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Stream restoration: a key to the survival and recovery of the Endangered Western Brook Lamprey (*Lampetra richardsoni*), Morrison Creek population

Joy Wade[1], Warren Fleenor[2], and Paul Grant[3,*]

[1]Pacific Biological Station, Fisheries and Oceans Canada, 3190 Hammond Bay Road, Nanaimo, British Columbia V9T 6N7 Canada

[2]Current Environmental, 558 England Avenue, Courtenay, British Columbia V9N 2N3 Canada

[3]Institute of Ocean Sciences, Fisheries and Oceans Canada, 9860 West Saanich Road, Sidney, British Columbia V8L 5T5 Canada

[*]Corresponding author: paul.grant@dfo-mpo.gc.ca

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Abstract

Aquatic ecosystems and species are increasingly threatened by anthropogenic activities. Stream restoration has therefore become a necessary conservation strategy to improve habitat quality and quantity, which are key components of productive, healthy, resilient aquatic ecosystems. The Morrison Creek watershed on Vancouver Island, British Columbia has been impacted by anthropogenic activities resulting in the degradation of aquatic habitat. For an Endangered, range-restricted species like Western Brook Lamprey (*Lampetra richardsoni*), Morrison Creek population, which only occurs in this one watershed, any habitat-related impacts have the potential to cause population level declines, thereby increasing the risk of extinction. Stream and riparian restoration were therefore undertaken to ameliorate the species' Critical Habitat, which no longer supported spawning and early rearing. Effectiveness of restoration was determined through the use of restored areas for spawning, increased hydraulic complexity, and reduced sedimentation. Lamprey (adults and larvae) and salmonids (*Oncorhynchus* spp.) had not been observed in this habitat since 2005; however, following habitat restoration in 2021, 10 different lamprey nests were observed being tended in the restored habitat in 2022. Salmonids were also observed using the newly created habitat for spawning in fall 2021 and fry and smolts used pools and riffles for rearing the following spring and summer. Our work demonstrates specific types of habitat restoration that are effective for lamprey conservation and validates that complex restoration activity can occur when there is effective collaboration.

Key words: Lamprey; conservation; restoration; Endangered species; Western Brook Lamprey; Morrison Creek Lamprey

Introduction

Stream restoration has become a necessary conservation strategy to help mitigate the significant declines in salmonids and other aquatic species attributed to declining habitat quality and quantity (Gessner *et al.* 2004; Opperman and Merenlender 2004; Rumps *et al.* 2007; O'Neal *et al.* 2016; Anderson *et al.* 2019). Although the direct or proximate causes of decline vary by species and geographic areas, it is often a result of the cumulative impacts of multiple stressors (Moyle and Leidy 1992). Species that have specialized life histories and/or are endemic with small distributions also tend to be among those most at risk of extinction (Moyle and Leidy 1992; Purvis *et al.* 2000).

The increasing knowledge of direct and indirect impacts to aquatic species has resulted in a greater understanding of the need to protect aquatic biodiversity and has resulted in large amounts of funding spent to improve freshwater habitat (Opperman and Merenlender 2004; Bennett *et al.* 2016; O'Neal *et al.* 2016; Roni *et al.* 2018; Anderson *et al.* 2019). While there is information available on restoration techniques to improve productivity (Roni *et al.* 2018), there is often a lack of monitoring to evaluate the effectiveness of restoration projects and the benefit to aquatic species is often uncertain (Bennett *et al.* 2016; Roni *et al.* 2018; Anderson *et al.* 2019). Typically, examples of responses to restoration actions are limited to reach-scale studies because of associated challenges to evaluate effectiveness at the watershed scale (Liermann and Roni 2008; Anderson *et al.* 2019). However, the need for monitoring is recognized and well documented (O'Neal *et al.* 2016) and reach-scale results can inform population-level effects of restoration, especially for species with small distributions.

The opportunity to monitor and evaluate the effectiveness of restoration activities existed within Arden Creek (49.6832°N, 125.0168°W) on Vancouver Island, British Columbia. Arden Creek (3 km long) is part of the Morrison Creek watershed, which also includes Morrison Creek (24 km) and spring-fed headwaters (543 ha). The watershed in its entirety supports a diverse range of aquatic species from Pacific Lamprey (*Entosphenus tridentatus*), Coho (*Oncorhynchus kisutch*), Pink (*Oncorhynchus gorbuscha*) and Chum (*Oncorhynchus keta*) Salmon, Threespine Stickleback (*Gasterosteus aculeatus*), and several trout species (*Oncorhynchus* spp.; Wade *et al.* 2015). It also contains the entire population of a unique and at-risk freshwater lamprey species, the Western Brook Lamprey (*Lampetra richardsoni*), Morrison Creek population also known as the Morrison Creek Lamprey.

In 2003, the Morrison Creek Lamprey was listed under Canada's *Species at Risk Act* (SARA Public Registry 2023) as Endangered because of its small distribution and ongoing declines in habitat quality in Arden Creek and the larger Morrison Creek watershed. This endemic freshwater population is unique in its reproductive and life history traits. Adults create nests or depressions in sand or gravel substrates to spawn in the spring (~April–June). Eggs hatch within 12–30 days, and larvae remain buried in the streambed, filter-feeding. Lamprey larvae generally rear for up to seven years before undergoing metamorphosis into adults (Dawson *et al.* 2015). Morrison Creek Lamprey undergoes metamorphosis in late summer or early fall (COSEWIC 2010). This population is unique in that after metamorphosis, adults emerge as either parasitic or non-parasitic forms, each with distinct ecological roles and physical traits. Non-parasitic adults, smaller and darker than their parasitic counterparts, cease feeding after metamorphosis, relying on energy reserves from their larval stage. They mature quickly after metamorphosis, spawn and subsequently die in the spring following their transformation. In contrast, parasitic adults delay spawning for a year, develop prominent teeth and a silvery colouration, and actively feed on salmonids during this period (COSEWIC 2010). This enables parasitic adults to grow larger and accumulate energy reserves which may potentially increase reproductive success the following spring. Like their non-parasitic form, they die after spawning, completing their life cycle. The presence of both parasitic and non-parasitic forms within a single population is highly unusual, and these forms are indistinguishable until after metamorphosis (COSEWIC 2010).

For most aquatic species, maintaining habitat quality is important for survival, but this is particularly true for range-restricted Endangered species whose ecology is poorly understood (Beamish 2013). Canada's *Species at Risk Act* (SARA) recognizes the importance of habitat that is necessary for the survival and recovery of species and provides legal protection for identified Critical Habitat. For the Morrison Creek Lamprey population, Critical Habitat has been identified and includes Arden Creek, underscoring the importance of safeguarding this unique habitat to ensure the population's persistence.

The habitat requirements for this population include sand and gravel substrate, pools, riffles, and hydraulic complexity for nest building, spawning, egg incubation, and rearing, in addition to adequate food supply (COSEWIC 2010; Wade and Grant 2022). Adults excavate a small depression (10–12 cm wide, 5 cm deep) used as a nest for spawning and egg incubation from April to June (COSEWIC 2010; Wade and Grant 2022). Spawning habitat includes areas with small riffles (i.e., turbulent water flowing over shallow substrates across short distances with either complete or partial channel coverage, which enhances dissolved oxygen levels in the system) in proximity and a mix of sand and gravel for nest building (1–100 mm diameter; Stone 2006; Gunckel *et al.* 2009) with low flow (0–0.7 m/s; Pletcher 1963; Stone 2006; Gunckel *et al.* 2009).

The habitat that supports larval lampreys is generally similar across species (Dawson *et al.* 2015). Larval-rearing habitats are typically characterized by reaches with hydraulic complexity, including cool, oxygenated, but slower flowing water, which facilitates the accumulation of sediments suitable for burrowing (Farlinger and Beamish 1984; Stone and Barndt 2005; Smith *et al.* 2011; Ferreira *et al.* 2013; Gonzalez *et al.* 2017). Larvae also tend to prefer stream margins (Farlinger and Beamish 1984; Stone and Barndt 2005). Although dense canopy has been shown to have a negative effect on larval habitat suitability (Stone and Barndt 2005), riparian vegetation can help maintain larval habitat by stabilizing stream banks and regulating water temperatures through the shade it provides (Macey and Potter 1978; Arakawa and Yanai 2021). Furthermore, the leaves and detritus from riparian vegetation contribute organic material that serves as a substrate and nutrient source for periphyton and microbes, which form a vital part of the food web supporting larval lamprey development (Evans and Weber 2019).

Arden Creek has experienced substantial degradation over time because of growing urbanization pressures. Key impacts include the removal of riparian vegetation, which has destabilized stream banks, a reduction in channel complexity that has diminished habitat diversity, and increased sediment loadings that have smothered aquatic substrates. Together, these changes have severely disrupted the creek's ecological integrity, threatening its ability to support healthy aquatic ecosystems (COSEWIC 2010). Although several small-scale bank stabilization and fish passage projects have been undertaken, the cumulative impacts of land use changes became increasingly evident after 2005, when lamprey and salmonids stopped spawning in Arden Creek. In 2019, these impacts were further exacerbated by the development of a disc golf course, which increased sediment inputs. This sedimentation led to a low-gradient stream profile with negligible water flow, creating stagnant, muddy areas with poor water quality and likely reduced dissolved oxygen levels, further degrading the habitat's suitability for aquatic species. A multi-stakeholder initiative was therefore developed to restore the legally protected Critical Habitat for Morrison Creek Lamprey.

While management strategies have been developed to identify conservation needs of lamprey, and lamprey have benefited from broader habitat restoration projects (Clemens *et al.* 2021), this is one of the few projects where restoration activity has specifically targetted lamprey, while indirectly benefiting co-occurring salmonids and other aquatic species. Herein, we give details on the restoration methods used and then present monitoring results to evaluate the effectiveness of our efforts on Morrison Creek Lamprey. These data provide valuable insights that could help prioritize other lamprey-specific benefits in future restoration projects, ensuring that the unique needs of lamprey are more effectively addressed in planning and implementation.

Methods

Restoration planning and activities

In-stream restoration plans were designed to match the physical and hydraulic characteristics of the stream with the needs of fish populations and ecological health, with a particular focus on Morrison Creek Lamprey and salmonids. Based on the best available knowledge, this included creating habitat suitable for lamprey spawning as well as suitable rearing habitat for ammocoetes (larval lamprey).

The treatment reach of Arden Creek circumnavigated two large school fields. These reaches were excavated in 1964 to reduce surface flow elevations of the fields resulting in straight, low gradient (<1%) channels, with highly incised banks. The channel was over-widened that resulted in slow flow velocities and low hydraulic complexity. The combination of sedimentation, reduced flow variability, and diminished hydraulic complexity rendered Arden Creek unsuitable for any life stage of lamprey or salmonid. Thus, it was necessary to recreate hydraulic conditions throughout the habitat that would support: 1) increased localized flow and overall hydraulic complexity, 2) decreased sedimentation, 3) bank stabilization, 4) the creation of refuges, and 5) increased spawning and early rearing habitat. In upstream and downstream areas, in-stream restoration involved the installation of features such as wing deflectors and woody debris structures to constrict and increase local flow and promote scouring. Small rocks, pea gravel, and sand were added in key areas to provide spawning habitat for lamprey and salmonids.

In-field surveying of Arden Creek occurred in 2021 based on standard restoration methods as described in Newbury and Gaboury (1993) and Slaney and Zaldokas (1997). Measurements, including stream profile elevations, water depth, and high-water conditions and were recorded approximately every 20–30 m, depending on the terrain. For each site, substrate type was recorded as silt (0–0.06 mm), sand (0.06–2.0 mm), gravel (2–64 mm), cobble (65–100 mm), or small rock (101–200 mm) based on categories modified from Wolman (1954). Terrestrial areas which could benefit from an increase in riparian diversity and density were also identified. This information was used in conjunction with Geographic Information Systems-based technologies to create a stream profile including a cross-section to inform engineering plans. Specific restoration sites were identified over an ~800 m length of Arden Creek and incorporated both in-stream and riparian restoration.

The engineering plans included the installation of two rock riffles, 74 boulder clusters, 77 pieces of large woody debris structures, and 28 wing deflectors (i.e., triangular projections placed in shallow over-widened stream channels to promote localized scour and hydraulic complexity). The structures were constructed on a triangular framework or base of boulders sequentially top-dressed with cobbles, then with a select bank pit run mixed with 10% pea gravel. The placement of cobbles followed by the gravel mix was intended to help seal the structures and promote local scour. Deflectors were oriented to promote a meandering channel path and constructed with the apex of the triangle to pinch the creek to an approximate width of 0.75–1.5 m from an existing bankfull width of 4.1 m. During construction, large accumulations of small woody debris, largely resulting from the Red Alder (*Alnus rubra* Bongard)-dominated riparian vegetation community, were removed from the channel by volunteers. This improved hydraulic conveyance of the treatment reach. Because very little substrate suitable for lamprey spawning and early rearing was found, the installation of pea gravel in and around these features was key to increasing habitat availability.

In all, 156 tonnes of 300–600 mm boulder, 104 tonnes of "overs" (mix of gravel and cobble substrate ranging from 100 to 260 mm diameter), 143 tonnes of select bank pit run gravel (2–64 mm), and 14 tonnes of fine gravel and pea gravel (1–15 mm diameter) were used in restoration activities. Pit run is unsorted, naturally occurring gravel deposit and was selected from exposed banks that have reduced fines as a result of being washed by rain. Pit run used for this project was relatively low in fines with a higher component of coarse sand.

Riparian restoration included three main activities: 1) planting of native trees and shrubs, 2) relocating portions of the trail system, and 3) delineating sensitive riparian habitat with fencing. To enhance the Critical Habitat of lamprey within restoration sites identified along the 800 m of Arden Creek, more than 1900 native plants (>25 different species) were planted with the assistance of students and volunteers. Both coniferous and deciduous plants were planted, including for example, Grand Fir (*Abies grandis* (Douglas ex D. Don) Lindley), Sitka Spruce (*Picea sitchensis* (Bongard) Carrière), Salmonberry (*Rubus spectabilis* Pursh), Thimbleberry (*Rubus parviflorus* Nuttall non. cons.), Western Sword Fern (*Polystichum munitum* (Kaulfuss) C. Presl), and Devil's Club (*Oplopanax horridus* (Smith) Miquel). This work occurred in the autumn of 2021 when rain was imminent to maximize the potential for survival of planted stock.

A 125 m section of trail running alongside Arden Creek was decommissioned and relocated to reduce its environmental impact. The decommissioned trail, identified as a significant source of sediment during rainy months, had caused damage to riparian vegetation and sediment release due to uncontrolled public access to the creek. The old trail was replaced with woody debris and native plants to stabilize the area and restore riparian habitat. A new trail, located ~3–5 m away from the creek to protect sensitive habitats, was constructed with compacted pit run to provide a durable and stable surface for recreational use. Furthermore, invasive plants such as Scotch Broom (*Cytisus scoparius* (L.) Link), English Holly (*Ilex aquifolium* L.), Himalayan Blackberry (*Rubus bifrons* Vest) were removed, and dead trees available on-site were used to flank the trail to provide a visual cue to discourage the creation of additional paths within the riparian area.

To encourage people to stay away from the creek and on trails, split rail cedar fencing was installed in the elementary school yard adjacent to Arden Creek as well as in the heavily used disc golf area. Native plants were planted between the creek and the fence. In total, 4300 m^2 of riparian habitat along Arden Creek was restored, 470 m of split-rail cedar exclusion fencing was installed, and more than 650 m of pedestrian trails were created.

Aquatic restoration took place between mid-July and mid-August 2021; riparian planting and fence building occurred in October and November 2021.

Pre- and post-restoration lamprey surveys

Pre-restoration surveys for adult Morrison Creek Lamprey have been conducted regularly by the Morrison Creek Streamkeepers and other stakeholders to monitor population presence and habitat use. In early July 2021, prior to in-stream construction, targetted surveys were carried out using a combination of visual observations, standardized kick sampling, and sampling and filtering of sediment with aquatic nets. Visual surveys focussed on potential presence of adults, while kick sampling and net collection were used to locate larval lamprey within fine sediment deposits.

Given that lamprey were not spawning in Arden Creek prior to restoration or used this creek for rearing, we wanted to determine if restoration activities resulted in a successful response for the target species. Post-restoration surveys of Arden Creek occurred between the end of May and beginning of July 2022 to identify active lamprey nesting during the known spawning window for Morrison Creek Lamprey (Wade and Grant 2022); this spawning window is similar to that reported for Western Brook Lamprey in other locations and depends on temperature (Stone 2006; Gunckel *et al.* 2009). Surveys were conducted by walking along the creek from the first restored feature to the last, downstream to upstream. Surveys took place between early morning and mid-afternoon. If lamprey were actively tending nests or engaging in spawning activity, the geolocation and number of lamprey were recorded.

Environmental data and nest dimensions were taken only if lamprey moved away from the nesting area to minimize any interruption of nesting activities. Temperature, pH, electrical conductivity (EC; µS/cm), and total dissolved solids (TDS; ppm) were measured using a handheld Hanna Combo meter (H1989129, Hanna Instruments, Woonsocket, Rhode Island, USA); dissolved oxygen (DO) was measured using an OxyGuard Handy Gamma meter (OxyGuard International, Farum, Denmark). These handheld instruments were used immediately downstream of active nests. Nest dimensions and depth were measured using a ruler. In addition, two HOBO TidbiT v2 (Onset Computer Corporation, Bourne, Massachusetts, USA) water temperature loggers were placed in separate locations in the creek to collect hourly temperature data during the spawning season (~April–June).

Results

In-stream restoration features were successful in increasing localized scour, improving hydraulic complexity, and improving refuge for fish (Figure 1) based on observations of localized increases in water movement and fish behaviour. Areas that previously had been stagnant settling areas for sediment deposition now had flowing water, which helped maintain alluvial substrate complexity with a well-graded mix of gravel and small stones. The constructed deflectors and large woody debris structures effectively increased local flow velocities (not quantitatively measured) and created scour points that mobilized deep (15–70 cm deep) accumulations of fine sediments in the over-widened channel. In the spring and throughout the summer, salmon fry were observed using riffles and taking refuge downstream of large woody debris features.

Pre-restoration surveys did not detect adult lamprey use since 2005 (DFO [Fisheries and Oceans Canada] unpubl. data), and no adult or larval lamprey were detected at any of the identified restoration sites during pre-restoration targetted surveys. Post-restoration, between 23 May and 5 July 2022, surveys were conducted 18 times along the restored area of Arden Creek (Table 1). A total of 10 unique lamprey nests were seen being tended by Morrison Creek Lamprey, and many nests were used more than once. No nesting or spawning activity was observed on the first (23 May) or last three days (27 and 28 June, and 5 July) of the observation period. The maximum number of active nests in any survey was four and the number of lamprey for each survey ranged from 0 to 17. Nest 2 was the most consistently active nest over the survey period with 23 lamprey seen actively tending the nest or spawning from 24 May to 22 June (Table 1).

Length and width of eight of the 10 nests were measured to calculate nest area. Nest 2, measured five times between 24 May and 22 June, increased in area from 504 cm^2 to 4125 cm^2, with little change in nest depth (8–9 cm). Overall, the depth of water in which active nests were observed varied from 6 to 26 cm and the nest area varied from 100 to 4125 cm^2. Lamprey were observed singly or in multiples using their oral disc to move stones from the nesting area and fanning the substrate with their bodies. On several occasions, females were seen anchored to rocks using their oral disc while a male attached to the head of the female and coiled around the female as part of their spawning behaviour. It was possible to distinguish the sexes based on the secondary sexual characteristics of lamprey as summarized in Kott *et al.* (1988). These mating occurrences would be interrupted by bouts of nest construction before recommencing. This behaviour is typical of that described for Western Brook Lamprey as well as other lamprey species (Stone 2006; Wade and Grant 2022).

Water quality ranges measured immediately downstream of the 10 active lamprey nests were: pH 6.40–7.95 (n = 13), EC 197–326 µS/cm (n = 13), TDS 98–151 ppm (n = 11), DO 9.00–9.96 mg/L (n = 7), and water temperature 11.1–14.7°C. Water temperature was also recorded on the two data loggers from 29 May to 6 July. The average temperature over the

FIGURE 1. Arden Creek stream restoration for the Western Brook Lamprey (*Lampetra richardsoni*), Morrison Creek population at the most downstream riffle near the confluence with Morrison Creek. a. pre-restoration, b. immediately after riffle installation, and c. one year post-restoration. Photos: Joy Wade and Paul Grant.

TABLE 1. Surveys of Western Brook Lamprey (*Lampetra richardsoni*), Morrison Creek population nesting in restored areas of Arden Creek, 2022. 1–10 refers to nest number.

Survey date	Number of lamprey in each unique nest										Total number of lamprey
	1	2	3	4	5	6	7	8	9	10	
23 May											0
24 May	2	3									5
27 May		1									1
28 May	3		1								4
30 May		2		1							3
1 June				3	1						4
3 June											0
8 June			5			2	9		1		17
8 June		1		1			3				5
9 June		2									2
10 June							1				1
11 June		3									3
16 June		4						4			8
20 June		4								6	10
22 June		3									3
27 June											0
28 June											0
5 July											0
Total	5	23	6	5	1	2	13	4	1	6	

entire time period was 13.4°C (range 9.8–17.5°C; Figure 2). Over the period in which lamprey were seen building nests and spawning and loggers were in place (29 May–2 June), the average temperature was 12.5°C (range 9.8–15.1°C). No lamprey were seen on nests after 22 June (Figure 2). The average water temperature for the remainder of the logger deployment (23 June to 6 July) was 14.8°C (range 11.1–17.7°C).

Discussion

Freshwater ecosystems are increasingly threatened by anthropogenic activities and are considered the most imperilled on Earth (Strayer and Dudgeon 2010; Lapointe *et al.* 2014). Species that depend on these systems are also experiencing some of the highest extinction rates across ecosystem types and are in need of immediate protection (Opperman and Merenlender 2004; Lapointe *et al.* 2014; Barnas *et al.* 2015). Species with specialized life histories, or those that are endemic with small distributions, tend to be at the greatest extinction risk (Moyle and Leidy 1992). While causes of decline vary and are often a result of cumulative effects, decline in habitat quality is widely recognized as one of the key proximate causes of decline among aquatic species (Moyle and Leidy 1992; Lapointe *et al.* 2014; Barnas *et al.* 2015).

Stream restoration has therefore become a necessary conservation strategy to help mitigate the significant declines in aquatic species (Opperman and Merenlender 2004; O'Neal *et al.* 2016; Anderson *et al.* 2019). The challenges are how to prioritize areas for restoration in the context of: 1) limited capacity and funding; 2) sufficient understanding of the species' biology, ecology, and habitat requirements across life stages; and 3) evaluating activities to ensure conservation goals are being met.

Restoration projects often prioritize species that have economic, social, or more obvious and quantifiable ecological value, such as salmonids (Bash and Ryan 2002; Barnas *et al.* 2015; Anderson *et al.* 2019) and tend to overlook other aquatic species such as lamprey, where public perception can pose a barrier to their conservation despite their significant ecological importance (Clemens *et al.* 2021; Clemens and Wang 2021). While management strategies have been developed specifically for lamprey to improve access to spawning and larval rearing (Clemens *et al.* 2021) and lamprey have benefited from other habitat restoration projects (Clemens *et al.* 2021), ours is one of the few projects where restoration activity has specifically targetted lamprey.

Somewhat uniquely for lamprey, the prioritization of Arden Creek for restoration was driven by public interest in conserving this population. Even with

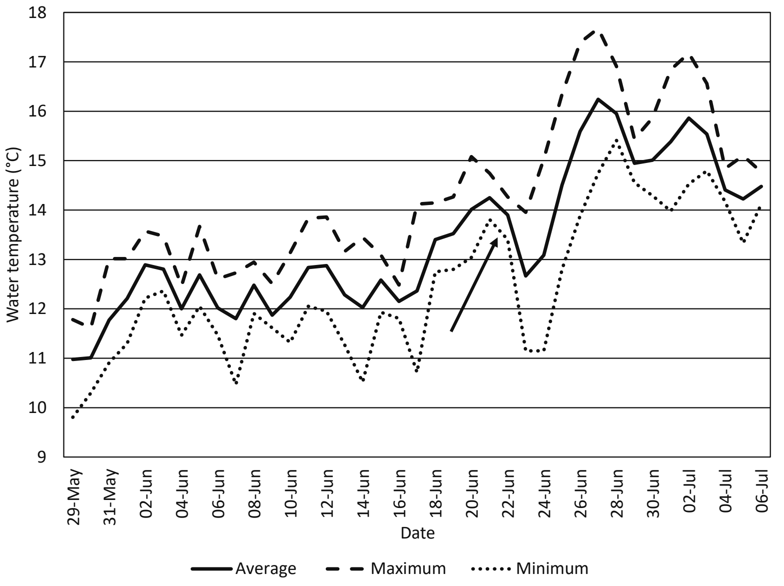

FIGURE 2. Daily water temperatures (average, maximum, and minimum values) from two water temperature dataloggers deployed in Arden Creek (May–July 2022). Arrow indicates when the last Western Brook Lamprey (*Lampetra richardsoni*), Morrison Creek population nesting activity was observed.

the legal requirements of habitat protection under SARA, our restoration work was only accomplished as a result of a collaborative effort among stewardship groups, communities, individuals, and government to help ensure the continued survival of an evolutionarily significant population at risk of extinction. This highlights the value and importance of improved coordination and collaboration among the aforementioned diverse entities to achieve successful conservation outcomes for aquatic species (Maitland *et al.* 2015; Clemens *et al.* 2021).

Restoration of aquatic habitats also requires sufficient understanding of the target species' biology, ecology, and habitat requirements across life stages, ecological processes, and the engineering required to enable these specific changes. In this case, Arden Creek and the Morrison Creek watershed had been affected by a number of anthropogenic activities over time. Prior to the restoration work, in-stream habitat in this area of Arden Creek was of little value to either Morrison Creek Lamprey or salmonids. This was primarily because of extensive fine sediment deposits throughout the targetted reach, caused by erosion that had degraded the stream. This had transformed it into an over-widened, low-gradient channel, characterized by areas of minimal flow and stagnant, low-oxygen conditions. Our measure of restoration success for Morrison Creek Lamprey, in the short-term, was the confirmed use of habitat for nest building and spawning. The in-stream restoration activity was successful in providing the necessary habitat for Morrison Creek Lamprey to build nests and spawn in an area of Arden Creek that had been devoid of such activity since 2005. Moreover, nest building and spawning was not just observed in the restored area in general, but specifically in the features and gravel that were added. Restoration also proved beneficial to salmonids. In the fall of 2021, both Coho and Pink Salmon were seen in the creek, using the new beds of sand and gravel for their spawning activities (DFO unpubl. data). The following spring, salmonid fry were found taking refuge behind large woody debris and holding in pools created by feature-driven pinch points diverse in substrate.

Restored areas now contain patches of alluvial, size-graded substrates interspersed within pools as well as shallow habitat and increased hydraulic complexity—particularly at riffles; all these features are known to be used by lamprey for nesting (Gunckel *et al.* 2009). As the restored riparian areas become more established, they too will contribute to spawning habitat by providing shade, woody debris, and bank stability, thus decreasing sedimentation. Controlled public access will also mitigate sediment sources and facilitate the establishment of functional riparian vegetation communities.

The restoration of this section of Arden Creek has successfully created habitat conditions that are now suitable for adult Morrison Creek Lamprey, marking a significant improvement in habitat quality. However, determining the suitability of the restored habitat for larval rearing will require long-term monitoring to fully evaluate its effectiveness. The restoration approach was carefully designed to address key habitat requirements, incorporating deeper sediments and fine gravel to provide potential larval rearing areas. Enhanced water flows were also established to improve oxygenation, a critical factor for supporting larval development (Gonzalez *et al.* 2017). While the restoration has transformed this once impaired section of the creek into a functional habitat capable of supporting both spawning adults and potentially rearing larvae, ongoing monitoring will be essential to confirm larval use and ensure the long-term success of the restored habitat.

Although critical knowledge gaps remain regarding the conservation of Morrison Creek Lamprey, there is sufficient understanding of their habitat requirements to guide effective restoration efforts. Ensuring that engineering outcomes create habitat characteristics that improve conditions such as flow, oxygen levels, and substrate type is essential not only for the survival and recovery of this species but also for supporting a diverse range of aquatic life. Substrate preferences for both adult and larval lamprey have been documented, highlighting the importance of suitable fine sediments for larvae and coarser substrates for spawning adults. Incorporating these habitat requirements into restoration designs benefits not just lamprey, but also enhances ecological health, processes, and the integrity of food webs for the entire aquatic ecosystem (Wade and Grant 2022).

Many authors have highlighted the importance, and often the lack, of monitoring to evaluate the effectiveness of restoration projects (Bash and Ryan 2002; Liermann and Roni 2008; O'Neal *et al.* 2016; Roni *et al.* 2018). Pre- and post-restoration surveys are essential to determine if conservation goals have been met. The temporal and spatial scales for monitoring should also be considered when designing effective monitoring programs. Monitoring at the watershed scale is more effective at detecting changes in abundance at the population level (Liermann and Roni 2008). However, there are often financial and capacity constraints that make this larger scale monitoring unfeasible for most projects (Liermann and Roni 2008; Anderson *et al.* 2019). Nevertheless, monitoring at the reach-scale can evaluate effectiveness of restoration activities, especially when the focus is on the habitat use of target and co-occurring species. Such monitoring plans should be conducted for multiple years to evaluate the long-term effectiveness of restoration on both species as well as habitat and ecosystem processes.

Lamprey are relatively cryptic non-charismatic species (Clemens and Wang 2021), which bring many unique challenges to their management and restoration (Clemens *et al.* 2021). Our study demonstrates the benefit of management actions for the conservation of an at-risk species and what can be accomplished when effective collaboration among stakeholders occurs. It also contributes to furthering our understanding of habitat requirements of lamprey as well as the specific types of restoration activities conducive to restoring severely degraded and previously non-functional habitat, which should be informative and applicable for other lamprey species.

Author Contributions

Writing – Original Draft: J.W., W.F., and P.G.; Writing – Review & Editing: J.W., W.F., and P.G.; Conceptualization: J.W. and P.G.; Investigation: J.W., W.F., and P.G.

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