Barriers to Adult Pacific Lamprey at Road Crossings: Guidelines for Evaluating and Providing Passage

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Cover photo: A severely perched culvert on Baker Creek, a tributary to the South Fork Coquille River in Oregon, prior to its removal and replacement with a natural channel design.

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1 BACKGROUND AND GOALS

Pacific Lamprey, *Entosphenus tridentatus*, is a culturally and ecologically important anadromous species that is native to watersheds from Baja, California north to Alaska. Within this range, thousands of road crossings of streams occur (CDFW 2019; ODFW 2020a; WSDOT 2020). These crossings typically consist of culverts or bridges and associated infrastructure that can inhibit upstream passage of adult Pacific Lamprey during their migration from the ocean to freshwater holding and spawning habitats. These sites often also impair passage of other native lampreys and other aquatic species. Partial passage barriers cause migration delays that can increase stress or vulnerability to predation, translating to lowered spawning success. Complete passage barriers prevent Pacific Lamprey access to upstream holding, spawning, and rearing habitats. The resulting habitat fragmentation reduces population productivity and resiliency. Therefore, identifying barriers to adult Pacific Lamprey and providing unimpaired passage is an important and effective strategy to restore this imperiled species (CRITFIC 2011; USFWS 2019; ODFW 2020b).

Many road crossings have been assessed for passage of anadromous salmonids. However, few sites have been evaluated specifically for adult Pacific Lamprey passage, due in part to the lack of awareness and guidance. In response, this document was developed with the following goals:

1. summarize current understanding of the factors that affect passage of adult Pacific Lamprey at road crossings and highlight key uncertainties and the studies needed to address them (Section 2),
2. describe a standard process for evaluating passage at road crossings (Section 3),
3. summarize considerations for prioritizing barrier sites for improving passage (Section 4),
4. summarize options for improving passage (Section 5),
5. raise overall awareness of Pacific Lamprey passage requirements.

This guide is meant to be a living document that will be updated and refined as the state of knowledge on factors affecting lamprey passage are refined and approaches for evaluating and providing passage are improved. Environmental conditions vary between road crossings, and passage assessment objectives and needs vary between watersheds, states, and agencies. Therefore, all approaches provided herein may not be applicable to all situations. This document draws from existing, well-developed fish passage assessment approaches focused on salmonids (e.g., Taylor and Love 2003; Clarkin et al. 2005; WDFW 2019) and updates and refines a Pacific Lamprey-specific approach developed by Stillwater Sciences (2014).

This document is focused on upstream passage of adult Pacific Lamprey and does not consider other species or life stages. However, evaluating and providing passage at road crossings for adult Pacific Lamprey can improve downstream passage of larval and juvenile Pacific Lamprey, as well as passage of other species. Importantly, as discussed in Section 5, when replacing or retrofitting road crossings that present a barrier to Pacific Lamprey, designs that result in unimpeded passage for all native aquatic organisms should be given precedence. Refer to *Best Management Guidelines for Native Lampreys during In-Water Work* (LTW 2020) for information on lamprey life histories and procedures for reducing impacts to lampreys during construction activities such as culvert removal or replacement.

2 FACTORS AFFECTING ADULT PACIFIC LAMPREY PASSAGE

This section reviews information on the swimming capabilities of adult Pacific Lamprey and other factors expected to influence passage at road crossings. This information was used to support development of: (1) field protocols for evaluating lamprey passage success at road crossings; (2) guidelines for determining the likelihood that a site is passable based on information collected in the field; (3) options and guidelines for remediation of barrier sites; and (4) a list of key data gaps and studies needed to fill them. Relevant factors reviewed include:

- swimming performance in relation to water velocity and depth,
- ability to attach and climb different substrates and structures of various sizes and shapes,
- leaping ability in relation to crossing structures, and
- effects of migration timing, fish size and maturation stage, water temperature, and other factors on swimming ability and passage success.

Each of these factors are reviewed in depth in the sub-sections that follow and summarized in Section 2.8.

In several instances, information on swimming performance and behavior of the more intensively studied Sea Lamprey, *Petromyzon marinus*, is provided for comparison, since this similarly sized species is expected to be relatively similar to Pacific Lamprey (Clemens et al. 2010). The Sea Lamprey has been studied to determine how to limit its population in the Great Lakes where it is not native and has had a detrimental impact on native fishes.

As described below, additional laboratory studies and field monitoring are needed to refine understanding of factors affecting adult Pacific Lamprey passage through road crossings. Thus, swimming performance values and other information provided herein should be applied conservatively when conducting passage assessments and developing road crossing designs, erring on the side of underestimating passage ability.

2.1 Swimming Performance and Behavior

Lampreys use an anguilliform mode of swimming, employing undulatory movements to propel themselves forward (Mesa et al. 2003; Quintella et al. 2009; Keefer et al. 2010). Most movement occurs at night (Robinson and Bayer 2005; McIlraith et al. 2015; Reid and Goodman 2016) and swimming is generally oriented towards the bottom and sides of the stream bed or other surfaces (Kirk et al. 2015; Reid and Goodman 2016). The anguilliform mode of swimming is generally considered to be less powerful compared with other fishes such as salmonids, particularly in turbulent or high-velocity water (Bell 1990; Mesa et al. 2003; Keefer et al. 2011; Figure 1). Pacific Lamprey, however, display a unique behavior that allows them to navigate through locations that may otherwise hinder passage. When confronted with high velocities or turbulence, they use their oral discs to attach to substrate and rest before continuing upstream in short bursts (Daigle et al. 2005; Kemp et al. 2009; Keefer et al. 2010, 2011; Kirk et al. 2015, 2016). If suitable attachment points are available, Pacific Lamprey can utilize this "burst-and-attach" behavior to help them navigate through road crossings when water velocities are higher than their maximum sustainable swimming speed (Kirk et al. 2015, 2016).

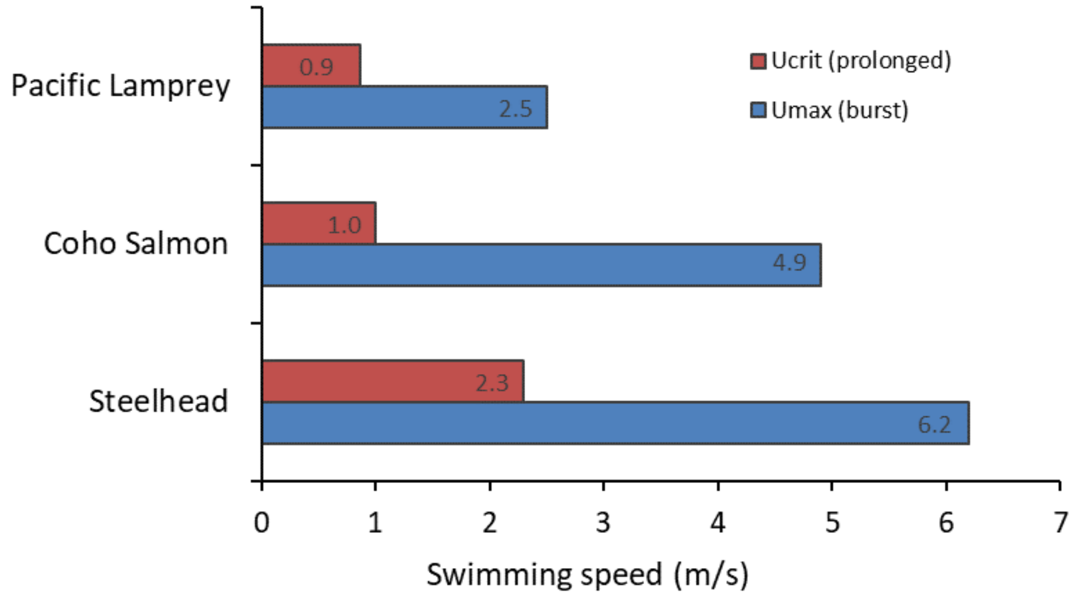


Figure 1. Estimated adult swimming speeds of Pacific Lamprey (Mesa et al. 2003, Keefer et al. 2010) compared with anadromous salmonids (Bell 1990, Lee et al. 2003).

Two metrics commonly used to describe swimming performance of fishes are critical swimming speed (U_{crit}) and burst swimming speed (U_{max}). U_{crit} is measured as the maximum velocity that can be maintained by a fish for a specific period (typically 30 minutes) before exhaustion. U_{crit} is a category of prolonged swimming calculated from tests where water velocity is progressively increased (Brett 1964; Jobling 1995; Mesa et al. 2003). Energy for critical swimming is provided primarily by aerobic metabolism (Jobling 1995). U_{max} is the highest speed fish are capable of attaining, usually only for very short periods of time (<20 seconds) (Jobling 1995). Energy for burst swimming is provided predominately by anaerobic metabolism. This mode of swimming is inefficient compared with lower speeds and is used principally for predator avoidance or navigating high-velocity areas.

Mesa et al. (2003) reported a mean U_{crit} of 0.86 m/s for untagged, sexually immature adult Pacific Lamprey collected from the Columbia River based on studies in a swim chamber at 15°C. U_{crit} represents approximate velocities that can be maintained for substantial periods of time without resting. Therefore, it can be inferred that Pacific Lamprey cannot swim long distances through areas with water velocities greater than $U_{crit,}$ or 0.86 m/s, where suitable attachment points for resting are not available, or where lamprey attachment is interrupted by porous surfaces, large gaps, acute angles, or other surface obstructions. Daigle et al. (2005) reported that the burst-and-attach mode of swimming for Pacific Lamprey becomes common when velocities exceed 0.6 m/s, suggesting that, when given a choice, lampreys likely attach and rest when velocities reach this level.

Because experimental swimming chambers prevent fish from using the full range of behaviors exhibited by free-swimming fish, performance measured in them can underestimate natural abilities (Peake 2004; Castro-Santos 2004, 2005, 2006, 2011). Moreover, fish can swim at velocities greater than U_{crit} (but less than U_{max}) for shorter periods than the 30 minutes typically used to determine U_{crit} (Peake 2004; Quintella et al. 2009; Russon and Kemp 2011). Therefore, Pacific Lamprey can likely swim through some shorter road crossings where water velocities exceed 0.86 m/s without attaching and resting. Nonetheless, 0.86 m/s serves as a suitable, if conservative estimate of prolonged swimming speed for assessing road crossings. In practice, when evaluating lamprey passage ability with hydraulic models, the U_{crit} value is only applied to estimate passage success through sites where suitable attachment points are not available (generally a small portion of road crossings).

Burst swimming speed has not been directly measured for Pacific Lamprey. Keefer et al. (2010) demonstrated that very few sexually immature adult Pacific Lamprey could pass fishway weirs when maximum water velocities exceeded 2.7 m/s. Keefer et al. (2010) also reported that burst-and-attach behavior was generally ineffective at velocities in the range of 2.5–3.0 m/s and inferred these velocities represent a barrier to lampreys. Based on these observations, 2.5 m/s is recommended as a reasonable, conservative value for U_{max} for assessing Pacific Lamprey passage at road crossings. Accordingly, when continuous substrate (such as a flat concrete bottom culvert) or regular attachment points (such as natural cobble substrate) are present, it is likely that most sexually immature adult Pacific Lamprey can navigate through areas with water velocities less than approximately 2.5 m/s. Notably, as discussed below, the maximum velocity for burst-and-attach swimming likely varies depending on site-specific hydraulic and substrate conditions, culvert length, fish sexual maturity and size, water temperature, and other factors. For this reason, road crossing designs should ideally provide lower water velocities for adult Pacific Lamprey across the range of stream flows at they are expected to migrate ("migration flows;" Section 3.3).

Table 1 summarizes reported values for Pacific Lamprey critical (U_{crit}) and burst (U_{max}) swimming speeds. Swim speed values reported for Sea Lamprey are included for comparison.

Table 1. Critical (U_{crit}) and burst (U_{max}) swimming speeds for adult Pacific Lamprey and Sea Lamprey.

Species	Swimming speed (m/s)	Source notes
Pacific Lamprey[1]		
Critical swimming speed (U_{crit})	0.86	Mean U_{crit} of untagged, sexually immature adults in a swimming tube at 15°C (Mesa et al. 2003).
Burst swimming speed (U_{max})	2.5	Approximation of U_{max} based on velocity at which sexually immature adult Pacific Lamprey had difficulty migrating through a weir using burst-and-attach behavior; water temperature not reported (Keefer et al. 2010).
Sea Lamprey		
Critical swimming speed (U_{crit})	1.0	Based on studies of anadromous Sea Lamprey in Portugal (Almeida et al. 2007, as cited by Quintella at al. 2009)
Burst swimming speed (U_{max})	>4.0	Based on studies of Great Lakes Sea Lamprey (Hanson 1980) and similar to the 3.9 m/s reported by Hunn and Youngs (1980, as cited by Quintella et al. 2009).

[1] Values reported for Pacific Lamprey were derived from studies of larger, sexually immature individuals passing fishways in the mainstem Columbia River or experimental flumes and may not be representative of swimming performance of smaller coastal or sexually mature individuals. For this reason, we suggest applying them in a conservative manner during assessment and design of road crossings, erring on the side of providing lower velocities.

Understanding the swimming endurance of Pacific Lamprey is also important for understanding how potential barriers restrict passage (Kirk et al. 2015, 2016). Swimming fatigue has been reported for Pacific Lamprey using burst-and-attach behavior to pass high-velocity areas (Kemp et al. 2009). Long culverts or other features with sustained velocities that are higher than the critical swimming speed and that require repetitive burst swimming may result in failed passage due to physiological exhaustion (Kirk et al. 2015; Hanchett 2020). For this reason, velocities at which Pacific Lamprey can successfully pass using burst-and-attach swimming may decrease with increasing length of a road crossing.

Turbulence or sudden velocity changes also affect frequency of attachment, time spent attached, and passage time, and overall passage success at high velocity locations (Kirk et al. 2016, 2017). Daigle et al. (2005) observed that lampreys are most vulnerable to displacement during the periods between successive attachments, noting that rapid changes in water velocity or direction can prevent fish from reattaching. Experiments conducted by Kirk et al. (2016) found that Pacific Lamprey attempting to migrate through a vertical-slot weir with water velocities of 2.4 m/s attached and held nearly 3 times longer in the presence of a turbulence-inducing wall compared to trials where it was absent. The role of turbulence in passage success and effective water velocities that lampreys can swim through at road crossings warrants further investigation.

2.2 Attachment Ability

As described above, when confronted with high velocities Pacific Lamprey often use their oral discs to attach to substrate and rest before continuing upstream. Their ability to attach to substrate within a road crossing is expected to be a key determinant of whether individuals can utilize burst-and-attach behavior to pass the feature. Keefer et al. (2010) demonstrated that Pacific Lamprey movement was restricted when suitable attachment surfaces were not present.

Much of the information on lamprey attachment ability comes from studies on Sea Lamprey (Adams 2006; Adams and Reinhardt 2008; Reinhardt et al. 2008). Although Sea Lamprey are expected to have slightly different oral disc morphology and may have different attachment abilities than Pacific Lamprey, these studies inform general understanding of attachment capabilities of Pacific Lamprey. Adult lampreys can attach to a wide range of surface materials, sizes, and shapes (Adams and Reinhardt 2008; Reinhardt et al. 2008; Moser and Mesa 2009; Moser et al. 2011). Ability to attach is contingent on the interaction between a substrates surface characteristics and a lamprey's oral disk anatomy (Adams and Reinhardt 2008). Surfaces constructed of non-porous, slightly rough material allows the most secure attachment, permitting the oral disk and associated fimbriae to form a tight seal (Adams 2006). Recent experiments have shown that Great Lakes Sea Lamprey can contort their oral disk to attach to surfaces containing shallow (1-mm), medium (2-mm), and to a lesser extent, deep (3-mm) grooves that are 3-mm wide (Adams and Reinhardt 2008). However, experimental fish could not successfully attach to grooves that were narrower and deeper (1 mm wide x 3 mm deep or deeper). Because of the potential for grooves or gaps in road crossing bottoms to impair passage, we recommend designs that eliminate them entirely.

It has been hypothesized that configuration and size of culvert corrugations can influence Pacific Lamprey attachment and passage ability, with smaller, more frequent corrugations being more difficult to attach to and use burst-and-attach behavior on (Moser and Mesa 2009; Stillwater Sciences 2014). Goodman and Reid (2017), however, found that Pacific Lamprey had 100% passage success through a wetted (1 cm depth) and inclined culvert with smaller corrugations than those typically used at stream crossings. This finding suggests that corrugation presence and size is likely not an important factor impeding lamprey attachment or movement at the low-water velocities evaluated in that study. However, additional studies are needed to evaluate the potential influence of culvert corrugation presence, size, and configuration on lamprey passage success across the range of water velocities that commonly occur at road crossings. For example, are the maximum water velocities that lampreys can navigate through lower on culvert corrugations relative to flat surfaces due to decreased ability to rapidly reattach while using burst-and-attach behavior? Does corrugation size and/or configuration influence ability of lampreys to use burst-and-attach behavior at higher water velocities? On uniformly flat surfaces lampreys can burst forward while maintaining their body's position flush (in plane) with the substrate, releasing suction on the substrate only momentarily before reattaching (Reinhardt et al. 2008; Keefer et al. 2011). It is not clear whether they can use this "inching forward" approach to traverse culvert corrugations at velocities approaching U_{max}. Additionally, it is not known whether it takes longer for lampreys to successfully reattach to non-flat surfaces, particularly tightly corrugated culverts. If it does, lampreys may be more likely to be swept downstream while attempting to attach; therefore, water velocities that Pacific Lamprey can successfully swim through using burst-and-attach behavior may decrease in presence of corrugations. For these reasons, when evaluating passage at corrugated culverts, a conservative approach is recommended (e.g. one that assumes effective swimming speeds and passage ability may be more limited in bare corrugated culverts than at sites with flat, continuous surfaces or natural substrates).

2.3 Climbing Ability

In addition to using burst-and-attach behavior to move forward on horizontal or low-gradient surfaces, Pacific Lamprey can ascend steep or vertical surfaces by attaching their oral disc to the surface, rapidly compressing and then straightening the body, while momentarily releasing suction (but maintaining contact) and then reattaching (Reinhardt et al. 2008; Kemp et al. 2009; Keefer et al. 2011; Zhu et al. 2011; Frick et al. 2017; Figure 2). While climbing vertical features, there must be enough flow over the lamprey to aerate its gills, but they do not have to be completely submerged (LTW 2017; Frick et al. 2017). Their ability to climb allows Pacific Lamprey to ascend and pass some waterfalls, boulder cascades, and other features that are considered barriers to salmon, steelhead, and other native lamprey species.

The ability and inclination of Pacific Lamprey to climb steep surfaces also has important implications for designing retrofits to improve passage at barrier sites. Lamprey passage structures consisting of inclined ramps or vertical wetted-walls have been successfully used to improve passage through both mainstem Columbia River dams and smaller, low-head dams (Moser et al. 2011; Jackson and Moser 2013; LTW 2017). More recently, a flexible 4-inch PVC tube was installed to provide an alternate passage route for lampreys to climb around a pool-and-weir fish ladder at a dam on the upper Eel River in California. Initial testing has shown dramatic improvement in passage success and decrease in passage time (Goodman and Reid 2017; D. Goodman, USFWS, pers. comm., 2018). As discussed in Section 5, downscaled versions of such ramps or tubes have potential to improve lamprey passage at perched road crossings or sites with infrastructure that impedes lamprey passage such as fishways, tailwater control weirs, or internal baffles. Such retrofits should only be applied at road crossings where (1) it is not feasible to replace the barrier with a bridge or properly sized open-bottom arch culvert and (2) where sufficient monitoring of passage success at the retrofit can be conducted.

Figure 2. Example of Pacific Lamprey climbing a vertical surface during evaluation of wetted-wall structures designed to improve passage at dams. Credit: D. Lumley, Yakama Nation Fisheries.

2.4 Leaping Ability

Due to their body type, relatively poor swimming ability, and lack of paired fins, Pacific Lamprey have extremely limited ability to leap. Consequently, their upstream passage is expected to be precluded by perched culverts or similar impediments that perched above the water surface (Moser and Mesa 2009; Figure 3). Some culverts have hydraulic control points downstream that can act to raise water surface elevation to the height of the culvert outlet when flows are high enough (Taylor and Love 2003; e.g., Appendix C, case studies 4 and 5), permitting lampreys to enter and pass upstream when hydraulic conditions allow. These factors must be considered during lamprey passage evaluations.

Figure 3. Example of perched and impassable road crossing, Strawberry Creek, Eel River basin, CA. Credit: Wiyot Tribe Natural Resources Department.

2.5 Water Depth

Road crossings must have sufficient water flow for Pacific Lamprey to successfully pass. Compared with other fish, lampreys can move through features with relatively shallow water. Moser et al. (2011) demonstrated that adult Pacific Lamprey can pass inclined ramps with water depths of 3 cm; Goodman and Reid (2017) observed the species navigating through a culvert and PVC tubes at depths of approximately 1 cm; and Frick et al. (2017) documented their ability to climb a vertical wetted wall at depths as shallow a 0.1 cm. Despite their ability to move through shallow water, we recommend a conservative approach that provides at least 3 cm of water depth for passage through a crossing when assessing passage constraints at a site or developing designs for providing adult Pacific Lamprey passage. Importantly, other native fish species typically require greater depths for successful passage (Clarkin et al. 2005; WDFW 2019). These greater depth requirements are reflected in various state and federal design guidelines. For example, in their hydraulic design guidelines for culverts, NMFS (2011) specifies minimum water depths of 30 cm (1.0 ft in) and 15 cm (0.5 ft) for adult and juvenile salmon and steelhead, respectively. Additionally, it possible that very shallow water in road crossings has potential to cause migration delays or increase predation on lampreys.

2.6 Other Factors

2.6.1 Body size and maturation

As with other fishes, larger adult Pacific Lamprey have greater absolute swimming speeds than smaller individuals (Beamish 1974; Clemens et al. 2010; Castro-Santos 2011). Slower swimming speeds are generally expected to translate to lower passage success for smaller fish. Keefer et al. (2009) reported that adult Pacific Lamprey passage through Columbia River dams was significantly size-dependent, with the largest fish being two to four times more likely to pass than the smallest fish. Likewise, Jackson and Moser (2012) found larger individuals had higher passage success at low-head irrigation diversion dams.

Other studies, however, suggest that sexual maturity may be more predictive of swimming performance than size (Kirk et al. 2016; Moser et al. 2019; Hanchett 2020). As Pacific lamprey migrate upstream to spawning areas and approach sexual maturity, they shrink in length and the distance between the first and second dorsal fin (a proxy for maturation level known as "dorsal distance) decreases (Clemens et al. 2009). Kirk et al. (2016) found that Pacific Lamprey with larger dorsal distance were more likely to pass high velocity vertical-slot weirs than more sexually mature individuals. This finding was corroborated by Hanchett (2020), who demonstrated an increase in passage success through an experimental flume with increasing dorsal distance after accounting for body length. Similarly, Moser et al. (2019) found that when attempting to pass through a fishway at Bonneville Dam, individuals with a smaller dorsal distance were more likely to use refuge boxes for resting than those with a larger dorsal distance, suggesting more sexually mature individuals may become more easily exhausted. The mechanism for decreased swimming performance by sexually mature individuals may be related to their smaller size and reduced energy reserves. Pacific Lamprey do not feed between the onset of freshwater migration and spawning and they shrink an estimated 18–30% in length during this time (Kan 1975; Beamish 1980; Chase 2001; Clemens et al. 2010; Jackson and Moser 2012).

The studies described above were based on passage at mainstem Columbia River dams. Further studies are needed to describe the influences of fish size and maturity level on adult Pacific Lamprey swimming performance and passage at road crossings. The effects of maturation level on swimming performance is particularly relevant to road crossings, since many of the individuals entering tributaries—where most road crossings are located—are expected to be sexually mature adults. Additionally, lamprey behavior and passage ability in small coastal streams may differ from that in the Columbia River or large inland streams due to differences in water temperature, maturation, and fish size. Adult Pacific Lamprey entering coastal watersheds are significantly smaller than those in the Columbia River basin (Clemens et al. 2019) and thus may have lower swimming speeds and reduced passage success.

Since the swimming speeds reported in Table 1 above were derived from studies of larger, sexually immature individuals passing fishways in the mainstem Columbia River or experimental flumes, they may not be representative of swimming performance of all adult Pacific Lamprey. For this reason, we suggest applying them in a conservative manner during assessment and design of road crossings, erring on the side of providing lower velocities.

2.6.2 Adult migration timing

Identifying the time periods when most upstream migration by adult Pacific Lamprey is expected to occur in a study stream is an important aspect of evaluating passage. It is also imperative for evaluating how passage at a given site varies with stream flow. Defining migration periods allows estimation of the range of stream flows that Pacific Lamprey typically experience upon reaching a road crossing (Section 3.3). These minimum and maximum migration flows are then used in hydraulic analyses to determine how hydraulic conditions and passage success at a given site vary with stream flow.

Two distinct Pacific Lamprey adult life history strategies (or "ecotypes") occur in some river systems: an "ocean-maturing" life history that likely spawns several weeks after entering fresh water from the ocean and a "stream-maturing" life history that typically spends approximately one year in freshwater prior to spawning (Clemens et al. 2013; Parker 2018). The period of adult freshwater residence of the stream-maturing life history can be divided into three distinct stages: (1) initial migration from the ocean to holding areas, (2) pre-spawning holding, and (3) secondary migration to spawning sites (Robinson and Bayer 2005; Clemens et al. 2010). The generalized life-history timing for each of these stages is shown in Table 2 and described below.

Timing of initial migration from the ocean varies between and within river systems, generally beginning in winter or spring and ending in summer (Robinson and Bayer 2005; Clemens et al. 2010; McCovey 2011; Starcevich et al. 2014). In some river systems, the initial migration typically ceases by mid-July when flows approach summer lows and water temperatures begin to peak (Clemens et al. 2012; McCovey 2011; Starcevich et al. 2014). In other rivers, particularly larger and more inland system, some movement may continue to occur into early fall (Robinson and Bayer 2005; Lampman 2011; McIlraith et al. 2015).

The pre-spawning holding stage begins when individuals cease upstream movement, generally in June or July, and continues until fish begin their secondary migration to spawn, generally in March or April (Robinson and Bayer 2005; Lampman 2011; Starcevich et al. 2014). While most individuals appear to remain stationary throughout the late summer, fall, and winter, some may undergo additional upstream movements in the winter associated with high-flow events (McCovey 2011; Starcevich et al. 2014).

Following the pre-spawning holding period, Pacific Lamprey undertake a secondary migration from holding areas to spawning areas. This movement generally begins in March and continues until, by which time most individuals have spawned and died (Robinson and Bayer 2005; Lampman 2011; Starcevich et al. 2014). During this secondary migration, movement from holding areas to spawning areas can be upstream or downstream (Robinson and Bayer 2005; Lampman 2011; Starcevich et al. 2014). Additionally, individual Pacific Lamprey have been documented spawning in multiple locations, moving substantial distances (up to 16 km) between spawning areas in the spring (Starcevich et al. 2014).

Since movement of adult Pacific Lamprey can occur throughout the year, they are expected to experience a range of stream flow conditions as they encounter road crossings, ranging from low flows in in early summer to higher flows in winter and spring. For this reason, we recommend selecting a broad range of migration flows to use in hydraulic analyses for assessing passage and designing new road crossings (e.g. from 5% exceedance flow to 95% exceedance flow during the migration period; Section 3.3).

Table 2. Generalized life history timing for freshwater stages of stream-maturing adult Pacific Lamprey of a single run cohort. References provided in text. Run timing varies, and we recommend using locally available information on life history timing where available.

Adult freshwater stage	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
Initial migration from ocean	■	■	■	■	■	■	■	■	■										
Pre-spawning holding						■	■	■	■	■	■	■	■	■	■				
Secondary migration and spawning															■	■	■	■	■

2.6.3 Water temperature

Lampreys, like most other fish species, do not have the ability to metabolically control their body temperature. Consequently, their temperature fluctuates nearly in unison with that of surrounding water and thus changes in water temperature greatly influence both migration patterns and physiological processes (Clemens et al. 2009; Keefer et al. 2009; Moser and Mesa 2009; Lampman 2011; Starcevich et al. 2014; Clemens et al. 2016). Fish swimming performance is reduced at water temperatures above and below levels they typically experience (Castro-Santos 2011) and therefore water temperature is expected to affect Pacific Lamprey passage ability. The influence of water temperature on adult Pacific Lamprey swimming performance or passage success at road crossings at has not been directly evaluated. Jackson and Moser (2012) found that water temperature was negatively correlated with passage success at low-head diversion dams at temperatures between approximately 5°C and 20°C (Jackson and Moser 2012). Keefer et al. (2013) found that passage efficiency of individual adult Pacific Lamprey at Bonneville Dam increased with increasing water temperature from approximately 13°C to 21°C but decreased at higher temperatures. Studies evaluating the influence of water temperature on swimming performance and passage success of Pacific Lamprey at road crossings are needed. Specifically, it would be valuable to identify low and high temperature thresholds that significantly reduce passage success under different hydraulic conditions.

2.6.4 Sound, vibration, and artificial light

Road crossings in more heavily trafficked and urban areas may have high levels of noise and vibration from passing vehicles or artificial lighting that have potential to impact adult Pacific Lamprey passage. Sounds and vibrations are known to influence fish behavior (Hawkins et al. 2015), but potential impacts of road vibrations and other traffic noise on Pacific Lamprey behavior and passage remain a data gap. Daigle et al. (2005) found that Pacific Lamprey were most active under infrared lighting compared with other types of lights. Because of their nocturnal nature and negative phototaxis, Moser and Mesa (2009) suggested lamprey could be obstructed by very bright or abruptly changing light conditions. Daigle et al. (2005) found that 1–3 lux lights did not appear to impede lamprey migration. The limited studies of Pacific Lamprey to date have not been comprehensive in terms of light spectra or intensity; thus, effects of any lighting are a reasonable potential concern for passage. In addition, Aronsuu et al. (2015) found that lights at bridges crossing a river delayed upstream migration for adult European River

Lamprey *Lampetra fluviatilis* and that even moonlight with intensity less than 0.2 lux depresses migratory activity. It is uncertain whether these findings are applicable to Pacific Lamprey, but further controlled studies on the topic are needed.

2.7 Road Crossing Infrastructure

Many road crossings have associated infrastructure that can impair adult lamprey passage. Some crossings have been modified using internal structures such as baffles or weirs designed to improve upstream passage of salmonids by retaining natural streambed substrates, reducing water velocity, or increasing water depth (Figure 4). Some crossings have fishways leading into perched culvert inlets or manmade hydraulic tailwater control structures (e.g., concrete or rock weirs) designed to raise the water level of the pool at a culvert outlet. Laboratory and field experiments indicate that, when water velocities are high, adult Pacific Lamprey have difficulty passing features that have squared corners or edges such as vertical steps or vertical slot weirs in fish ladders (Moser et al. 2002; Daigle et al. 2005; Keefer et al. 2010). Such sharp angles prevent lampreys from maintaining attachment as they attempt to move around a corner or over a step (Moser et al. 2002; Moser and Mesa 2009). These same studies demonstrated that Pacific Lamprey have significantly higher passage success through fishways with rounded, instead of squared, corners on bulkheads. Examples of infrastructure at road crossings that can inhibit or delay lamprey passage are shown in Figure 4 and Appendix C (pre-project photos in case studies 3 and 7).

Figure 4. Examples of internal structures and modifications at road crossings that can impede lamprey passage in the Eel River basin, CA. Internal baffles with squared corners in undersized crossing (top left), step-pool fishways with square edges at outlet (top right and bottom left), and tailwater control weir with vertical drop and square edges (bottom right). Credit: Wiyot Tribe Natural Resources Department.

When they do not impede lamprey passage as physical obstructions (e.g., with right angles), tailwater control weirs or internal baffles may improve lamprey passage success by increasing the percentage of streams flows that are passable. For example, tailwater control weirs may help lamprey enter a perched culvert, slow water velocities at the outlet or within the crossing during high flows, and increase depths during low flows.

Concrete outlet aprons with relatively short (4–8 inches) vertical steps with right angles are particularly common at road crossings (Figure 5). Due to uncertainties in the ability of Pacific Lamprey to pass over these features, we recommend taking a conservative approach when evaluating lamprey passage that assumes these sites prevent passage unless the water surface elevation meets or exceeds the elevation of the top of the vertical surface. This conservative approach may underestimate Pacific Lamprey passage success, since lampreys can probably swim over some small steps or drops or possibly attach to the horizontal surface beyond a small enough step.

Overall, due to their variable and complex influences on water velocity, depth, substrate composition, and other factors affecting passage, it is difficult to use standard field and analytical protocols to establish whether road crossings with baffles, weirs, fishways or other retrofits present passage barriers to Pacific Lamprey. For this reason, passage status at many of these sites may remain uncertain without detailed, site-specific studies and biological monitoring.

Figure 5. Example of culvert outlet apron with a vertical step at a crossing Munson Creek, Tillamook River watershed, Oregon. Credit: A. Gillette, ODOT.

2.8 Summary of Factors Affecting Passage

Table 3 summarizes factors affecting adult Pacific Lamprey passage at road crossings and lists key uncertainties that require further study. The values and information provided can be applied to help designate passage status of assessed crossings and develop lamprey-friendly road crossing designs. However, due to the considerable uncertainty in many factors, this information should be applied conservatively, erring on the side of underestimating passage ability. Additional laboratory studies and field monitoring of Pacific Lamprey swimming performance and passage success at road crossings are needed to refine these values.

Table 3. Summary of swimming performance and factors affecting passage of adult Pacific Lamprey (PL) at road crossings.

Factor	Explanation / value	Source / rationale	Key uncertainties
Swimming performance			
Critical swimming speed (U_{crit})	At sites lacking attachment points for resting, assume PL can pass when water velocities <0.86 m/s.	Mean critical swimming speed of sexually immature adult PL at 15°C = 0.86 m/s (Mesa et al. 2003).	- May underestimate PL swimming performance during passage through road crossings. -Relationships between U_{crit} and lamprey size and maturation. - Relationships between U_{crit} and water temperature
Burst swimming speed (U_{max})	At sites with suitable attachment points for resting, most PL can pass using burst-and-attach behavior when water velocities <2.5 m/s.	Velocities of 2.5–3.0 m/s impeded sexually immature adult PL passage through a weir, despite availability of attachment points (Keefer et al. 2010).	- Time to exhaustion at burst swimming speed. - Effect of irregular surfaces (e.g., corrugated culverts) on maximum water velocities that can be navigated using burst-and-attach behavior. -Relationships between U_{max} and lamprey size and maturation. - Relationships between U_{max} and water temperature.
Time to exhaustion using burst-and-attach swimming behavior	Unknown. For hydraulic analysis and design, assume PL can engage in burst-and-attach swimming for 20 minutes before exhaustion if suitable attachment points available.	Conservative estimate, based on studies showing physiological exhaustion can occur following repetitive burst-and-attach behavior (Kemp et al. 2009; Kirk et al 2015; Hanchett 2020).	- Time to exhaustion using burst-and-attach swimming behavior. - Factors affecting exhaustion.
Minimum water depth	Water depth ≥3 cm (0.1 ft) recommended.	Conservative, protective value that recognizes passage can occur through shallower depths in some cases (Moser et al. 2011; Goodman and Reid 2017; Frick et al. 2017).	- Behavioral avoidance of shallow water and migration delays. - Relationship between depth and distance PL can pass. - Effects of depth on swimming speeds. - Risk of predation associated with depth and migration delay.

Factor	Explanation / value	Source / rationale	Key uncertainties
Attachment, leaping, and climbing capabilities			
Attachment substrate material	PL can attach to a wide range of non-porous artificial and natural materials. Damaged or rusted out culverts or grates may preclude attachment.	Adams and Reinhardt (2008); Reinhardt et al. (2008); Moser and Mesa (2009); Moser et al. (2011); Goodman and Reid (2017)	- Variation in energetic demand between different attachment surfaces and relationship to exhaustion time.
Attachment substrate shape and configuration	PL can attach to a wide range of substrate shapes and sizes. Discontinuities in surface (e.g., deep, narrow slots or grates) and 90° corners at baffles, weirs, or fish ladders may inhibit passage.	Adams and Reinhardt (2008); Reinhardt et al. (2008); Kemp et al. (2009); Moser and Mesa (2009), Moser et al. (2011); Goodman and Reid (2017)	- Influence of culvert corrugation presence, size, and configuration on ability to burst-and-attach, and on passage success at the range of water velocities that commonly occur at road crossings.
Climbing ability	PL can climb most wetted vertical or steeply sloped surfaces (assuming substrate suitable for attachment); however, they have difficulty passing vertical features ending in abrupt right angles or overhanging ledges.	Reinhardt et al. (2008); Kemp et al. (2009); Keefer et al. (2011); Zhu et al. (2011); Frick et al. (2017)	- Ability to attach to and climb slightly perched culvert outlets or concrete outlet aprons with short vertical steps and 90° edges.
Leaping ability	PL cannot leap. Crossing outlets perched above downstream water surface elevation are assumed impassable at that flow.	Conservative assumption based on Moser and Mesa (2009) and professional judgment.	- Ability to swim up slightly perched culverts and outlet aprons with 90° edges.
Other factors			
Body size	Larger adult PL generally expected to have greater absolute swimming speeds and passage success than smaller individuals	Assumed based on Beamish (1974); Keefer et al. (2009); Clemens et al. (2010); Castro-Santos (2011); Jackson and Moser (2012)	- Relationship between PL size and swimming speeds. - Relationship between PL size and passage success at common types of road crossings and associated infrastructure.
Sexual maturity	PL swimming performance and passage success expected to decline with increasing sexual maturity	Kirk et al. (2016); Moser et al. (2019); Hanchett (2020)	- Relationship between PL maturity and swimming speeds. - Relationship between PL maturity and passage success at common types of road crossings and associated infrastructure.

Factor	Explanation / value	Source / rationale	Key uncertainties
Adult migration timing	Initial PL migration from ocean typically occurs from winter through summer. Secondary migration to spawn generally occurs in spring and early summer.	Robinson and Bayer (2005); McCovey (2011); Clemens et al. (2012); Starcevich et al. (2014); Lampman (2011); McIlraith et al. (2015)	-Timing varies between and within watersheds and primary movement periods should be characterized for each study area to support passage assessment and design.
Water temperature	Water temperature influences migration patterns and passage efficiency at dams and is expected to influence swimming performance and passage at road crossings.	Clemens et al. (2009, 2016); Keefer et al. (2009, 2013); Lampman (2011); Jackson and Moser (2012); Starcevich et al. (2014)	- Relationship between water temperature and PL swimming speeds. - Relationship between water temperature and PL passage success at common types of road crossings and associated infrastructure.
Sound and vibration	Sound and vibration can impact fish behavior, but effects on PL at road crossings are unknown.	Hawkins et al. (2015)	-Effects of road noise and vibrations on PL behavior at road crossings.
Artificial light	PL exhibit negative phototaxis and passage may be adversely affected by bright lights.	Daigle et al. (2005); Moser and Mesa (2009); Aronsuu et al. (2015)	-Effects of light on PL behavior at road crossings, including levels that are avoided and impacts of abrupt changes in light levels.
Road crossing infrastructure	Fishways, internal baffles, and tailwater control weirs often do not consider PL passage needs and may have negative or positive impacts on passage. Sites with vertical steps and 90° edges likely inhibit passage. Rounded corners/edges on road crossing infrastructure facilitates passage.	Moser et al. (2002); Daigle et al. (2005); Moser and Mesa (2009); Keefer et al. (2010)	- Effects of common road crossing infrastructure on PL passage. -Ability to swim up or attach to and climb outlet aprons with 90° edges and short vertical drops.

3 EVALUATION OF PASSAGE AT ROAD CROSSINGS

This section presents key concepts, methods, and resources that can be used to conduct assessments of adult Pacific Lamprey passage at road crossings. The exact methodologies applied will depend on goals and objectives, spatial scale of assessment, and available resources. Section 3.1 provides guidance on prioritizing sites for field evaluation in large-scale passage assessments. Section 3.2 describes provides guidance for collecting data needed to assess whether a road crossing is a barrier. Section 3.3 describes considerations for calculating Pacific Lamprey migration flows for each site. Section 3.4 summarizes analyses for predicting hydraulic conditions at migration flows based on field data. Section 3.5 describes considerations and analyses for determining the passage status (i.e., barrier, partial barrier, non-barrier) of assessed sites.

3.1 Site Selection and Prioritization for Assessment

If the objective is to assess passage for adult Pacific Lamprey throughout a property or watershed with a large number of road crossings, then assessments should prioritize sites that are most likely to (1) occur in streams within the historical distribution of Pacific Lamprey, (2) impede lamprey passage, and (3) block the most habitat upstream. The process for identifying and prioritizing sites within a study area for field and/or hydraulic analysis is summarized in Figure 6 and described below.

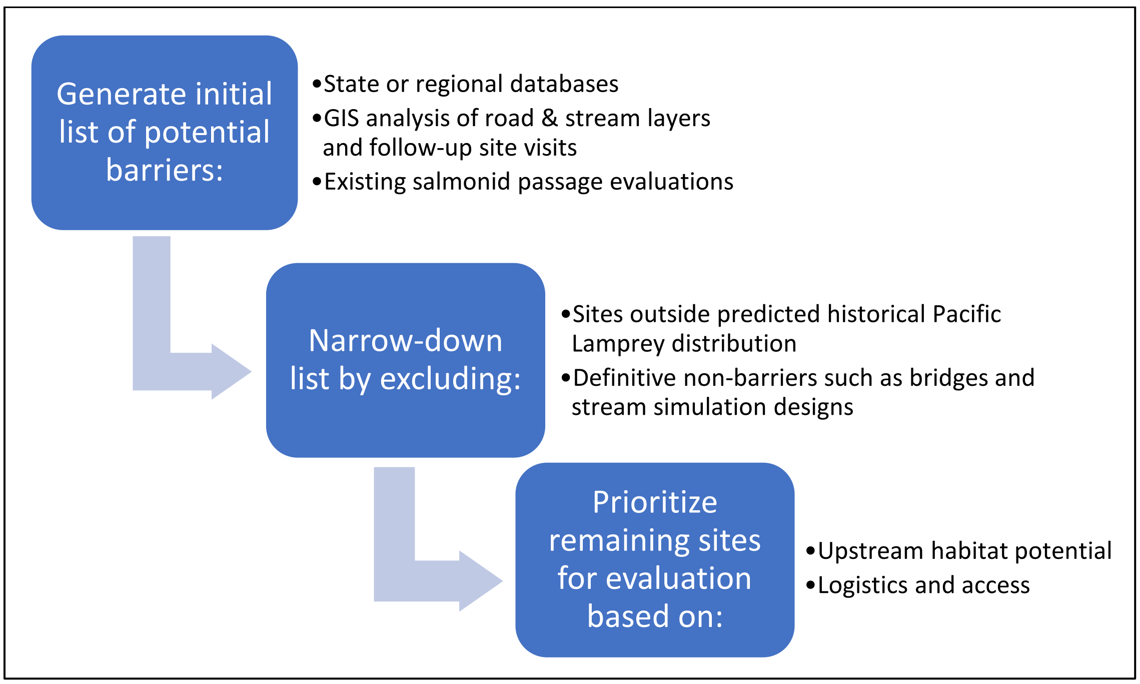


Figure 6. General process for identifying and prioritizing potential passage barriers for further evaluation.

3.1.1 Generate initial list of potential barriers

For basinwide or other large-scale assessments, compile an initial list of potential barriers to adult Pacific Lamprey to consider for passage assessment. The following state or regional databases that list road crossings and other potential barriers to fish passage (such as diversions, dams, tide gates, and natural features such as waterfalls) are a good starting point for developing this list in many watersheds:

1. The California Fish Passage Assessment Database (PAD) https://www.calfish.org/tabid/420/Default.aspx
2. ODFW Natural Resources Information Management Program Fish Passage Barriers dataset https://nrimp.dfw.state.or.us/nrimp/default.aspx?pn=fishbarrierdata
3. WSDOT - Fish Passage Inventory http://geo.wa.gov/datasets/WSDOT::wsdot-fish-passage-inventory
4. Alaska Fish Passage Inventory Database (FPID) https://www.adfg.alaska.gov/index.cfm?adfg=fishpassage.database.

In addition to providing a relatively complete listing of sites that may pose fish passage problems in many watersheds, these databases provide site-specific information, such as results of previous salmonid-focused passage assessments, which can be used to: (1) determine whether further assessment is warranted and (2) help evaluate lamprey passage status.

Additional potential barriers in a study area that may not be identified in the aforementioned databases may be identified by reviewing existing fish passage evaluation reports focused on salmonids (e.g., Lang 2005; RTA 2005) or through examination of road crossings identified from GIS or other mapping software. Additional road crossings may also be identified during on-the-ground reconnaissance of the study area. If sites not listed in the above database are identified and assessed for lamprey passage, please provide the site information and assessment results to the appropriate state contact to ensure they are included in the databases.

3.1.2 Narrow down list of potential barriers

To streamline and focus a passage assessment, the initial list of potential barriers can be narrowed-down to exclude: (1) sites outside of the predicted historical distribution of Pacific Lamprey and (2) sites that can definitively be classified as non-barriers from available information.

Road crossing databases may include numerous sites crossing small, high-gradient streams not expected to support Pacific Lamprey, currently or historically. Historical and current Pacific Lamprey distribution records from the region can be used to develop a set of criteria for excluding sites from further evaluation, such as minimum channel width, minimum contributing drainage area, or maximum channel slope in upstream reaches. For example, in a basinwide evaluation of Pacific Lamprey passage, Stillwater Sciences (2014) initially applied a minimum drainage area criterion of 2 km^2 to exclude crossings of very small streams. This criterion, was selected to be conservative, erring on the side of including streams that smaller than that typically used by Pacific Lamprey based on upper distribution data from the Eel River basin and other northwestern streams (e.g., Stone 2006; Gunckel et al. 2009; Starcevich and Clements 2013; Dunham et al. 2013). Recent and historical Pacific Lamprey distribution records for some watersheds are available through the Pacific Lamprey Data Clearinghouse maintained by USFWS and hosted by USGS (2020).

After excluding sites based on contributing drainage area, other criteria, or information on historical distribution, the initial list of potential barrier sites can be further reduced based on site-specific information provided in state databases or existing fish passage assessment reports. For example, records that are definitively not barriers, such as large bridges without passage-impairing infrastructure or stream simulation designs (Section 5), can be omitted from the list.

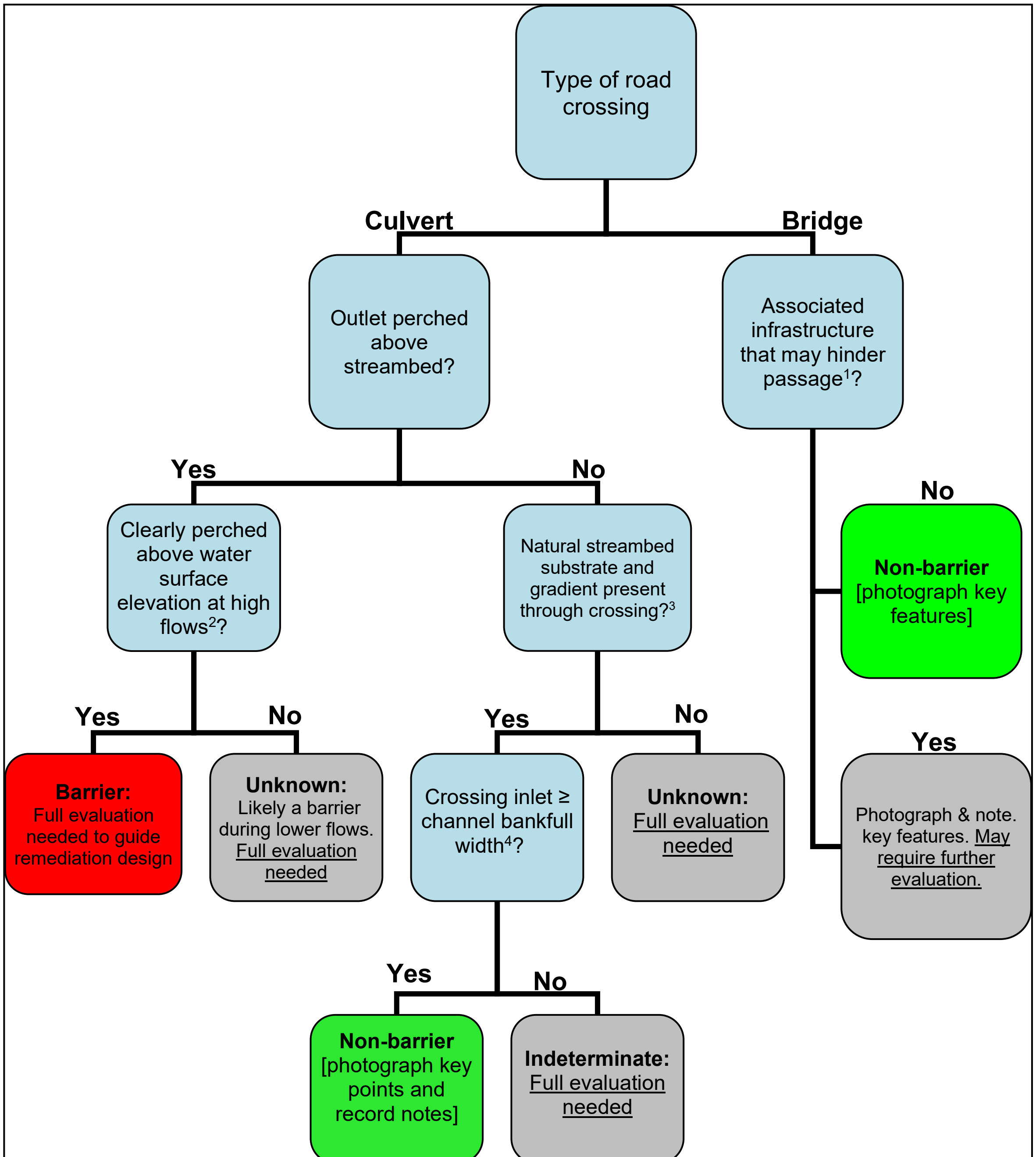
3.1.3 Prioritize for field evaluation

Once narrowed, the list of sites can be further prioritized for field evaluation based on predicted upstream habitat potential for Pacific Lamprey spawning and rearing and other considerations such as sequence in the channel network (e.g., prioritize downstream most sites), landowner access, accessibility, safety, or proximity to high priority sites. In general, sites with larger contributing drainage area and greater extent of low-gradient habitat should be prioritized for evaluation. Larger streams (active channel width >10 m) are more likely to be used by Pacific Lamprey and have a greater amount of suitable habitat per unit length than smaller streams (Stone 2006; Gunckel et al. 2009; Stillwater Sciences and Wiyot Tribe Natural Resources Department 2016). Low-gradient (<2%) channels generally contain more high-quality Pacific Lamprey adult spawning and larval rearing habitats in comparison with higher gradient channels due to greater deposition of fine sediments and spawning gravels (Torgersen and Close 2004; Lê et al. 2004; Gunckel et al. 2009). Therefore, relative upstream habitat potential can be approximated based on contributing drainage area and length of low-gradient channel upstream of each potential barrier. For example, to help prioritize field assessment, Stillwater Sciences (2014) calculated contributing drainage area and length of channel with gradient <2% upstream of each potential barrier site but downstream of locations in the channel network where contributing drainage area was smaller than 2 km^2 (the smallest drainage areas assumed to support Pacific Lamprey in that evaluation). Sites with the largest contributing drainage area and greatest length of low gradient channel were prioritized for assessment.

3.2 Field Assessment

3.2.1 Initial evaluation filter

Upon arriving at a road crossing site, an initial passage evaluation filter can be used to rapidly and objectively determine whether further evaluation of passage for adult Pacific Lamprey is required (Figure 7). At some sites this initial filter or professional judgement may be sufficient for evaluating passage. For instance, if the site consists of a properly-sized open bottom arch culvert with natural streambed, it can confidently be designated as a non-barrier and photographed for documentation. Conversely, if the site has an extremely perched culvert outlet with no opportunity to backwater, it can confidently be designated as a total barrier to adult Pacific Lamprey due to their inability to jump. In some cases where the site is clearly a total barrier, full evaluation may still be necessary to inform the design process for providing passage. In other cases, a site may not appear to constitute a barrier to lamprey migration at the observed stream flow, but it should be fully evaluated since it may present a velocity barrier at higher migration flows. For example, an undersized culvert may allow passage at low flows, but excessive velocities may prevent passage at high flows. Data collected during a full evaluation allows hydraulic analyses to predict the range of stream flows at which such a partial barrier site is passable (Section 3.4).



1 Examples include trash racks, vertical steps, or significant channel constriction from abutments.
2 Use active channel indicators at outlet to approximate high flow water surface elevation.
3 Streambed substrate is continuous throughout the crossing and the streambed gradient and particle size similar to the adjacent channel.
4 Measured upstream of structure and away from its zone of influence (i.e. upstream of aggradational wedge caused by inlet control).

Figure 7. Initial passage evaluation filter used to help designate barrier status and whether field sites required evaluation.

3.2.2 Full evaluation

Collection of data on physical characteristics of the crossing and adjacent channel is the primary field activity needed to assess whether a given site presents a barrier to adult Pacific Lamprey passage. When sufficient resources are available, lamprey presence-absence and/or habitat surveys upstream and downstream of the site are recommended to help validate designation of passage status and provide information to support prioritization for remediation. These steps are summarized below.

Physical characteristics of crossing and channel

The following guidelines for assessing the physical characteristics of a road crossing and the adjacent channel are based on existing protocols for salmonids (Taylor and Love 2003; Clarkin et al. 2005; WDFW 2019), but modified for adult Pacific Lamprey following Stillwater Sciences (2014).

Assessing physical characteristics of a road crossing consists of the following elements:

- describing the location and characteristics of the site,
- surveying a longitudinal profile of the channel through the crossing,
- conducting a cross-sectional survey of the tailwater control (i.e., the hydraulic control point in the channel that controls water surface elevation at the culvert outlet),
- photographing key features, and
- making a detailed sketch of the site showing features and the adjacent channel.

Example datasheets for recording information on the above elements are provided in Appendix A. Refer to Taylor and Love (2003), Clarkin et al. (2005), and WDFW (2019) for more detailed instructions on collecting each data element.

Site information

At each road crossing site, the following physical characteristics should be measured and recorded (if present):

- location information including stream name, landownership, and GPS coordinates,
- shape and dimensions,
- structure material,
- size and type of culvert corrugation,
- presence of baffles, weirs, or other internal structures,
- skew from road,
- inlet and outlet configurations,
- description of tailwater control,
- condition of crossing,
- description of stream bed substrate particle size and retention within the crossing,
- description of lamprey attachment points (substrate surfaces where lampreys can attach and rest or use burst-and-attach swimming), and
- description and notes on features that may impact passage or inform subsequent analyses.

If feasible, a series of water depth and velocity measurements can also be taken at key points within the crossing to inform hydraulic conditions at the surveyed stream flow and help validate subsequent hydraulic modelling.

Longitudinal profile and tailwater control cross-section

The primary purposes for collecting for conducting longitudinal profile and tailwater control cross section surveys are (1) to put the road crossing in the context of the adjacent channel gradient, and (2) to allow prediction of water depths and velocities at the site across a range of flows using hydraulic analysis (Section 3.4). A longitudinal profile provides relative elevations of, and distances between, the road crossing inlet, outlet, and adjacent channel features, allowing calculation of crossing and channel slopes. The tailwater control is the hydraulic control point in the channel downstream of a crossing that controls the water surface elevation at the culvert outlet. The location controlling the tailwater elevation is often located at the riffle crest immediately below the outlet pool. Surveying the tailwater control cross-section allows prediction of water-surface elevations at the crossing outlet and within the crossing across the range of migration flows (Section 3.3). Tailwater surface elevation increases with increasing stream flow, sometimes allowing lampreys access to what may be a perched culvert at lower flows. Detailed methods for conducting longitudinal profile and tailwater control cross section surveys at road crossings for hydraulic analysis can be found in Harrelson et al. (1994), Taylor and Love (2003), Clarkin et al. (2005), WDFW (2019), or other fish passage guidance documents.

Photographs and site sketch

At a minimum, the following key features should be photographed to support analyses of passage, prioritization for remediation, and remediation designs:

- crossing inlet,
- crossing outlet,
- substrate and lamprey attachment points within the crossing,
- unique or notable features of the crossing, such as baffles, weirs, or damage that may impact passage,
- tailwater control (hydraulic control point for water surface elevation in pool downstream of crossing),
- representative photos of adjacent channel upstream and downstream of the site, and
- photos showing road fill above crossing.

In addition to photographs, include a detailed site sketch. This sketch should show the location and orientation of the crossing and associated infrastructure, the road, and key channel features that may aid in data analysis, results interpretation, and passage designation. Elements to consider including are:

- site ID#,
- date,
- north arrow,
- direction of stream flow,
- culvert/channel alignment,
- tailwater control cross-section location,
- outlet pool,
- lay of survey tape (if needed),

- photo locations and numbers (as appropriate),
- wingwalls and inlet / outlet aprons,
- multiple structures,
- baffle configurations,
- weirs and other instream structures,
- debris jams inside, upstream and downstream near site,
- depositional gravel bars,
- trash racks, screens, standpipes etc. that may affect passage,
- damage to or obstacle inside structure, and
- location of riprap or other bank armoring.

An example site sketch is provided in Appendix A.

Lamprey presence-absence and habitat surveys

Surveys to assess presence/absence of Pacific Lamprey downstream and upstream of a crossing site can be employed to help validate passage status designations based on the physical information described above. For example, if larval or adult Pacific Lamprey are found upstream, a crossing cannot be designated as a total barrier. Alternatively, if the species is not found in suitable habitat upstream, but are found immediately downstream of a crossing, the crossing is likely a barrier to Pacific Lamprey (assuming physical characterization is consistent with this designation). Additionally, if a barrier is eventually selected for removal/retrofit, these surveys will provide baseline data for post-implementation passage effectiveness monitoring.

Such surveys generally entail electrofishing suitable larval lamprey habitat upstream and downstream of potential barriers. The ability to confidently demonstrate presence or absence of larval lamprey with electrofishing increases with increasing area of suitable habitat sampled (Reid and Goodman 2015; Harris et al. 2019). If time allows and habitat is present, surveying a minimum of three patches of suitable larval lamprey habitat (low-velocity areas containing fine sand or silty substrate) upstream and downstream of each site is recommended. Reid and Goodman (2015) found that sampling three sites with suitable habitat was sufficient for providing high confidence in demonstrating occupancy or absence of larval lamprey. Consideration for understanding detection probabilities can be found in Reid and Goodman (2015) and Harris et al. (2019) and example lamprey presence-absence survey approaches at road crossings can be found in Stillwater Sciences (2014) and Reid (2016). Guidelines for lamprey-specific electrofishing operation, and identification and handling of larval lampreys can be found in LTW (2020).

Importantly, all lampreys captured during these surveys should be identified to genus (either *Entosphenus* or *Lampetra*) by examining caudal fin and ventral pigmentation (Goodman et al. 2009). Field guides for lamprey species identification include:

- Columbia Basin Lamprey Identification Guide (Lampman 2017),
- Lampreys of the Central California Coast: Field ID Key Version 19 (Reid 2012).

If permitted, tissue may also be collected from a subset of captured larvae and used to genetically validate field identification of species and/or allow identification of smaller individuals (<60 mm) that cannot be identified morphologically.

If electrofishing surveys are not permitted or access is not possible, collection and analysis of environmental DNA (eDNA) samples is another option that can be considered for detecting presence of Pacific Lamprey upstream of a potential barrier site (e.g., Carim et al.2017).

If resources allow, lamprey habitat assessments upstream of evaluated road crossings can also be conducted to help describe relative quality of Pacific Lamprey gravel/cobble spawning and fine-sediment rearing habitats to aid in prioritization for restoring passage (e.g., Stillwater Sciences 2014; Reid 2016, 2017). Depending on resources available, these surveys can range from rapid and qualitative in the immediate vicinity of the road crossing to extensive, quantitative surveys over a longer distance. Depending on spatial extent, such habitat surveys may provide only a snapshot of upstream lamprey habitat and should be used in conjunction with other available information (such as GIS-predicted channel gradient and drainage area) when making conclusions about the overall habitat potential above each site).

3.3 Migration Flows

Evaluation of passage at road crossings should only consider the range of flows that adult Pacific Lamprey are expected to encounter during upstream migration ("migration flows"). For most small-to-moderate stream sizes where road crossings typically occur, the upstream migration of adult Pacific Lamprey is assumed to be delayed during extreme high-flow events due to high velocities and turbulence and also during the lowest flows when shallow water depths through riffles may impede upstream movement.

Predicting these migration flows at a given road crossing site is an important component of evaluating passage status at the site and migration flows are required input for hydraulic models. Estimating the percentage of flows at which such a partial barrier is passable is necessary for determining the severity of barrier and helping prioritize the need to provide passage. For example, a site that is passable at all but the highest migration flows, would be lower priority than a site only passable at lower migration flows.

One approach to estimate migration flows at given site is to: (1) define the "high migration flow" as the 5% exceedance flow during the lamprey migration period and (2) define the "low migration flow" as the 95% exceedance flow during the same period. Figure 8 provides a hypothetical example of a flow duration curve for a gauged stream during the migration period, with 5% and 95% exceedance flows indicated.

Because adult Pacific Lamprey are found in freshwater throughout the entire year and have the potential to move during any month, migration flows should conservatively be calculated for the entire year. For watersheds where more information on migration is available, the migration period can be adjusted. For example, Stillwater Sciences (2014) calculated migration flows for December–July, the "core migration period" for adult Pacific Lamprey in the Eel River.

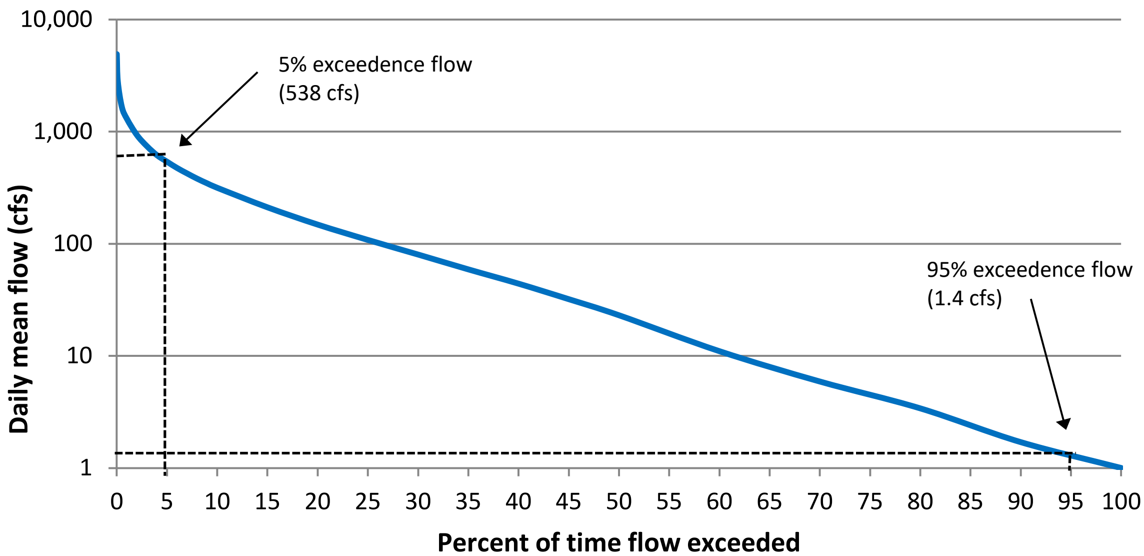


Figure 8. Example flow duration curve used to estimate fish migration flows. Data from Bull Creek, 1961–2013 (USGS gauge 11476600).

Because many road crossing sites are on ungauged streams, it may be necessary to estimate migration flows based on data from nearby gauged streams with similar elevations, aspect, and rainfall patterns. In these cases, migration flows at ungauged sites can be calculated by multiplying exceedance flows (95% and 5% in this case) at gauged sites by the ratio of the gauged stream's drainage area to the ungauged stream's drainage area at the study site. This simplified approach assumes that discharge and exceedance flows are proportional to drainage area. Refer to Taylor and Love (2003), WDFW (2019), or the FishXing model user manual (FishXing 2006) for more information on defining and calculating exceedance probabilities and migration flows.

3.4 Hydraulic Analysis

At many sites it is not possible to designate passage status from field evaluation alone. In these cases, hydraulic modelling can be applied to predict water velocities, depths, and whether a culvert outlet is perched across the range of lamprey migration flows for the site. Results of these analyses are then used to infer whether a crossing is passable based on the swimming capabilities of adult Pacific Lamprey (Section 2.8). Such hydraulic models can also be applied to support design of culverts or other road crossings that provide suitable passage conditions for lampreys and other fish. At a minimum, data required for hydraulic analysis includes:

- crossing shape, length, inlet and outlet elevations, slope,
- tailwater control cross-section elevations,
- species-specific swimming performance values (e.g., critical and burst swimming, speeds), and
- migration flows predicted for the site.

One model developed to analyze hydraulic conditions and fish passage through road crossings is called FishXing. Detailed information about the model and the free software can be downloaded from the FishXing website (https://www.fs.fed.us/biology/nsaec/fishxing/). Stillwater Sciences

(2014) applied the model to assess Pacific Lamprey passage and detailed the process and required inputs.

Importantly, hydraulic models are intrinsically simplified representations of actual conditions occurring at each site. For example, they typically predict average velocity at each point along the length of a crossing, but irregularities in structures and substrates, as well as complex flow patterns, may create lower or higher velocity areas within the crossing that make successful passage more or less likely. Consequently, model results should be interpreted cautiously and used in conjunction with field observations and other available evidence when determining potential for lamprey passage success. Additionally, these models are primarily designed to work for relatively hydraulically simple road crossing structures and channels and may not provide reliable results at more complex locations such as sites with irregular internal baffles, weirs, or other infrastructure.

3.5 Passage Status Designation

As described above, for some road crossing sites, such as extremely perched culverts, it is possible to confidently designate adult Pacific Lamprey passage status based on use of the initial evaluation filter and/or professional judgement. However, a multi-pronged approach is often required to evaluate the extent to which a site represents a barrier to migration. Evidence from one or more of the following sources may be used to inform designation of passage status:

- results of the initial passage evaluation filter,
- field observations and professional judgment,
- data from physical characterization of the crossing,
- water depth and velocity measurements from key points within the crossing,
- hydraulic modeling of water velocities, depths, and height of culvert perch across the range of migration flows,
- Pacific lamprey presence-absence data above and below a site and/or,
- existing information from previous assessments or fish passage databases.

Based on evidence from these sources, crossings should be assigned one of the following barrier designations for adult Pacific Lamprey (Table 4).

Table 4. Passage designations for road crossings.

Passage designation	Description
Total barrier	Barrier to passage at all migration flows
Partial barrier	Barrier to passage at only a portion of migration flows
Non-barrier	Not a barrier to passage at any migration flows
Unknown	Insufficient information available to make a passage designation

In general, a road crossing site is considered a *total barrier* if:

- The outlet is perched above the water surface elevation of the outlet pool over the range of migration flows.

- Water velocities at the entrance to or within the crossing exceed the conservative maximum burst-and-attach swimming speed of Pacific Lamprey (2.5 m/s) across the range of migration flows.
- Physical features or high velocities associated with crossing infrastructure clearly prevent upstream passage across the range of flows evaluated.

A site is considered a *partial barrier* if it has a perched outlet, insufficient water depths, or excessive velocities to allow lamprey passage at only a portion of migration flows. Hydraulic analysis can be used to determine the range of passable flows for a partial barrier. A site is considered a *non-barrier* if it unambiguously allows lampreys passage across the entire range of migration flows. Finally, a site may be designated as "*unknown*" if insufficient information is available to assess passage or if it is too complex to predict perch height, water depths, or velocities at different stream flows.

Appendix B contains example results of passage assessment and designation of passage status. Additional examples of passage assessment can be found in Stillwater Sciences (2014) and Reid (2016, 2017).

After conducting assessment of Pacific Lamprey passage at one or more road crossings, assessment results should be provided to the appropriate state database manager so that they can be included in their database (Section 3.1.1). Dissemination of this information is important to help ensure lamprey passage needs are considered by managers and restoration practitioners who are planning passage projects.

4 PRIORITIZATION FOR PROVIDING PASSAGE

Numerous approaches and tools have been developed to prioritize removal of barriers to fish passage (e.g., Kemp and O'Hanley 2010; O'Hanley 2011; Stillwater Sciences 2014; Chelgren and Dunham 2015; Lin et al. 2019; WDFW 2019). The best approach to use will be dependent upon on watershed size, objectives, and available resources. The following are some primary considerations for the barrier removal prioritization process:

- extent of barrier (percent of migration flows predicted to be passable),
- relative quantity and quality of upstream habitat,
- sequence of barriers in the river network (generally prioritize downstream sites over upstream sites),
- likelihood and extent to which providing passage would benefit other aquatic species,
- benefits to downstream habitat by restoring geomorphic processes and wood transport,
- condition of the structure (how soon it will need to be replaced),
- the likelihood of structure failure due to flooding, and
- relative cost and feasibility of providing passage (road fill volume, utilities to be temporarily relocated, traffic volumes and need to keep road open during construction, landowner support for removal, etc.).

Various scoring-and-ranking approaches, decision-support tools, and optimization tools have been developed to objectively prioritize sites for remediation based on some of the above considerations. Examples include:

- FISHPass, a web-based decision-support tool for prioritizing remediation of fish passage barriers in California https://www.cafishpassageforum.org/fishpass,
- OptiPass: Migratory fish passage optimization tool (O'Hanley 2014).

While the focus of this document is on evaluating and providing passage in streams expected to be used by Pacific Lamprey, there may be also be value for lampreys and other fish in evaluating and removing undersized or damaged culverts in small or steep streams, even if there is little or no suitable habitat upstream. Such culverts often interrupt important ecological and habitat forming processes such as bedload transport and movement of large wood. Restoring these fluvial geomorphic processes can improve habitat quantity and quality in downstream reaches.

5 GUIDELINES FOR PROVIDING PASSAGE

This section provides general guidelines for designing road crossings to promote passage of adult Pacific Lamprey. Refer to (LTW 2020) for information on reducing impacts to lamprey during construction activities such as culvert removal or replacement. Designs that maximize passage of adult Pacific Lamprey while considering the needs of other aquatic species are needed to remediate barriers or construct new crossings. Appendix C provides case studies of sites that presented total or partial barriers to Pacific Lamprey where passage has been provided, either through removal or retrofit. These case studies describe the problem, the solution implemented, and lessons learned for improving similar designs.

Where possible, barrier culverts should be replaced with a bridge or open-bottom culvert design using the stream simulation design approach (USDA Forest Service Stream Simulation Working Group 2008). Stream simulation is a method of designing crossing structures (usually culverts), with the aim of creating a channel within the crossing that functions like the natural channel (Figure 9). The premise is that the crossing channel should present no more of an obstacle to aquatic species than the adjacent natural channel. Key elements of a stream simulation design listed by USDA Forest Service Stream Simulation Working Group (2008) include:

- Continuous streambed that simulates natural channel width, depth, slope, and substrate of adjacent channel (both upstream and downstream).
- Contains diverse water depths and velocities, hiding and resting areas, and moist-edge habitats that support connectivity for multiple aquatic species.
- Accommodates flood discharges and sediment and debris inputs without compromising passage or impairing geomorphic and ecological processes in adjacent reaches.
- Channel inside the crossing structure is at least as wide as bankfull width in a natural reference reach.
- Defined low-flow channel that maintains surface flow at lowest flows (95% exceedance).
- Stream banks are rebuilt through structure and remain dry at most flows, maintaining hydraulic separation from the culvert wall.

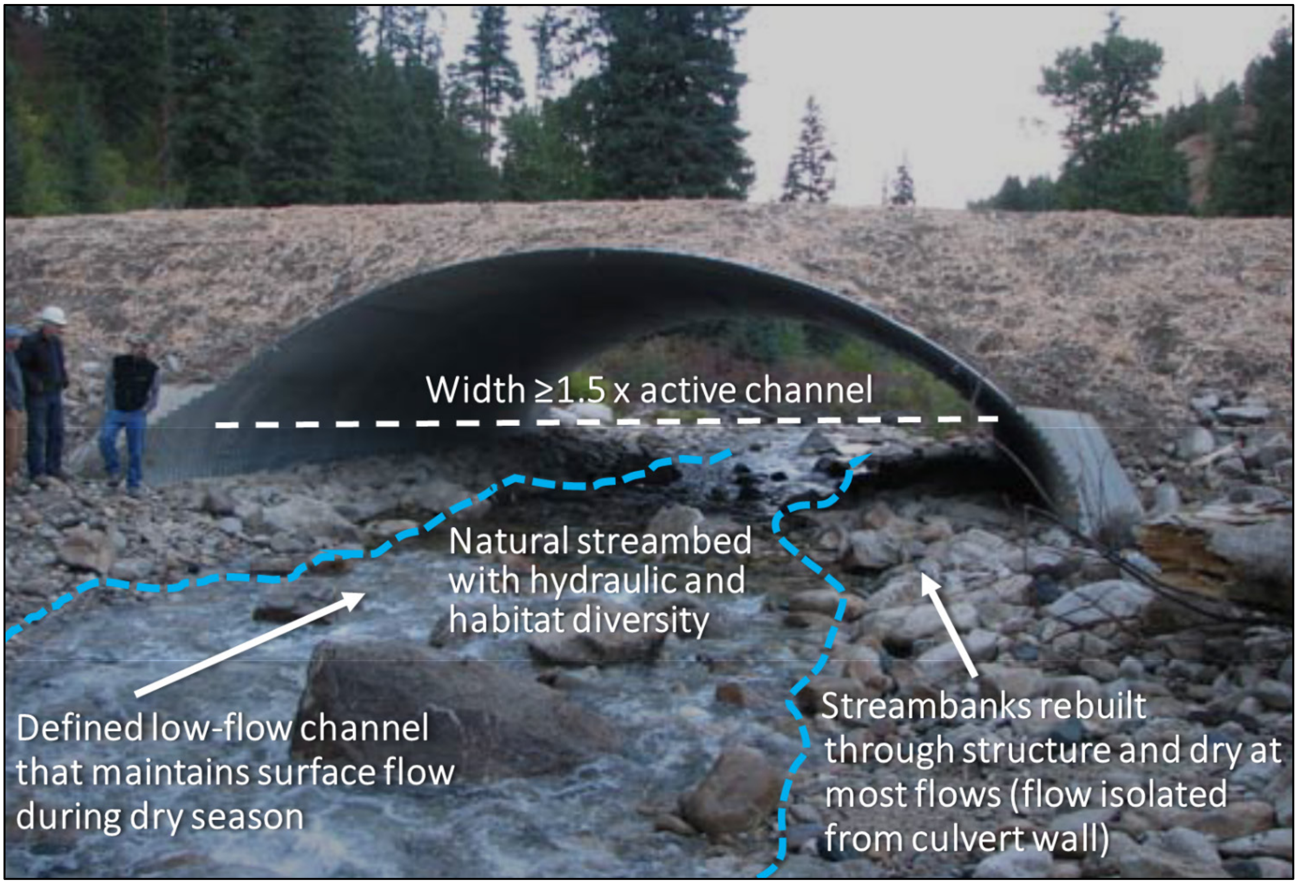


Figure 9. Example of a culvert replacement built with stream simulation design elements, Roaring River, Idaho. Credit: USDA Forest Service.

When replacement of a barrier site with a stream simulation design is not feasible, the following design guidelines should be applied where relevant, taking into consideration the factors affecting adult Pacific Lamprey passage (Section 2.8):

- Designs for culvert and associated infrastructure should provide water velocities that are less than the burst-and-attach swimming speed of adult Pacific Lamprey (2.5 m/s) across the range of migration flows.
- Where essential for design, ensure concrete weirs, outlet aprons, or baffles have smooth, rounded surfaces (e.g., Appendix C, case studies 3 and 6). Avoid 90° angles, gaps, and sharp corners in high velocity areas. Sharp angles prevent lampreys from maintaining attachment as they attempt to move around a corner or over a vertical step.
- Corners and edges should be rounded with a 4-inch (10 cm) radius, minimum, with larger radii used in areas with high velocities.
- At sites with concrete outlet aprons, consider grinding squared edges to create rounded surfaces that provide for an uninterrupted attachment surface.
- When weirs or fishways are present and necessary, consider creating alternative lamprey passage routes such as orifices along the bottom.
- Ensure culvert bottoms have natural substrate, or at least continuous attachment points constructed with non-porous materials. Lamprey attachment and passage may be impaired

by porous surfaces such as grates or discontinuities in substrate on the bottom of the crossing or at transitions from the outlet or inlet to the adjacent channel.

- Ensure the margins of culvert bottoms (along the walls) are free of potential obstructions such as sharp-angled baffles or grooves or seams that are greater than 2-mm wide. During high flows, the margins are typically preferred migration routes (Kirk et al. 2015; Reid and Goodman 2016).
- At high-velocity locations, consider constructing velocity refuges or rest areas with adequate attachment points (e.g., Tummers et al. 2018; Appendix C, case studies 4 and 5).
- Minimize turbulent flows and provide gradual transitions from low- to high-velocity areas with smooth surfaces for attachment. Lamprey may be swept downstream between successive attachments by rapid changes in water velocity or direction (Daigle et al. 2005).
- Ensure culvert outlets are not perched above the water surface of the outlet pool during migration flows and avoid infrastructure requiring leaping to pass.
- Where replacement of a perched culvert is not possible or is cost-prohibitive, consider retrofitting the site with lamprey passage systems or lamprey ramps (Moser et al. 2011) or tubes (Goodman and Reid 2017) that provide an alternative route for lamprey to pass the crossing.
- For slightly to moderately perched culverts, consider increasing the elevation of the tailwater hydraulic control with a boulder weir or other weir designed to raise the water surface so that lamprey can enter the culvert over a wider range of stream flows (e.g., Appendix C, case studies 4, 5, 6, and 7). Such weirs can also reduce water velocities at the outlet and within the crossing to facilitate passage. Ensure the tailwater weir is designed to allow unimpaired passage of lamprey and other aquatic species.

Since retrofits such as ramps or tubes designed to improve adult Pacific Lamprey passage do not typically remedy passage limitations from high water velocities, provide passage for non-climbing aquatic species, or restore natural fluvial geomorphic processes, they should only be applied when replacement with a bridge or stream simulation design culvert is not possible. For sites where retrofits or other modifications are necessary, it is imperative to conduct regular monitoring and maintenance to ensure these modifications are working as intended and have not been damaged or compromised by high flow events or debris. It is also important to ensure that retrofits such as ramps and tubes do not delay passage of lampreys such that they become more vulnerable to predation. Finally, it is essential to confirm that these designs do not impede passage of other native aquatic species.

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Appendices

Appendix A

Example Passage Evaluation Datasheets

The following example datasheets for assessing adult Pacific Lamprey passage at road crossings are included below:

- Passage assessment site checklist used to ensure each element of a field survey is completed.
- Initial passage evaluation filter used to help designate barrier status and whether field sites require further evaluation.
- Site information form.
- Long Profile and Tailwater Cross Section Survey datasheet.
- Reference Page that includes a legend of survey abbreviations and elements to include in a site sketch.
- Example site sketch from Stillwater Sciences (2014).

These examples are based on Stillwater Sciences (2014) and can be modified as appropriate for a particular passage assessment project. Refer to Section 3.2 and existing detailed passage guidance documents (e.g., Taylor and Love 2003; Clarkin et al. 2005; WDFW 2019) for more detailed instructions on collecting data for each element.

Passage Assessment – Site Checklist

Site Name or ID:______________________

Date: _______ /_______ /_______

Stream name:_______________

Field site checklist:

(1) ☐Use initial passage filter to identify data that needs to be collected at site

(2) ☐Fill out "Site Information Form"

(3) ☐Survey longitudinal profile

(4) ☐Survey tailwater cross-section

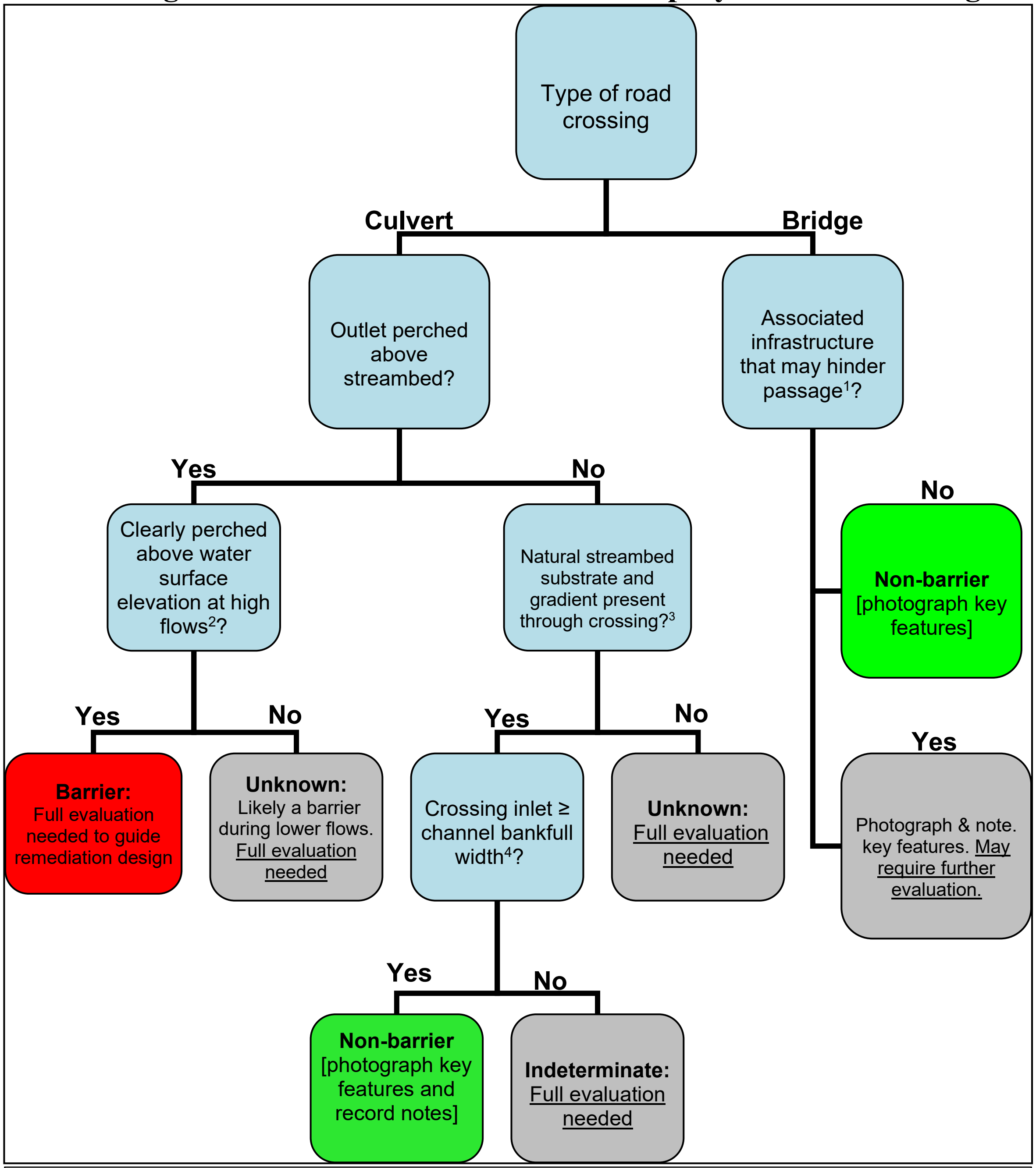
(5) ☐Take photographs of key features at site and record photo #s

(6) ☐Make a site sketch to show key features

(7) ☐QA/QC: review all passage datasheets for completeness and legibility

(8) ☐Implement larval lamprey distribution and habitat surveys upstream and downstream of road crossing

Initial Passage Evaluation Filter for Pacific Lamprey at Road Crossings



[1] Examples include trash racks, vertical steps, or significant channel constriction from abutments.
[2] Use active channel indicators at outlet to approximate high flow water surface elevation.
[3] Streambed substrate is continuous throughout the crossing and the streambed gradient and particle size similar to the adjacent channel.
[4] Measured upstream of structure and away from its zone of influence (i.e. upstream of aggradational wedge caused by inlet control).

Pacific Lamprey Passage Assessment – Site Information (pg. 1 of 2)

Date: _____ /______ /______ Site ID:____________

LOCATION INFORMATION

Survey crew initials ______________________________

Road name / number: _____________________ **Land ownership:** _______________________

Watershed__________________ **Stream:** ______________________ **Tributary to:** ______________________

Latitude (N):_______________________ **Longitude (W):**__________________ -or- **GPS waypoint:**____________

CROSSING STRUCTURE

Shape
□Circular
□Box
□Open-bottom arch
□Pipe-arch
□Ford
□Vented ford
□Bridge
□Other: ________________

Dimensions (inches)
Width: _________Height: _________
Rust line: ___________ (feet above culvert bottom)
Slope breaks in pipe? □No □Yes

Ford data: sag _______
F_1 ________
F_2 ________

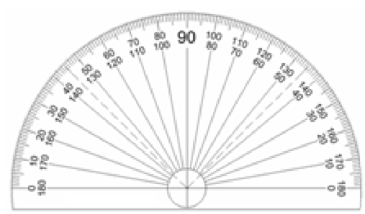
Multiple structures at Site?
□No □Yes
Describe & photo if yes:

Structure shape comments____

Structure material
□Spiral CMP
□Annular CMP Steel Aluminum
□Structural plate
□Concrete
□PVC
□Wood or log
□Other: _____________________

Corrugations
□2 2/3 x ½ inch
□3 x 1 inch
□5 x 1 inch
□6 x 2 inch (SSP only)
□None
□Other: ______________________

Skew from road



Degrees _________

Inlet type
□Projecting
□Mitered
□Wingwall □<30° □30-45° □>45°
□Headwall
□Apron
□Trashrack
□Other: ____________________________

Outlet configuration
□at stream grade
□cascade over rock
□free-fall into pool
□free-fall onto rock
□outlet apron
□Other: __________________
____

Baffles, weirs, or other internal structures?
□No □Yes -- Describe:______________________
____
____

Fish ladder at outlet? □No □Yes
Describe material, size, & shape:______________
____
____

Tailwater control: □pool tailout □log weir □boulder weir □concrete weir □other____

Crossing condition: □Breaks inside culvert (Location_________________) □Fill eroding □Debris plugging inlet (% blockage___)
□Bent inlet □Bottom worn through □Poor alignment with stream □Debris in culvert (rock or wood) □Bottom rusted through
□Water flowing under culvert □Other ___________________________
Describe overall condition____
____
____

Additional site comments:

Pacific Lamprey Passage Assessment – Site Information (pg. 2 of 2)

Date: _____ /______ /______ Site ID:____________

STREAMBED SUBSTRATE RETENTION IN STRUCTURE

□No substrate in structure
□Discontinuous layer of substrate in structure: begins at _______ ft ends at ________ft (*measured from inlet*)
□Substrate is continuous throughout structure
If present, substrate depth at inlet ________ft substrate depth at outlet ________ ft
□Unknown / not accessible

SUBSTRATE PARTICLE SIZES (*rank 1 to 3 in by type of substrate occupying the most streambed area*)

Location	**Bedrock** (>4096 mm)	**Boulder** (256-4096 mm)	**Cobble** (64-256 mm)	**Gravel** (2-64mm)	**Sand** (<2 mm)	**Silt/Clay**	**Other**	**Notes**
In crossing								
At downstream tailwater control								

LAMPREY ATTACHMENT POINTS

(1) Downstream of crossing outlet

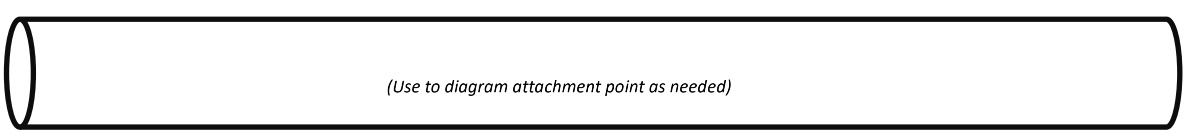
Distance from first suitable attachment point within crossing to first suitable attachment point downstream of crossing ______________(ft)
Describe attachment point/s:____

(2) Upstream of crossing inlet

Distance from last suitable attachment point within crossing to first suitable attachment point upstream of crossing ______________(ft)
Describe attachment point/s:____

(3) Within crossing:

□Natural stream bed throughout crossing with ample suitable attachment points.
□Corrugations present (*size & type described above*)
□Significant damage to corrugations that may preclude attachment? Describe locations and type:___________
____
□Smooth, flat throughout: describe surface material:____
□Discontinuous attachment points or porous materials: describe type/s, locations, and distances between suitable attachment points apart:____



Upstream

<u>BANKFULL</u> CHANNEL WIDTHS (ft): (*measure outside of culvert influence*)

Bankfull width (m): (1)________ (2) ________ (3) ________ (4) _________ (5) _________ Average ________
Distance from site (m): (1)________ (2) ________ (3) ________ (4) _________ (5) _________
U/S or D/S from site?: (1)________ (2) ________ (3) ________ (4) _________ (5) _________

Long Profile and Tailwater Cross Section Survey Datasheet

DATE:_____/______/_______ **Site ID#______________**

SURVEY CREW:______________ **Structure _____of______**

Long Profile Survey (*all measurements in feet*)

Station	BS (+)	HI	FS (-)	Elevation	Water surface depth	Station Description and Notes
				100.00	n/a	Temporary Benchmark

Tailwater Cross Section Survey:

Station	BS (+)	HI	FS (-)	Elevation	Water surface depth	Station Description and Notes

**See reference page for survey terminology and list of key points for long profiles and cross sections.*

Passage Assessment — Datasheet Reference Page

Survey terms / abbreviations

Station = distance along profile from starting point
BS (+) = backsight: rod reading at point of known elevation
FS (-) = foresight: rod reading taken at any point
HI = height of instrument

Long Profile survey points (key):

TWC-RP = tailwater control of first resting pool upstream of inlet
PU_1 = Points upstream of inlet (take several to show channel slope upstream of and downstream of TWC-RP)
Inlet = Inlet invert (lowest elevation in culvert inlet)
PW_1 = Points within culvert (take at least one to show water surface profile)
Outlet = Outlet invert (lowest elevation at culvert outlet)
MD = Max depth = take elevation of channel and water depth at deepest location of outlet pool
TWC = tailwater control of outlet pool (taken in thalweg of tailwater control)
PD_1 = Points downstream of outlet (take several to show channel slope downstream of TWC)

Tailwater Control survey points (key):

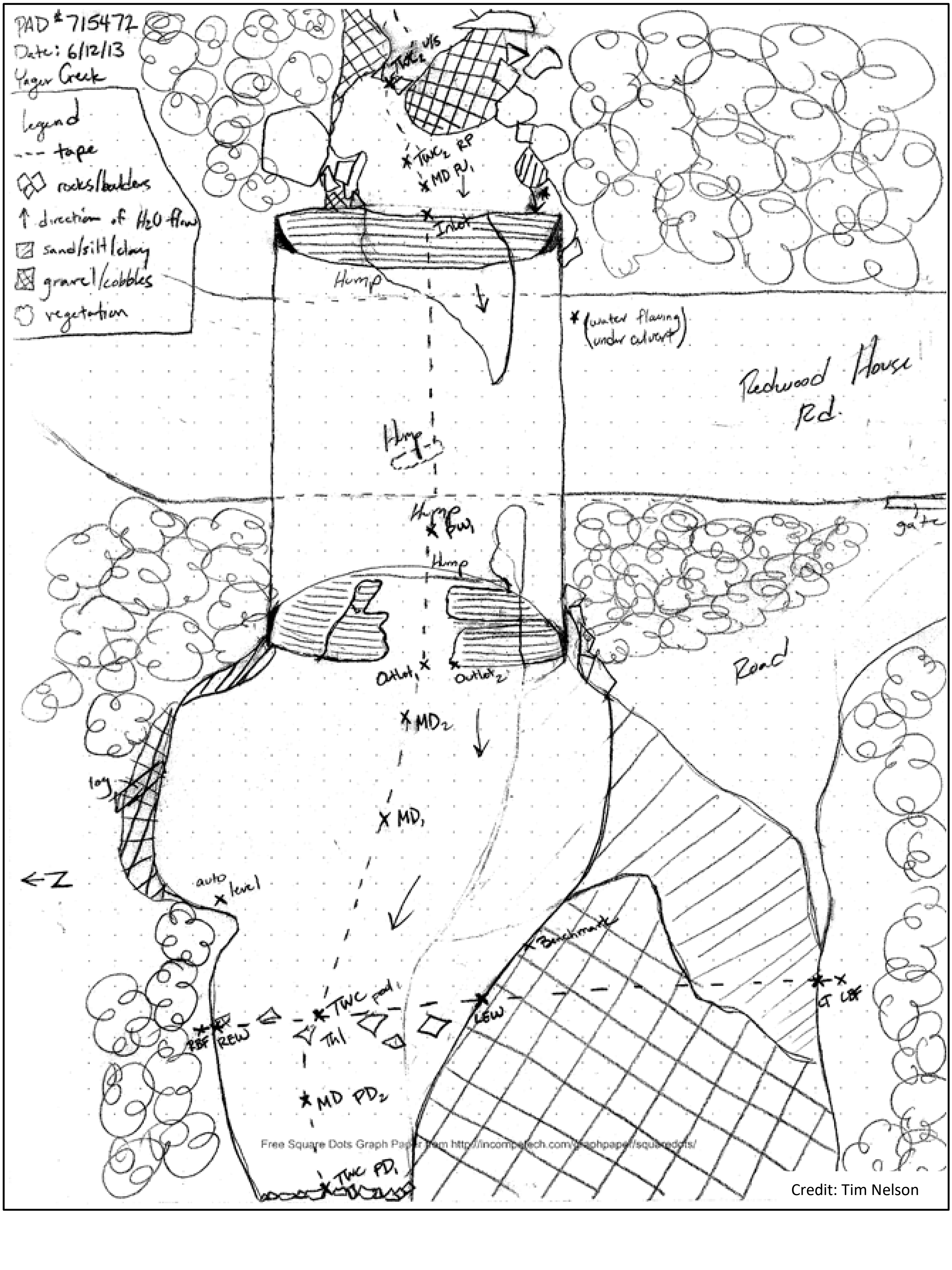
LBF = left bankfull	Thalweg
LEW = left edgewater	RT = Right toe of bank
LT = left toe of bank	REW = right edge water
CS_1 = points within cross section	RBF = right bankfull

Elements to include in Site Sketch:

- PAD ID#
- Field Date
- North Arrow
- Direction of stream flow
- Culvert/channel alignment
- Lay of tape (if needed)
- Photo point locations and numbers (as appropriate)
- Wingwalls and inlet / outlet aprons
- Multiple structures
- Baffle configurations
- Weirs and other instream structures
- Debris jams inside, upstream and downstream near site, depositional bars
- Trash racks, screens, standpipes etc. that may affect passage
- Damage to or obstacle inside structure
- Location of Riprap for bank armoring or jump pool formation
- Tailwater cross-section location

Example Road Crossing Survey Site Sketch

Yager Creek, Eel River Basin, California (Stillwater Sciences 2014)



Credit: Tim Nelson

Appendix B

Case Studies of Pacific Lamprey Passage Evaluation

This appendix presents examples of lamprey passage assessment, including summaries of data and observations collected at each site, channel characteristics, passage designation, and evidence for the designation based on the initial evaluation filter, hydraulic analysis, field observations, larval lamprey surveys, and other assessments. These case studies are meant to provide brief examples of passage assessment results and the designation process for adult Pacific Lamprey. Please contact the listed project contact for more information. More case studies will be added to this living document as they become available. Please email info@pacificlamprey.org if you are interested in contributing a case study that demonstrates evaluation of Pacific Lamprey passage at a road crossing.

Table B-1. List of passage assessment case studies. Last update: June 29, 2020.

Case study #	**Stream Watershed State**	**Brief Description**	**Contact**
1	Long Valley Creek Eel River California	Large, long corrugated metal culvert with perched outlet and tailwater control weir at outlet. Assessed by Wiyot Tribe and Stillwater Sciences in 2013.	Abel Brumo abel@stillwatersci.com
2	Yager Creek Eel River California	Damaged and undersized pipe-arch corrugated metal culvert outlet, assessed by Wiyot Tribe and Stillwater Sciences in 2013.	Abel Brumo abel@stillwatersci.com

PASSAGE ASSESSMENT CASE STUDY #1: LONG VALLEY CREEK, CALIFORNIA

Location information

PAD ID	Stream name	Tributary to	Sub-basin	Survey date	Road name	Latitude (N)	Longitude (W)
707091	Long Valley Creek	Outlet Creek	Upper Main Eel	8/19/2013	Hwy 101 / Road Fill	39.57969	-123.44275

Work performed at site

Crossing physical characteristics	Long profile	Tailwater control cross-section	FishXing analysis	Ammocoete surveys	Habitat surveys
Yes	Yes	Yes	Yes	No	Yes

Crossing physical characteristics

Crossing shape	Structure material	Corrugation size (inches, W X H X diagonal)	Span (ft)	Rise (ft)	Length (ft)	Crossing slope (average)	Slope breaks in crossing?	Multiple structures at site?
Circular	Annular CMP	6.5 X 2.5 X 4.1	19.3	17.3	449.8	0.68%	No	No

Skew from road	Inlet type	Outlet configuration	Baffles, weirs, or other internal structures	Fish ladder at outlet?	Tailwater control d/s of outlet	Crossing condition
0°	Projecting	Free-fall into pool	No, but tailwater control weir present.	No	Pool tailout at observed low flows, but "v-notch" weir likely controls at higher flows.	Overall fair-good condition; Rusted through in narrow slits in a few places

Substrate and suitable lamprey attachment points within crossing

Substrate retention	Dominant substrates in crossing (listed in order of abundance)	Distance from suitable attachment in crossing to suitable attachment:		Notes on attachment points within crossing
		Downstream of outlet (ft)	Upstream of inlet (ft)	
Thin, discontinuous layer of substrate on bottom	Silt, Sand, Gravel	<1	<1	Large corrugations

Channel characteristics

Contributing drainage area at site (km^2)	Length of channel upstream with gradient <2% (km)	Bankfull channel width (mean; ft)
31.5	10.8	44.2

Additional site comments

Stream does not actually cross under HWY 101, but crosses under a large amount of adjacent highway fill. Flow was very low, with stagnant water and grass growing in channel during the survey. The crossing is very long and has two minor doglegs within. The outlet was perched approximately 4" above water surface elevation of tailwater on survey date. A concrete tailwater control weir with a "V-notch" approximately 30 ft downstream of outlet that was presumably designed to backwater and slow velocities at outlet. During observed flows, outlet pool water surface elevation was controlled by the downstream pool tail, but the weir likely affects water surface elevation and velocities at outlet at higher flows. Long Valley Creek has potential to be an excellent lamprey stream due to large size and significant amount of low gradient habitat.

Passage designation

Designation	Barrier type	Migration flows evaluated (cfs)[1]	Range of passable flows predicted (cfs)	Notes
Partial barrier	Perched outlet, velocity	1.0–219.5	47.5–86.2	FishXing predicts site is a perched outlet barrier at low to moderate migration flows and velocity barrier at higher flows.

[1] High and low migration flows were defined as the 5% and 90% exceedance flows, respectively, during the core Pacific lamprey migration period of December through July.

Evidence for passage designation

Source	Summary, rationale, and assumptions
Initial passage filter	Indeterminate
Hydrualic analysis (FishXing model)	FishXing predicts perched outlet will backwater at flows >47.5 cfs, and we conservatively assume that lampreys cannot enter culvert at lower flows. Water velocities predicted to exceed burst swimming speed at flows >86.2 cfs. We assume burst-and-attach behavior is possible on the large corrugations, but it is uncertain whether the maximum burst speed can be reached in corrugated culverts. Results should be viewed with caution due to uncertain effects of culvert doglegs and V-notch weir downstream of outlet. The weir may backwater outlet at lower flows than predicted from tailwater control cross-section measured at downstream pool tail. Weir also likely slows water velocities at outlet, where highest velocities predicted to occur. For these reasons, FishXing may underestimate range of passable flows.
Field evaluation observations and data	Outlet is perched ~4" above water surface elevation at observed low flows and likely prevents lampreys from entering culvert. Crossing length (450 ft) may lower passage success, but large corrugations would presumably allow attachment. Estimated bankfull width is over twice culvert diameter. High water velocities at outlet of tailwater control weir V-notch could be a passage obstacle at higher flows and prevent lampreys from reaching culvert outlet.
Ammocoete surveys	Sampling could not be conducted due to issue with E-fisher breaking electrical circuit in Long Valley Creek, which was likely related to high conductivity of stagnant, murky water. E-fisher worked fine in adjacent streams. Pacific lampreys have yet to be documented in Long Valley Creek, but are likely present due to relatively large and low-gradient channel.
Other evaluations	Crossing was designated a partial barrier to salmonids based on professional judgment by CDFW.

Additional potential barriers in stream

Long Valley Creek parallels HWY 101 for approximately 6 miles and is crossed by it five times (PAD IDs: 707090, 707091, 707092, 707094, 707095). We photo documented PAD ID 707092, a bridge, and determined it had minimal impact on passage. We also photo documented PAD ID 707094, a bridge with baffles and concrete in the channel between abutments, and concluded it may impede passage at high flows, but is most likely passable at moderate flows. PAD IDs 707090 and 707095 are bridges and not expected to be barriers but should be visited to confirm. In addition to the HWY 101 crossings, Satellite imagery indicates at least three other bridge crossings that are not listed in the PAD. These sites are unlikely to be total barriers to lamprey migration but should be evaluated due to the high habitat potential of Long Valley Creek.

Crossing photographs

Outlet	Inlet
	

PASSAGE ASSESSMENT CASE STUDY #2: LONG VALLEY CREEK, CALIFORNIA

Location information

PAD ID	Stream name	Tributary to	Sub-basin	Survey date	Road name	Latitude (N)	Longitude (W)
715472	Yager Creek	Van Duzen River	Van Duzen	6/12/2013	Redwood House Rd.	40.54411	-123.91543

Work performed at site

Crossing physical characteristics	Long profile	Tailwater control cross-section	FishXing analysis	Ammocoete surveys	Habitat surveys
Yes	Yes	Yes	Yes	Yes	Yes

Crossing physical characteristics

Crossing shape	Structure material	Corrugation size (inches, W X H X diagonal)	Span (ft)	Rise (ft)	Length (ft)	Crossing slope (average)	Slope breaks in crossing?	Multiple structures at site?
Pipe-arch	Annular CMP	6 X 2 X 3.6	16.0	8.0	66.4	1.57%	Yes, due to debris jammed under culvert	No

Skew from road	Inlet type	Outlet configuration	Baffles, weirs, or internal structures	Fish ladder at outlet?	Tailwater control d/s of outlet	Crossing condition
80°	Projecting	At stream grade	No	No	Pool tailout	Very poor. Bottom rusted through & water flowing under culvert. Debris jammed under culvert causing humps.

Substrate and suitable lamprey attachment points within crossing

Substrate retention	Dominant substrates in crossing (listed in order of abundance)	Distance from suitable attachment in crossing to suitable attachment:		Notes on attachment points within crossing
		Downstream of outlet (ft)	Upstream of inlet (ft)	
No substrate in culvert	n/a	4	<1	Significant damage to corrugations on center of culvert bottom, but edges of bottom are not rusted through and would presumably allow attachment when wetted during moderate to high migration flows.

Channel characteristics

Contributing drainage area at site (km^2)	Length of channel upstream with gradient <2% (km)	Bankfull channel width (mean; ft)
16.7	9.4	43.1

Additional site comments

Culvert is failing and needs to be replaced ASAP. Starting about 4 ft from the culvert outlet, the bottom is “humped-up” and raised ~0.5–2 ft above the water surface elevation, likely preventing passage at low flows. Water appears to be running almost entirely beneath, rather than through, culvert. The outlet is in a large, deep, low-velocity pool with a distinct tailwater control. Site is located in reach of upper mainstem of Yager Cr. also known as South Fork Yager Cr., which is upstream of the confluence with the much larger North Fork Yager Cr. watershed.

Passage designation

Designation	Barrier type	Migration flows evaluated (cfs)[1]	Range of passable flows predicted (cfs)	Notes
Partial barrier	Depth, velocity	1.5–156.1	1.5–116	Field observations indicate likely barrier at low migration flows due to damage.

[1] High and low migration flows were defined as the 5% and 90% exceedance flows, respectively, during the core Pacific lamprey migration period of December through July.

Evidence for passage designation

Source	Summary, rationale, and assumptions
Initial passage filter	Indeterminate
FishXing analysis	FishXing model results should be viewed cautiously due to misshapen state of culvert and uncertainties in parameterizing the channel slope downstream of the tailwater control. Nevertheless, the model indicates that the culvert is not passable at flows higher than approximately 115 cfs, when velocities exceed the Pacific lamprey maximum burst swimming speed (2.7 m/s). The model run assumed that burst-and-attach behavior is possible on the large culvert corrugations. FishXing does not predict a depth barrier at low flows, but field observations indicate that the damaged culvert bottom creates a barrier at low flows and thus the model likely overestimated percent of passable flows.
Field evaluation observations and data	The culvert has a relatively gentle slope with ample attachment points. Lampreys could enter the culvert outlet at the relatively low flows present during the 6/12/2013, but the “humped-up” bottom that starts approximately 4 ft from the outlet would not allow passage through the culvert at these flows. It is unknown how much flow would be required to allow migration past the raised bottom, which, along the left side of the culvert, was approximately 0.5 ft above the water surface elevation of the outlet pool on the survey date. It appears that passage would be possible at moderate flows due to presence of tailwater control. It is possible that lampreys could cross under the raised portions of the culvert during low flows, but this potential passage route could change over time depending on bottom damage and sediment and debris accumulation.
Ammocoete surveys	No ammocoetes were located during limited sampling immediately upstream or downstream of the crossing. Several suitable fine sediment habitat patches were sampled.
PAD	None relevant
Other evaluations	To our knowledge no other systematic passage evaluations have been done at this site.

Additional potential barriers in stream

The PAD lists another crossing of mainstem Yager Cr. by Redwood House Rd. (PAD ID 715471) approximately 4 miles upstream. Google Earth indicates that this site may not actually be a crossing, but its status should be evaluated. The PAD also lists two high-gradient natural features approximately 5 miles downstream in mainstem Yager Cr. that are considered potential migration obstacles to salmonids. Evaluation of these sites for lamprey passage was beyond the scope of this study, but they are not likely to be barriers since steelhead have been observed upstream according to the PAD.

Crossing photographs

Outlet	Inlet (looking d/s towards outlet)
	

Appendix C

Case Studies of Providing Passage for Pacific Lamprey

This appendix presents case studies showing efforts to restore and/or improve passage for adult Pacific Lamprey and other aquatic species. As described in Section 5, where funding is available and logistically feasible, replacement of undersized, damaged, or perched culverts with properly sized open-bottom arch designs that simulate a natural channel and accommodate high flows and passage of substrate and wood is the preferred approach. However, in cases where replacement is not feasible, retrofits can be affordably and quickly applied to improve passage. Ideally, such retrofits should be periodically monitored and maintained to ensure they continue to allow fish passage and are not damaged or hydraulically altered due to accumulation of sediment or debris.

These case studies are brief overviews of solutions applied for improving lamprey passage at likely barriers to adult migrations. Please contact listed project contacts, who authored these examples, for more information about design considerations, costs, and lessons learned. More case studies will be added as they become available. Please email info@pacificlamprey.org if you are interested in contributing a case study that demonstrates restoration of Pacific Lamprey passage at a road crossing.

Table C-1. List of case studies of providing passage for Pacific Lamprey. Last update: June 29, 2020.

Case study #	**Stream Watershed State**	**Brief description**
1	Coho Creek Necanicum Oregon	Replacement of undersized, perched culvert with stream simulation design
2	Baker Creek Coquille Oregon	Replacement of large, perched culvert and fishway with restored natural channel
3	Cedar Creek S. Fork Eel California	Perched rock slope protection apron retrofit with fishway design modified for lamprey passage
4	Canyon Creek Umpqua Oregon	Backwatering of perched culvert with boulder weir and roughened channel and installation of localized velocity reduction
5	Pass Creek Umpqua Oregon	Backwatering of perched culvert with boulder weir and roughened channel and installation of localized velocity reduction
6	Marley Creek Grand Ronde Oregon	Perched culvert repair and retrofit with rounded baffles, paved invert liner, and roughened riffle
7	Eel Creek Ten Mile Lakes Oregon	Backwatering of perched culvert by increasing tailwater control elevation and retrofit of culvert baffles

Case Study #1: Stream Simulation at Road Crossing Coho Creek, Necanicum Watershed, Oregon

Background

Coho Creek is a small coastal tributary to the Necanicum Estuary in Oregon. The culvert had a 2-ft perch and was a full barrier to fish passage for both lamprey species and adult and juvenile salmonids due to the jump height, velocities that exceed fish swimming capabilities in the 160-ft pipe, and inadequate flow depths (Figure 1). The culvert was also a failure risk creating a human safety hazard on the only access/egress road to a local elementary school and a Community Tsunami Evacuation Route. Prior to restoration, the culvert was slip lined with a plastic pipe in an attempt to prevent catastrophic failure that would have released approximately 3,500 yd^3 of 20-ft high road fill into a high-quality wetland downstream. There was approximately one mile of spawning and rearing habitat upstream. The active channel width in the vicinity of the culvert was 10 ft, the active channel depth was approximately 1.5 ft, the substrate was dominated by gravel, the gradient was 3%, and the habitat bedforms were dominated by riffle and pool features.

Figure 1. Coho Creek outlet prior to restoration. The perched, undersized and failing culvert was slip lined with a plastic pipe to prolong life.

Providing Lamprey Passage

Use of stream simulation design was chosen to correct the issues for passage of all aquatic species including Pacific Lamprey, restore normalized stream flow and bedload transport processes, and improve transportation infrastructure. The process and outcome of implementing the stream simulation design are described below.

Survey, Assessment, and Design

USFWS hired River Design Group (RDG) on behalf of the School District and the Necanicum Watershed Council to conduct site reconnaissance and design. This included a channel profile (thalweg, water surface, bankfull, and floodplain) and stream cross sections. The survey extended 490 ft upstream and 370 ft downstream of the culvert, a total lineal distance of 1,015 ft. Other data collected included water velocities and pebble count data. A hydraulic model and design alternatives for the site were developed looking at fish passage flows at the 5% and 95% exceedance as well as return intervals spanning from a 2-year to a 100-year event.

All design alternatives were required to meet both Oregon and National Marine Fisheries Service Fish Passage standards for stream simulation and were reviewed at each design stage. The final selected design solution was a 16-ft wide x 160-ft long culvert with 7 ft 1 in height and a streambed slope of 3%. The culvert had an open bottom with a stream simulation designed stream bed including a low flow channel and hydraulic shadow areas using oversized (2-3-ft) rocks that were partially buried.

Implementation – Staging, Utilities, and Excavation

This project involved substantial site preparation, material staging, and utility work (Figure 2). In addition to having an extremely deep road fill, this site had fiber optic cable, water, and buried power lines running on each side of the road. All utilities had to be managed and continuous service provided for the duration of the project. In addition, emergency vehicle road access had to be accommodated, which required building one lane at a time. Project staging, utility location, and road excavation began early, prior to the July 1 in-water work window.

Figure 2. Deep road fill was excavated and stockpiled, the failing culvert was carefully removed allowing for reuse of the temporary plastic liner. Degree of failure of the culvert is visible at right

Streambed Simulation Construction

Proper construction of streambed simulation features is as critical as the design elements (Figure 3). Having the designer on site to oversee construction and to inspect and approve stream simulation materials is important to ensure it is installed per specifications. The contractor prepared the area for footers per design specifications at the appropriate grade. Footers were installed one section at a time and then welded together. Grade and location were measured and checked as each footer was placed. The gravel, rock rib, and boulder gradation specifications were based on instream conditions and hydraulic analysis. Gravels were specified to be free of fines, thoroughly mixed and placed in the culvert to specified depth. In addition, 30 2-3 ft partially buried oversized boulders were placed near the surface of the gravel (50% embedded) to create hydraulic shadows and maintain the low flow channel form. After the gravel was placed, the surface was washed to allow the fines to work into open spaces and form a seal. Sand was washed in until the gravel was sealed and wash water flowed on top of the gravel (Figure 4).

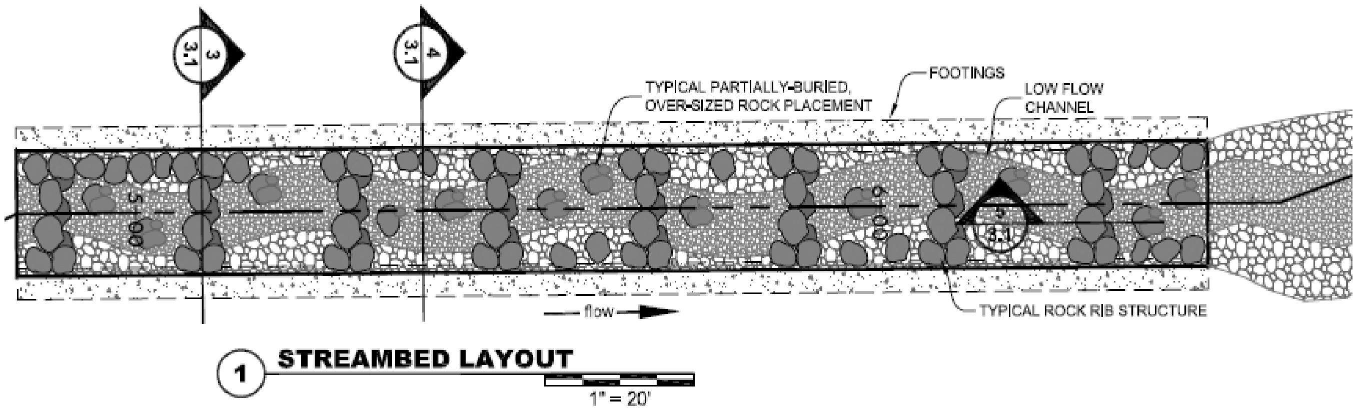


Figure 3. Streambed simulation design detail. Designed by River Design Group, 2011.

Figure 4. Proper sizing and installation of streambed materials is critical to success, including washing in fine sediment to 'seal' the streambed features. This ensures that when flow is returned to the channel, a low flow channel is maintained rather than flow going subsurface.

Completed Streambed Simulation Project

The completed structure has several key features (Figure 5). It has a natural stream bottom with a defined low flow channel that provides fish passage at the low flow (95% exceedance). There is hydraulic diversity at a full range of flows and is passable to fish at the high fish passage flow (5% exceedance). The streambed and streambanks have been rebuilt inside the structure to mimic upstream and downstream conditions. The flood width meets or exceeds 1.5 times active channel width. In general, a simulated streambed approach strives to duplicate streambed geometry of the nearby channel reach within the new culvert, resulting in a streambed surrogate that is passable to fish by being geomorphically and hydraulically similar to the surrounding channel.

Figure 5. Completed structure has a defined low flow channel with minimum flow depths, hydraulic diversity, streambed and streambanks rebuilt inside the structure to mimic upstream and downstream conditions, and flood widths that meet or exceed 1.5 times active channel width.

Project Contact:

Amy Horstman, amy_horstman@fws.gov
U.S. Fish and Wildlife Service, Columbia River Fish and Wildlife Conservation Office
503-704-7508

Case Study #2: Removal of the Baker Creek Culvert Coquille Watershed, Oregon

Background and Problem

Figure 1. Pre-project photo: Large culvert perched high above stream and ineffective fishway on right.

Perched culverts are a common passage problem for upstream migrating adult Pacific Lamprey because there are no continuous attachment surfaces and lampreys can't jump. A 12 ft X 250 ft culvert perched approximately 18 ft above the stream bed (Figure 1) was removed from Baker Creek, a tributary of the South Fork Coquille River, Oregon, to eliminate this barrier. During the early 1950's a large culvert was installed through a section of failing wooden railroad trestles. This perched culvert was a total fish barrier when it was originally installed and for many years no migratory fish were able to move upstream into Baker Creek. In 1994, a Denil fish ladder (also known as an Alaskan fishway) was constructed to allow fish passage. The 25-ft wooden ladder was placed through a hole cut into the side of the culvert. Baffles were also added to the inside upper portion of the culvert to help passage through the steep grade. While this retrofit allowed for limited salmonid fish passage, there was very low, if any, potential for adult Pacific Lamprey passage. The Denil fish ladder was designed for salmonid passage with straight edges and did not consider lamprey passage needs. Additionally, high water velocities through the long culvert presented additional passage challenges.

The Coquille River is one of the most productive lamprey watersheds on the Oregon Coast, and Baker Creek has great potential for lamprey habitat—making this project a high priority. The goal of the project was to enhance natural hydrologic and biological processes in the Baker Creek watershed by restoring stream connectivity and volitional fish passage to 2 miles of vital rearing and spawning habitat and thermal refugia for Pacific Lamprey and other native anadromous species.

Providing Lamprey Passage

The perched culvert was not serving any purpose for transportation, as there is a bridge directly upstream; therefore, the best restoration action was to eliminate the culvert and allow Baker Creek to naturally flow under the existing bridge. The property owner, Weyerhaeuser Timber Co., fortified the road and bridge the year prior to the culvert removal to protect against potential flow and elevation/gradient changes in Baker Creek. In 2019, the culvert, over 40,000 yd^3 of overburdened fill, and the fish ladder were removed from Baker Creek. Before construction began, the Coquille Watershed Association, ODFW, and BLM employees conducted a fish salvage effort at the site that saved 232 fish—including two adult Pacific Lamprey (Figure 2). A 20-ft wide pilot channel with a 6% grade was constructed to restore natural hydrologic connection (Figure 2). As designed, the first winter of high flows cut the banks back to their original channel size, exposing historic stumps that had been buried under the fill. Natural recruitment of woody debris occurred after the first winter (Figure 3), and additional wood placements will be done the summer of 2020 to further promote instream complexity. The removal of the culvert and placement of log structures has allowed for natural gravel export processes to provide spawning habitat in gravels and rearing habitat in fine sediment.

Figure 2. Project implementation photos: Fish salvage before removal of the culvert (top). Exposed culvert and slope grading during removal of the culvert (bottom).

Figure 3. Pilot channel shortly after completion (top). Project site after first winter, showing natural recruitment of large wood. Constructed log jams will be placed in 2020 using the recruited wood in addition to larger pieces.

Post-Project Monitoring and Lessons Learned

After the first winter, the pilot channel naturally scoured enough to expose the original stumps that had been recruited prior to the culvert's installation in the 1950s. We are already seeing woody debris and natural gravel recruitment, but additional in-stream work (LWD structure installation), riparian planting, and monitoring of stream channel is slated to continue through 2020.

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Case Study #3: Retrofit of Perched Culvert with High Water Velocities Cedar Creek, South Fork Eel Watershed, California

Figure 1. Pre-retrofit photo: culvert rock slope protection apron is perched above the water surface, Denil fish ladder for adult salmonid migration.

Background

The Cedar Creek project is located 200 ft under U.S. Highway 101, approximately 2 miles south of Leggett in Mendocino County, California. This project was initiated to repair the invert of a 21-ft high by 22-ft wide 763-ft long, cast-in-place, reinforced concrete arch culvert and to rehabilitate fish passage. The culvert was the largest structure to be buried under a 200-ft deep fill when built in 1969. Cedar Creek is an important tributary to the South Fork Eel River, and an existing Denil fish ladder, culvert weirs, and plunge pool were considered to represent as a partial barrier to salmonid and Pacific Lamprey migration. Because of the large size and high habitat quality of the watershed upstream of the culvert (38 km^2) and the thermal refugia provided by this coldwater tributary, providing fish passage at this site was a high priority.

Hydraulic solutions employed to address salmonid migration barriers at perched culverts can pose passage problems for migrating adult Pacific Lamprey because there are no continuous attachment surfaces. Prior to the retrofit, the outlet was onto concreted rock slope protection (RSP) that was perched approximately 6 ft above the water surface. The existing concrete apron and the culvert were not a complete barrier to the migration of Pacific Lamprey, as larvae had been documented upstream. It is likely that lamprey as could attach to and climb the wetted surface of the smooth apron and the sides of the interior of the culvert at some stream flows. However, the need to improve salmonid passage necessitated the installation of a new fishway that also accommodates lamprey passage.

Providing Lamprey Passage

Geomorphic solutions, such as stream simulation designs, are the preferred approach for all fish passage problems. However, because this culvert is so large, long and deep in the fill prism, it was not feasible to remove the culvert and fill prism and to construct a large bridge. To resolve the barriers to salmonid migration a hydraulic solution and fishway were necessary to make up the elevation difference of approximately 6 ft at the outlet. Since a typical weirs and baffles have sharp edges that impair Pacific Lamprey passage, the designer developed and worked with resource agencies to obtain approval for a design solution that modified weirs on one side of the fishway and baffles within the culvert to facilitate Pacific Lamprey migration. Design elements for Pacific Lamprey included a 6-inch radius on the top of one side of the fishway weirs and on baffles within the culvert (Figures 2 and 3).

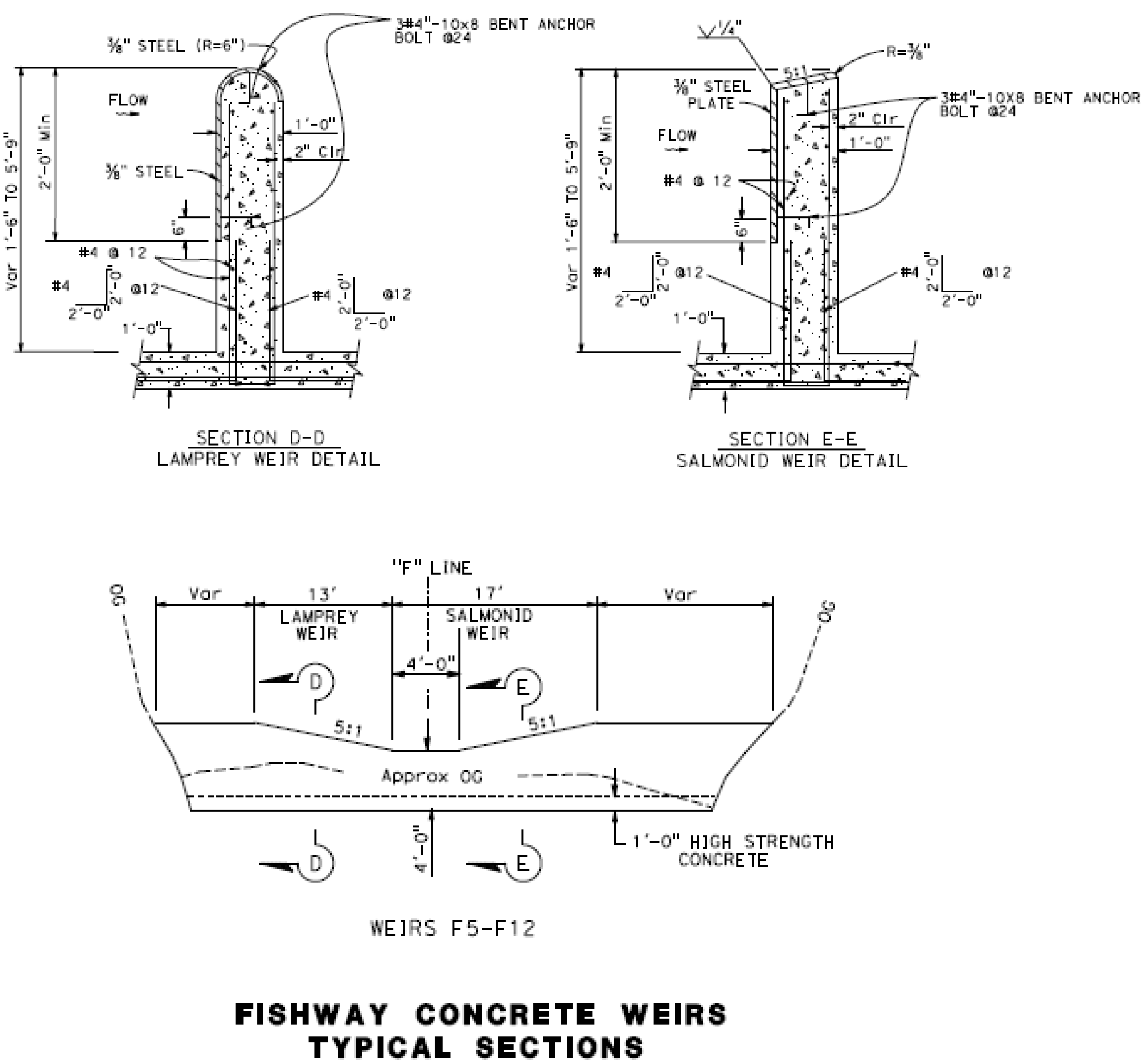

Figure 2. Design typical of profile and elevation of lamprey and salmonid fishway concrete weirs.

Figure 3. Post- project photo. Fishway with modified weir profiles installed downstream of the culvert. Rounded lamprey weir on left and squared salmonid weir on right.

Post-Project Monitoring and Lessons Learned

USFWS biologists are interested in future study of this location for lamprey migration benefit/effect. As a result of this project, an 8 mile stretch of previously restricted habitat upstream is improved for the migration of salmonids. Also, initial design criteria for salmonid passage was determined to be a potential barrier to another species and was addressed with creation of the "Lamprey" weir. This weir design will be used in future projects to address Pacific Lamprey passage and has brought much need attention to the species. There are plans to study the new weir design in a laboratory setting, to understand if it has benefits for salmonids as well. In the case that the lamprey weir design was not attractive to salmonid and resident fish species, a modified design that facilitates both salmonid and lamprey passage is recommended. CDFW is set to remove the remnants of a CDFW fish hatchery downstream which is a partial barrier to salmonids and possibly Pacific Lamprey.

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Case Study #4: Retrofit of Perched Culvert with High Water Velocities Canyon Creek, Umpqua Watershed, Oregon

Background

Perched culverts are a common passage problem for upstream migrating adult Pacific Lamprey because there are no continuous attachment surfaces and lampreys can't jump. Prior to the retrofit, the outlet of this culvert was perched approximately 2.5 ft above the water surface, preventing adult lampreys from entering the culvert (Figure 1). In addition, the site has a moderate slope, creating very high-water velocities that could obstruct upstream movement during some stream flows that occur during Pacific Lamprey migration.

Figure 1. Pre-retrofit photo: culvert is perched above the water surface and undersized.

Providing Lamprey Passage

To correct the issues for passage and geomorphology, use of stream simulation design would have been best. As a lower cost alternative to full replacement, this culvert was repaired and retrofitted with passage elements, saving over $1.2 million dollars. ODOT decided to mitigate the problems by backwatering the culvert. The design elements for Pacific Lamprey include:

- Boulder weir and roughened channel installed downstream of culvert to back-water outlet across a range of flows. (Figures 2 and 3).
- "Fish Blocks" installed throughout invert of culvert to provide localized velocity reduction and resting locations for migrating fish, including lampreys.

The blocks have a 90° corner on the downstream side, which would be better for lampreys if they were rounded. However, since lamprey may be using margins on side of culvert at waterline during upstream migration, square corners may not be an issue.

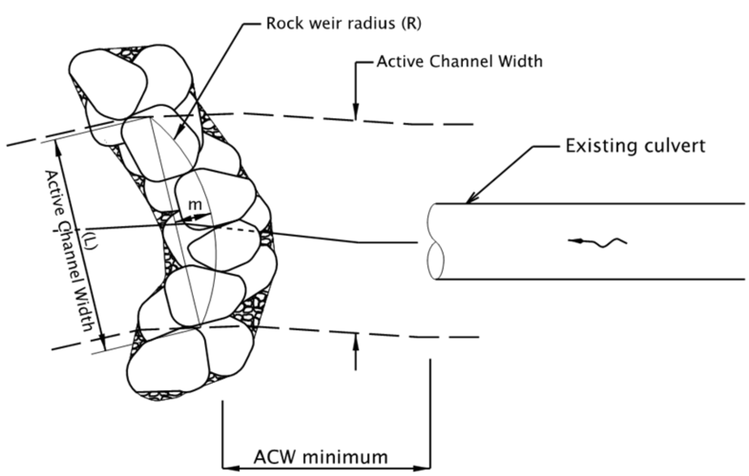

Figure 2. Design diagram of boulder weir and roughened channel to be installed below the perched culvert.

Figure 3. Post project photos. Fish blocks installed throughout the invert of the culvert to provide localized velocity reduction and resting areas for migrating fishes.

Figure 4. Post project photo: new boulder weir and roughened channel (designated by arrow) installed downstream of the culvert.

Post-Project Monitoring

Preliminary visual monitoring of the site has shown no significant settlement or degradation of passage elements. This project will be monitored 1, 3, and 5 years post-construction to ensure the passage elements continue to function as designed. This monitoring will be completed by visual observation by qualified biologists.

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Case Study #5: Retrofit of Perched Culvert with High Water Velocities Pass Creek, Umpqua Watershed, Oregon

Background

Perched culverts are a common passage problem for upstream migrating adult Pacific Lamprey because there are no continuous attachment surfaces and lampreys can't jump. Prior to the retrofit, the outlet of this culvert was perched approximately 1.0 ft above the water surface, preventing adult lampreys from entering the culvert (Figure 1). In addition, the culvert was undersized, creating very high-water velocities that prevented adult Pacific Lamprey from entering the culvert.

Figure 1. Pass Creek pre-retrofit, showing undersized culvert with perched outlet.

Providing Lamprey Passage

To correct the issues for passage and hydrogeology, use of stream simulation design would have been best. As a lower cost alternative to full replacement, this culvert was modified by ODOT with the following design elements to facilitate Pacific Lamprey passage:

- Boulder weir and roughened channel installed downstream of culvert to back-water outlet (Figure 2).
- "Fish rocks" installed throughout invert of culvert to provide localized velocity reduction and resting locations for migrating lamprey and other fishes (Figure 3).
- Smoothed concrete installed over existing CMP material providing for better attachment surfaces (Figure 3).

Post-Project Monitoring

Preliminary visual monitoring of the site has shown no significant settlement or degradation of passage elements. This project will be monitored at 1-, 3-, and 5-year intervals as part of the culvert repair agreement between ODOT and ODFW. Visual monitoring of the passage improvements will be conducted to ensure the goals of the project will continue to be met.

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Figure 2. Pass creek post retrofit, showing boulder weir and roughened channel installed downstream of culvert to back-water outlet, eliminating perched condition and allowing fish and lamprey to swim into the culvert without jumping.

Figure 3. Pass Creek, post retrofit, showing smoothed concrete and "fish rocks" installed throughout invert of culvert to provide localized velocity reduction (left). Another example of "fish rocks" is shown (right) from a separate project, as the Pass Creek fish rocks were somewhat undersized for expected velocities.

Case Study #6: Marley Creek Fish Passage Project Grande Ronde Watershed, Oregon

Background

The Marley Creek Culvert Repair and Fish Passage Project under Hwy 244 near Starkey, Oregon was completed in summer of 2019. The goals of the project included (1) alleviating a high priority barrier to upstream migrant native fish and (2) repairing a failing culvert. The culvert was repaired with a paved invert liner (Figure 1) and was not replaced due to the very high costs for replacement and other constraints associated with the project area. Prior to the project, the culvert was perched (Figure 2).

Figure 1. Culvert with rounded baffle design.

Providing Lamprey Passage

As part of the culvert repair, the invert of the culvert was paved with smoothed concrete, allowing for adult lamprey attachment. Rounded corner baffles were installed in the culvert to reduce velocities and provide more depth during low flow periods. A roughened riffle was installed downstream of the culvert outlet to alleviate a 2-ft perch, allowing swim in conditions for ESA-listed steelhead, redband trout, Pacific Lamprey, and other native fish species (Figure 2). The project reestablished access to over 5 miles of aquatic habitat in Marley creek.

Post-Project Monitoring

Preliminary visual monitoring of the sites has shown no significant settlement or degradation of passage elements. This project will be monitored at 1-, 3-, and 5-year intervals as part of the culvert repair agreement between ODOT and ODFW. Visual monitoring of the passage improvements will be conducted to ensure the goals of the project will continue to be met.

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Figure 2. Marley Creek Culvert Outlet pre-project (top), with large perch creating barrier to upstream migrating fish and lamprey. After the project was completed, backwater conditions allow upstream fish migrations and rounded baffles were installed inside the culvert to add depth and reduce velocities.

Case Study #7: Retrofit of Baffled, Perched Culvert under Highway 101 Eel Creek, Ten Mile Lakes Watershed, Oregon

Background

Oregon Department of Transportation previously modified an existing culvert under Highway 101 in Lakeside for salmonid passage by the adding of baffles inside the culvert (north side of culvert), and constructing a jump pool below the culvert to allow salmon a resting area and acceleration room to jump over the first baffle and into the culvert. However, Pacific Lamprey had difficulty negotiating the 90° corners of the baffles, and during low flow, the culvert was effectively perched (Figure 1). These conditions created a partial passage barrier for Pacific Lamprey.

Figure 1. Pre-project photo showing how the baffle created a perched condition/waterfall on the right side of culvert.

Providing Lamprey Passage

To eliminate the perched condition of the culvert outlet during low flows and allow fish to swim into the culvert without jumping, the hydraulic control point downstream of the jump pool was raised, thus deepening the pool above the outfall of the culvert (Figure 2). The roughened chute (streambed downstream of the jump pool) was also enhanced to stabilize the pool's downstream margins and create an appropriate transition to the original streambed (Figure 2). To improve passage for lamprey inside the culvert, the baffles were modified in 2017. The middle portion of each baffle was cut down and replaced with a small ramp that sloped up on both sides (Figures 3). During the de-watering process, fish salvage operations collected 217 adult Pacific Lamprey. These fish were relocated downstream and temporary barriers were erected to prevent upstream travel back into the construction area.

Figure 2. Post- project photos showing the modified baffle at culvert outlet and increased elevation of the outlet pool providing continuous passage into the culvert without requiring a jump (left) and the roughened channel downstream of the culvert (right).

Figure 3. Photos of the modified baffle and ramp in dry and watered conditions. Middle portion of the baffle was cut down and a ramp was installed on each side of that cut to provide lamprey with a continuous attachment surface.

Post-Project Monitoring

Post-implementation monitoring by visual inspection was conducted periodically during 2018 and 2019, during both high and low flow conditions. The last observations were made June 2019. The modified interior baffles and ramps in the culvert remain intact and functioning. The culvert, jump pool, and roughened chute all remained intact, except for some minor erosion. The increased surface water elevation of the jump pool during the summer low-water season continues to provide year-round passage for lamprey into the culvert.

As part of a separate monitoring effort using radio tags, 10 adult Pacific Lamprey were documented passing the culvert during the 2018-2019 observation period, confirming year-round passage availability. Electrofishing efforts from May 2018 through May 2019 successfully captured 103 adult Pacific Lamprey in the roughened chute area below the culvert, showing lamprey still use this habitat for holdover behavior. This is considerably less than the 200+ lamprey captured in one day by de-watering during the culvert construction. This may indicate that electro-shocking is less effective at capturing lamprey than de-watering, or that the changes made to the roughened chute during construction may have made the area less suitable as lamprey holdover habitat, or fewer lampreys hold below the culvert because passage conditions are improved. In a dunal system, large boulders and rip-rap brought in for construction may provide safe holdover habitats for adult lamprey. Future work may consider more boulders and spawning gravel placement in the area to enhance these habitats already in use.

Overall, the project was very successful and has met the goals of improving both salmon and lamprey passage. The culvert enhancements, jump pool, and roughened chute have all held up well to the high winter flows of both 2018 and 2019, and provide passage during the summer low-flow periods.

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Appendix D

Glossary of Terms

Unless otherwise referenced, the definitions provided herein were taken directly or modified from one or more of the following sources: Harrelson et al. (1994), Taylor and Love (2003), USDA Forest Service Stream Simulation Working Group (2008), or WDFW (2019).

Active channel: The active channel is defined by the elevation of the highest water level that has been maintained for a sufficient period of time to leave evidence on the channel banks, such as the point where the natural vegetation changes from predominantly aquatic to predominantly terrestrial or the bank elevation at which the cleanly scoured substrate of the stream ends and terrestrial vegetation begins.

Adult lamprey: "Life stage in which lamprey are in various states of sexual maturation (including immature through spawning). Unlike juveniles, sexually immature adults are no longer feeding and are actively migrating upstream to spawning grounds…." (Clemens 2019).

Aggradational wedge: stream bed substrate that often accumulates upstream of the inlet of undersized road crossings and raises the channel bed elevation.

Anadromous: Particular life history strategy whereby juveniles rear and feed in the ocean to adult sizes, and then migrate back into freshwater to reproduce. Their offspring reside in freshwater for variable amounts of time before migrating downstream and into the ocean.

Apron: A structure constructed at either the inlet or outlet of a road crossing to protect the structure from erosion and storm damage. Aprons are usually a pad or slab of non-erosive material such as concrete.

Baffle: Pieces of wood, concrete, or metal that are mounted in a series on the floor and/or wall of a culvert or flume to increase hydraulic roughness and thereby reduce average cross-sectional water velocity and increase depth in the culvert.

Bankfull width: The wetted width of a stream channel at bankfull stage. Bankfull stage corresponds to the discharge at which the stream is moving sediment, forming or removing bars, forming or changing bends and meanders, and creating the average morphologic characteristics the of channel. Bankfull discharge generally occurs when water just begins to overflow into the active floodplain.

Burst-and-attach swimming: A mode of swimming adult lampreys use when confronted with high water velocity of turbulence, where they use their oral discs to briefly attach to substrate before continuing upstream in a short burst of swimming before reattaching and repeating the process (Daigle et al. 2005; Keefer et al. 2011; Kirk et al. 2016).

Corrugation: The undulations present in corrugated steel pipe and structural steel plate culverts. Corrugations provide surface roughness which increases with increasing width and depth of corrugation dimensions.

Cross-section survey: A survey to characterize elevations of the channel bed and banks across the channel from one bank to the other. A tailwater control cross-section survey is used in hydraulic analysis to characterize the hydraulic control point in the channel downstream of a crossing that controls the water surface elevation at the culvert outlet.

Culvert: A specific type of stream crossing, used generally to convey water flow through the road prism base. Typically constructed of either steel, aluminum, plastic, or concrete. Shapes include circular, oval, squashed-pipe (flat floor), bottomless-arch, square, or rectangular.

Exceedance flow: A stream flow that is exceed for a specified percentage of time at a given site during a specified period (e.g., annually or during the migration period for the study species). Usually calculated from a multiyear record of flows from a gauging station. In the fish passage context, the 95% and 5% exceedance flows during the migration period are often used to define the low and high migration flows, respectively.

Fishway: Fishways, commonly called *fish ladders* or *fish passes*, are structures built to facilitate passage of fish through, over, or around an instream barrier. Fishways are often designed for a particular fish species of interest and may not promote passage of all fish species; e.g. salmon fishways are not always designed to promote passage of Pacific Lamprey.

Gradient: The slope of a stream-channel bed or water surface. The elevation rise divided by distance, expressed as a percentage.

Inlet: Upstream entrance to a culvert or other road crossing.

Invert: Lowest elevation point on the bottom of a culvert.

Juvenile lamprey: "Life stage existing only in parasitic lampreys. Resident lampreys that do not feed during their adult stage [after transformation] (i.e., brook lampreys) do not exhibit a juvenile life stage…This is the preferred term for parasitic lampreys that have transformed from larvae into eyed, small versions of the adults…. That is, in addition to eyes, this life stage bears sharp teeth and an oral sucker. Juveniles are sexually immature…." (Clemens 2019).

Lamprey attachment points: substrate surfaces where lampreys can attach and rest or use burst-and-attach swimming.

Larval lamprey (also known as ammocoete): "Eyeless, filter-feeding life stage that usually resides in the substrate (soft silt and sand substrates with organic material is usually preferred)" (Clemens 2019).

Longitudinal profile survey: a survey to characterize elevation and slope of the channel and road crossing along thalweg (deepest point of each cross section).

Migration flows: the range of stream flows at which migrating fish are expected to be moving upstream at a site (also known as passage flows). For Pacific Lamprey it was conservatively assumed to range between the 95% and 5% flow exceedance probability.

Open-bottom arch culvert: A type of culvert with rounded sides and top attached to concrete or steel footings set below stream grade. The natural stream channel and substrate run through the length of the culvert, providing streambed conditions similar to the actual stream channel.

Outlet: Downstream entrance to a culvert or other road crossing.

Perched outlet: A condition in which a culvert outlet is suspended over the downstream water surface, requiring a migrating fish to leap to enter the culvert (see Perched Culvert definition).

Perched culvert: A culvert where the outlet is elevated above the downstream water surface, creating a water surface drop. Perched culverts are often the result of high velocity flow eroding the channel downstream of a culvert.

Resident fish: Life history strategy whereby a species spends its entire life in freshwater.

Riprap: Large, durable materials (usually fractured rocks or broken concrete) used to protect sloped surfaces from erosion. Commonly used to prevent erosion of streambanks or lake shores

Rise: The maximum, vertical, open dimension of a culvert; equal to the diameter in a round culvert and the height in a rectangular culvert.

Road fill: Soil material that is used to fill road embankments around and above a culvert.

Roughness: Channel characteristic that causes a drag on flow, limiting velocity and increasing diversity of velocities and flow patterns. Roughness elements include grains, bedforms, woody debris, manmade structures, and bank irregularities.

Span: The horizontal dimension of the culvert, i.e., the width of the culvert spanning the channel, or the diameter in a round culvert.

Stream crossing: Any human-made structure generally used for transportation that crosses over or through a stream channel including a paved road, unpaved road, railroad track, biking or hiking trail, golf-cart path, or low-water ford. A stream crossing includes both the structure that passes stream flow and the associated fill material within the crossing prism.

Stream Simulation Design: An approach for designing road crossing (usually culverts), with the aim of creating a channel within the crossing that functions like the natural channel (e.g. USDA Forest Service Stream Simulation Working Group 2008).

Tailwater control: the hydraulic control point in the channel downstream of a crossing that controls the water surface elevation at the culvert outlet. The location controlling the tailwater elevation is often located at the riffle crest immediately below the outlet pool. Tailwater control is also the channel elevation that determines residual pool depth.

Ucrit **(critical swimming speed):** measured as the maximum velocity that can be maintained by a fish for a specific period of time (typically 30 minutes) before exhaustion. U_{crit} is a category of prolonged swimming calculated from tests where water velocity is progressively increased (Brett 1964; Jobling 1995; Mesa et al. 2003). Energy for critical swimming is provided primarily by aerobic metabolism (Jobling 1995).

Umax **(burst swimming speed):** the highest speed fish are capable of attaining, usually only for very short periods of time (<20 seconds). Energy for burst swimming is provided predominately by anaerobic metabolism. This mode of swimming is inefficient compared with lower speeds and is used principally for predator avoidance or navigating high-velocity areas.

Weir: A low dam across a stream channel that causes water to back up behind it, with flow plunging over it. Weirs are often notched to concentrate low-flow water conditions.

Wingwall: Concrete walls angling from either side of a culvert inlet, designed to provide structural stability, act as retaining walls for fill slopes, or funnel flow into the culvert opening.