Appendix H: Sizing Fish Ladder Pools Based on Energy Dissipation and Fish Run Size

H.1 Introduction

Appendix H provides three methods for calculating the minimum pool volume needed to pass salmonids migrating upstream through fishways safely and readily. These methods are energy dissipation in fishway pools (Section H.2), fish migration run size (Section H.3), and general sizing guidelines (Section H.4). After checking each calculation, the dimensions used should be that which yields the largest fishway pool.

The minimum pool volume should be based on the largest volume computed by the following three methods:

1. *Pool volume based upon the upper allowable limit in the time-rate of energy dissipation per unit of water volume in a fishway pool. This is termed the energy dissipation factor (EDF) by North American fish passage engineers; EDF is expressed as foot pounds per second per cubic feet (ft-lb/ft^3/s). European fish passage engineers use the same criterion parameter but refer to it as the power dissipation factor, which is expressed as watts per cubic meter (Larinier 1990).*

2. *Pool volume based upon the estimated annual size of the fish run.*

3. *General pool sizing guidelines presented in Chapter 5 of the NOAA Fisheries West Coast Region Anadromous Salmonid Passage Design Manual (Manual). For pool and weir ladders, pools should not be smaller than 8 feet long, 4 feet wide, and 6 feet deep. For pool and orifice ladders, pools should not be smaller than 8 feet long, 6 feet wide, and 6 feet deep. Pools for vertical slot ladders vary with slot width; for a ladder with 12-inch-wide slots, the pools should be 8 feet wide by 10 feet long.*

H.2 Pool Volume Based on Energy Dissipation Factor

The first method for calculating the size of pools in fish ladders is based on energy dissipation. Reducing turbulence and associated air entrainment is generally considered advantageous in the design of fish passage facilities. The EDF is a recognized metric that correlates well with observations of reduced turbulence and air entrainment (Towler et al. 2015a). Fish ladder pools are often designed based on maintaining the EDF in each pool below a specific level. This is especially true for pool and weir and pool and orifice ladder designs. This method is based on successful fishway designs and has been used primarily to design pool and weir ladders and vertical slot ladders.

Energy is the ability to do work. In Imperial/U.S. units, energy is given in foot pounds (ft-lb). Power is the time-rate of transference of energy from one form to another and is described as units of foot pounds per second (ft-lb/s). EDF is the rate of transference of energy power (ft-lb/s) per volume of water in fishway pools. This rate of power (or energy) dissipation can be thought of as an indication of the turbulence in each pool. High energy dissipation (i.e., high water power) usually indicates excessive aeration and turbulence levels in the pool. Pools with high energy dissipation and excessive turbulence may not have sufficient resting areas that fish need in these situations and that support good fish passage performance. While no specific EDF criterion is offered beyond the general guidance offered in Section H.2.1, designers are cautioned to ensure that the EDF value is relatively small (Towler et al. 2015b).

A key assumption for sizing ladder pools is that all of the energy coming into a pool from upstream needs to be absorbed and dissipated in the pool. If a pool is undersized for the amount of energy inflow, not all of the energy will be dissipated, and excess energy can carry into the next downstream pools. Since most pools in a specific ladder are equal in size, excess energy can accumulate as it is carried down the ladder and create unstable hydraulic conditions in the ladder. These unstable conditions include flow surging, a transition from plunging to streaming flow (and vice versa), and flow overtopping the ladder weir. Each condition, and combinations of conditions, can adversely affect fish passage through the ladder.

The entire pool volume does not contribute equally to dissipating energy. Areas of dissipation within the pool volume vary based on the size and shape of the pool and its orientation to flow. The majority of energy is dissipated at the point where the jet from the upstream pool enters the downstream (receiving) pool. Fish have no alternative but to navigate this area of high energy dissipation when moving upstream through the fishway. EDF calculations primarily evaluate the turbulent conditions at the point of jet entry (Bates 1992; WDFW 2000). Love and Bates (2009) recommend not including pool lengths greater than 8 feet or pool depths deeper than 4 feet in EDF calculations.

H.2.1 Energy Dissipation Factor Requirements

For fish ladder pools, the EDF of 4 ft-lb/ft^3/s has been established and is generally accepted for the passage of salmonids (Bell 1991). Other species may require a lower EDF.

For example, American shad (Alosa sapidissima) require a water dissipation of 3 ft-lb/ft^3/s (Bates 1992).

The earliest reference to an EDF requirement for ladder pool size was found in Bell (1991). Towler et al. (2015a, 2015b) provide additional discussions of the use of EDF in fishway design.

The EDF can be calculated using Equation H-1.

$$EDF = \frac{(\gamma)(Q)(H)}{V} \tag{H-1}$$

where:
EDF = energy dissipation factor (ft-lb/ft^3/s)
γ = unit of water, 62.4 lb per ft^3
Q = auxiliary water supply flow, in ft^3/s
H = energy head of pool-to-pool flow, in feet
V = pool volume in ft^3

Inserting an EDF value of 4 ft-lb/ft^3/s into Equation H-1 and rearranging the equation to solve for the minimum pool volume yields the following equation (H-2; Bates 1992).

$$V = \frac{(\gamma)(Q)(H)}{4(ft \times lb/s)/ft^3} \tag{H-2}$$

where:
V = pool volume in ft^3
γ = unit of water, 62.4 lb/ft^3
Q = auxiliary water supply flow, in ft^3/s
H = energy head of pool-to-pool flow, in feet

H.3 Pool Volume Based on Fish Run Size

The second method for calculating the size of pools in fish ladders is based on the size of the fish run.

In river systems with large populations of fish, it is also necessary to ensure that the volume of each individual fish ladder pool is large enough to accommodate the estimated fish run.

Correctly sizing the ladder pools based on fish run size requires consideration of three circumstances that may occur during the functional life of a ladder:

- *Exceptionally large runs due to natural variation in freshwater and ocean productivity that result in large year classes and annual escapement*

- *Adult migration timing that is compressed into a short period due to environmental or hydrologic conditions*
- *Management actions that can result in increased run size in the future such as harvest allocations, hatchery production, fish passage improvements, and supplementation*

The fish ladder pool volume has to be large enough to accommodate the run without causing delay to migrating fish, including consideration of the circumstances listed above. As cited in Clay (1995), Lander (1959) states a fishway that is too small will delay passage based on laboratory studies reported by Elling and Raymond (1959), where adult movement in a test flume was hindered by fish density. Clay (1995) also states that overcrowding of fish in a limited area slows their passage timing based on experiences from the Fraser River (DFC and IPSFC 1955). Bates (1992) and Clay (1995) provide a more in-depth discussion on sizing ladders based upon run size.

H.3.1 Minimum Pool Volume

Based on a head differential between pools of 1 foot, fishway pools should have a minimum water volume as shown in Equation H-3 (Bates 1992; Clay 1995).

$$V = (C) \times (v)/(60 \times r) \tag{H-3}$$

where:

V = minimum pool volume (ft^3)
C = maximum fish passage rate (number of fish per hour)
v = volume required per fish (ft^3 per fish)
r = rate of fish movement (pools per minute)

Listed below is information on a hypothetical fish run:

- C = 5,000 fish per hour (this equates to a maximum annual fish run of about 500,000 fish per year; Section H.3.2.1)
- r = 5 minutes per pool, or 0.2 pools per minute
- Estimated average fish size = 10 lb per fish
- Required holding volume per pound = 0.4 ft^3/lb of fish
- v = volume required per fish, or 4 ft^3 (10 lb/fish × 0.4 ft^3/lb)

Using this hypothetical fish run information and inputting the data into Equation H-3, the estimated minimum pool volume needed based on this example is 1,667 ft^3. Using this method for calculating the size of pools in fish ladders, this is the pool volume required to safely accommodate passage in a fish ladder without overcrowding. This volume translates to a ladder pool with the following dimensions: 10 feet long by 5 feet deep by 33.5 feet wide. This calculated pool volume, and the resultant pool dimensions, are approximately the size of fish ladders at mainstem hydroelectric dams on the Columbia River (see Appendix G for a description of design criteria for these ladders).

H.3.2 Recommended Input Variables

NMFS recommends that the minimum number of fish passing per hour, holding volume per pound of fish and per fish, and the rate of fish movement between ladder pools per minute be used when sizing a fish ladder for anadromous salmonids based on run size using Equation H-3.

H.3.2.1 Maximum Fish Passage Rate in Number of Fish per Hour

The maximum fish passage rate, in number of fish per hour, should be between 1% and 2% of the maximum average annual run size (Bates 1992).

H.3.2.2 Holding Volume per Pound of Fish

The recommended holding pool volume per pound of fish is 0.4 ft^3/lb (Bates 1992).

Note that Bell (1991) provides a less conservative value of 0.2 ft^3/lb. This value may have been based on values reported by the U.S. Bureau of Commercial Fisheries and U.S. Fish and Wildlife Service for Chinook salmon (*Oncorhynchus tshawytscha*) and sockeye salmon (*O. nerka*) and steelhead (*O. mykiss*) of 0.19 and 0.24 ft^3/lb (USACE 1960; see Appendix J, Section J.2.2 for a table of contents for USACE 1960). The larger value represented the holding volume needed by larger test fish. NMFS recommends that the largest holding volume per pound of fish value presented in Bell (1991) and USACE (1960) for a specific species be used because it is more conservative and provides a larger volume per fish. As referenced in Clay (1995), Jackson (1950) assumes a minimum volume of 2 ft^3 per fish when calculating the capacity of the Hell's Gate Fish Ladder on the Fraser River in Canada. Based on an average weight of 6 lb per sockeye and a minimum holding volume of 2 ft^3 per fish, a general holding volume per pound of fish (0.33 ft^3/lb) can be calculated. Clay (1995), in his example of calculating pool volume, assumes a conservative 4 ft^3 per fish (average weight of 6 to 7 lb), which yields 0.67 to 0.57 ft^3/lb.

H.3.2.2.1 Holding Volume per Fish

Holding volume per fish can be calculated by multiplying the holding volume per pound of fish by the average weight of the target species presented in Table H.1.

Table H.1. Average fish weight (Bell 1991) and holding volume.

Species	Average Weight (lb)*	Average Holding Volume (ft^3) based on 0.4 ft^3/lb
Fall-run Chinook Salmon (*O. tshawytscha*)	20	8
Spring-run Chinook Salmon (*O. tshawytscha*)	15	6
Summer-run Chinook Salmon (*O. tshawytscha*)	14	5.6
Coho Salmon (*O. kisutch*)	8	3.2
Pink Salmon (*O. gorbuscha*)	4	1.6
Chum Salmon (*O. keta*)	10	4
Sockeye Salmon (*O. nerka*)	6	2.4
Summer-run Steelhead (A run) (*O. mykiss*)	6	2.4
Summer-run Steelhead (B run) (*O. mykiss*)	9	3.6
Winter-run Steelhead (*O. mykiss*)	8	3.2

Note:
* Bell (1991) lists the average weights of many other species.

H.3.2.4 Rate of Fish Movement Between Pools per Minute

The rate of fish movement between ladder pools should be 5 minutes per pool or 0.2 pools per minute (Bates 1992; Clay 1995).

Equation H-3 can be recalculated to solve for C, the maximum fish passage rate. Equation H-3 can also be used to calculate the capacity of a standard pool of a fishway in terms of pounds of fish per hour.

For example, a standard fishway pool that is 5 feet deep by 8 feet wide by 10 feet long yields a pool volume of 400 ft^3. After inserting this value into Equation H-3, the standard fishway size has a capacity to pass approximately 1,200 fish per hour based on an average fish size of 10 lb and a holding volume of 0.4 ft^3/lb of fish. This capacity of fish per hour can be converted to pounds of fish per hour by multiplying the number of fish by their average weight, which in this example results in an estimated capacity of 12,000 lb of fish per hour. The capacity of a ladder can be calculated for each species present based on the average weight of those fish.

Bell (1991) recommends using rates of fish movement that are between 2.5 and 4 minutes per pool. The U.S. Bureau of Commercial Fisheries and U.S. Fish and Wildlife Service reported values for spring-run and fall-run Chinook salmon, sockeye salmon, and steelhead that ranged from 1.1 to 3.2 minutes per pool over a series of tests that involved 29 replicates (USACE 1960; see Appendix J, Section J.2.2 for a table of contents for USACE 1960). NMFS recommends that the most conservative rate value provided by Bell (1991) or USACE (1960) be used to calculate the rate of fish movement between ladder pools per minute when sizing a fish ladder for anadromous salmonids based on run size using Equation H-3.

H.3.3 Design Run Size, Peak Day, and Peak Hour Estimates

NMFS recommends that the following values be used when sizing a fish ladder for anadromous salmonids based on run size.

H.3.3.1 Size Estimate of the Maximum Annual Run Size

An estimate of the size of the maximum annual fish run should be made to properly size the ladder pools.

Information on run size can be obtained from multiple sources. These include historical information on harvest, information from adjacent watersheds, fish counts, redd counts expanded to the population, number of fish that can be supported by the estimated amount of available spawning habitat, population models, and biological determinations. State agencies, tribal organizations, and federal agencies can all be sources of run size information.

While the size of the annual run for each species present or that will be present in the future is important, the designer should create a composite run of all fish expected to use the ladder throughout the year and compare this to the peak run events. The ladder should be sized for the worst-case conditions (i.e., the largest number of fish per hour) that are estimated to occur over the life of the project.

H.3.3.2 Peak Daily Count

Peak daily count is usually about 10 % of the maximum annual run (Bates 1992).

H.3.3.3 Peak Hourly Count

Peak hourly count is approximately 10% to 20% of the peak daily count.

NMFS prefers to use a conservative estimate of 20% of the peak daily count (Bell 1991). If 20% of the peak daily count is used, and the peak day is calculated as being 10% of the annual run, then the peak hourly count is approximately 2% of the annual run size.

H.4 General Guidelines on Pool Size

H.4.1 General Pool Dimensions

The third method for calculating the minimum fishway pool volume needed to safely pass upstream migrants is presented in the general guidelines provided in Chapter 5, Section 5.5.3.3 of the Manual. The pool dimensions for pool and weir ladders should be a minimum of 8 feet long (upstream to downstream), 4 feet wide, and 6 feet deep (Clay 1995). For pool and orifice ladders, including the half Ice Harbor-style of ladder, the pool should be a minimum of 8 feet long (upstream to downstream), 6 feet wide, and 6 feet deep (Clay 1995).

For ladders in small streams, Bell (1991) provides minimum dimensions for some pool and weir fishway designs. The minimum pool should not be less than 6 feet long, 3 feet deep, and 4 feet wide. NMFS recommends that the fishway slope not exceed a ratio of 1:8 (rise:run). For pools less than 8 feet long, the drop between pools should be reduced proportionally. To allow for the proper dissipation of the orifice flow, the pool dimensions for a pool and orifice ladder should not be reduced (Clay 1995).

H.5 References

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