BL/s (brown trout) in volitional swimming tests (Castro-Santos et al. 2013). Although burst speed in BL/s has been determined in various species-specific tests, swimming capability in general is a function of fish size and swimming style as a result of body form and shape (Lindsey 1978). Consequently, fish species that swim the same way may be grouped into categories by swimming style based on their similar means of propulsion; this broadens the application of the swimming performance metric to encompass a wider range of fish populations and barriers. Moreover, use of the BL/s metric critically influences and inflates the range of projected burst swimming speeds (m/s), and subsequent maximum leaping capability of fish, to unrealistic levels when applied directly across a range of fish sizes (Appendix 1). To address these limitations, Katopodis and Gervais (2015, 2016) processed historical swimming performance datasets across salmonid species which share Subcarangiform swimming style. Based on these datasets, they developed the following dimensionless swim speed equation that is independent of fish length and accounts for the variability associated with swimming performance measured in BL/s:

$$U_* = U/\sqrt{gl}$$

Where: U_* = dimensionless swim speed

U = swim speed (m/s)

g = gravitational constant; 9.81 m/s^2

l = fish length (m)

1.3.2 Quantifying Leaping and Swimming Potential

We determined maximum leaping performance—defined as the aerial leap a fish can attain as a projectile travelling at maximum burst speed—using equations from Powers and Orsborn (1985), detailed calculation methods from SFPUC (2010), and trajectory mechanics calculations from the Georgia State University HyperPhysics website (Nave 2016) (Appendix 2). To quantify theoretical leaping performances by fish size, we used the dimensionless swim speed equation by Katopodis and Gervais (2015) and solved across a range of fish length categories. Given the objective of ensuring fish passage success at barriers is minimized and a wide standard deviation in recorded swimming performances, we selected the upper limit of fish burst swimming performance (U_* = 4.0, Katopodis pers. comm.) of dimensionless burst swim speeds for non-anadromous, Subcarangiform fishes, produced from the most instantaneous documented swimming bursts (i.e., between 2–3 second bursts) (Katopodis and Gervais 2015, 2016).

To quantify theoretical swimming potential, we similarly used the upper limit of U_* (U_* = 2.8, Katopodis pers. comm) produced from swimming bursts lasting approximately 15 seconds (range of 9–20 seconds, Katopodis and Gervais 2015). Given that swimming speed and time are correlated, we incorporated fatigue coefficients from Di Rocco and Gervais (2020)—derived from dimensionless swim speed versus time regression for salmonid swimming performance (Katopodis and Gervais 2016)—and predicted swimming speeds relative to distance and water velocity across a range of fish length categories, following the distance equations from Di Rocco and Gervais (2020):

$X_* = M(V_*)^a$
Where: $X_* = X/l$

$V_* = V/\sqrt{gl}$
Where:

X_* = Dimensionless swimming speed
X = Swimming distance (m)
V_* = Dimensionless water velocity
V = Water velocity (m/s)
l = fish length (m)
g = gravitational constant; 9.81 m/s^2
M and a = coefficients derived from dimensionless speed versus time regressions, using upper 95% prediction interval for salmonid group (M = 375 and a = 2.993)

We generated feasible swimming and leaping performance charts to determine theoretical barrier passage by fish size category for leaping barriers (Figure 4), and for swimming velocity barriers that span a range of potential barrier dimensions at different stream scales (Figure 5).

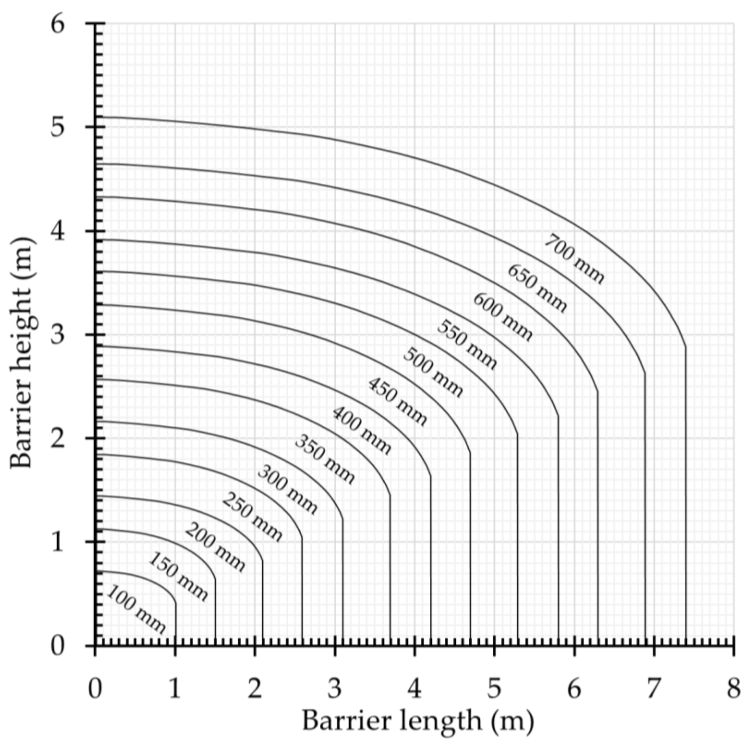


Figure 4. Leaping curves for non-anadromous fishes of Subcarangiform swimming style. The total area that lies beneath an associated size range curve (fish length in mm) represents the theoretical range of leaping barriers passed by fish size class.

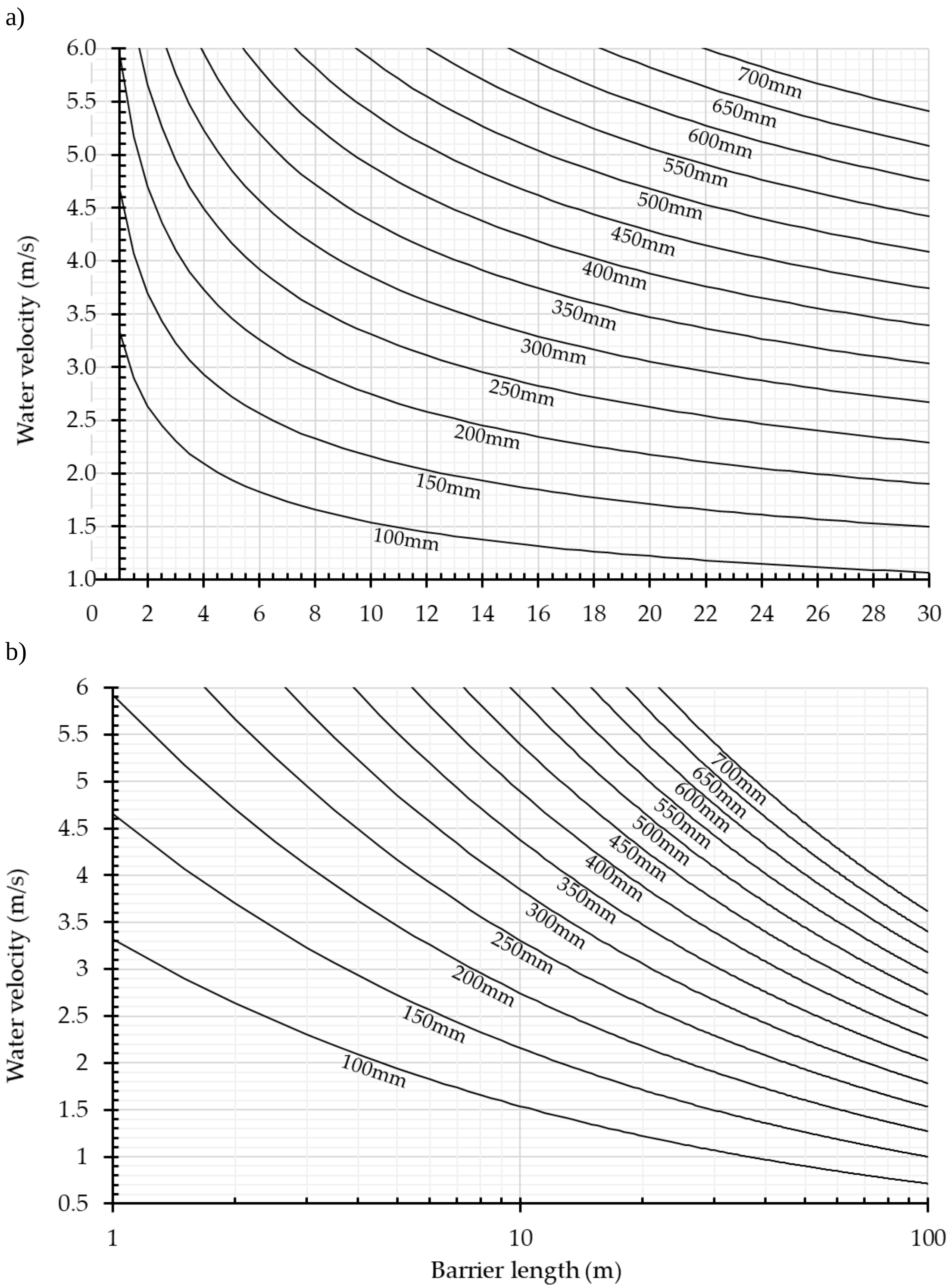


Figure 5. Swimming velocity charts for non-anadromous fishes of Subcarangiform swimming style, spanning a range of barrier dimensions and scopes, for a) site scale and b) reach scale barriers. The total area that lies beneath an associated size range line (fish length in mm) represents the theoretical range of swimming velocity barriers passed by fish size class.

1.3.3 Quantifying Minimum Swimming Depth

We reviewed fish morphometric data from literature (Shah et al. 2011; Vasave and Saxena 2013) and technical sources (Furniss et al. 2006; FishXing Version 3 2006), which suggest a BD to total length ratio of approximately 0.22 for the genus *Oncorhynchus.* Based on minimum swim depth at 1.5x fish BD, we developed the following depth criteria for fish passage through chutes (Table 1).

Table 1. Minimum chute swimming depths for genus *Oncorhynchus* fish by size

Minimum water depth (cm)	Estimated fish body depth (cm)	Fish total length (mm)
3	2.2	100
5	3.3	150
7	4.4	200
8	5.5	250
10	6.6	300
12	7.7	350
13	8.8	400
15	9.9	450
16	11.0	500
18	12.1	550
20	13.2	600
21	14.3	650
23	15.4	700
25	16.5	750

1.3.4 Characterizing Turbulence

To incorporate the relative contribution of turbulence to overall fish passage difficulty at barriers, we identified elements that cumulatively increase fish passage difficulty through turbulence barriers and categorical visual measures for each. We developed categories for white-water **Turbulence Type** and **Turbulence Intensity** from extensive video and photo media collected during preliminary barrier assessments. We also developed sub-categories for **Swimming Pathway Complexity** from extensive literature review of fish interactions with turbulence.

White-water Turbulence Type

The following are descriptions of three broad categories of white-water turbulence types based on appearance, that characterize eddy size distributions and turbulence uniformity. The categories are presented in assumed descending order of turbulence uniformity and increasing order of swimming passage difficulty (Appendix 3).

- **Spillover turbulence** – Caused by an increase in velocity as the stream spills over a uniform drop that is nearly channel-wide or slightly funnelled. Water remains mainly in contact with the feature as it flows over it, and flow is mostly unidirectional with relatively uniform turbulence. Eddies are typically small and uniformly distributed, and swimming pathways are straight and unobstructed.

- **Funnelled turbulence** – Flows are funnelled into a trough, chute, or narrowing which may temporarily consolidate flow volume and increase depths for swimming. However, flows may fold or spiral over themselves and begin to lose contact with the streambed, increasing velocity fluctuations and the intensity of white-water. There is increased potential for larger eddies and eddy size transitions. Swimming pathways may be direct or indirect.

- **Diffuse turbulence** – Flows are broadcast into many directions resulting in violent, frothy white-water and spray. Stream flow is not consolidated into functional flow paths for swimming and water frequently leaves or 'bounces' off the streambed surface resulting in broken, indirect swimming pathways with fluctuating velocities and multiple eddy size transitions.

White-water Turbulence Intensity

The following are descriptions of the three broad categories of white-water turbulence intensity based on appearance and presented in increasing order of passage difficulty. Descriptions characterize air entrainment resulting from uneven roughness elements and chaotic turbulence, relative stream energy, and potential of increased disruption and confusion in fish swimming cues (Appendix 4).

- **Infused** – Slightly more white-water than non-white-water, or approximately equal proportions of each. Although mixed or laced together, differentiation between white-water and non-white-water is not difficult. A definite obstacle but likely passible by certain fish size classes at various flows.

- **Agitated** – Flows are primarily white-water. Passage is difficult, but the white-water turbulence alone is not likely a reliable barrier to prevent invasion from the best of swimmers, or from chance events associated with chaotic turbulence that may propel fish.

- **Saturated** – Discerning anything non-white from the frothy white-water and spray is nearly impossible. Passage is extremely unlikely.

Swimming Pathway Complexity

The complexity of swimming pathways through turbulence is categorized based on the following three components, and their categories, which cumulatively increase passage difficulty (Table 2).

- **Directness of route** – Assesses whether a successful swimming pathway requires en-route changes in swimming direction that may disrupt upstream travel.

- **Eddy uniformity and distribution** – Assesses whether a successful swimming pathway must transect eddies of difference sizes and turbulence that may disrupt upstream travel.

- **Plunge pool orientation** – Assesses whether flow interaction with the plunge pool acts to inhibit detection of a functional route through the turbulence barrier by misdirecting fish in a non-functional pathway or travel direction.

Table 2. Components of swimming pathway complexity and descriptions of their categories

A) Directness of route	B) Eddy uniformity and distribution	C) Plunge pool orientation
1 – Direct Passage route through the barrier feature is straight and direct from the plunge pool to the nearest resting area. **2 – Indirect** Successful passage through the barrier feature requires en-route course correction from the plunge pool to the nearest resting area.	**1 – Uniform** Eddy size along the passage route through the barrier feature is relatively uniform from the plunge pool to the nearest resting area. **2 – Interrupted** The pathway from the plunge pool through the barrier feature transects one major eddy size transition before the nearest resting area. **3 – Obstructed** The pathway from the plunge pool through the barrier feature transects multiple eddy sizes and turbulence transitions before the nearest resting area.	**N – Normal** Barrier orientation allows normal flow-through with the plunge pool below, promoting a normal swimming cue and passage in a net upstream direction. **1 – Inhibitive** The barrier orientation is positioned so that flows interacting with the plunge pool do not cue a swimming response in a net upstream direction, such as flows entering a plunge pool at oblique angles to the general direction of streamflow, confusing directional swimming cues.

1.3.5 Flood Inundation

An important consideration influencing the reliability of barriers to prevent invasion is the degree to which they become inundated during flood events and passage difficulty is reduced. Barrier assessment during floods is unsafe; however, a practical site-level approach can be applied during safe flow conditions to estimate the 'height' of flood water levels in relation to a barrier feature. Estimating the degree of barrier inundation during a 50-year recurrence interval flood event (50-year flood) can be accomplished using a combination of qualitative observation (evidence of past flood debris in trees) and established quantitative channel measurements. The flood-prone level (H_{hp}) is approximately twice the level of a stream's bankfull-depth (D_{bf}), where bankfull represents annual or biennial flooding (freshet) approximately reaching the rooted woody vegetation at the channel transition (Rosgen 1996) (Figure 6).

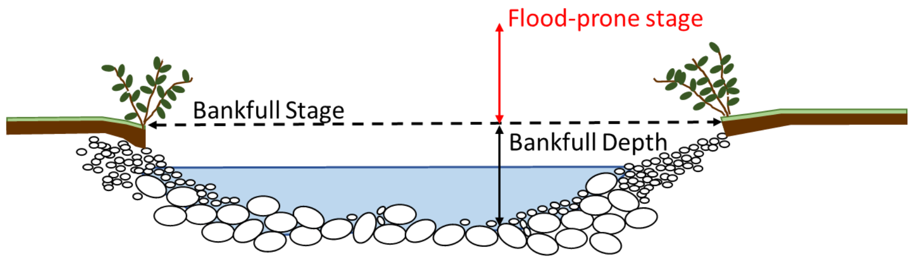


Figure 6. Illustration of 50-year flood-prone height relative to bankfull depth, per Rosgen 1996.

While the impacts to streamflow levels and heights in constricted valleys and canyons is difficult to predict, local evidence of scour may help estimate local bankfull and flood-prone water levels. Estimates of flood level velocities and turbulence are not predictable; however, the relative flood height in relation to barrier height is an element that can be estimated, recorded, and categorized. We have identified the following broad barrier inundation categories to estimate potential impacts on fish barriers as a result of flood level flows (Table 3).

Table 3. Barrier inundation categories and estimated impact on barrier reliability

Category	Condition	Predicted effect during flood
Low water barrier	Barrier height is below the stream's bankfull height, passable during higher flows and freshets	Inundated
Seasonal barrier	Barrier height is above the bankfull height but below the local estimated flood height, passable during flood events	Likely Inundated
Effective barrier	Barrier height is above local estimated flood height but may be reduced during flood. Likelihood of passage during flood depends on local fish sizes and abilities to ascend reduced barriers.	Reduced Barrier
Permanent barrier	Barrier height remains far above local estimated flood height or past flooding evidence and well beyond the estimated swimming and leaping abilities of even the largest fish.	Impassable

2.0 PRE-ASSESSMENT PLANNING

2.1 Barrier Locations – Cataloguing

Prior to initiating ground surveys to search for new barriers, assess known barriers, or rank upstream habitats, cataloguing of current barrier information is essential. We generated a comprehensive list of known barrier features across the WSCT range through information exchange with local Alberta Environment and Parks biologists, past fisheries and habitat inventory searches (Fisheries and Wildlife Management Information System), backcountry trail maps, hiking/tourism resources, county and municipality maps, and internet sources and imagery such as Google Earth® and Bing Maps®.

2.2 Barrier Locations – Mapping

Geographic and landscape conditions that contribute to the occurrence of fish passage barriers often make it difficult to acquire accurate waypoint information in the field as barriers often occur in remote canyon areas with poor satellite reception. Prior to ground surveys, it is beneficial to plot existing barrier waypoints onto spatial imagery such as Google Earth® or LiDAR to ensure locations align with features visible on the imagery. Confirmation of locations prior to ground surveys will help locate known barriers more precisely, and potentially identify previously unknown features or series of features nearby that are associated with the same geographic landform. Using both ground-acquired and GIS-assigned waypoints is an effective way to ensure known barriers are located and additional nearby barriers are discovered. To facilitate barrier searches, GIS modelling tools such as valley confinement can help focus search areas. Narrow valleys, high gradient areas, valley pinch and knick-points, and abrupt elevation changes are all places where fish passage barriers may occur. Identification of these locations prior to field surveys can help focus ground (or aircraft) searches, as well as delineate upstream watershed areas for potential stream-specific management and recovery strategies and actions.

2.3 Timing of Assessments

Where possible each barrier should be assessed on a minimum of two separate occasions: during the spring freshet window at high flows, and during a lower flow period in late summer or fall. These two time periods account for the change in barrier height due to water level and coincides with the conditions likely encountered by both spring and fall spawning trout migrations. The timing of peak flow periods can be determined by consulting hydrograph information from regional gauging stations. The spring freshet window in the southern portion of the WSCT range is narrow, lasting approximately one month from mid-May to mid-June, before receding to summer streamflow levels. The freshet can vary in duration from as little as one week, up to one month. Lower flow periods tend to extend much longer than the freshet window allowing for a longer assessment period during the lower base flow months of late summer and fall. Stream flows may also change the barrier modes that prevent fish passage. A spring swimming velocity barrier in a chute may change to a water-depth barrier in the summer or cease to be a barrier. Similarly, a waterfall leaping barrier at a tributary mouth to a large river during the summer may cease to be a barrier during freshet when the river channel inundates the waterfall crest of the tributary.

2.4 Seasonal Flow Categories

To facilitate classification and analysis of barrier assessment data, we have grouped seasonal flows into the following categories relative to water level, assigned based on visual characteristics of the stream channel at the levels encountered at the time and location of assessment:

- **Spring Flows**

  Streams are at high, or spring flows, when the stream channel is at or near bankfull at the time of assessment. Water clarity is typically silty or stained as sediments remain entrained in the water column. Fording or wading of streams is generally unsafe during this period. Spring spawning migration behaviours are best observed during this window which can prove insightful to verify potential swimming paths through chutes and leaping heights at waterfalls.

- **Summer Flows**

  During summer flows, areas of the streambed and channel have become exposed, such as along stream margins, and areas of deposition such as gravel bars and inside bends of meanders are no longer submerged. Water clarity is increased as finer suspended sediments have mainly settled out. Wading, navigating, and accessing sites along the channel is typically safer and more feasible during summer flows.

- **Low Flows**

  Flows are considered low when much of the streambed is exposed. Riffle reaches may appear to have unsuitable swimming depths for adult-sized fish. Side channels and pools may become disconnected from the thalweg, and flows within the thalweg may become braided, and/or fragmented longitudinally by dry channel or sub-surface reaches. Foot access along the stream channel is easiest and safest during low flows.

3.0 ASSESSING BARRIERS

A comprehensive assessment of features within the barrier must first be completed before a final classification and definition of the overall barrier can be made. Since we cannot predict which mode(s) fish will use (i.e., leaping or swimming), each feature is first measured as a leaping barrier (i.e., leaping height and distance) regardless of barrier type. When a feature is also deemed a swimming barrier (i.e., a chute), additional swimming barrier mode measures are taken (i.e., stream velocity, water depth, and turbulence). When barriers consist of several consecutive features (i.e., a cascade), each successive feature is identified, enumerated, and measured to collectively assess overall fish passage of the barrier at prevailing flows during the assessment. Once the entire barrier has been characterized, the measurements and factors that either limit or permit fish passage can be assessed later to comprehensively determine the size range of fish passage and barrier score.

Assessments are best performed from below the barrier in an upstream, fish-migration direction, in crews of three people. Working from the base of the waterfall, surveyors collect measurements based on the conditions for a successful leap. Minimum barrier dimensions for eligibility of assessment are approximately 0.75 m in height and 1.0 m in length; juvenile trout as small as 100 mm can attain a maximum vertical leap of 0.75 m and a horizontal leap of 0.90 m, while spawning-sized WSCT (i.e., 150 mm, Fisheries and Oceans Canada 2014) can attain a maximum vertical leap of over 1.1 m and horizontal leap of over 1.5 m.

3.1 Stage 1. Assess as a Leaping Barrier

Of key importance to the final evaluation and scoring of a barrier feature is identifying its primary barrier mode (i.e., a leaping or swimming barrier to fish). This is done after the initial assessment of each feature as a leaping barrier; it is not always an obvious determination and may require post-assessment review of information.

Assign and record the primary barrier mode onto the data form (Appendix 5) as leaping only when the barrier feature is mainly a vertical obstruction with free falling water or leaping is the only means to ascend it. When there is ambiguity as to the primary barrier mode (i.e., whether the barrier can be leapt or swam), conservatively assign and record the primary barrier mode onto the data form as swimming; leaping variables will still contribute to the overall evaluation since every feature is first assessed as a leaping barrier prior to determining the primary barrier mode.

Based on observational records from fish barrier assessments conducted at bankfull conditions in the WSCT core area of Southwest Alberta, we found barrier angle to be a useful guide for determining barrier feature type (i.e., waterfall or chute) and the subsequent primary barrier mode. As slope approached approximately 23 degrees, barriers began to exhibit waterfall characteristics, with water leaving the streambed surface into a free fall trajectory (i.e., leaping barrier); barriers with a slope less than 23 degrees demonstrated mainly chute characteristics, with water remaining in contact with the streambed surface (i.e., swimming barrier). Features with slopes at or near the transition angle of 23 degrees were somewhat ambiguous and therefore are assigned as swimming barriers under the current framework.

3.1.1 Step 1. Measure Barrier Dimensions

Barrier height (*H*) and **barrier distance (*X*)** (Figure 7) are collected using a precision laser rangefinder. We used a TruPulse® 200x (Laser Technology Inc.) capable of measuring height, slope, and distances with precision to ± 4 cm. Take measurements facing the barrier head-on (perpendicular) in the straightest line possible. Steady the rangefinder with a prop-rod such as a wading staff or walking stick to reduce incidence of user error like head-tilt. Target the boil line of the plunging water and the lowest plane of the waterfall crest (fish landing area) to determine both height and distance measurements (auto-calculated by the rangefinder). Waterfall **angle (°)** and **slope length (X_m)** (crucial for chute assessments) may also be determined from these initial readings (Figure 7). To ensure accuracy of measurements, several height and distance measurements should be taken until consistent readings are achieved with the rangefinder. Occasionally the waterfall crest or the boil line targets may be obscured due to glare, obstruction, or severe white-water elements. On these occasions a second crew member should provide a reflective target (e.g., bicycle reflector fastened to a telescopic pole) to aid in precision target acquisition. If barrier height measurements seem questionable, they can be cross-validated using a measuring pole.

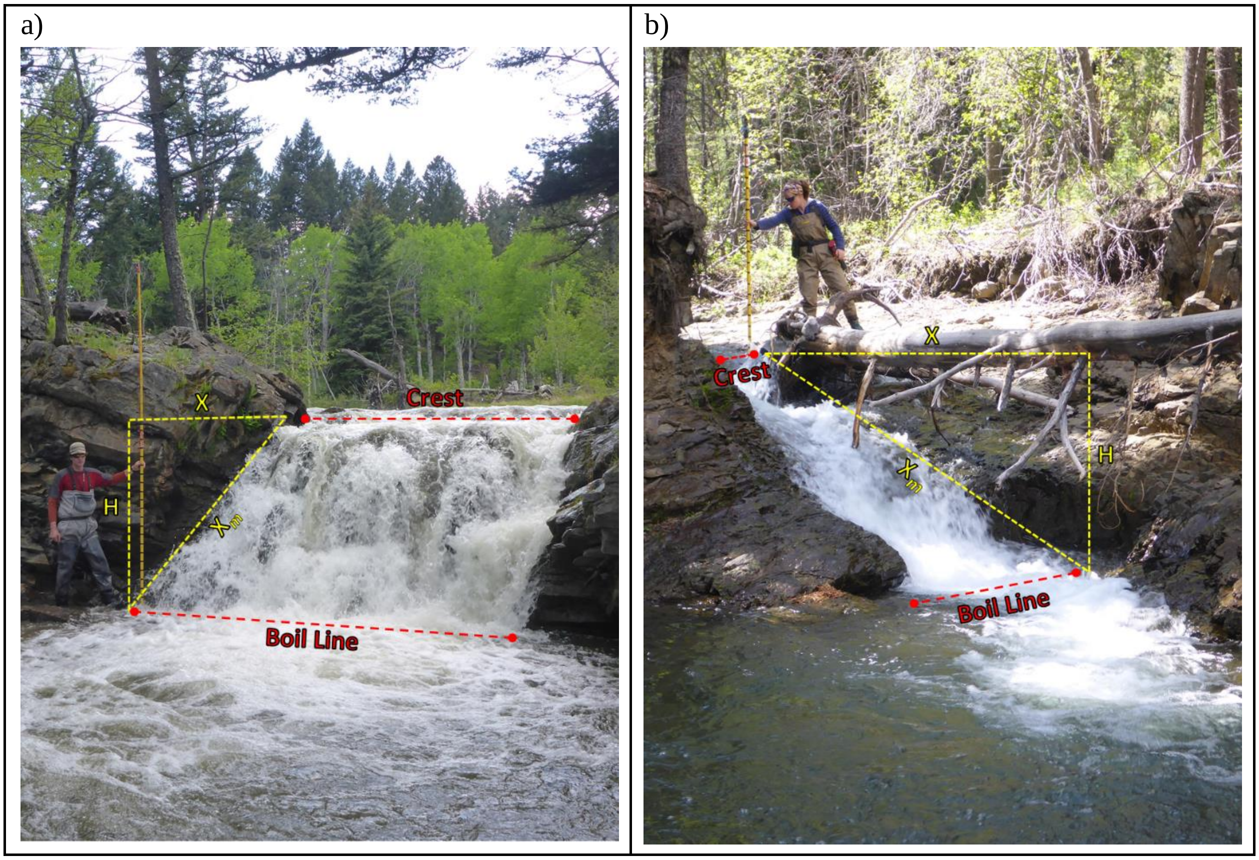


Figure 7. Crest and boil line target locations, and associated barrier height (*H*), barrier distance (*X*) and slope length (X_m) measurements of a) waterfall and b) chute leaping barriers.

3.1.2 Step 2. Plunge Pool Measurements

Measure the maximum $\boldsymbol{D_{pp}}$ to the nearest decimetre (dm) where the fish initiates its leap at the boil line using a graduated staff or a sounding line. A weighted sounding line may be attached to a telescoping pole to safely reach into the channel or a measuring staff may be used when flow and depth are safe for wading (Figure 8, a–b). Where no boil line or suitable leaping area is available at the barrier approach, measure an additional $\boldsymbol{D_{pp}}$ at a more suitable leaping area and record the associated proximity and modified dimension measurements per Step 1.

To determine if maximum leaping performance is hindered by penetrating water turbulence, assess relative **penetration depth (**$\boldsymbol{D_p}$**)** of the plunging water into the plunge pool below (Figure 8) to determine if plunging turbulence extends to the full water column beyond the streambed (i.e., exceeding the pool depth). If it does not, estimate the approximate depth (m) of plunging turbulence. A waterproof digital camera affixed to a selfie-stick or rod can help estimate relative plunging depths when water clarity is suitable (Figure 8, c–d).

Measure **back eddy velocity (**$\boldsymbol{V_{eddy}}$**)** to determine if a back eddy is present in the plunge pool—a back eddy could facilitate leaping performance of fish by increasing maximum burst speed. To measure $\boldsymbol{V_{eddy}}$ we used a FH950 portable velocity meter (Hach®) with a 20-foot cable and a transducer mounted to a telescopic pole, and extended the transducer into the water column positioning it in an upstream direction and parallel to stream flows (Figure 8, e–f). If velocity in the boil line reads a negative value, a back eddy is present, and the negative velocity value (m/s) is recorded as the $\boldsymbol{V_{eddy}}$.

3.1.3 Step 3. Crest Measurements

After measurements below the waterfalls are completed, access the top of the waterfall (if possible) to measure **crest velocity ($\boldsymbol{V_c}$)** in the fish landing zone using the velocity meter and telescoping pole (Figure 8, e–f), and measure a **crest depth ($\boldsymbol{D_c}$)** (cm) in the landing area using a graduated staff or graduations on the velocity meter pole. Collect wetted and rooted width measurements a short distance upstream of the waterfall using the rangefinder to characterize the stream channel at prevailing flows. If any part of the barrier is not accessible due to confined canyon terrain or dangerous flows, a useful assessment can still be completed by estimating the depth measurements (i.e., $\boldsymbol{D_{pp}}$, $\boldsymbol{D_c}$) and approximating the velocity (i.e., $\boldsymbol{V_c}$) by measuring comparable swift water in the vicinity of the barrier at prevailing flows.

Figure 8. Leaping barrier measurement of plunge pool depth using a) sounding line and b) measuring staff. Examples of c) shallow plunge pool turbulence and d) deep plunge pool turbulence. A velocity transducer e) affixed to an extending pole and f) used to measure crest velocity.

3.2 Stage 2. Assess as a Swimming Barrier

If the barrier is consistent with a chute barrier type, assess it as a swimming barrier. Identify potential swimming pathway(s) through the barrier where the majority of stream flows are channeled, beginning at the base where flows interact with the plunge pool area. Identify if the plunge pool and barrier-approach orientation is a **normal** flow-through arrangement or **inhibitive** (i.e., directing fish in a non-productive swimming direction or pathway) (Figure 9). Assess pathway(s) through the barrier recording whether they are **direct** (straight) or **indirect** (crooked), and if distribution of eddy sizes and turbulence is **uniform**, **interrupted** by a major eddy size transition, or **obstructed** by multiple eddy size and turbulence transitions (Figure 10). Record swimming mode measurements and observations along the pathway including chute **slope-distance (**X_m**)**, **in-chute velocity (**V_{ch}**)**, **in-chute depth (**D_{ch}**), turbulence type,** and **turbulence intensity**. Both **slope distance (**X_m**)** and **angle (°)** of the chute are calculated during the leaping barrier assessment.

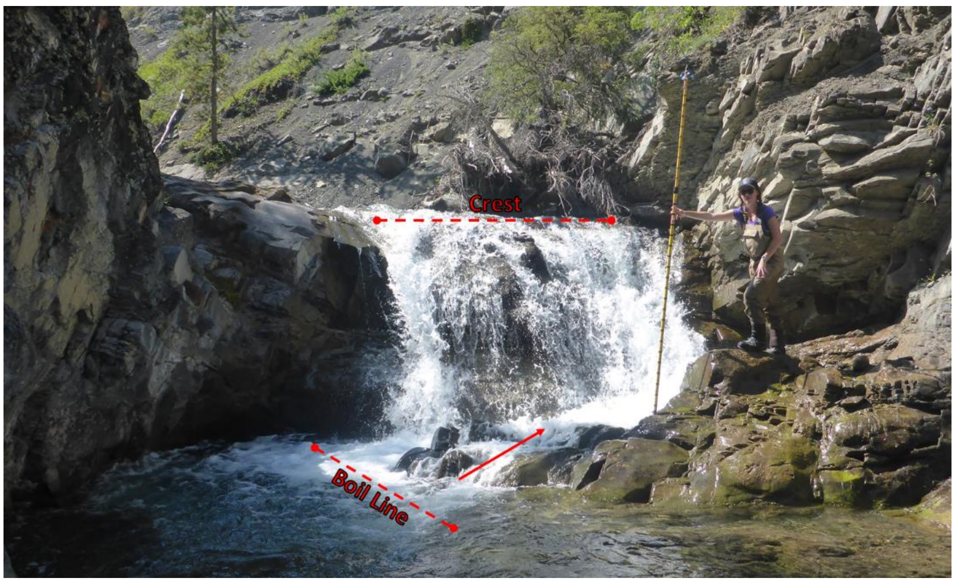


Figure 9. Example of an inhibitive plunge pool barrier approach (albeit a leaping barrier). Arrangement of the boil line and the direction of flows cue migrating fish in a non-functional pathway (arrow) that is oblique to the upstream direction of travel leading onto a shelf of plunging water, bedrock, and rubble.

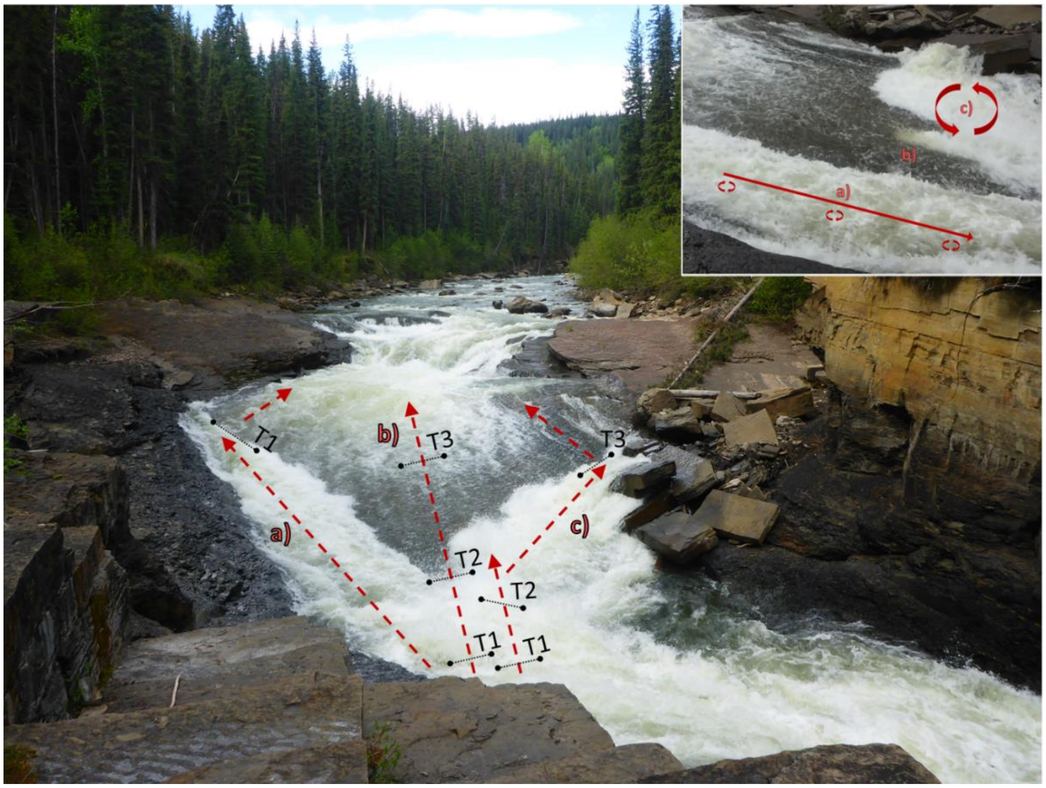


Figure 10. Head on view (main) and side profile (upper right) of a chute barrier with three examples of pathways through turbulence (dashed arrows): **a) indirect and interrupted**: pathway bypasses intense fluctuating turbulence and large eddies at the base of the chute, continues through uniform turbulence and makes one major course correction near the top of the chute, across one eddy size transition (T1); **b) direct and obstructed**: pathway proceeds through a turbulent area of large fluctuating eddies at the base of the chute (T1), transitions into uniform turbulence with high velocity and small eddies (T2), and into a second area of large fluctuating eddies near the top of the chute (T3); and **c) indirect and obstructed**: pathway proceeds through a turbulent area of large fluctuating eddies at the base of the chute (T1), continues across an area of converging flows (T2), makes a major course correction through more uniform but high intensity turbulence, followed by a second major course correction transitioning from intense large fluctuating eddies into smaller uniform eddies with higher velocity (T3).

Take in-chute measurements at three locations, if possible, along the prospective pathway (near the base, mid-chute, and below the crest) (Figure 11) so an average can be determined for final barrier scoring and evaluation. When measuring velocity, the telescoping pole must be held firmly in position, often tight against the bedrock slope for the flow meter to stabilize and chart an accurate velocity reading. This can be particularly challenging in swift-water flows. The transducer should be upright and facing upstream, per manufacturer's recommendations, and parallel to the flow direction and the chute angle. Reaching into a chute from the bank often alters the transducer angle; therefore, it is necessary to re-position the transducer with the setscrew to achieve the required orientation in the water column.

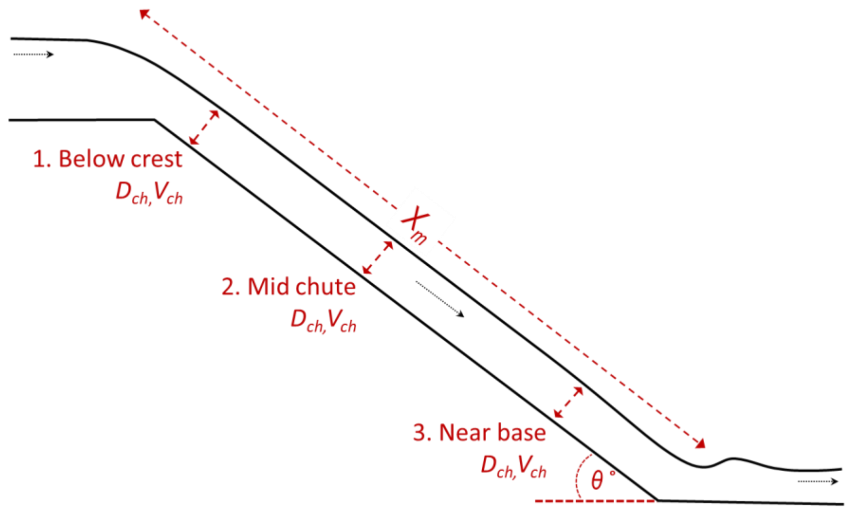


Figure 11. In-chute depth (*D*) and velocity (*V*) measurement locations when assessing as a swimming barrier.

Take in-chute depth measurements (m) at locations similar to the velocity readings (Figure 11). In-chute depths can be approximated using the velocity pole if necessary. Swimming depth is more often a primary barrier mode than velocity is, particularly during low flows when in-chute depth is not sufficient to fully submerge the transducer and obtain a velocity reading. When this occurs, the primary barrier mode becomes swimming depth and should be recorded as such. Conversely, during spring flows, the velocity meter may be incapable of accurate measurements due to turbulence elements and white-water occurring within the chute. Under these circumstances, record on the data form that turbulence has influenced the accuracy of velocity measurements and is likely a primary barrier mode affecting swimming performance and ability. Where depth or velocity measurements cannot be obtained due to access or safety limitations, estimate these measurements as indicated in Stage 1 for leaping barriers.

3.3 Stage 3. Compound Barriers – Assessing Cascades

A compound cascade may have numerous chute and waterfall elements over a short distance (Figure 12). For each successive features, number, measure, and classify them onto the data form to organize multiple feature data (Appendix 5). The most difficult limiting feature of the easiest route will typically determine the overall barrier score (Figure 12). If cascade features occur in succession without separation (i.e., waterfall directly to a waterfall or chute, or chute directly to a waterfall or chute), measurements of V_c and D_c are crucial (particularly D_c) to determine fish passage limitations as a result of successive features not separated by a resting area (plunge pool) (Figure 13).

Figure 12. Compound cascade that can be assessed as a chute and two waterfalls (yellow arrows) or as four consecutive waterfalls (red arrows). Final barrier ranking will be determined by the most difficult limiting feature along the easiest route at prevailing flows (likely Feature 2, red arrow).

Figure 13. Successive cascade features without resting separation assessed as a waterfall and a chute. Shallow crest at Feature 1 may be a limiting factor, preventing fish passage or precluding access to or navigation of Feature 2, due to inadequate depths for leaping and/or swimming at the approach.

A completed data form with measurements recorded of all individual features within the barrier is required for effective evaluation. Where feature measurements of depth (i.e., D_{pp}, D_c, and D_{ch}) and stream velocity (i.e., V_c and V_{ch}) cannot be obtained, approximate them as mentioned in Stage 1 and record that information on the data form to enable completeness of barrier datasets and effective future evaluation of the barrier.

On occasion cascades may span long distances, such as those caused by landslides or rockfalls (Figure 14), where measurement of individual features is neither practical nor feasible. In such cases, complete detailed assessments of the most downstream feature and select major features within the cascade sequence. Measure the entirety of the landform for total distance and slope; log those measurements on a GPS, with individual features enumerated and waypoints taken throughout, to ensure the total extent of the barrier can be represented in a GIS.

Figure 14. Example of an extensive Boulder Cascade caused by a rockfall that buried 178 metres of stream channel.

3.4 Photo and Video Capture

Take representative photos and number each barrier feature for cataloguing purposes. Take a minimum of one photo from below the feature at stream level looking upstream for the most representative depiction of barrier height, as waterfalls viewed from crest height appear taller than they are (Figure 15). Include a profile (side-view) photo when possible for added perspective and validation of barrier angle measurement from Stage 1, as barriers observed head-on from below will appear steeper than they are (Figure 15). Also include a human scale subject and measuring pole in the photos to illustrate relative barrier size and account for changing perceptions that occur when viewing the barrier from different perspectives.

Potentially the most useful medium to fully characterize barriers is 5–10 seconds of video footage taken from below the barrier, looking upstream. Only video can illustrate hydrologic features such as flow direction through chutes, turbulence elements, and overall stream power to estimate potential migration pathways through the barrier. Video is also crucial for desktop review and assessment of barrier passage, scoring, and evaluations. Underwater video (i.e., with selfie stick) is also useful to verify fish presence below barriers to confirm upstream extents of fish distributions on individual waterbodies.

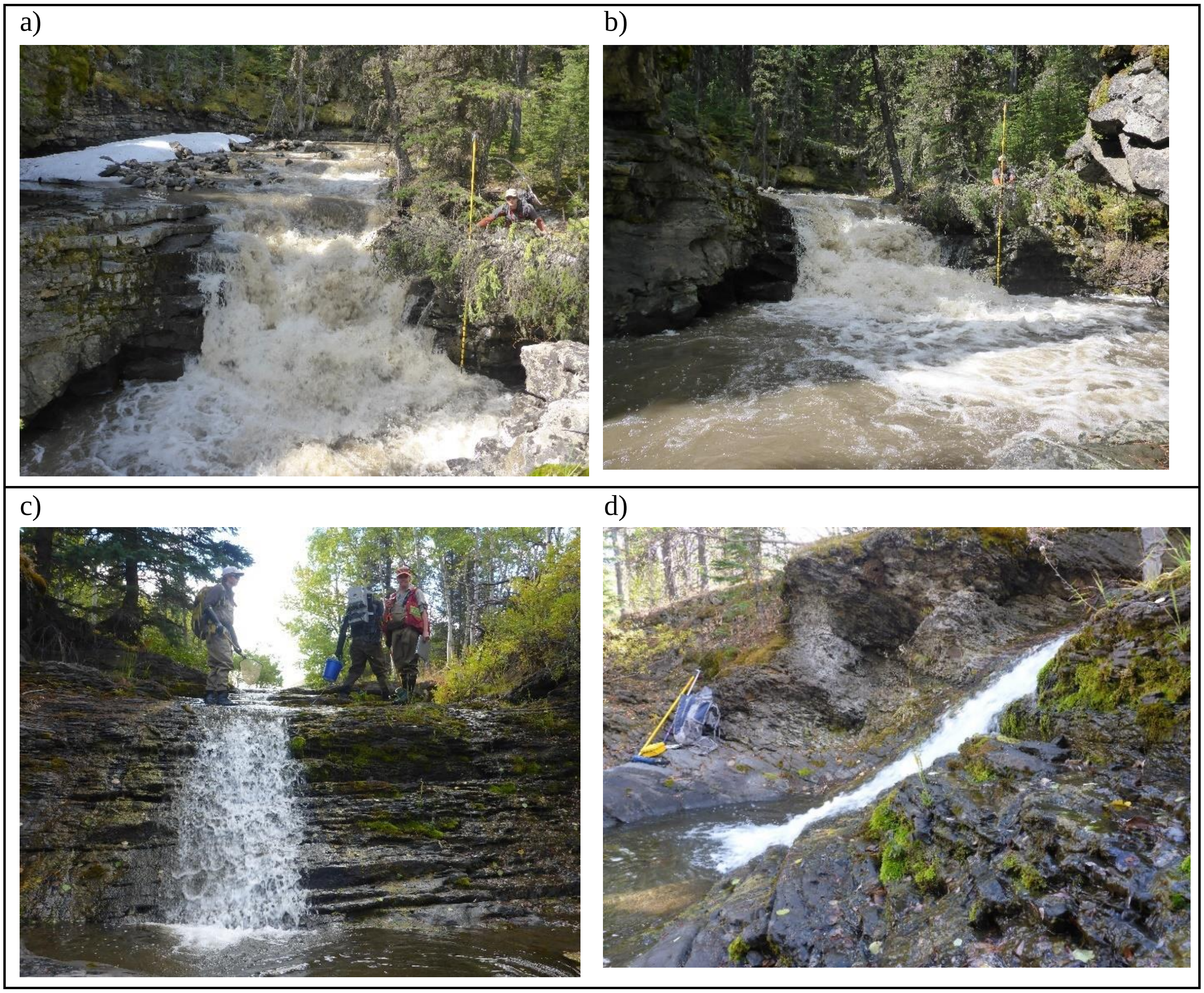


Figure 15. A waterfall barrier that appears taller and steeper when viewed from crest height (a) than from pool level below (b). A waterfall barrier that appears nearly vertical when viewed head-on (c) but is more gradual when viewed in profile (d).

3.5 Stage 4. Estimating Barrier Inundation

Estimate flood level at a riffle or run stream reach (Rosgen 1996) that is not directly impacted by scouring and widening effects of the barrier itself (if possible), either at a nearby upstream reach or while approaching the barrier from downstream. Barrier inundation category can be determined from a few simple measurements. The **bankfull depth (D_{bf})** is calculated as the sum of maximum **thalweg depth (D_{th})** and the vertical distance from the water surface to the bankfull channel boundary (**bankfull height** [H_{bf}]). Estimate the maximum D_{th} using a measuring staff or sounding line to the nearest decimetre. Using the TruPulse 200x laser rangefinder, measure H_{bf} safely from either bank using the auto-calculated height from the two distance/incline measurements (Figure 16). Calculate the sum of D_{th} and H_{bf} to determine D_{bf} to the nearest decimetre. Double D_{bf} to determine flood prone level and subtract D_{th} to estimate the **flood height (H_{fl})** from the water surface relative to the barrier. Select one of the barrier inundation categories that best describes the relationship between crest, bankfull, and flood level heights.

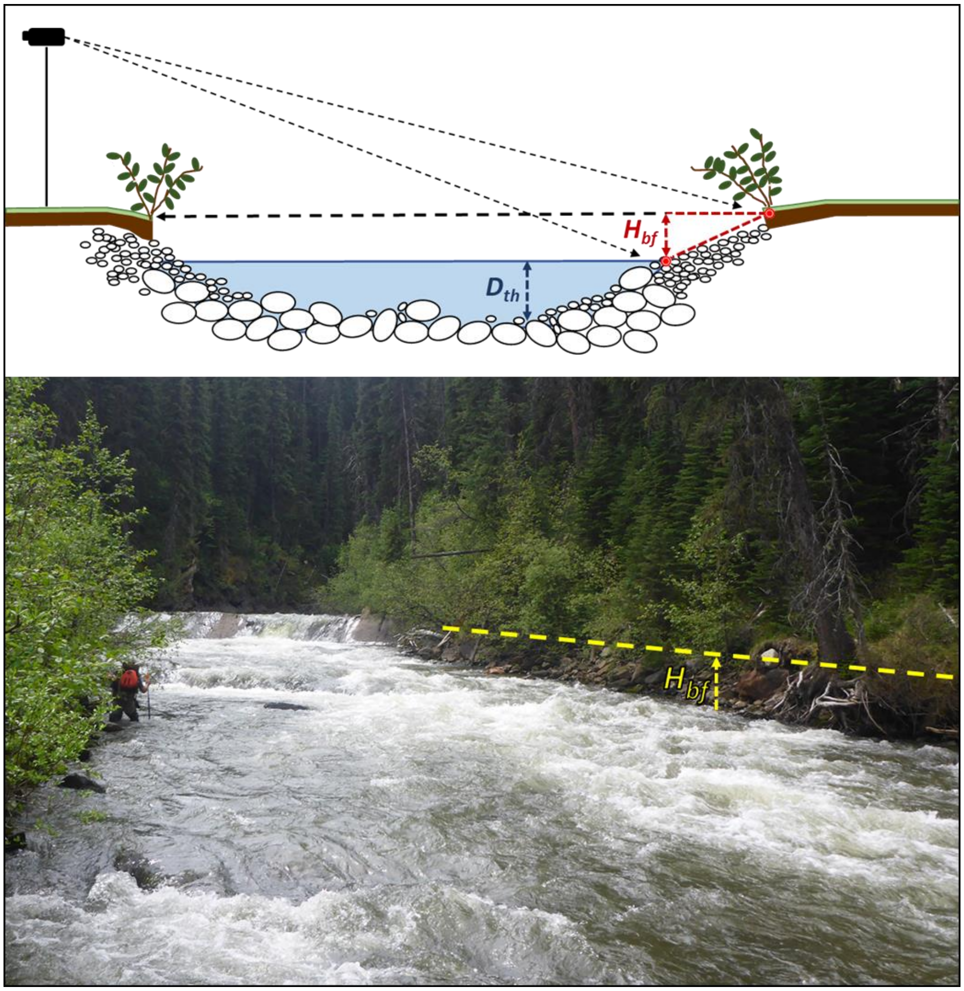


Figure 16. Location of bankfull level, and measurements for estimating bankfull stage and flood height.

4.0 BARRIER CLASSIFICATION

Before barriers can be effectively evaluated and ranked in terms of passage, a comprehensive classification and cataloguing system was necessary to identify and characterize the complex range of barrier forms that exist. We have developed a system to classify barriers based on Type, Class, Mode and Descriptor. Most barriers are composed of several features with a single overarching barrier type to describe the whole. The classification system used to describe individual features and the overall barrier type is the same. Assignment of the overall barrier type is completed last, after all feature types within the barrier have been examined. All levels of barrier classification are subject to change with flow level and are accurate only during flows at which they are assessed.

4.1 Barrier and Feature Types

The first level of classification includes the following three barrier **Types,** previously discussed in Section 1.2: 1. Waterfall, 2. Chute, and 3. Cascade. When waterfalls and chutes occur singly (i.e., a barrier that is composed of a single feature), the feature type is also the overall barrier type. When several chutes and/or waterfalls occur in rapid succession or combination, the overall barrier type is collectively a Cascade, but features within the barrier are labelled individually as waterfalls or chutes.

4.2 Barrier Class

The second level of classification is barrier **Class**, which describes the complexity of each feature by type. The following barrier classes and definitions have been modified from Powers and Orsborn 1985 (Table 4).

Table 4. Definitions of barrier classes by type

Type	Class	Definition
Waterfall	Single	Entire stream flows through a single opening offering one path for fish passage.
	Multiple	Flow divides into more than one channel offering several passage routes of varying difficulty.
Chute	Simple	Uniform cross-section and slope, generally straight, with supercritical flow throughout.
	Complex	Cross-section varies, several changes in slope, winding channel, white-water at all stages.
Cascade	Compound	Combination of falls and/or chutes.
	Turbulent	Severe instream roughness elements churn the flow into surges, boils, eddies, and vortices.
	Boulder	Large instream boulders constrict flows creating hydraulic drops from upstream to downstream, resting areas intermittent, turbulent pools.

4.3 Barrier Mode

The third and most essential level of classification is the barrier **Mode**, describing the fish transportation mode of ascension at each barrier feature. The four modes, previously discussed in Section 1.3, are: 1. Leaping barriers, 2. Swimming velocity barriers, 3. Swimming depth barriers, and 4. Swimming turbulence barriers. More than one mode per barrier feature may be required to effectively describe it, depending on the nature of the barrier and what the surveyor wants to communicate as important regarding fish passage. However, there should be only one primary barrier mode, with subsequent modes recorded as secondary or tertiary. A minimum of one primary mode must be identified per feature.

4.4 Barrier Descriptor

The final level of classification is a **Descriptor** of the barrier feature. Several descriptors already exist across the public domain for many barrier features on the landscape. These descriptors are a useful semi-standard means to characterize and communicate the composition of barriers without lengthy subjective descriptions (Table 5 and Appendix 6). More than one descriptor may be required per feature to effectively describe it, depending on the nature of the barrier, flows, and what the surveyor wants to communicate as important regarding fish passage. As barrier assessments progress along the east slopes of Alberta, new descriptors may be identified and added to this manual.

Table 5. Barrier descriptors

Descriptor	Definition
Block	Wider than it is tall, rectangular shape. Usually falls from the entire width of the stream with one primary drop, while maintaining contact with the underlying cliff. It does not have to be a solid sheet of water across its entire width.
Cascading	Descends in quick succession over a series of multiple drops or steps, sloping rock surfaces, or rugged, irregular-shaped sloping surfaces.
Cataract	Large volume, powerful, dangerous vertical waterfalls.
Chute/flume	Stream passage is very narrow, forcing water through at high pressure, usually between steep walls (i.e., a steep cascading waterfall that is confined to a narrow channel).
Ephemeral (ribbon)	Very thin or ephemeral waterfalls from very small, narrow streams. A small ribbon of water.
Fan/veil	Spreads horizontally as it descends while remaining in contact with bedrock. Breadth of the water increases during its descent.
Horsetail	Descending water maintains constant or semi-constant contact with the bedrock as it falls; barrier can be almost vertical, as well as gradual.
Multistep/stepped	Series of connected waterfalls, each with their own plunge pool.
Plunge	Water drops vertically, losing most or all contact with the rock face.

Descriptor	Definition
Punchbowl	Water descends in a constricted form through a narrow channel, and then spreads out into a wide pool below.
Segmented	Water forms multiple, separate flows descending like distinct streams. Characterized by several concurrent drops occurring from the same level, usually separated by small islands or protruding rock.
Slide/slab	Water glides down a relatively smooth-surfaced slope, maintaining continuous contact with underlying bedrock. Typically, a gentle slope but can also occur on steeper slopes as well.
Tiered/terraced	The drop height of the waterfall is divided into multiple distinct drops in relatively close succession to one another without plunge pools in between.

5.0 BARRIER EVALUATION AND SCORING

Barrier evaluation and scoring are desktop activities that occur after field assessments are completed. **Evaluation** includes a quantitative determination of the size range of Subcarangiform swimmers that can theoretically pass a respective barrier based on measures related to leaping, swimming velocity, and swimming depth modes, and a qualitative categorical assessment to assess the extent to which barrier turbulence prevents fish passage. **Barrier score** ranks barriers based on the evaluation results and relative to the local fish size structure (i.e., from archived or active inventory data).

5.1 Barrier Evaluation

Absolute barriers to upstream fish passage can be conclusively determined based on swimming and leaping performances presented in Section 1.5; however, such barriers represent a small percentage of existing barriers on the landscape. The majority of barriers restrict fish passage to varying degrees by various fish size ranges, as a result of cumulative combinations of factors. Complete upstream barriers to **leaping** at prevailing flows can be quantitatively determined using leaping performance and swimming velocity charts, plunge pool depth, crest velocity, and crest depth variables (Table 6). Similarly, size ranges of fish that may successfully ascend partial leaping barriers at prevailing flows can also be quantitatively determined using the same measures.

Table 6. Limiting factors and conditions that determine complete barriers to leaping

Limiting factor	Condition
a) Minimum fish size (mm) to successfully leap over barrier (leaping chart, Figure 4)	Dimensions of barrier exceed the overall ability for trout to leap it (i.e., are outside of the leaping chart area).
b) Plunge pool depth, D_{pp} (mm) and c) Crest depth, D_c (mm)	Plunge pool depth or crest depth is less than the length of the smallest fish that can successfully leap barrier dimensions (i.e., the plunge pool or crest depth cannot accommodate a fish large enough to leap the barrier dimensions).
d) Minimum fish size (mm) to successfully overcome crest velocity (swimming velocity chart, Figure 5)	The minimum fish size required to overcome crest velocity is larger than factors b) and/or c) can accommodate (i.e., the fish size required to successfully overcome crest velocity is larger than the plunge pool or crest depth can accommodate).

Complete upstream barriers to **swimming** at prevailing flows can also be quantitatively estimated using the swimming velocity chart and chute swimming depth criteria (Table 7). However, chute barriers that prevent fish passage strictly as a result of chute velocity and distance variables are seldom encountered due to the extraordinary swimming abilities of salmonids. Typically, stream velocity will dictate the minimum fish size that can ascend a chute, whereas chute depth determines the maximum fish size that can ascend a chute, resulting in a range of fish sizes that can pass through the chute.

Table 7. Limiting factors and conditions that determine complete barriers to swimming

Limiting factor	Condition
a) Minimum fish size (mm) to successfully swim over barrier (swimming velocity chart, Figure 5)	Stream velocity and chute length exceed the overall ability for trout to swim over barrier (rare).
b) Chute depth and velocity	Chute depth cannot accommodate a fish large enough to overcome chute velocity and length (more common).

Turbulence is another key factor limiting fish passage at swimming barriers. However, a quantifiable way to characterize turbulence effects on fish passage (by fish size range) does not exist. As such, we developed a categorical system to assess turbulence incorporating key principles that cumulatively prevent fish passage, the sum of which determines the turbulence passage difficulty rating (Table 8).

Table 8. Flow model for determining the relative contribution of cumulative turbulence passage difficulty rating at preventing fish passage at barriers

Pathway	1. Direct									2. Indirect								
White-water Intensity	1. Infused			2. Agitated			3. Saturated			1. Infused			2. Agitated			3. Saturated		
Turbulence Uniformity	1. Uniform	2. Interrupted	3. Obstructed	1. Uniform	2. Interrupted	3. Obstructed	1. Uniform	2. Interrupted	3. Obstructed	1. Uniform	2. Interrupted	3. Obstructed	1. Uniform	2. Interrupted	3. Obstructed	1. Uniform	2. Interrupted	3. Obstructed
Turbulence Type	**Passage difficulty rating**																	
1. Spillover	4	5	6	5	6	7	6	7	8	5	6	7	6	7	8	7	8	9
2. Funnelled	5	6	7	6	7	8	7	8	9	6	7	8	7	8	9	8	9	10
3. Diffuse	-	-	8	-	-	9	-	-	10	-	-	9	-	-	10	-	-	11
*Plunge Pool orientation	*If Inhibitive add 1																	

5.2 Barrier Scoring

Barrier scoring is based on the outcomes of the quantitative barrier evaluations for leaping and swimming velocity/depth modes, and the qualitative turbulence passage difficulty rating. Scoring criteria is based primarily on the size range of fish that can theoretically ascend the barrier relative to the local fish population's size structure. Each of the four barrier modes is scored in increments of 0.25, using a framework similar to Dunham et al. (2011). The final score of each barrier is based on the sum of the combined barrier mode scores (at prevailing flows), which is based on the additive passage difficulty each mode poses. Each feature within a barrier is similarly assigned a score in the same way; however, the overall barrier score is based on the highest scored feature within it (i.e., most difficult feature for fish passage) within the barrier along the easiest pathway. Final overall ranking of any barrier is based on the most passable of the two seasonal assessment scores assigned at the different flow conditions.

5.2.1 Leaping Barrier Mode

All barrier features are given a leaping score regardless of the primary barrier mode that was assigned. If a feature was defined as a total leaping barrier, it is assigned a total leaping barrier score of 1. Subsequent scoring of the leaping mode is based on the outcomes of barrier feature evaluations of fish size range and local fish size structures (Table 9).

5.2.2 Swimming Depth/Velocity Barrier Modes

Since the range of fish sizes that may ascend a barrier by swimming is bound by swimming depth and chute velocity, we have combined swimming depth and swimming velocity barrier modes into a single score. Overall scoring criteria is the same for both swimming and leaping barrier modes despite differences in measured variables (Table 9).

Table 9. Scoring criteria for leaping and swimming depth/velocity barrier modes

Score	Leaping and swimming barrier scoring criteria
1.00	Total upstream barrier
0.75	Passable, but not to fish in the immediate population
0.50	Passable to select fish sizes (i.e., the local maximum size, for leaping mode)
0.25	Partial barrier, passable to some fish in most years (i.e., the local median size)

5.2.3 Swimming Turbulence Barrier Mode

Swimming turbulence is a qualitative visual assessment and scoring is based on the combined sum of elements within the turbulence. We have developed the following scoring criteria for swimming turbulence barrier mode based on the cumulative passage difficulty rating (Table 10).

Table 10. Scoring criteria for swimming turbulence barrier mode based on turbulence passage difficulty rating

Turbulence passage difficulty rating	Final Turbulence Score
9+	1.00
7–8	0.75
5–6	0.50
4	0.25

5.3 Final Barrier Scoring

Final barrier scoring is determined using the dichotomous flowchart in Appendix 7. The final score per barrier is the sum of the barrier mode scores. The maximum barrier score is 3 and the theoretical minimum score is 0.75, albeit few barriers with the minimum would be considered for assessment. When the primary barrier mode is leaping, the swimming depth/velocity and turbulence modes receive maximum mode scores of 1 by default; this is based on the assumption that free-falling water is not a suitable swimming medium. Barriers that are passable to swimming still receive a leaping mode score of 1 if the dimensions of the chute exceed fish leaping abilities to clear it. Consequently, the sum of the barrier mode scores (leaping + swimming + turbulence) characterizes relative barrier passage difficulty.

Note that barrier scores are relative to local fish size structures and the primary mode of barrier ascension. An absolute leaping barrier receives a default score of 3.0 when barrier dimensions exceed the leaping ability of the largest recorded (potentially invasive) fish known to inhabit the broader stream network of interest. In Southwest Alberta, where maximum length of invasive rainbow trout is typically less than 60 cm, an absolute barrier to rainbow trout invasion would be the respective leaping curve dimensions that prevent passage of fish ≤ 60 cm in length (i.e., barriers ≥ 4.3 m high and/or 6.3 m long). Where barrier dimensions do not prevent passage of the largest known individuals in the broader system, but still prevent passage to local fish sizes, the barrier is considered a complete barrier to the local population and assigned the leaping score of 0.75.

Examples of barrier scores relative to local fish size structures and primary ascension modes are presented in Appendix 8.

5.4 Final Barrier Characterization

Final characterization of each barrier is important to communicate reliability and permeability of the barrier, even though recorded measurements and observations are archived in spreadsheets or database files.,. Characterizations should include a combination of key elements such as barrier Type, Class, Mode, and Descriptor (Section 4.0), final barrier Score (Section 5.3) and Inundation category (Section 1.8).

When characterizing a complete barrier include the limiting factor identified in the flowchart (Appendix 7) that prevents fish passage (e.g., D_{pp} leaping barrier, velocity/depth swimming barrier, etc.). A suggested characterization structure for a complete barrier is: Score, Inundation category, Descriptor, Class, Type, flowchart limiting factor (e.g., 3.0, Permanent, Terraced, Multiple, Waterfall, D_{pp} leaping barrier). When characterizing an incomplete barrier and no limiting factor fully prevents passage, include the primary mode. A suggested characterization structure for an incomplete barrier is: Score, Inundation category, Descriptor, Class, Type, Primary Mode, (e.g., 2.25, Effective, Slide, Simple, Chute, swimming turbulence barrier).

5.5 Range Expansion Scoring

Scoring barriers according to their ability to protect upstream habitat from invasion enables ranking of candidate habitats above barriers based on their feasibility for establishing or re-establishing native species populations upstream of barriers. Scoring for range expansion feasibility will not be additive but include both positive and negative values based on whether barriers prevent (+) or permit (-) invasive fish from downstream. Final additive barrier scores will be assigned invasion resistance scores, using a scoring system similar to Galloway et al. (2016) (Table 11).

Table 11. Proposed invasion resistance scoring by barrier score range

Barrier Score	Invasion Resistance Score
2.75–3.00	1.0
2.25–2.50	0.5
1.75–2.00	-0.5
<1.75	-1

6.0 LITERATURE CITED

Alberta Environment and Parks. 2015. Roadway Watercourse Crossing Inspection Manual. Government of Alberta. ISBN 978-1-4601-2038-5.

Amaral, S.D., P. Branco, A.T. da Silva, C. Katopodis, T. Viseu, M.T. Ferreira, and J.M. Santos. 2016. Upstream passage of potamodromous cyprinids over small weirs: the influence of key-hydraulic parameters. Journal of Ecohydraulics, 1(1-2), 79-89.

Amaral, S.D., P. Branco, C. Katopodis, M.T. Ferreira, A.N. Pinheiro, and J.M. Santos. 2018. To swim or to jump? Passage behaviour of a potamodromous cyprinid over an experimental broad-crested weir. River Research and Applications, 34(2), 174-182.

Amaral, S.D., A.L. Quaresma, P. Branco, F. Romão, C. Katopodis, M.T. Ferreira, and J.M. Santos. 2019. Assessment of Retrofitted Ramped Weirs to Improve Passage of Potamodromous Fish. Water, 11(12), 2441.

Bingham D., P. Buckskin, and H. Osborne. 2016. Isolation, Migration, and Local Recruitment Drive Persistence of Cutthroat Trout in Tributaries near American Falls Reservoir. North American Journal of Fisheries Management, 36(3), 590-605, DOI: 10.1080/02755947.2016.1165765.

Carpenter, F. 2016. Understanding the Importance of Intermittently Fragmented Stream Habitat for Isolated Westslope Cutthroat Trout (*Oncorhynchus clarki lewisi*) in the Colville National Forest, Washington. Portland State University. Dissertations and Theses. Paper 3315. DOI: 10.15760/etd.3295.

Castro-Santos, T., F. Sanz-Ronda, and J. Ruiz-Legazpi. 2013. Breaking the speed limit—comparative sprinting performance of brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*). Canadian Journal of Fisheries and Aquatic Sciences, 70(2), 280–293, DOI: 10.1139/cjfas-2012-0186.

COSEWIC. 2012. COSEWIC assessment and status report on the Bull Trout *Salvelinus confluentus* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. iv + 103 pp. (www.registrelep-sararegistry.gc.ca/default_e.cfm).

COSEWIC. 2014. COSEWIC assessment and status report on the Rainbow Trout *Oncorhynchus mykiss* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xi + 60 pp. (www.registrelep-sararegistry.gc.ca/default_e.cfm).

COSEWIC. 2016. COSEWIC assessment and status report on the Westslope Cutthroat Trout *Oncorhynchus clarkii lewisi*, Saskatchewan-Nelson River populations and Pacific populations, in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. xvi + 83 pp. (http://www.registrelepsararegistry.gc.ca/default.asp?lang=en&n=24F7211B-1)

Cotel, A.J. and P.W. Webb. 2012. The challenge of understanding and quantifying fish responses to turbulence-dominated physical environments. In *Natural Locomotion in Fluids and on Surfaces* (pp. 15-33). Springer, New York, NY.

Davis, C.D., C.W. Epps, R.L. Flitcroft, and M.A. Banks. 2018. Refining and defining riverscape genetics: How rivers influence population genetic structure. Wiley Interdisciplinary Reviews: Water, 5(2), e1269.

Di Rocco, R., and R. Gervais. 2020. *SPOT: Swim Performance Online Tools*. Available from http://www.fishprotectiontools.ca/.

Dunham, J., K. Gallo, D. Shively, C. Allen, and B. Goehring. 2011. Assessing the feasibility of native fish reintroductions: a framework applied to threatened bull trout. North American Journal of Fisheries Management, 31(1), 106-115.

Fausch, K.D., B.E. Rieman, M.K. Young, and J.B. Dunham. 2006. Strategies for conserving native salmonid populations at risk from nonnative fish invasions: tradeoffs in using barriers to upstream movement. Conservation Biology, 23(4), 859-870.

Fisheries and Oceans Canada. 2014. Recovery Strategy for the Alberta populations of Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*) in Canada [Final]. Species at Risk Act Recovery Strategy Series. Fisheries and Oceans Canada, Ottawa. iv + 28 pp + Appendices.

FishXing Version 3. 2006. Pacific Northwest Research Station: Forest Service Engineering T&D Program, Federal Highway Administration and Stream Systems Technology Center, Rocky Mountain Research Station, U.S. Fish and Wildlife Service.

Fox, B.D., B.P. Bledsoe, E. Kolden, M.C. Kondratieff, and C.A. Myrick. 2016. Eco-hydraulic Evaluation of a Whitewater Park as a Fish Passage Barrier. JAWRA Journal of the American Water Resources Association, 52(2), 420-442.

Franca, M.J. and M. Brocchini. 2015. Turbulence in rivers. In *Rivers–Physical, Fluvial and Environmental Processes* (pp. 51-78). Springer, Cham.

Furniss, M., M. Love, S. Firor, K. Moynan, A. Llanos, J. Guntle, and R. Gubernick. 2006. FishXing: Software and Learning Systems for Fish Passage through Culverts, Version 3.0. www.fsl.orst.edu/geowater/FX3/help/SwimData/FX3_SwimTable.xls. Accessed March 4, 2019.

Galloway, B.T., C.C. Muhlfeld, C.S. Guy, C.C. Downs, and W.A. Fredenberg. 2016. A framework for assessing the feasibility of native fish conservation translocations: applications to threatened Bull Trout. North American Journal of Fisheries Management, 36(4), 754-768.

Hotchkiss, R.H. and C.M. Frei. 2007. Design for fish passage at roadway-stream crossings: synthesis report. Federal Highway Administration, Publication FHWA-HIF-0-033, McLean, Virginia.

Katopodis, C. and R. Gervais. 2016. Fish swimming performance database and analyses. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/002. vi + 550 p.

Katopodis, C. and R. Gervais. 2015. Session B9: Size Matters Even for the Ubiquitous Fish Speed Metric of BL/S. International Conference on Engineering and Ecohydrology for Fish Passage. 11. http://scholarworks.umass.edu/fishpassage_conference/2015/June24/11.

Kilgore, R.T., B.S. Bergendahl, and R. Hotchkiss. 2010. HEC-26: Culvert Design for Aquatic Organism Passage: First Edition. U.S. Department of Transportation, Federal Highway Administration

Publication Number: HIF-11-008.

Lacey, R.W., V.S. Neary, J.C. Liao, E.C. Enders, and H.M. Tritico. 2012. The IPOS framework: linking fish swimming performance in altered flows from laboratory experiments to rivers. River Research and Applications, 28(4), 429-443.

Liao, J.C. 2007. A review of fish swimming mechanics and behaviour in altered flows. Philosophical Transactions of the Royal Society B: Biological Sciences, 362(1487), 1973-1993.

Lindsey, C.C. 1978. 1 - Form, Function, and Locomotory Habits in Fish. In *Fish Physiology*, 7, 1-100. doi:10.1016/s1546-5098(08)60163-6.

Maine Department of Transportation. 2004. Fish Passage Policy and Design Guide: 2nd Edition. Maine Department of Transportation.

McCleary, R., C. Spytz, H. Schindler, R. Anderson, and M. Climie. 2007. Stream Crossing Inspections Manual. Version 3. C.R. Bamsey, ed. Clear Lake Ltd., Edgerton, AB.

Nave, C. 2016. HyperPhysics website. Georgia State University, Department of Physics and Astronomy, http://hyperphysics.phy-astr.gsu.edu/hbase/traj.html#tracon. Accessed October 7, 2018.

Odeh, M., J.F. Noreika, A. Haro, A. Maynard, T. Castro-Santos, and G.F. Cada. 2002. Evaluation of the effects of turbulence on the behavior of migratory fish. Final Report to the Bonneville Power Administration, Contract, 22.

Powers, P. and J. Orsborn. 1985. Analysis of barriers to upstream fish migration. U.S. Dept. of Energy, Bonneville Power Adm., Div. of Fish and Wildlife, Final Project Rep., 120 p.

Puzdrowska, M. and T. Heese. 2019. Detailed Research on the Turbulent Kinetic Energy's Distribution in Fishways in Reference to the Bolt Fishway. Fluids, 4(2), 64.

Reiser, D.W., C.M. Huang, S. Beck, M. Gagner, and E. Jeanes, 2006. Defining Flow Windows for Upstream Passage of Adult Anadromous Salmonids at Cascades and Falls. Transactions of the American Fisheries Society, 135:3, 668-679, DOI: 10.1577/T05-169.1.

Rosgen, D.L., 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, Colorado.

San Francisco Public Utilities Commission (SFPUC). 2010. Assessment of Fish Upstream Migration at Natural Barrier In the Upper Alameda Creek SubWatershed. Technical Memorandum Prepared by URS Corporation (AECOM) and HDR inc. for San Francisco Public Utilities Commission 35 pp. + app.

Shah, T., M. Balkhi, A. Najar, and A. Asimi. 2011. Morphometry, length-weight relationship and condition factor of farmed female rainbow trout [(*Oncorhynchus mykiss* (Walbaum)] in Kashmir. Indian Journal of Fisheries, 58(3), 51-56.

Silva A.T., C. Katopodis, J.M. Santos, M.T. Ferreira, and A.N. Pinheiro. 2012. Cyprinid swimming behaviour in response to turbulent flow. Ecological Engineering, 44, 314–328 http://dx.doi.org/10.1016/j.ecoleng.2012.04.015.

Stephens, T.A., B.P. Bledsoe, B.D. Fox, E. Kolden, and M.C. Kondratieff. 2015. Effects of whitewater parks on fish passage: a spatially explicit hydraulic analysis. Ecological engineering, 83, 305-318.

The Alberta Westslope Cutthroat Trout Recovery Team. 2013. Alberta Westslope Cutthroat Trout Recovery Plan: 2012 – 2017. Alberta Environment and Sustainable Resource Development, Alberta Species at Risk Recovery Plan No. 28. Edmonton AB. 77pp.

Vasave, S. and A. Saxena. 2013. Morphological and Meristic Studies of Rainbow Trout (*Oncorhynchus mykiss*) and Snow Trout (*Schizothorax richardsonii*). Journal of Agriculture and Food Technology ISSN 2090 – 424X. College of Fisheries, G. B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand – 263 145.

Webb, P.W. 1975. Hydrodynamics and energetics of fish propulsion. Bulletin of the fisheries research board of Canada, 190, 1-159.

Wofford, J.E., R.E. Gresswell, and M.A. Banks. 2005. Influence of barriers to movement on within-watershed genetic variation of coastal cutthroat trout. Ecological Applications, 15(2), 628-637.

Yeomans-Routledge, A., S. Faulkner, H. Wright, F.J.A Lewis. 2012. Narrows Inlet Hydro Project, Obstacles to Migration and Barriers. Consultant's report prepared by Ecofish Research Ltd. for Narrows Inlet Limited Partnership. 38 pp.

7.0 APPENDICES

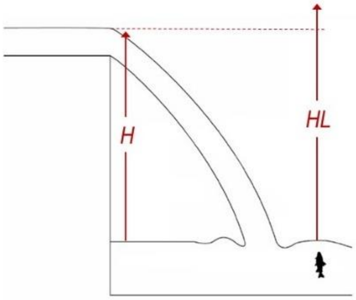
Appendix 1. Example of swimming speeds and leap heights inflated to impractical levels when the BL/s speed metric is applied

Fish length (mm)	Projected sustained swim speeds (m/s) from literature-based swimming performance ranges (BL/s)		Projected burst swim speeds (m/s) from literature-based swimming performance ranges (BL/s) and maximum projected vertical leap height (m)		
	2.5 BL/s	8 BL/s	10 BL/s	25 BL/s	Maximum vertical leap height (m)
100	0.25	0.80	1.00	2.50	<0.10–0.32
150	0.38	1.20	1.50	3.75	0.10–0.72
200	0.50	1.60	2.00	5.00	0.19–1.27
250	0.63	2.00	2.50	6.25	0.32–1.99
300	0.75	2.40	3.00	7.50	0.46–2.86
350	0.88	2.80	3.50	8.75	0.62–3.90
400	1.00	3.20	4.00	10.00	0.81–5.08
450	1.13	3.60	4.50	11.25	1.02–6.45
500	1.25	4.00	5.00	12.50	1.23–7.96

Appendix 2. Calculation requirements for developing leaping curves, modified from SFPUC (2010)

Equation 1 – Maximum vertical leap (*HL*) given fish burst speed:

$HL = (V_{burst}(\sin\theta L))^2/2(G)$

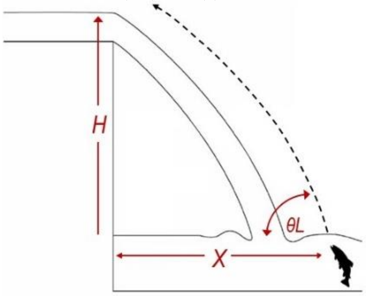


Where:

V_{burst}	= Burst swimming speed (m/s)
$\sin\theta L$	= Fixed vertical leap angle (90˚), RADIANS(90) = 1.57079633
G	= Gravity (Fixed) = 9.80665 m/s^2
H	= Barrier height (m)
X	= Barrier horizontal distance (m)
θL	= Leap angle, function of H and X
HL	= Leap height (m)
XL	= Leap range (m)
L	= Leap

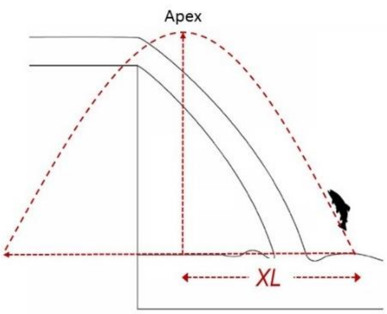
Equation 2 – Fish leap angle (θL) given barrier height and distance:

$\theta L = \tan^{-1}(3(H/X))$



Equation 3 – The horizontal distance (range) of the fish's leap at the highest point (apex) of the leap:

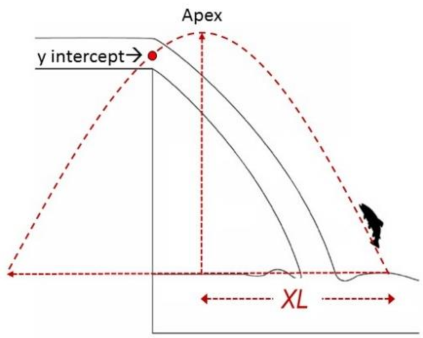
$XL = (V_{burst})^2(\cos\theta L((\sin\theta L)/G)$



Appendix 2. continued

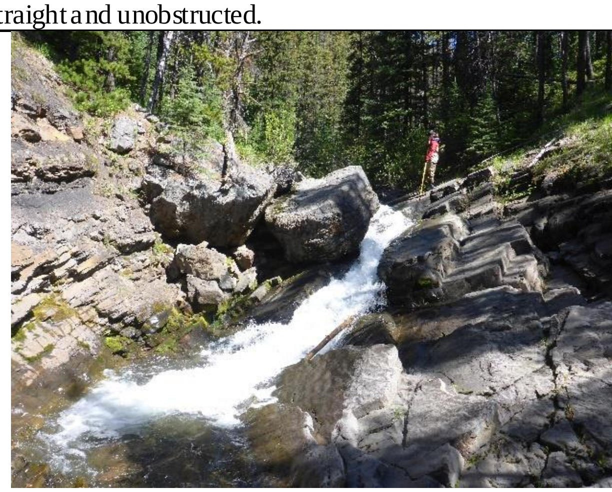
Equation 4 – The fish's height at the crest of the falls (y-intercept) after it ascends and descends in a parabolic trajectory. Fish may still clear the barrier on the decent even if XL is less than X:

$y = (X(V_{burst}(\sin\theta L))/(V_{burst}(\cos\theta L))) - (1/2G(X^2/(V_{burst}(\cos\theta L))^2)$

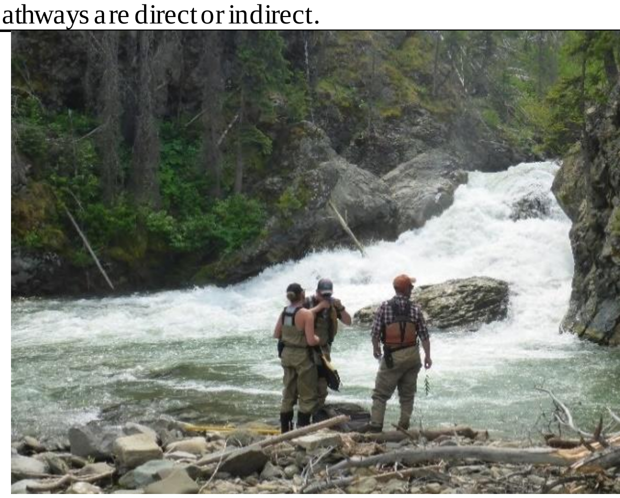


Appendix 3. White-water turbulence categories by type for visual characterization of swimming difficulty

1 – Spillover – Flow spills over a uniform drop nearly channel-wide or slightly funnelled. Water remains mainly in contact with the feature and flow is mostly unidirectional with relatively uniform turbulence. Eddies are typically small and uniformly distributed, swimming pathways are straight and unobstructed.



2 – Funnelled – Flows are funnelled into a trough, chute, or narrowing, which consolidates flow volume and increases depths. Flows fold or spiral and lose contact with the streambed, which increases velocity fluctuations and white-water intensity. Has larger eddies and eddy size transitions, and pathways are direct or indirect.



3 – Diffuse – Flows broadcast into many directions, with violent frothy white-water and spray, and unconsolidated stream flows. Water frequently 'bounces' off the streambed resulting in broken, indirect swimming pathways with fluctuating velocities and multiple eddy size transitions.

Appendix 4. White-water turbulence categories by intensity for visual characterization of swimming difficulty

1 – Infused Slightly more white-water than non-white-water, or approximately equal proportions of each. Although mixed or laced together, differentiation between white and non-white-water is not difficult. A definite obstacle but likely passible by certain fish size classes at various flows.	
2 – Agitated Flows are primarily white. Passage is difficult, but the white-water turbulence alone is not likely a reliable barrier to prevent invasion from the best of swimmers, or from chance events associated with chaotic turbulence that may propel fish.	
3 – Saturated Discerning anything non-white from the frothy white-water and spray is nearly impossible. Passage is extremely unlikely.	

Appendix 5. Barrier assessment data forms for leaping (page 1) and swimming (page 2) modes

Stream: Date: Crew: P.1

Barrier ID: Easting: Photos:

Northing:

BARRIER TYPE	BARRIER CLASS			PRIMARY BARRIER MODE			BARRIER DESCRIPTORS	FLOOD INUNDATION (m)	
Waterfall ☐	Single ☐	Multiple ☐		Leaping ☐	Swimming ☐			D_{th} =	$H_{fp} = (D_{bf} \times 2) - D_{th}$
Chute ☐	Simple ☐	Complex ☐		FLOWS DURING SURVEY				H_{bf} (VD) =	
Cascade ☐	Compnd ☐	Turbulent ☐	Bouldr ☐	Spring ☐	Summer ☐	Low ☐		D_{bf}=	

FEATURE			PRIMARY MODE	LEAPING MODE													
				Feature dimensions				Plunge Pool						Crest			Min fish
No. Type (Easting,Northing)	CLASS	DSCRIPTR	$Leap_{vs}Swim$	Ht - (m) (HT)	Lgth-***X*** (m) (HD)	Angle(θ) (INC °)	Slp-(X_m) (SD)	D_{pp} leap	D_{pp} max	$D_{pen} \geq D_{pp}$	D_{pen} (m)	Bkedy (y/n)	V_{eddy}	V_c	D_c	WW / RW	leap curve

Datasheet photo ☐

Video taken ☐

Comments:

Stream: Date: Crew: P.2

Barrier ID: Easting: Photos:

Northing:

FEATURE			SWIMMING MODE(S)																
			Pathway				Turbulence		In-chute *D (cm)*			In-chute *V (m/s)*			Fish Size (mm)		Swim Modes[1,2,3]		
No. TYPE	CLASS	DSCRIPTR	#	D/I	Unif	Pool (n/1)	Type	Intensity	D1	D2	D3	V1	V2	V3	*D*	*V*	Vel.	Dpth	Turb.

Flood / Turbulence / Pathway Complexity Key						
Code	**Inundation**	**Uniformity**	**Type**	**Intensity**	**Pathway**	**pool arrang**
1	Low water	Uniform	Spillover	Infused	Direct	Inhibitive
2	Seasonal	Interrupted	Funnelled	Agitated	Indirect	
3	Effective	Obstructed	Diffuse	Saturated		
4	Absolute					

Comments:

Datasheet photo ☐ Video taken ☐

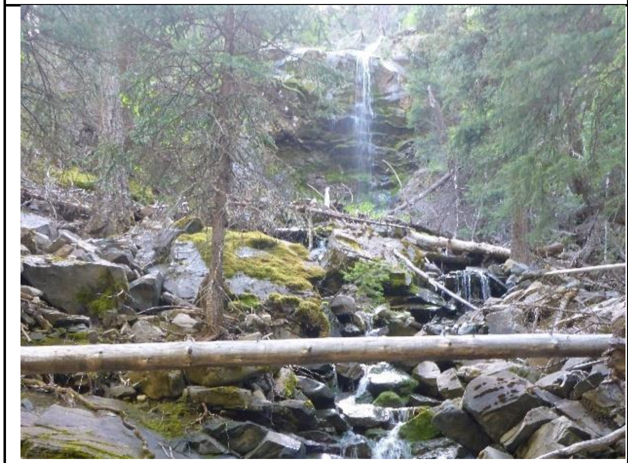
Appendix 6. Waterfall descriptors for barrier feature classification

Block waterfall

Cascading waterfall

Cataract waterfall

Chute/flume waterfall



Ephemeral (background), scree (foreground)

Fan/veil waterfall

Appendix 6. Waterfall descriptors for barrier feature classification (continued)

Horsetail waterfall

Multistep/stepped waterfall

Plunge waterfall

Punchbowl waterfall

Segmented waterfall

Slide/slab waterfall

Appendix 6. Waterfall descriptors for barrier feature classification (continued)

Tiered/terraced waterfall

Appendix 7. Flow chart for assigning barrier scores

A) Assigning Leaping Mode Score

1. From the leaping curves (Figure 4), determine the minimum fish size required to successfully leap the barrier dimensions *H* and *X*. Proceed to 2.

2. Is the plunge pool depth greater than or equal to the TL of the minimum fish size required to leap the barrier?

Yes → Proceed to 3. No → D_{pp} leaping barrier

Can the barrier be swam as well?

Yes → Leaping mode, score = 1.0, proceed to B) Swim Scoring.

No → D_{pp} leaping barrier, total barrier, score = 3.0.

3. From the swimming curves (Figure 5), determine the minimum fish size required to overcome instantaneous crest velocity V_c. Proceed to 4.

4. Based on the swimming depth table (Table 1), does D_c permit a fish large enough to overcome V_c?

Yes → Proceed to 5. No → Crest swimming barrier, total barrier, score = 3.0.

5. Is the largest fish in the local population greater than or equal to the minimum fish size for a successful leap?

Yes→ Proceed to 6. No → Leaping barrier

Can the barrier be swam as well?

Yes → Leaping mode, score = 1.0, proceed to 6.

No → Leaping barrier to local population, score = 3.0.

6. Based on the local fish population size structure, select the remaining score that best describes barrier efficacy.

i) Passable to the largest recorded invasive individual in the broader system, but not to sizes in the immediate population → Leaping score = 0.75.
Proceed to B) Swim Scoring.

ii) Passable to the local maximum fish size, but not the local mean or median size → Leaping score = 0.5.
Proceed to B) Swim Scoring.

iii) Passable to the local mean or median size of invasive species → Leaping score = 0.25 → Not a leaping barrier. Proceed to B) Swim Scoring.

Appendix 7. Flow chart for assigning barrier scores (continued)

B) Assigning Swimming Mode Score

1. From the swimming curves (Figure 5), determine the minimum fish size required to overcome the average chute velocity V_{ch} given the slope distance X_m. Proceed to 2.

2. Based on the swimming depth table (Table 1), does the average chute depth D_{ch} permit a fish large enough to overcome V_{ch} given the slope distance X_m?
Yes → Proceed to 3. No → Velocity/depth swimming barrier, total barrier, score = 3.0.

3. Is the largest fish in the local population greater than or equal to the minimum fish size to overcome the V_{ch} given the X_m?
Yes→ Proceed to 4. No → Velocity swimming barrier to local population. Swim score = 0.75.
Is combined leaping and swimming score > 1.5?
Yes → Barrier, score = 3.0, local fish barrier.
No → Proceed to C) Final Scoring.

4. Is D_{ch} deep enough to permit a fish large enough to overcome the V_{ch} given the X_m?
Yes→ Proceed to 5. No → Depth swimming barrier. Swim score = 1.0.
Proceed to C) Final Scoring.

5. Based on the local fish population size structure, select the remaining score that best describes barrier efficacy.

i) Passable to the largest recorded invasive individual recorded in the broader system, but not to sizes in the immediate population → Swim score = 0.75.
Proceed to C) Final Scoring.

ii) Passable to the local maximum fish size, but not the local mean or median size → Swim score = 0.5.
Proceed to C) Final Scoring.

iii) Passable to the local mean or median size of invasive species→ Swim score = 0.25 → Not a swimming barrier. Proceed to C) Final Scoring.

C) Final Scoring Summary and Barrier Characterization

1. From the turbulence passage difficulty rating table, assign a final turbulence score.
2. For barriers not assigned a default absolute barrier score of 3.0, calculate the sum of the Leaping, Swimming, and Turbulence mode scores to determine final barrier score.
3. Assign a flood inundation category according to Table 3.
4. Characterize the barrier including Final Score, Inundation category, Descriptor, Class, Type, flowchart limiting factor or Primary Mode.

Appendix 8. Examples of barrier evaluation fish size ranges, and barrier scores from assessed barriers. Note that scoring is relative to local fish size structures and primary ascension mode.

		
Primary mode: Swimming Passable fish size: 100 – 300 mm Local invader max: ~220 mm Score: 1.00	Primary mode: Swimming Passable fish size: 100 – 350 mm Local invader max: ~220 mm Score: 1.25	Primary mode: Leaping Passable fish size: 100 – 350 mm Local invader max: ~420 mm Score: 1.50
		
Primary mode: Swimming Passable fish size: 100 – 350 mm Local invader max: ~440 mm Score: 1.75	Primary mode: Swimming Passable fish size: > 150 mm Local invader max: ~375 mm Score: 2.00	Primary mode: Swimming Passable fish size: 100 – 400 mm Local invader max: ~350 mm Score: 2.25
		
Primary mode: Leaping Passable fish size: > 300 mm Local invader max: ~480 mm Score: 2.50	Primary mode: Leaping Passable fish size: > 350 mm Local invader max: ~330mm Score: 2.75	Primary mode: Leaping Passable fish size: > 550 mm Local invader max: ~220mm Score 3.0

GLOSSARY

- **Aerobic swimming** – Prolonged swimming occasions where oxygen is consumed.
- **Agitated** – Intermediate category of white-water intensity that characterizes turbulence, in which flows are primarily white with air entrainment.
- **Anaerobic swimming** – Short swimming bursts where oxygen is not consumed.
- **Bankfull** – The water level stage that just begins to spill out of the stream channel and into the floodplain and vegetation along the banks.
- **Bankfull depth (D_{bf})** –The sum of maximum thalweg depth and bankfull height.
- **Bankfull height (H_{bf})** – The vertical distance from the water surface to the bankfull channel boundary.
- **Barrier** – Anything that physically prevents or impedes fish moving in an upstream or downstream direction from accessing potential habitat.
- **Barrier class** – The second tier of classification that differentiates between barriers.
- **Barrier descriptor** – The fourth tier (most proximate/specific) of classification that differentiates between barriers.
- **Barrier distance (X)** – Horizontal straight-line distance of a barrier from the standing wave to the waterfall crest. Denoted as HD on a TruPulse 200X.
- **Barrier evaluation** – The size range of Subcarangiform fish species that can theoretically pass a respective barrier.
- **Barrier height (H)** – The vertical distance of a barrier from the standing wave to the waterfall crest. Denoted as HT on a TruPulse 200X.
- **Barrier mode** –Fish transportation mechanism of ascension at each barrier feature and the third tier of classification that differentiates between barriers.
- **Barrier score** – Barrier difficulty rank on a scale of 1 to 3, relative to local fish size structure, and accounts for not yet quantifiable measures of turbulence.
- **Barrier type** – The first tier (broadest level) of classification that differentiates barriers into either waterfalls, chutes, or cascades.
- **Block** – Descriptor that characterizes barriers that are wider than tall; rectangular in shape contain falls that span the entire width of the stream with one primary drop, while maintaining contact with the underlying cliff; and does not have to be a solid sheet of water across the barrier's entire width.
- **Boil line** – An area of upwelling water (standing wave) below an elevational drop in the stream channel, caused by a plunging stream of water.
- **Boulder cascades** – Class of cascade barrier with large instream boulders that constrict flows creating hydraulic drops from upstream to downstream; resting areas may be intermittent; very turbulent pools.
- **Burst speed** – The fastest swimming speed used by fish for capturing prey, avoiding danger, and navigating high velocity flows. It is an anaerobic sprint with a short endurance time of <20 seconds.
- **Cascade** – Barrier type where a series of waterfalls and/or chutes of varying intensities are characterized by turbulence and white-water resulting from complex and/or chaotic roughness

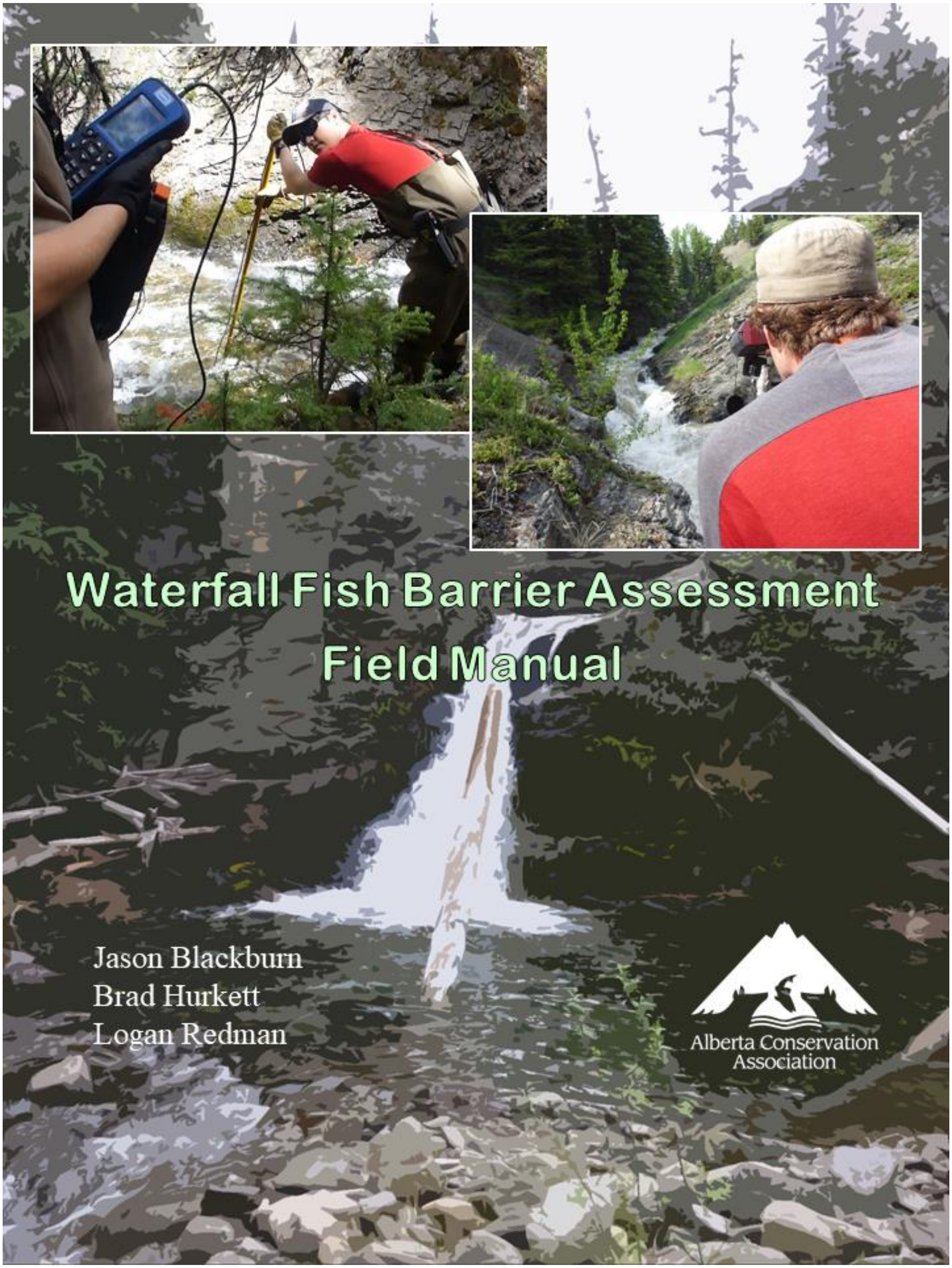
elements. Broadly encompasses anything that is multi-featured with turbulence and white-water present. It is within the first tier (broadest level) of classification that differentiates barriers.

- **Cascading** – Descriptor that characterizes barriers that descend in quick succession over a series of multiple drops or steps, sloping rock surfaces, or rugged irregular-shaped sloping surfaces.
- **Cataract** – Descriptor that characterizes large volume, powerful, dangerous, vertical waterfalls that possess a large volume of water.
- **Chute** – Barrier type with a steep gradient where the water stays mainly in contact with the streambed throughout the course of the feature. Usually less than a 23-degree angle. It is within the first tier (broadest level) of classification that differentiates barriers.
- **Chute/flume** – Descriptor that characterizes a chute barrier in which the stream passage is very narrow, forcing water through at high pressure, usually between steep walls.
- **Chute length (X_m)** – The oblique distance along the sloping water surface of a barrier. Denoted as SD on a TruPulse 200X.
- **Complex chute** – Class of chute barrier with a cross-section that varies, has several changes in slope, and/or a winding channel with white-water at all stages.
- **Compound barriers** – Barriers that have more than one feature.
- **Compound waterfall** – Class of waterfall barrier with a combination of single falls and/or simple chutes.
- **Crest depth (D_c)** – The stream depth at the crest of a barrier where a leaping fish would 'land'.
- **Crest water velocity (V_c)** – The stream velocity in m/s at the crest of a barrier where a leaping fish would 'land'.
- **Critical flow** – When stream flow and surface disturbance waves move at the same speed. Surface waves generated by a disturbance such as a falling stone will appear stationary at the upstream point of the wave while the downstream wave moves twice as fast as the flow of the river.
- **Critical (increasing) velocity test** – Fish of a certain length are subjected to increasing velocities in a stepwise fashion at fixed time intervals until the fish ceases to swim. Swimming speeds are maintained from minutes to hours. This is the most widely used method to measure swimming performance.
- **Diffuse turbulence** – Flows are broadcast into many directions resulting in violent, frothy white-water and spray. Stream flow is not consolidated into usable flow paths for swimming and water frequently leaves or 'bounces' off the streambed surface resulting in broken, indirect swimming pathways with fluctuating velocities and multiple eddy size transitions.
- **Dimensionless equation** – A quantitative mathematical generalization of effects/processes without set units of measure or physical dimensions, which can be scaled to user-specified units or dimensions to solve a specific problem quantitatively.
- **Directness of route** – Category of swimming pathway complexity that describes whether a straight (**Direct**) or a convoluted (**Indirect**) route is required to ascend a turbulence barrier.
- **Eddy uniformity** – Category of swimming pathway complexity that describes whether a fish must pass through turbulence of similar sized eddies (**Uniform**), through a major transition in eddy size (**Interrupted**), or through multiple transitions in eddy size (**Obstructed**).
- **Ephemeral (ribbon)** – Descriptor that characterizes barriers on very small or ephemeral streams. A small narrow ribbon of falling water.

- **Fan/veil –** Descriptor that characterizes waterfalls that spread horizontally as they descend while remaining in contact with bedrock. The breadth of the water in the waterfall increases during decent.
- **Feature –** Sub-component of a barrier that individually acts to stop or impede fish from accessing potential habitat.
- **Fish body depth (BD)** – The distance between ventral and dorsal surfaces of a fish.
- **Fixed velocity test** – Fish are forced to swim in an enclosed tunnel where water velocity is fixed and the time to fatigue is measured. A fatigue curve plots endurance time as a function of swimming speed by species and length. This test may produce data over a range of fish endurance times including burst and prolonged speeds.
- **Flood height (H_{fp})** – The distance from the stream water surface to the flood-prone level, measured as twice the sum of maximum thalweg depth and bankfull height, minus thalweg depth ($2(D_{th} + H_{bf}) - D_{th}$).
- **Flood-prone level** – Stream water level during a 50-year recurrence interval flood event which is approximated twice the bankfull depth.
- **Funnelled turbulence –** Flows are funnelled into a trough, chute, or narrowing which may temporarily consolidate flow volume and increase depths for swimming. However, flows may fold or spiral over themselves and begin to lose contact with the streambed which increases velocity fluctuations, intensity of white-water, and frequency of eddy size transitions.
- **Horsetail** – Descriptor that characterizes barriers where descending water maintains constant or semi-constant contact with the bedrock as it falls; barrier can be almost vertical, as well as very gradual.
- **Hydraulic drop** – The transition from subcritical to supercritical flow produces a hydraulic drop, resulting in a sudden decrease in depth. Hydraulic drops often occur at the crest of chutes or rapids.
- **Hydraulic jump –** The transition from supercritical to subcritical flow produces a hydraulic jump, a region of extreme turbulence where large amounts of energy are expended. In a hydraulic jump, flow velocity drops suddenly, and water depth increases suddenly producing a standing wave. Hydraulic jumps and standing waves form at the base of waterfalls, chutes, and spillways.
- **Hydrograph** – A chart showing the rate of flow versus time past a specific point in a river, typically expressed in cubic meters per second (cms).
- **In-chute depth (D_{ch})** – The depth of flowing water through or down a chute.
- **In-chute velocity (V_{ch}) –** The stream velocity measured inside or down a chute.
- **Infused –** Category of white-water intensity that characterizes turbulence, in which there is relatively low levels of air entrainment in the water column. Differentiation between white and non-white-water is not difficult.
- **Leaping barrier** – The height and/or distance of the barrier impedes fish from ascending it. When height and/or distance exceeds the fish's leaping ability at burst speed, it is a complete barrier.
- **Low Flows** – During low flows much of the streambed is exposed. Riffle reaches may appear to have unsuitable swimming depths for adult-sized fish. Side channels and pools may become disconnected from the thalweg, and flows within the thalweg may become braided, and/or fragmented longitudinally by dry channel or sub-surface reaches. Wading and fording is typically safest during low flows.
- **Morphometric** – Measurement of the external shape and dimensions of a living organism (see **Fish body depth** definition).

- **Multiple fall** – Class of waterfall barrier where the flow divides into more than one channel offering several passage routes of varying difficulty.
- **Multistep/stepped** – Descriptor that characterizes a barrier with a series of connected waterfall features, each with their own plunge pool.
- **Non-anadromous** – Fish that do not migrate between freshwater and the ocean.
- **Saturated** – Category of white-water intensity that characterizes turbulence, in which extreme levels of air entrainment result in frothy white-water and spray.
- **Plunge** – Barrier descriptor that characterizes waterfalls that drop vertically, losing most or all contact with the rock face.
- **Plunge pool** – An excavated basin at the foot of a waterfall caused by falling water.
- **Plunge pool depth (D_{pp})** – The water depth from stream surface to the streambed in a pool below plunging water.
- **Plunge pool orientation** – Category of swimming pathway complexity based on whether the position of the plunge pool facilitates detection of a function swimming pathway (**Normal**) or prevents fish passage via turbulence cues that misguide or confuse upstream travel direction (**Inhibitive**).
- **Prolonged swim speed –** An intermediate category between burst and sustained swim speed involving both aerobic and anaerobic processes with endurances ranging from >20 seconds up to approximately 30 minutes.
- **Punchbowl** – Descriptor that characterizes barriers where water descends in a constricted form through a narrow channel and then spreads out into a wide pool below.
- **Segmented –** Descriptor that characterizes barriers that form multiple, separate flows as they descend like distinct streams. Characterized by several concurrent drops occurring on the same level, usually created by small islands or protruding rock.
- **Simple chute** – Class of chute barrier with a uniform cross-section and slope, generally straight, with supercritical flow throughout.
- **Single fall** – Class of waterfall barrier where the entire stream flows through a single opening offering one path for fish passage.
- **Slide/slab** – Descriptor that characterizes a chute barrier where water glides down a relatively low angle slope, maintaining continuous contact with bedrock.
- **Slope distance** – Equivalent to chute length.
- **Spillover turbulence** – Caused by an increase in velocity as the stream spills over a uniform drop that is nearly channel-wide or slightly funnelled. Water remains mainly in contact with the feature as it flows over it; flow is mostly unidirectional with relatively uniform turbulence. Eddies are typically small and uniformly distributed, swimming pathways straight and unobstructed.
- **Spring flows** – Flows are at or near bankfull. Water clarity is typically silty or stained as sediments remain entrained in the water column. Fording or wading of streams is generally unsafe during this period.
- **Subcarangiform** – A fish swimming style, which includes trout and salmon, where the rear half of the body performs most of the work.
- **Subcritical flow –** Slow flows with a low energy state. Surface waves generated by a disturbance such as a falling stone will travel both upstream and downstream.

- **Summer flows** – During summer flows some areas of the streambed and channel have become exposed, such as along the margins, and areas of deposition like gravel bars and inside bends of meanders are no longer submerged. Water clarity is increased as finer suspended sediments have mainly settled out.
- **Supercritical flow** – Very fast flow with a high energy state. Surface waves generated by a disturbance such as a falling stone cannot travel upstream but are completely carried downstream.
- **Sustained swim speed** – Slower aerobic swimming for cruising and foraging that can be maintained indefinitely without fatigue.
- **Swimming pathway complexity** – Description of turbulence related elements that cumulatively impair the ability of fish to ascend through a swimming barrier, including directness of route, the uniformity and distribution of eddy size, and plunge pool orientation.
- **Swimming depth barrier** – Flow depth over the barrier impedes fish from ascending it. When depth is insufficient for a fish to effectively propel itself over the barrier while swimming, it is a complete barrier.
- **Swimming velocity barrier** – Stream velocity impedes fish from ascending it. When stream velocity exceeds the fish's burst swimming speed performance over a given time and distance, it is complete barrier.
- **Swimming turbulence barrier** – White-water elements impede fish with fluctuating water velocity and orientation difficulties and/or by decreasing the water's fluid density which reduces a fish's swimming power.
- **Thalweg** – The main line that connects the lowest points along a stream channel where the fastest and majority of the flow occurs.
- **Tiered/terraced** – Descriptor that characterizes barriers with a total height that is divided into multiple distinct drops in relatively close succession to one another without plunge pools.
- **Transducer** – Sensor that converts variations in pressure into an electrical signal for measuring flow velocity.
- **Turbulence** – A fluid motion of water characterized by chaotic changes in pressure, velocity, and flow direction.
- **Turbulent cascade** – Class of cascade barrier with severe instream roughness elements that churn the flow into surges, boils, eddies, and vortices. No resting areas.
- **Volitional swimming test** – Measures fish movements through an open channel of fixed length. Fish enter the channel freely swimming upstream against the flowing water, and swimming speed is controlled by the fish. The higher water velocities generated in the open channel enables testing of higher swimming speeds. Tests typically involve swimming speeds maintained for 60 seconds or less.
- **Water velocity (*V*)** – The velocity of flowing water in m/s.
- **Waterfall** – An abrupt change in water velocity where water passing over the brink of the crest separates from the streambed at some point. It does not require total free-fall and may remain or come into contact with the bedrock/precipice face at various points throughout. Usually exceeds a 23-degree angle. It is within the first tier (broadest level) of classification that differentiates barriers.
- **White-water** – Turbulent water in which entrainment of air bubbles creates a white appearance.


Waterfall Fish Barrier Assessment
Field Manual
Jason Blackburn
Brad Hurkett
Logan Redman
Alberta Conservation
Association

BARRIER ASSESSMENT STEP-BY-STEP INSTRUCTIONS:

1. Enter site location, date, barrier ID, and crew information, and check prevailing seasonal flow category: Spring, Summer, Low.

2. Enumerate and ID features onto the datasheet, that are ≥ 75 cm high and/or ≥ 100 cm long labelling them by type, class, and descriptor(s).

3. Assign each feature a primary barrier mode: swimming or leaping.

4. Measure leaping barrier dimensions of each feature with TruPulse®: H (HT), L (HD), θ (INC), Xm, (SD).

5. Measure depths:
   a) each plunge pool: $D_{pp\text{-}leap}$, $D_{pp\text{-}max}$, $D_{pen,}$ (>pool-bottom (Y/N)), estimate in dm
   b) each crest**:** D_c fish landing area
   c) if **"**swimming**",** D_{ch} each chute/pathway: 1) below crest, 2) mid, 3) near base

6. Measure velocity:
   a) each plunge pool: Backeddy (Y/N), V_{eddy}
   b) each crest: V_{crest} fish landing area
   c) if "swimming", V_{ch} each chute/pathway**:** 1) below crest, 2) mid, 3) near base

7. Measure wetted width (*ww*) and rooted width (*rw*) above the barrier.

8. Determine from leaping curves the minimum fish size that can leap each feature: Min fish.

9. Label swimming barriers corresponding to page 1 feature ID numbers, identify swimming pathway(s) to be measured and perform any missed chute measurements (θ, $X_{m,}$ $D_{ch,}$ V_{ch}) along the identified pathway(s).

10. Characterize in-chute turbulence and assign appropriate categories by:
    a) Turbulence Type: Spillover, Funnelled, Diffuse
    b) Turbulence Intensity: Infused, Agitated, Saturated

11. Characterize swimming pathway complexity through turbulence, by:
    a) Directness of route (Direct/Indirect)
    b) Eddy uniformity (Uniform/Interrupted/Obstructed)
    c) Plunge pool orientation (Normal/Inhibitive)

12. Determine from the swim chart and depth table the fish size range that can swim each feature: Fish size *V* and *D*.

13. Rank swimming modes (velocity, depth, turbulence) in order of difficulty (1=most difficult): 1, 2, 3.

14. Estimate flood inundation, recording D_{th} and H_{bf} (VD) and calculate their sum to determine D_{bf}. Double the D_{bf} and subtract D_{th} to determine H_{fp}.(i.e., $2(D_{th} + H_{bf}) - D_{th}$). Indicate the appropriate flood inundation category (Low water/Seasonal/Effective/Absolute).

15. Photograph each feature and record photo numbers.

16. Record and narrate video of each feature and record video numbers.

17. Assign the overall barrier type, class, mode, and descriptor.

18. Complete and label overall barrier sketch if applicable.

19. Record photo and video number ranges onto data form header.

20. Record any additional waypoints collected within a barrier, by feature number, in empty space on the datasheet.

21. Photograph completed datasheets and verify media was captured (Y/N).

COMPLETING A WATERFALL FISH BARRIER ASSESSMENT

This field manual provides detailed methods for measuring and recording data during waterfall fish barrier assessments to ensure datasets are consistent, comparable, and correctable across the native trout species range. The information presented here follows the order of events required to complete the assessment and record the data on the Barrier Assessment Data Form.

1. ENTER SITE LOCATION, DATE, BARRIER ID, AND CREW INFORMATION, AND CHECK PREVAILING SEASONAL FLOW CATEGORY

Waterbody: Stream Name

Barrier ID: Unique identifier per barrier. One barrier ID may have multiple barrier features.
E.g., B_B001
B – first letter of HUC6 drainage
001 – three-digit barrier number

Date: Day/Month/Year

GIS Location: Determined from desktop search to locate barriers (*not included on data form*).
UTM Easting:
UTM Northing:

GPS Location: Ground-truthed location collected with GPS unit.
UTM Easting:
UTM Northing:

Crew: Names of surveyors

Photos: The numbered range of photo and video files taken at a barrier location.

Flows: Indicate in one of the three check boxes which of the following conditions best describes those encountered during the time of the barrier assessment:

Spring Flows
Streams are at high, or spring flows, when the stream channel is at or near bankfull at the time of assessment. Water clarity is typically silty or stained as sediments remain entrained in the water column. Fording or wading of streams is generally unsafe during this period. Spring spawning migration behaviours are best observed during this window which can prove insightful to verify potential swimming paths through chutes and leaping heights at waterfalls.

Summer Flows

During summer flows, areas of the streambed and channel have become exposed, such as along stream margins, and areas of deposition such as gravel bars and inside bends of meanders are no longer submerged. Water clarity is increased as finer suspended sediments have mainly settled out. Wading, navigating, and accessing sites along the channel is typically safer and more feasible during summer flows.

Low Flows

Flows are considered low when much of the streambed is exposed. Riffle reaches may have unsuitable swimming depths for adult sized fish. Side channels and pools may become disconnected from the thalweg, and flows within the thalweg may become braided, and/or fragmented longitudinally by dry channel or sub-surface reaches. Foot access along the stream channel is easiest and safest during low flows.

2. ENUMERATE AND ID FEATURES THAT ARE ≥ 75 CM HIGH AND/OR ≥ 100 CM LONG LABELLING THEM BY TYPE, CLASS, AND DESCRIPTOR(S)

Barrier Types:

Determine the overall barrier type once all features have been assessed. Indicate in one of the three check boxes which of the following types best describes the overall barrier type during the time of the assessment:

Waterfall an abrupt change in water velocity where water passing over the brink of the crest separates from the streambed at some point. It does not require total free-fall and may remain or come into contact with the bedrock/precipice face at various points throughout. Usually exceeds a 23-degree angle.

Chute a steep gradient where the water mainly stays in contact with the streambed throughout the course of the feature. Usually less than a 23-degree angle.

Cascade stream reach where series of waterfalls and/or chutes of varying intensities are characterized by turbulence and white-water resulting from complex and chaotic roughness elements. Broadly encompasses anything that is multi-featured, with turbulence and white-water present.

Barrier Class:

Indicate in one of the check boxes which of the following classes best describes the overall barrier, by its type, during the time of the assessment:

Type	Class	Definition
Waterfalls	**Single:**	Entire stream flows through a single opening offering one path for fish passage.
	Multiple:	Flow divides into more than one channel offering several passage routes of varying difficulty.
Chutes	**Simple:**	Uniform cross-section and slope, generally straight, with supercritical flow throughout.
	Complex:	Cross-section varies, several changes in slope, winding channel, white-water at all stages.
Cascades	**Compound:**	Combination of falls and/or chutes.
	Turbulent:	Severe instream roughness elements churn the flow into surges, boils, eddies, and vortices. No resting areas.
	Boulder:	Large instream boulders constrict flows creating hydraulic drops from upstream to downstream, resting areas intermittent, very turbulent pools.

Barrier Descriptors:

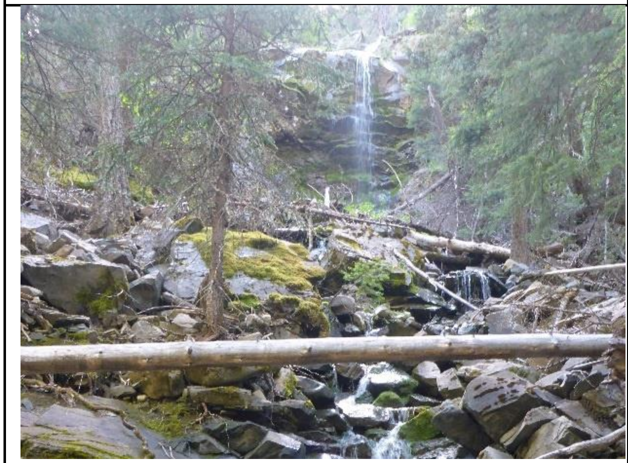
List any of the following descriptors that a) best describe, and b) most resemble the overall barrier during the time of assessment:

a) Barrier descriptor definitions

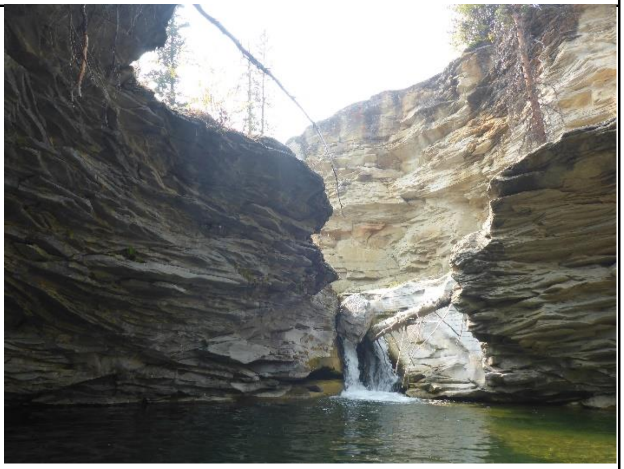
Descriptor	Definition
Block	Wider than it is tall, rectangular shape. Usually falls from the entire width of the stream with one primary drop, while maintaining contact with the underlying cliff. It does not have to be a solid sheet of water across its entire width.
Cascading	Descends in quick succession over a series of multiple drops or steps, sloping rock surfaces, or rugged, irregular-shaped sloping surfaces.
Cataract	Large volume, powerful, dangerous vertical waterfalls.
Chute/flume	Stream passage is very narrow, forcing water through at high pressure, usually between steep walls (i.e., a steep cascade that is confined to a narrow channel).
Ephemeral (ribbon)	Very thin or ephemeral waterfalls from very small, narrow streams. A small ribbon of water.
Fan/veil	Spreads horizontally as it descends while remaining in contact with bedrock. Breadth of the water increases during its descent.

Descriptor	Definition
Horsetail	Descending water maintains constant or semi-constant contact with the bedrock as it falls; barrier can be almost vertical, as well as gradual.
Multistep/stepped	Series of connected waterfalls, each with their own plunge pool.
Plunge	Water drops vertically, losing most or all contact with the rock face.
Punchbowl	Water descends in a constricted form through a narrow channel, and then spreads out into a wide pool below.
Segmented	Water forms multiple, separate flows descending like distinct streams. Characterized by several concurrent drops occurring from the same level, usually separated by small islands or protruding rock.
Slide/slab	Water glides down a relatively smooth surfaced slope, maintaining continuous contact with underlying bedrock. Typically, a gentle slope but can occur on steeper slopes as well.
Tiered/terraced	The drop height of the waterfall is divided into multiple distinct drops in relatively close succession to one another without plunge pools in between.

b) Barrier descriptor photo index:

	
Block waterfall	Cascading waterfall
	
Cataract waterfall	Chute/flume waterfall
	
Ephemeral (background), scree (foreground)	Fan/veil waterfall

b) Barrier descriptor photo index (continued):

	
Horsetail waterfall	Multistep/stepped waterfall
	
Plunge waterfall	Punchbowl waterfall
	
Segmented waterfall	Slide/slab waterfall

b) Barrier descriptor photo index (continued):

Tiered/terraced waterfall

3. ASSIGN EACH FEATURE A PRIMARY BARRIER MODE: SWIMMING OR LEAPING

Primary Barrier Mode:

Indicate in one of the check boxes whether the Leaping or the Swimming barrier mode best describes the most likely means of ascending the most difficult feature within the barrier overall. Where there is ambiguity, default to the Swimming barrier mode.

4. MEASURE LEAPING BARRIER DIMENSIONS OF EACH FEATURE: H (HT), L (HD), θ (INC), X_m (SD)

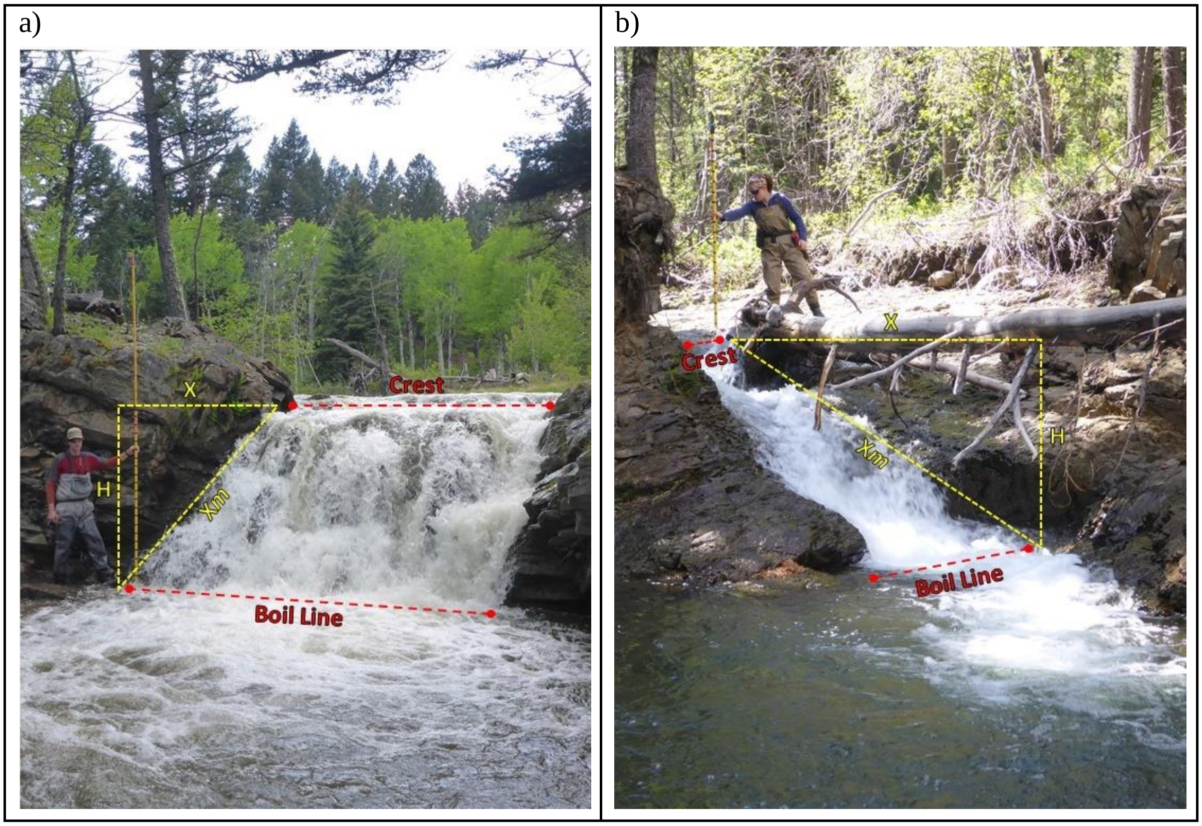
Barrier Measurements - Leaping mode

The following leaping barrier measurements are taken of each barrier feature, by feature number, and recorded on page 1 of the Barrier Assessment Data Form. It is essential to have corresponding measurements, photo, and video for each barrier feature to effectively score and rank the barrier post-assessment. Data and media must be labelled so that they are traceable back to each barrier feature.

Feature:

Number individual features within the barrier. Identifying them by type, class, and descriptor, and assign their primary barrier modes, using the same criteria previously indicated for overall barrier classification.

Feature Dimensions:
Leaping barrier dimensions of height (*H*), length (*L*), angle (°) and slope distance (X_m), are simultaneously measured using a precision laser rangefinder (HT, HD, INC, and SD, respectively), targeting the crest and boil lines for both a) waterfalls and b) chutes.



Barrier Height – *H* (m):
The barrier *H* is the water surface elevation change (vertical distance) between the predicted leaping location below the barrier (i.e., at the standing wave) and the landing location above the barrier (i.e., on the crest). Measure *H* (HT) at the lowest point of elevational change of the leaping barrier where suitable water conditions exist. Record *H* in metres (m) with minimum precision to the nearest decimetre (i.e., the first decimal), although higher precision is attainable and preferred as the TruPulse 200X measures up to ± 4 cm.

Barrier Length – *X* (m):
The barrier *X* is the horizontal distance (HD) between the leaping and landing location. This measurement is typically generated by the laser rangefinder while performing the height measurement. As with height measurements, barrier length is also recorded in metres (m) with minimum precision to the nearest decimetre.

Barrier Angle – *θ* (°):
The barrier θ is generated by the laser rangefinder (INC) while performing height and length measurements. Record θ to the nearest degree. Barrier angle can also be measured from above the barrier, looking down, and aligning the rangefinder along the plane of the barrier face.

5. **MEASURE DEPTHS**

Plunge Pool Depth – $D_{pp\text{-leap}}$ and $D_{pp\text{-max}}$ (m):

Measure $D_{pp\text{-leap}}$ with a measuring staff or sounding line at the deepest point of the plunge pool near the standing wave where fish initiate their leap. Measurement of $D_{pp\text{-max}}$ is simply the deepest part of the pool serving as supplemental fish-holding and habitat information. Record all plunge pool depth measurements in metres with minimum precision to the nearest decimetre, and preferred precision to the nearest centimetre.

Plunge Pool Water Penetration Depth – D_{pen} (dm):

The subjective measurement of D_{pen} is the depth that falling water penetrates into the plunge pool. Indicate (Y/N) if the falling water extends to the pool-bottom and beyond. Estimate the plunging water depth to the nearest decimetre by approximating the proportion of the measured D_{pp} that turbulence penetrates.

Plunge Pool Backeddy Velocity – V_{eddy} (m/s):

Measure the V_{eddy} using a digital flow meter mounted to a telescopic pole along the boil line of the barrier feature. Indicate (Y/N) if a back eddy or upwelling in the plunge pool exists. If one exists (Y), record the subsequent negative velocity in metres per second (m/s); if one does not exist (N), record the subsequent positive velocity in m/s.

6. **MEASURE VELOCITY**

Crest Velocity – V_c (m/s):

Measure the V_c, recorded in m/s, using a digital flow meter mounted to a telescopic pole, along the crest line at the anticipated landing area of leaping fish.

Crest Depth – D_c (m):

Using a graduated measuring staff, measure crest depth along the crest line at the anticipated fish landing area where maximum water depth occurs. Crest depth is recorded in metres with minimum precision to the nearest decimetre, and preferred precision to the nearest centimetre.

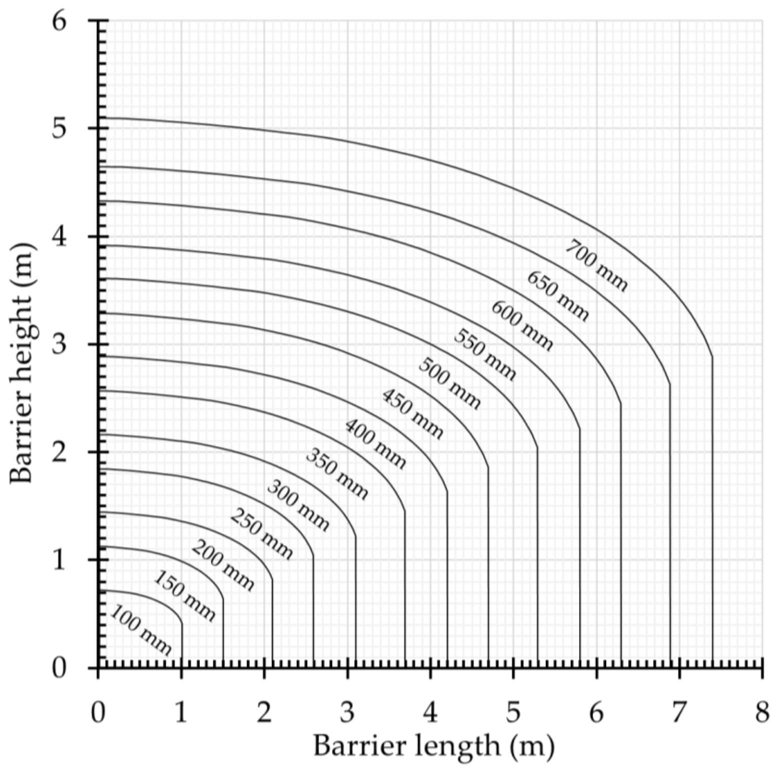
7. **MEASURE STREAM WIDTHS**

Upstream Wetted and Rooted Width – WW/RW (m):

Measure WW and RW upstream of the barrier to characterize relative stream size and channel condition during the time of assessment. Take measurements a short distance upstream of the crest using a rangefinder or measuring tape and record in metres, with minimum precision to the nearest decimetre.

8. DETERMINE FROM LEAPING CURVES THE MINIMUM FISH SIZE THAT CAN LEAP EACH FEATURE

Minimum Fish – Min Fish (mm):
Using the following leaping curves, determine the minimum size class of non-anadromous Subcarangiform fish that can ascend the barrier by leaping, recorded in millimetres.



9. LABEL SWIMMING BARRIERS CORRESPONDING TO PAGE 1 FEATURE ID NUMBER, IDENTIFY SWIMMING PATHWAY(S) TO BE MEASURED AND PERFORM ANY MISSED CHUTE MEASUREMENTS (θ, X_m, D_{ch}, V_{ch})

Barrier Measurements – Swimming Mode

After leaping measurements are performed, the following swimming barrier measurements are taken at barrier features identified as chutes and recorded on page 2 of the Barrier Assessment Data Form.

Slope – θ (°):
Chute slope is analogous to barrier angle (INC), which was measured and recorded during leaping barrier measurements.

Slope Distance X_m – (m):
The X_m is the slope distance (SD) a fish would need to swim up the chute; it is not the same as barrier length. It is an essential measurement for determining fish passage by swimming and is generated by

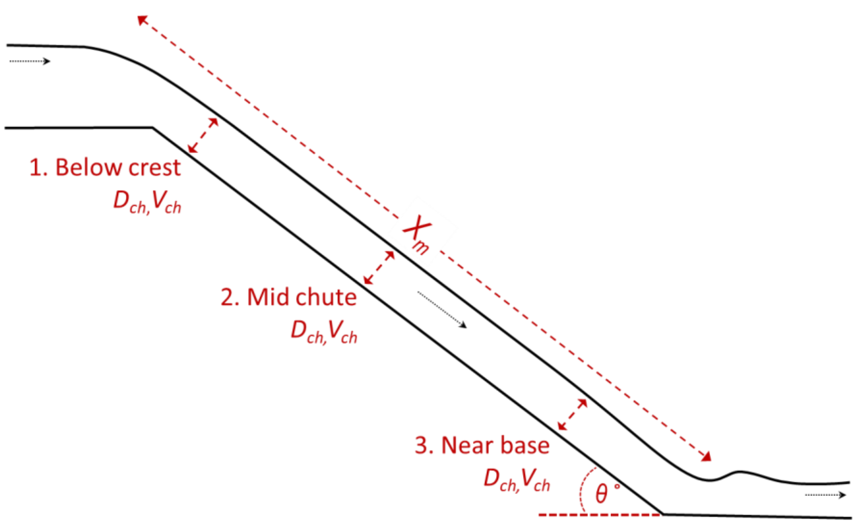
the laser rangefinder while performing height and length measurements for leaping. Slope distance is recorded in metres with minimum precision to the nearest decimetre.

In-chute Depths – D_{ch} (m):

Using a graduated measuring staff or telescoping velocity meter pole, measure water depths at three locations within the chute where possible: 1) just below the crest, 2) mid-way up the chute, and 3) near the base of the chute. The average chute water depth will determine the fish size range that is restricted by swimming depth within the chute. Record D_{ch} in metres with minimum precision to the nearest centimetre.

In-chute Velocity – V_{ch} (m/s):

Measure the V_{ch} using a digital flow meter mounted to a telescopic pole at three locations within the chute where possible: 1). just below the crest, 2) mid-way up the chute, and 3) near the base of the chute. The average V_{ch} will determine the fish size range that is restricted by stream velocity. Once velocity measurements have stabilized on the flow meter, record V_{ch} in m/s. Measurements of D_{ch} and V_{ch} can be taken simultaneously using the same telescoping pole if it is graduated, at the following in-chute locations:

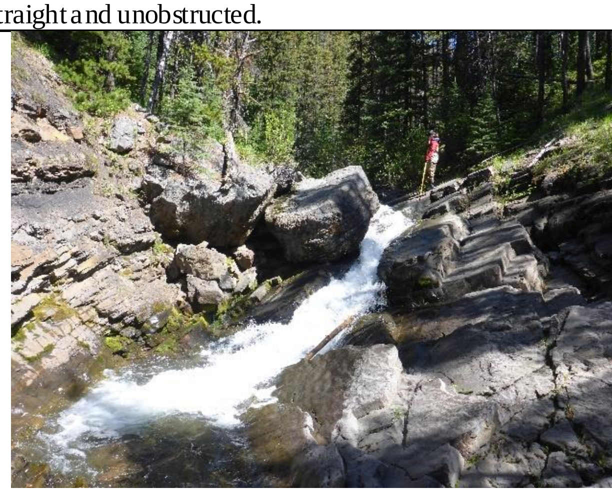


10. CHARACTERIZE IN-CHUTE TURBULENCE

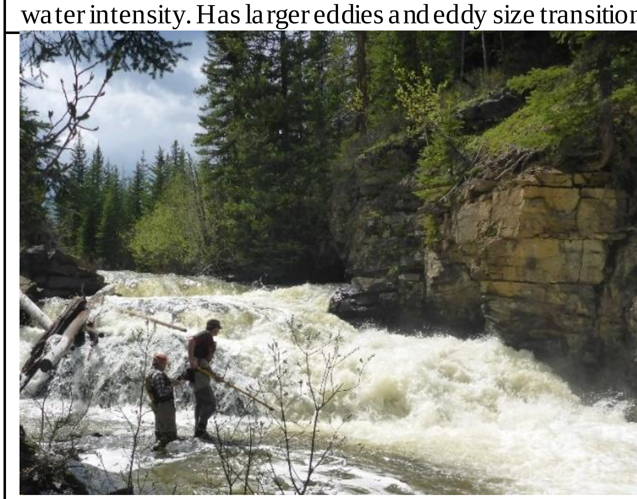
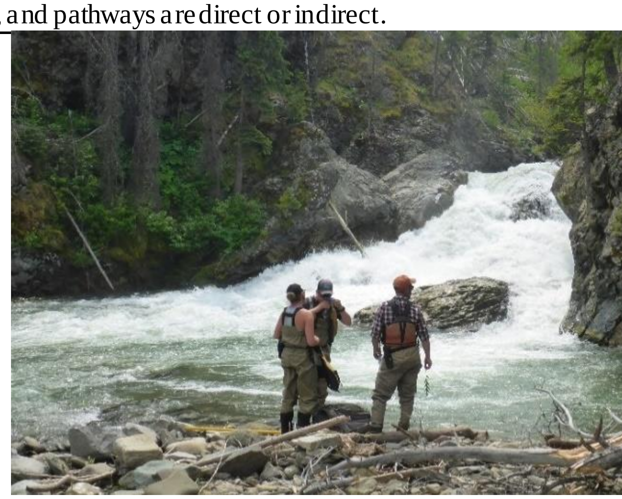
Determine the turbulence Type and white-water Intensity that best characterizes turbulence at the time of assessment, and assign the appropriate ordinal values using the following examples, and the key provided on the data form:

Turbulence Types:


1 – Spillover – Flow spills over a uniform drop nearly channel-wide or slightly funnelled. Water remains mainly in contact with the feature and flow is mostly unidirectional with relatively uniform turbulence. Eddies are typically small and uniformly distributed, swimming pathways are straight and unobstructed.

2 – Funnelled – Flows are funnelled into a trough, chute, or narrowing which consolidates flow volume and increases depths. Flows may fold or spiral and lose contact with the streambed, which increases velocity fluctuations and white-water intensity. Has larger eddies and eddy size transitions, and pathways are direct or indirect.

3 – Diffuse – Flows broadcast into many directions, with violent frothy white-water and spray, and unconsolidated stream flows. Water frequently 'bounces' off the streambed resulting in broken, indirect swimming pathways with fluctuating velocities and multiple eddy size transitions.

White-water Intensity:

1 – Infused Slightly more white-water than non-white-water, or approximately equal proportions of each. Although mixed or laced together, differentiation between white and non-white-water is not difficult. A definite obstacle but likely passible by certain fish size classes at various flows.	
2 – Agitated Flows are primarily white. Passage is difficult, but the white-water turbulence alone is not likely a reliable barrier to prevent invasion from the best of swimmers, or from chance events associated with chaotic turbulence that may propel fish.	
3 – Saturated Discerning anything non-white from the frothy white-water and spray is nearly impossible. Passage is extremely unlikely.	

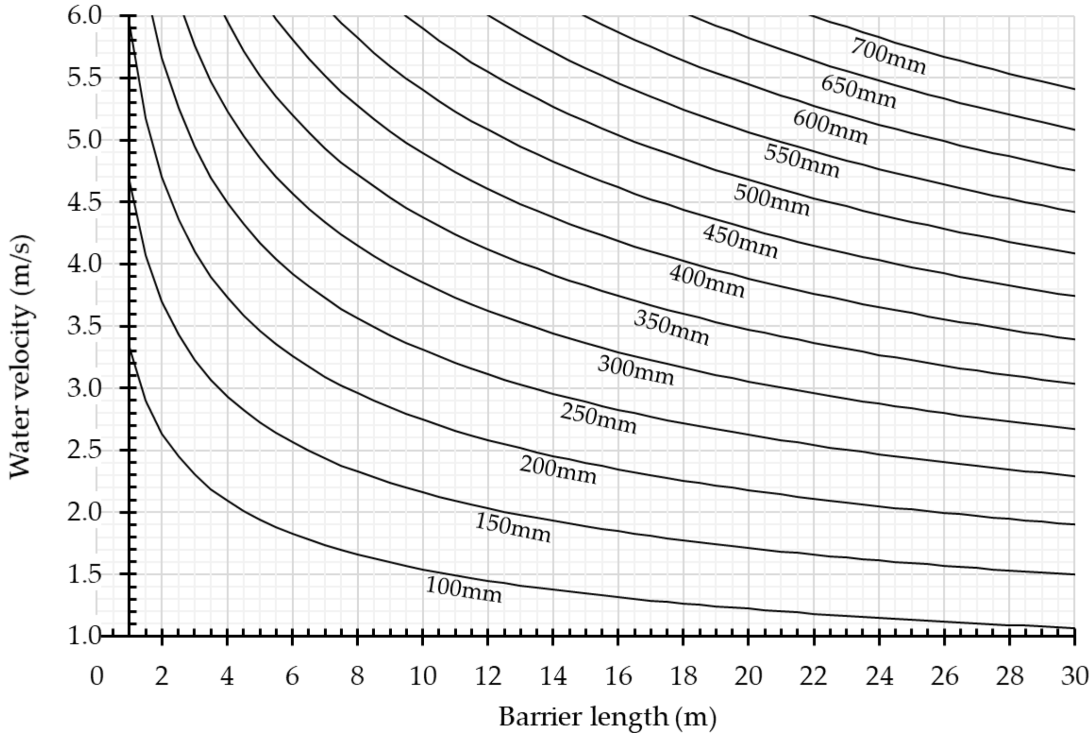
11. CHARACTERIZE SWIMMING PATHWAY COMPLEXITY THROUGH TURBULENCE

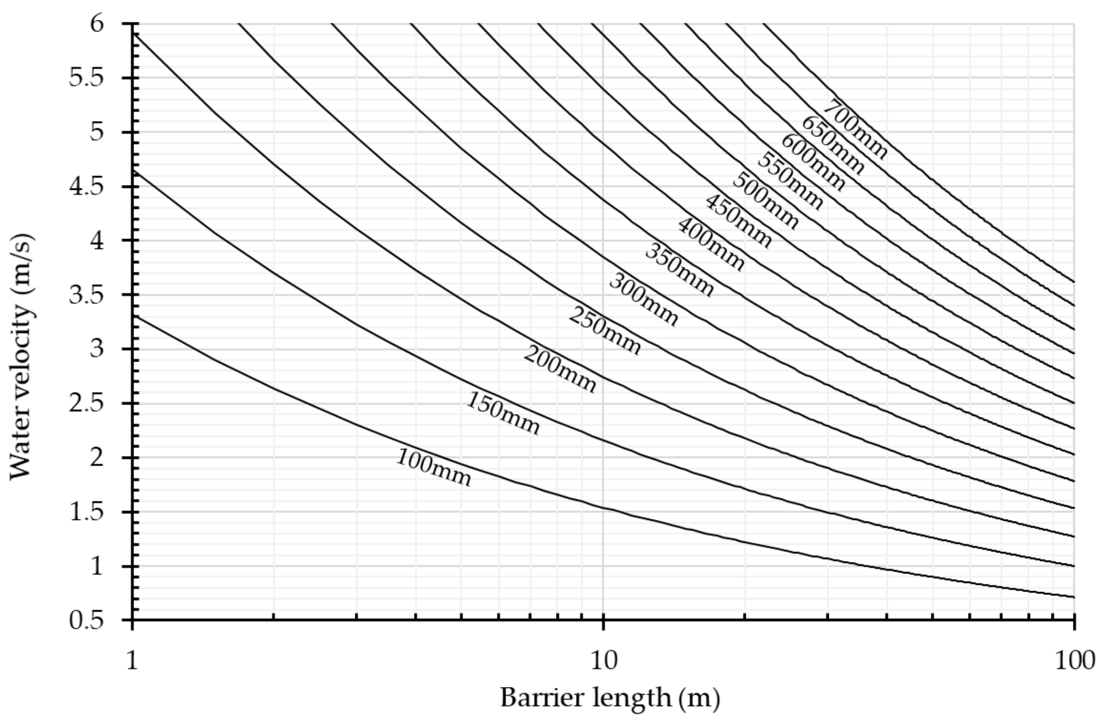
Assign a description that best characterizes the elements of swimming pathway complexity by category, using the appropriate ordinal (and nominal) values below.

A) Directness of route	B) Eddy uniformity and distribution	C) Plunge pool orientation
1 – Direct Passage route through the barrier feature is straight and direct from the plunge pool to the nearest resting area. **2 – Indirect** Successful passage through the barrier feature requires en-route course correction from the plunge pool to the nearest resting area.	**1 – Uniform** Eddy size along the passage route through the barrier feature is relatively uniform from the plunge pool to the nearest resting area. **2 – Interrupted** The pathway from the plunge pool through the barrier feature transects one major eddy size transition before the nearest resting area. **3 – Obstructed** The pathway from the plunge pool through the barrier feature transects multiple eddy sizes and turbulence transitions before the nearest resting area.	**N – Normal** Barrier orientation allows normal flow-through with the plunge pool below, promoting a normal swimming cue and passage in a net upstream direction. **1 – Inhibitive** The barrier orientation is positioned so that flows interacting with the plunge pool do not cue a swimming response in a net upstream direction, such as flows entering a plunge pool at oblique angles to the general direction of streamflow, confusing directional swimming cues.

12. DETERMINE THE FISH SIZE RANGE THAT CAN SWIM EACH FEATURE – fish size (*V*) and (*D*)

a) Determine minimum fish size that may ascend the barrier based on stream velocity – *V*.





b) Determine maximum fish size that may ascend the barrier based on swimming depth – *D*.

Minimum water depth (cm)	Estimated fish body depth (cm)	Fish total length (mm)
3	2.2	100
5	3.3	150
7	4.4	200
8	5.5	250
10	6.6	300
12	7.7	350
13	8.8	400
15	9.9	450
16	11.0	500
18	12.1	550
20	13.2	600
21	14.3	650
23	15.4	700
25	16.5	750

13. RANK SWIMMING MODES (VELOCITY, DEPTH, TURBULENCE) IN ORDER OF DIFFICULTY

Swimming Modes (Velocity, Depth, Turbulence)

Indicate which of the swimming modes contributes the most to limiting fish passage, in the columns provided. If more than one mode contributes to limiting passage, rank them in descending order of difficulty from the most (1) to the least (3) difficult. If any of the swim modes do not apply, denote as not applicable (N/A) in the column. A minimum of one swimming mode should be indicated if the primary mode for the feature was recorded as swimming.

14. ESTIMATE FLOOD INUNDATION

Measure and record D_{th} and H_{bf} (VD) and calculate their sum to determine D_{bf}. Double the D_{bf} and subtract D_{th} to determine H_{fp}. Indicate the appropriate flood inundation category based on D_{bf} and H_{fp} values relative to crest height (H).

Category	Condition	Predicted effect during flood
Low water barrier	Barrier height is below the stream's bankfull height, passable during higher flows and freshets, ($H < H_{bf}$)	Inundated
Seasonal barrier	Barrier height is above the bankfull height but below the local estimated flood prone height, passable during flood events, ($H > H_{bf}$ but $< H_{fp}$)	Likely inundated
Effective barrier	Barrier height is above estimated flood height but may be reduced during flood. Likelihood of passage during flood depends on local fish sizes and abilities to ascend reduced barriers, ($H > H_{fp}$)	Reduced barrier
Absolute barrier	Barrier height appears far above local estimated flood height or past flooding evidence, well beyond the estimated abilities of the largest fish.	Permanent barrier

15. PHOTOGRAPH EACH FEATURE AND RECORD PHOTO NUMBERS

Take a minimum of one photograph per barrier feature and two photographs of the overall barrier, although several photos may be taken. Take a representative photo from below the overall barrier facing upstream (i.e., standing at water surface level), with a human-scale subject. A profile photo of each barrier should also be taken when possible.

16. RECORD AND NARRATE VIDEO OF EACH FEATURE AND RECORD VIDEO NUMBERS

Record at least one representative 10-second digital video of the overall barrier from below, facing upstream, although several videos may be taken. A profile video of the overall barrier should also be taken when possible. Video narration should include waterbody name, barrier ID, and feature number. An underwater video in plunge pools is also useful to confirm fish presence below barriers.

17. ASSIGN THE OVERALL BARRIER TYPE, CLASS, MODE, AND DESCRIPTOR

Based on feature and barrier classification criteria, assign an overall barrier classification.

18. COMPLETE AND LABEL OVERALL BARRIER SKETCH IF APPLICABLE

Barrier Sketch *(not specified on data form)*

Where space permits, a rough sketch identifying and labelling features within a complex barrier can be beneficial for post-field data entry and analysis—to accurately identify photos and data associated with each feature within a barrier.

19. RECORD PHOTO AND VIDEO NUMBER RANGES ONTO DATA FORM HEADER FOR MEDIA LABELS

Post-assessment management of media files may require systematic labelling as several photos and videos may be required to comprehensively characterize a barrier for future data entry, analysis, and desktop scoring and evaluation. Files may be labelled using the following composite of barrier ID, feature number, and camera-generated file number, which retains the sequence in which digital files were taken:

E.g., B_O185_F1_P1080773
B_O185 - Barrier ID
F1 – Feature #
P1080773 - Camera-generated

20. RECORD ADDITIONAL WAYPOINTS COLLECTED WITHIN A BARRIER, BY FEATURE NUMBER, IN EMPTY SPACE OF THE DATASHEET

Location data management:

Ensure additional waypoints collected in the field to help locate barriers and barrier features are recorded in a way that enables discernment of their locations both geographically and within the barrier itself.

21. PHOTOGRAPH COMPLETED DATASHEETS AND VERIFY MEDIA WAS CAPTURED (Y/N)

Datasheet Photo and Video confirmation:

Upon final completion of a barrier assessment, confirm in the checkbox that video of the barrier was recorded. Photograph the completed datasheet, to ensure alignment between barrier data and media for future desktop barrier scoring and evaluation, and indicate in the checkbox provided.

DATA FORMS AND EQUIPMENT:

The following are the materials, equipment, and data forms to complete a barrier assessment:

-Waterproof digital camera with video
-Selfie stick
-GPS unit, maps, waypoint lists
-Precision rangefinder
-Flow meter
-Sounding line with cannon ball weight
-Graduated telescopic measuring pole
-Telescopic pole for flow meter transducer
-Wading staffs
-Rangefinder target
-Barrier datasheets on waterproof paper, pencils, clipboard
-Barrier Field Handbook
-Backpack and cruiser vests for gear
-Waders and boots
-PFDs during high flows
-Personal throw bags
-Leather gloves for scrambling steep valleys and cliffs
-Personal First Aid Kits
-Satellite phone

Stream: Date: Crew:

Barrier ID: Easting: Photos:

Northing:

BARRIER TYPE	BARRIER CLASS			PRIMARY BARRIER MODE			BARRIER DESCRIPTORS	FLOOD INUNDATION (m)	
Waterfall ☐	Single ☐	Multiple ☐		Leaping ☐	Swimming ☐			**D_{th} =**	**H_{fp} =** $(D_{bf} \times 2) - D_{th}$
Chute ☐	Simple ☐	Complex ☐		FLOWS DURING SURVEY				**H_{bf} (VD) =**	
Cascade ☐	Compnd ☐	Turbulent ☐	Bouldr ☐	Spring ☐	Summer ☐	Low ☐		**D_{bf}=**	

FEATURE			PRIMARY MODE	***LEAPING MODE***													
				Feature dimensions				Plunge Pool						Crest			Min fish
No. Type (Easting,Northing)	CLASS	DSCRIPTR	$Leap_{vs}Swim$	Ht - (m) (**HT**)	Lgth-***X*** (m) (**HD**)	Angle(θ) (**INC °**)	Slp-(X_m) (**SD**)	D_{pp} leap	D_{pp} max	$D_{pen} \geq D_{pp}$	D_{pen} (m)	Bkedy (y/n)	V_{eddy}	V_c	D_c	WW / RW	leap curve

Datasheet photo ☐

Video taken ☐

Comments:

FEATURE			SWIMMING MODE(S)																
				Pathway			Turbulence		In-chute *D (cm)*			In-chute *V (m/s)*			Fish Size (mm)		Swim Modes[1,2,3]		
No. TYPE	CLASS	DSCRIPTR	#	D/I	Unif	Pool (n/1)	Type	Intensity	D1	D2	D3	V1	V2	V3	*D*	*V*	Vel.	Dpth	Turb.

Flood / Turbulence / Pathway Complexity Key						
Code	**Inundation**	**Uniformity**	**Type**	**Intensity**	**Pathway**	**pool arrang**
1	Low water	Uniform	Spillover	Infused	Direct	Inhibitive
2	Seasonal	Interrupted	Funnelled	Agitated	Indirect	
3	Effective	Obstructed	Diffuse	Saturated		
4	Absolute					

Datasheet photo ☐ Video taken ☐

Comments: