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Comparative Biotic Monitoring of a Modified Denil Fishway and a Pool and Weir Fishway on a Small Tributary in the Upper Trout Region

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Abstract: Modified Denil fishways have a centred gabion containing gravel and are intended to enable the free passage of riverbed-oriented species and invertebrates. An experimental plant was built at a small hydropower station which provided a newly arranged Denil fishway and a pool and weir fishway parallel to one another. It was possible to alternately operate the systems for monitoring purposes owing to the parallel design, allowing an appropriate comparison and analysis of the results to be carried out. The primary objective of this study is to qualitatively and quantitatively compare the size selectivity and ascent numbers between the new development and the conventional construction type. An important component of this study is the test to prove the passage of bullheads in the modified Denil fishway using an experimental set-up. The results of this study depict a similar size distribution of ascended fish in both construction types and thus provide no evidence of selectivity for small fish sizes. Likewise, no deficit of the modified Denil fishway compared with the pool and weir fishway could be proven within the scope of a monitoring. The successful passage of bullheads could be demonstrated in the experiment as well as during monitoring.

Keywords: biotic monitoring; Denil fishway; fish passage; upper trout region; pool and weir fishway

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1. Introduction

Following the introduction of the EU Water Framework Directive [1] into Austrian law, and thus in accordance with the Water Rights Act [2], the construction of fishways became a necessary method of improving river connectivity throughout EU member states. While conventional designs, such as the natural bypass channel and variants of the pool and weir fishway, dominated the early stages of the renovation process, further alternatives have emerged due to challenging spatial and economic conditions. In Austria, alternatives are mostly limited to automated systems in the form of fish locks, fish elevators, and fish ascent screws, which are often justified by their small space requirements and cost-efficient properties [3].

Denil fishways have always been particularly space-efficient, with the added benefit of a comparably easy subsequent installation into already existing structures, due to their precast construction. There has been valid criticism of their use due to suboptimal flow conditions created by the steep gradient and overall design, which has resulted in explicit advice against their construction according to the Austrian guidelines for fishway design [4]. The present study presents further developments of a new Denil fishway design, with the aim of investigating its functionality in the upper trout region.

The basic principle of counter-current fishways is derived from the invention of the Belgian engineer Gustave Denil [5]. These fishways consist of an inclined channel with a 10 to 25 percent gradient, in which counter-currents are created by the installation of baffles. These counter-currents reduce the flow velocities in the passageway, which is situated in the middle of the cross-section. Thus, standard Denil fishways show high-flow velocities near the water surface that are considerably reduced towards the riverbed [6]. While near-natural constructions or cascade-like fishways, such as vertical slot fishways or pool and weir fishways, create rest areas along the passageway, counter-current fishways must generally be passed through by fish without stopovers. This aspect makes the usefulness of these types of fishways dependent on their length and slope [7,8].

Various types of Denil fishways have been established during numerous tests and further developments [5,6,9–11]. Thus, the most common types of counter-current fishways are the standard Denil (U-shaped Denil), Larinier (superactive-type baffles), and steeppass fishways [9]. Fishways built according to the Denil concept are described in the literature as selective in terms of fish size and species, with the rate of selection being high for young fish and small fish, while salmonids are generally assumed to be able to pass through them [7,8,12–14].

In international monitoring studies, however, the passage efficiency of Denil fishways has been the subject of controversial discussion. Noonan et al. [15], for example, observed a significantly lower efficiency of Denil fishways compared to other types, whereas Bunt et al. [16,17] proved a good passage efficiency for individual groups of species. Similarly, Mallen-Cooper and Stuart [18] showed a high passage efficiency for Denil fishways, even for small fish, by reducing their slope to 8.3%.

A modified model of an open-bed Denil fishway was tested in the hydraulic engineering laboratory of TU Graz in a 1:1 scale model, and the respective hydraulic parameters were compared to those of a standard Denil fishway [19]. Hydraulic tests have shown that upwardly directed vertical flow velocities appear close to the riverbed in conventional standard Denil fishways and mostly exceed the flow velocities in the main direction of flow [19,20]. This phenomenon can have a negative effect, particularly on the passage of small fish. Due to this problem, small fish become disoriented and, as a result, can expect to be lifted into a near-surface zone with high-flow velocities, resulting in them being carried back downstream.

The development of this modified Denil fishway (MDF) contains a centred gabion filled with gravel, which is intended to enable better passage of riverbed-oriented species and invertebrates. Hence, the negative aspects of standard Denil fishways could be largely eliminated so that the velocities dominate in the main flow direction [19].

The prototype of this new fishway was built in the Barbel region, with a slope of 19.5%, to test its functionality in a lowland river. This investigation could provide evidence for the ascent of 10 species of fish [20,21]. Particularly remarkable were the high rates of upstream passages of the gudgeon (*Gobio gobio*) [20,21], which is a small-sized, poor-swimming, and bottom-dwelling fish species [4]. The common presence of this species confirmed the hydraulic results obtained by Schneider and Dorfmann [19], respective of Seidl et al. [20]. As only the brown trout (*Salmo trutta f. fario*), which is rated as a species with high swimming performance, and the bottom-dwelling bullhead (*Cottus gobio*) inhabit the upper trout region of Austrian rivers, it can be inferred from the results found by Zach [21] that the new type of fish ladder in this fish region has the potential for high functionality. The present study was designed to test the hypothesis that the newly developed MDF shows neither size selectivity of small fish sizes nor reduced ascent rates when compared with the conventional pool and weir fishway (PWF). The investigations were conducted following the Austrian monitoring guideline [22], which qualitatively and quantitatively analyses the observed ascents. In addition, the passability of the new development for bottom-oriented small fish species of bullhead was tested in a trial arrangement.

Proof of bullhead passage was of special importance because the upstream passage of this highly riverbed-oriented species had not yet been verified in Denil fishways. The bullhead is a species that is very common in alpine trout and grayling regions. It does not have a swim bladder and thus has to move along the riverbed. According to the literature [3], it is a poor swimmer.

Before the hydropower plant was built, 18 impassable transverse structures that were higher than 0.3 m in height were located between the water intake and the confluence of the two streams, Hirschbach and Feistritz (see Section 2.1), on a stretch of 800 m. Utzinger et al. [23] described how steps with a height of 0.18 to 0.2 m represent a barrier for bullheads, and they found no individuals upstream of any such anthropogenic obstacles. All existing transverse structures were made passable downstream of the weir. Since the Hirschbach River has a moderate average gradient of around 4%, this river section presents a habitat for bullheads. In contrast to the situation for brown trout, which are of interest for fishing, stocking measures with bullheads are of minor interest.

To verify these findings, an experimental set-up was built at a small hydropower station, which provided a MDF and a PWF running in parallel. A PWF generates high-flow velocities in the slots and rest areas in the pool. These high velocities must be overcome at a short distance by fish that are willing to ascend. Since the pool and weir fishway is to be understood as a tested, well-known, and well-designed construction type for the trout region, the aim of the present investigation is to measure the newly developed Denil fishway by monitoring it comparatively with the pool and weir fishway. The comparison of the size distribution and ascent rates of the ascended fish species are of particular importance and will be described in this paper.

2. Methodology

2.1. Study Area

The hydropower plant (HPP) Horn, where the fishways have been built, is situated in Austria on the Hirschbach River, a tributary of the Feistritz River, in the northeast of the Province of Styria (Figure 1). It is a small diversion plant where the water is withdrawn by a Coanda screen. Over the course of an expansion project for this HPP, a new weir was built; additionally, several blockages along the Hirschbach River were removed, re-opening it for fish migration between the Feistritz River and the HPP.

The Hirschbach River is classified as epirhithral (upper trout region), with the brown trout (*Salmo trutta f. fario*) and bullhead (*Cottus gobio*) within its natural spectrum of species. In order to meet the statutory ecological standards [1], the construction of a passable fishway, together with the release of an adequate quantity of residual water, is required. Fish ladders are to be dimensioned in such a way that passability is ensured for the size-determining fish species, brown trout, with a fork length of 300 mm [4].

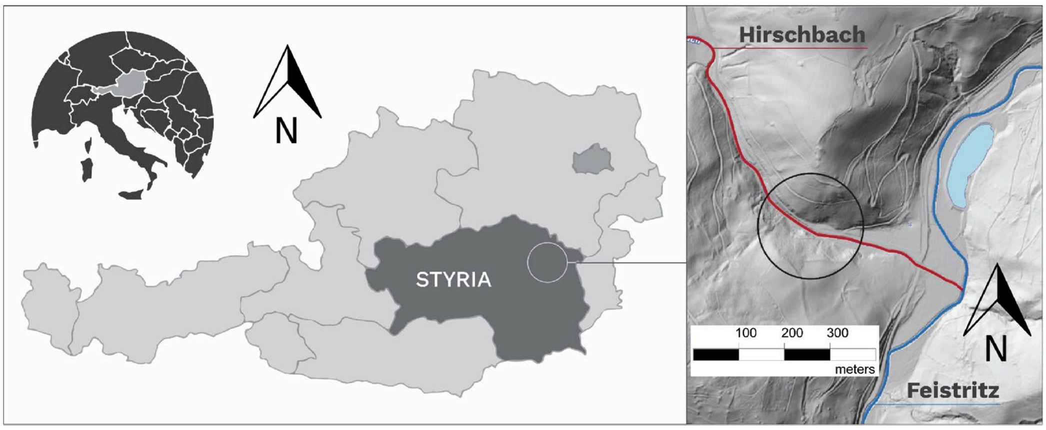

Figure 1. The project area is located in Styria (Austria) at the Hirschbach River.

Table 1 provides an overview of the hydrological and ecological characteristics of the tributary of the Hirschbach River.

Table 1. Hydrological and ecological parameters (source: Hydrologisches Gutachten Land Steiermark GZ: ABT14-18Hi-2016/7).

Hydrological Parameter	Unit	Value
Catchment area	[km²]	22
Mean discharge	[l/s]	343
Mean annual low discharge	[l/s]	130
Lowest discharge	[l/s]	66

Figure 2 shows the MDF parallel to the PWF. The parallel design made it possible to operate the monitoring systems on an alternating basis so that an appropriate comparison and an analysis of the results could be carried out.

Figure 2. Weir and fishways at HPP Horn.

In Austria, it is an official requirement that a fishway function adequately for 300 days according to the Q330 water level of the exceeding duration curve, which is the water level that must be exceeded for 330 days a year so that passage is guaranteed for 300 days, between Q330 and Q30 [4]. As a result of this, the difference in water levels is 1.4 m, based on which the two fishways have been dimensioned.

2.1.1. Modified Denil Fishway

The MDF differs from the standard Denil fishway by its integrated substrate gabion. In addition to the installation of the bottom substrate, the baffle geometry of the fishway has also been revised so that it now encloses the substrate body with an open bottom (Figures 3 and 4).

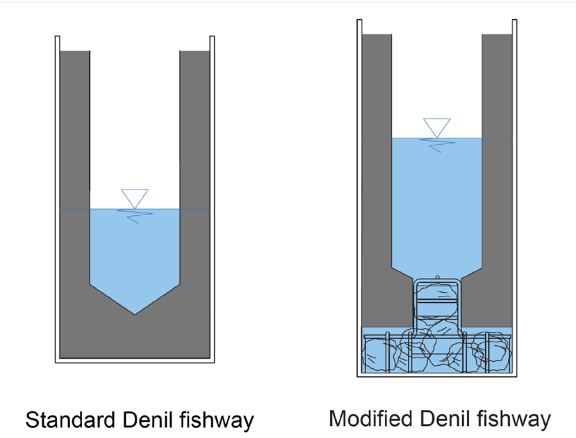

Figure 3. Standard Denil fishway and Modified Denil fishway (MDF).

Figure 4. (**Left**): baffle geometry and substrate gabion. (**Right**): modified Denil fishway (MDF) in operation.

2.1.2. Pool and Weir Fishway (PWF)

A PWF consists of a number of pools formed by weirs [24–26]. The dimensioning of this type of fishway is based on the Austrian design guideline for fish ladders [4], wherein the arrangement of the weirs must alternate, and the ramp must have an uninterrupted design and a natural bottom. In this study, a technical PWF was built [27]. The rectangular channel is separated into pools with cross-walls equipped with a deep slot. The position of these slots changes from left to right from pool to pool (Figure 5).

The individual pools have a length of 1 m and a width of 1.7 m, the head difference between each pool is 0.2 m, and the width of the slots between the pools is 0.15 m. The pools have been designed in accordance with the guideline [4], in such a way that the water depth in the cross-wall exceeds 0.4 m, and the energy dissipation is below 160 W/m^3.

Figure 5. Flow characteristics of the pool and weir fishway (PWF).

2.2. Abiotic Principles

Since the functionality of fish passes must be understood as a function of hydraulic conditions, flow velocity measurements were carried out for both systems. For the PWF, the flow velocity measurements were limited to the critical area of the fishway: the slots. The measurements were carried out using an impeller flow meter (Schiltknecht MiniWater 20, Fa. Schiltknecht, Switzerland, Gossau). The measurements were made in the immediate slot area at the PWF and in the middle of the length of the MDF. In the PWF, the measuring points were placed along a vertical in the middle of the slot (Figure 6). The measurements in the MDF were carried out in three equidistant measurement verticals perpendicular to the channel bottom (Figure 7).

Discharge measurements for both systems were carried out using the salt dilution method with a SOMMER MRS-4 measuring instrument. The flow rate was set to achieve a minimum depth (h) of 0.25 m in the MDF and a minimum depth (Ho) of 0.4 m at the PWF cross walls.

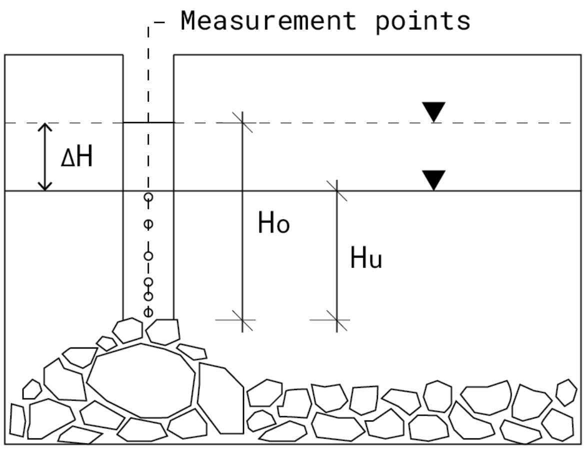

Figure 6. Measurement arrangement in the pool and weir fishway (PWF).

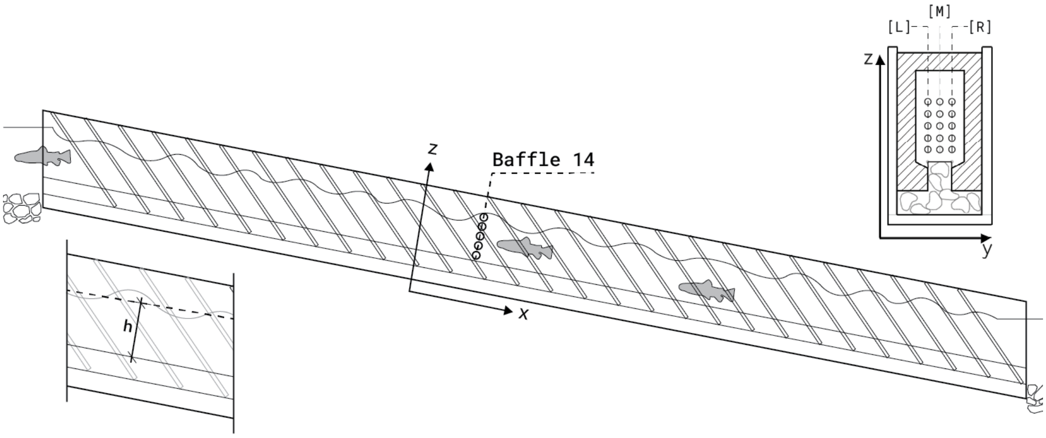

Figure 7. Measurement arrangement in the modified Denil fishway (MDF).

2.3. Biotic Principles

Tests were carried out using an adapted fish trap monitoring programme based on the Austrian monitoring guideline for fishways [22]. According to this guideline, a fishway is considered functional when ascent is possible for all naturally occurring species in all stages older than one year.

The following criteria are used:

- Qualitative upstream migration (fish species and life stages);
- Quantitative upstream migration (abundance).

In order to define the ascent potential, electrofishing was carried out in the tailwater, and the fish that were caught were measured and recorded. Fishing was performed by wading up the river twice using a portable generator (1.5 kW, 300 V).

In order to test a variety of experimental set-ups, the biotic study was divided into three phases, which will be discussed in the following sections. The timetable of this study can be seen in Figure 8.

A mobile fish-catching device, in the form of a cone trap, was provided (see location in Figure 9), which was placed at the respective exit area of the currently active fishway in the collecting pool. A cone trap is a funnel-shaped element that is placed in the water at the end of the fishway. Ascending fish pass through the 0.5 m long funnel and through a square-shaped opening of 0.1 m × 0.1 m at its end and thus end up in the collecting pool. Due to the narrowing of the cone trap at its end, it is highly difficult for fish that have already passed through it to find their way back through the small opening and thereby escape the collecting pool. The fishway that was not being tested was blocked by a board. The fish that managed to move into the collecting pool via the cone trap were prevented from escaping into the basin by closing the pool with a perforated board with holes of just 10 mm. This way, the fish in the collecting pool between the cone trap and the perforated board could be caught with a landing net to be measured, recorded, and subsequently released. Since the water supply was reduced considerably during the course of counting the fish, it was necessary to search areas of the fish ladder that had become dry, rescuing any stranded fish.

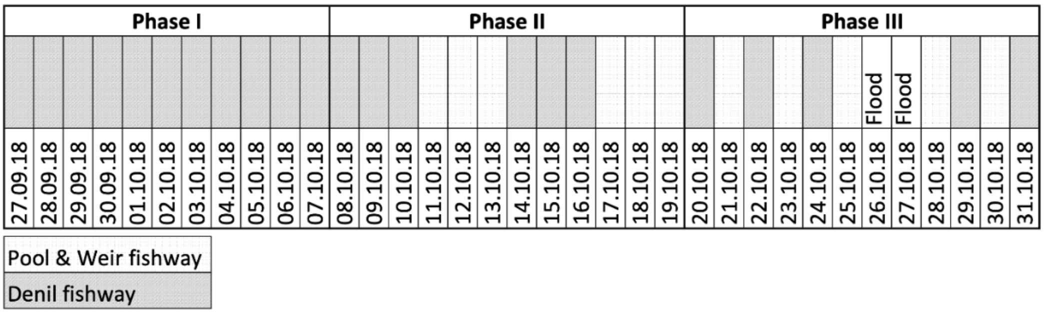

Figure 8. Timeline of the biotic monitoring with the observation periods of the modified Denil fishway (MDF) and pool and weir fishway (PWF).

2.3.1. Phase I: Bullhead Test in the Modified Denil Fishway (MDF)

To determine if bullheads are capable of ascending the prototype fishway, 59 individuals were collected from the Feistritz River, located 800 m downstream. Since bullheads have not yet become resident again, following the restoration measures in the River Hirschbach, the functionality of the fishways with regard to bullheads was tested with a number of individuals taken from the Feistritz River, which is also a part of the same genetic pool. The bullheads, which had fork lengths between 80 and 150 mm, were measured, recorded, and then released without caching activities into the downstream pool connected to the MDF.

The additional fish population brought in was largely prevented from escaping the testing facility to the tailwater or to the PWF by installing a wire mesh barrier.

In the course of the test period of 10 days, the collecting pool located upstream was inspected daily, and fish that had passed the fishway were measured and recorded.

2.3.2. Phase II: Three-Day Sampling Cycles

During this phase, the fishways were operated in alternation for three days at a time, and the ascents of fish were observed, measured, and recorded on a daily basis. The 3-day observation phase was chosen to eliminate any possible negative influences caused by the daily change in the operating fishway.

During the period from 8 to 19 October 2018, the two fishways were tested in two cycles, with a total of 6 days of monitoring for each fishway.

2.3.3. Phase III: Daily Exchange of Cone Traps

After Phase II, the two fishways were again tested in alternation. During this phase, the cone trap was swapped between the two fishways daily for 12 days, beginning on 20 October and continuing to 1 November. The respective ascent rates were recorded throughout the cycle.

The shorter observation interval made it possible to better account for any changes in weather over the active time of the two fishways to prevent possible falsification or misinterpretation of the rate of ascent.

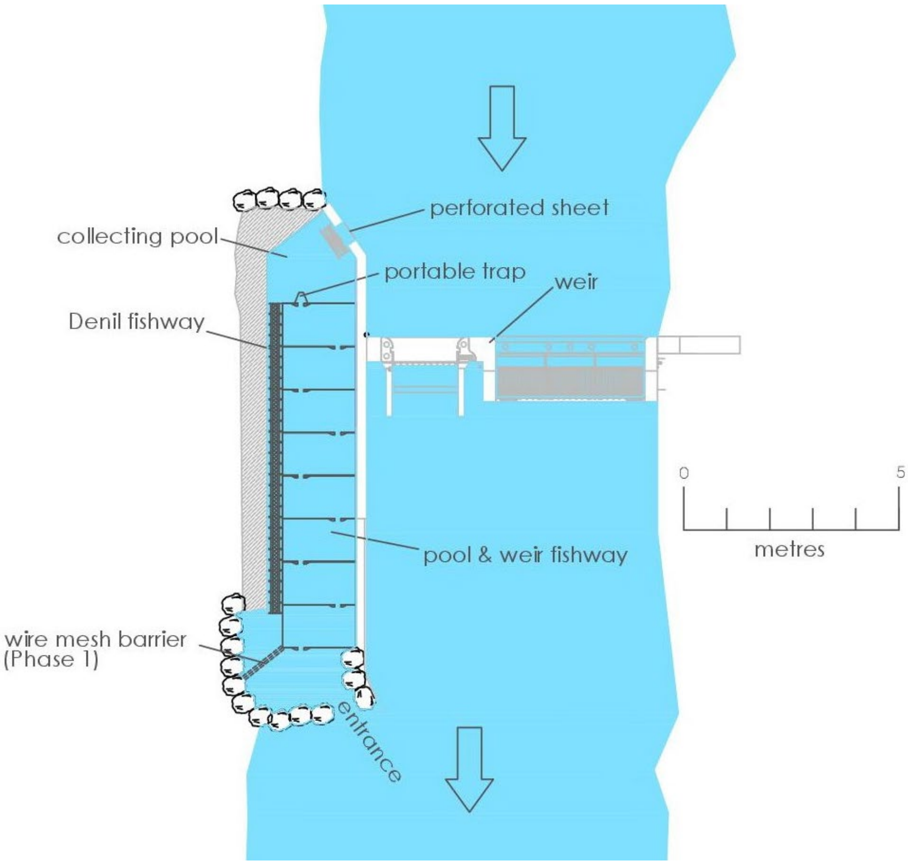

Figure 9. Layout of the test system at the weir for Phases II and III.

2.3.4. Statistical Analyses

The statistical analyses were carried out using R software (ver. 4.0.5) [28]. These analyses were conducted to test whether environmental conditions had an effect on ascent rates and thus conferred an advantage to one of the two systems. A statistical test procedure was used to determine if a significant difference in the size distribution of the ascended fish could be inferred. Checks were carried out to determine whether both systems were sampled under the same external conditions and whether fluctuations in water temperature during the observation period had an influence on the ascent rates of the two fishways. Analyses were performed using one-way Spearman's rank correlation to test the relationship between increasing water temperature and increasing ascent rates. To test the hypothesis that the MDF has no size selectivity compared to the PWF, a two-tailed Wilcoxon rank sum test was performed for the length frequencies of the ascents. In addition, a one-tailed Wilcoxon rank sum test was conducted to test the assumption that ascended individuals in the PWF were smaller than those in the MDF.

3. Results and Discussion

3.1. Abiotics

In the pool and weir fishway, flow velocities ranged between 1.4 m/s and 1.5 m/s (Figure 10A). Thus, these values are in accordance with the hydraulic conditions of comparable types of fishways [29–31]. Flow velocities in the Denil fishway ranged from 0.29 m/s near the bottom to 2.25 m/s near the surface, with the bottom third showing velocities of less than 1 m/s (Figure 10B). The decrease in flow velocities towards the bottom also makes the ascent of small fish possible [32]. This is also supported by the findings of Tudorache, who set the value for critical swimming speeds of juvenile brown trout at 0.65 m/s. Clough and Turnpenny [33] assessed that the critical burst swimming speed of brown trout with a fork length of 10 to 20 cm is between 1 and 2 m/s. Since the high flow velocities in the PWF are reduced only in the immediate slot area, which is swum through over a short distance, successful passage for small fish can also be assumed for this fishway.

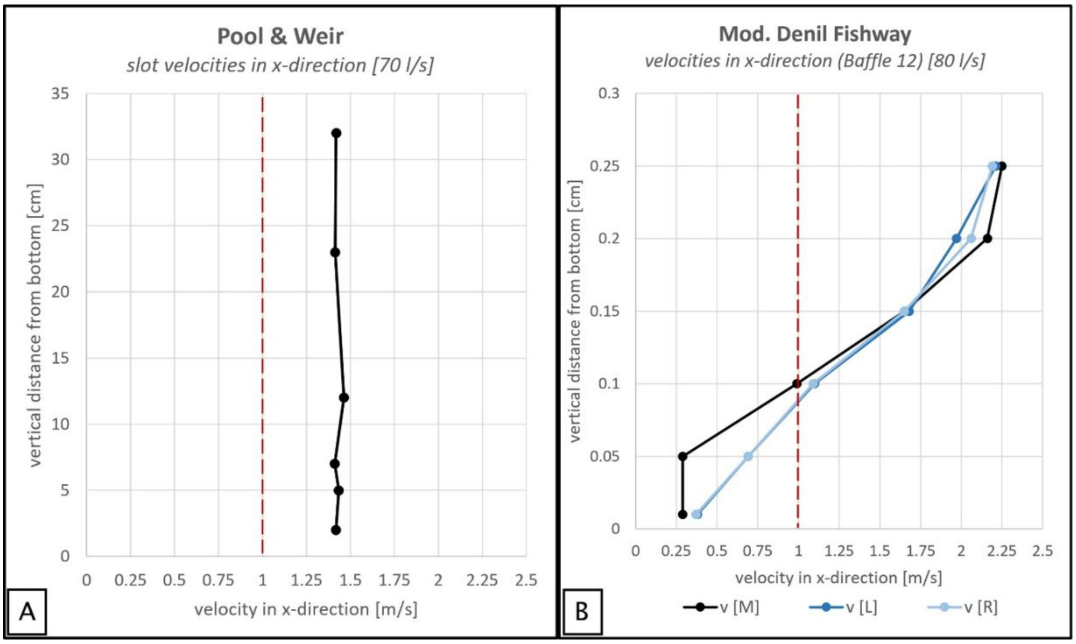

Figure 10. Velocity profile in the pool and weir fishway (PWF) slots (**A**) and velocity profiles in the modified Denil fishway (MDF) (**B**).

The measurements showed that the required water depths are met at a discharge rate of 80 L/s in the MDF and at 70 L/s in the PWF. These flow conditions were maintained for the entire monitoring period.

3.2. Biotics

3.2.1. Bullhead Test in the Modified Denil Fishway (MDF) (Phase I)

Bullheads began to appear during day 4 of the phase I test, with 12 individuals (>20%) fully ascending the MDF during the 10-day trial (Figure 11). Bullheads successfully ascending the fishway ranged between 95 and 125 mm.

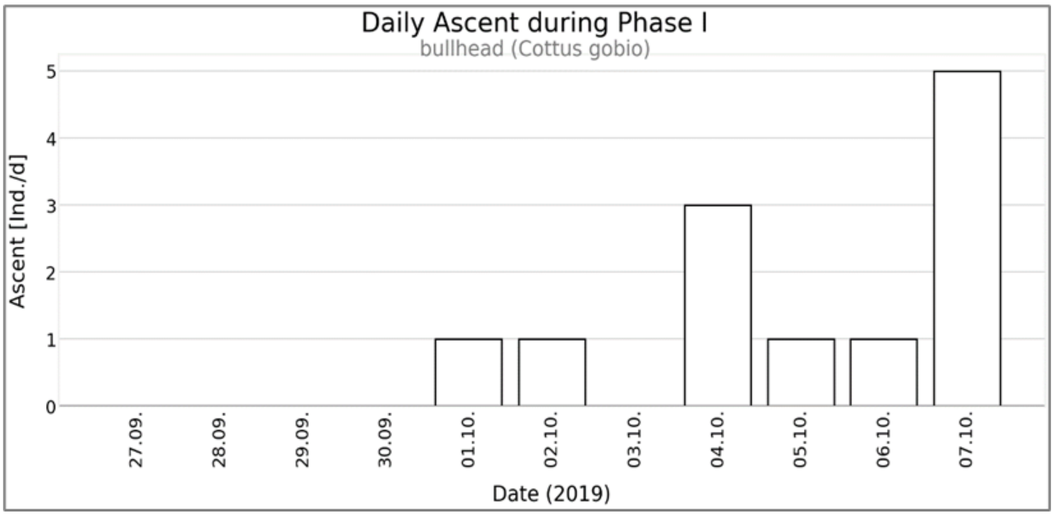

Figure 11. Ascent rates of bullheads in the test set-up (Phase I).

A total of four out of seven size classes of the fish stocked in the tailwater verifiably passed through the fishway (Figure 12). The smaller size class of 80–89 mm, as well as the two upper size classes (130–139 mm and 140–149 mm), remained unobserved. The ascent rate of bullheads during the test and the additional passage of three bullheads during the monitoring procedure (Phases II and III, see Section 3.2.2) are proof of the passability of the MDF for this species.

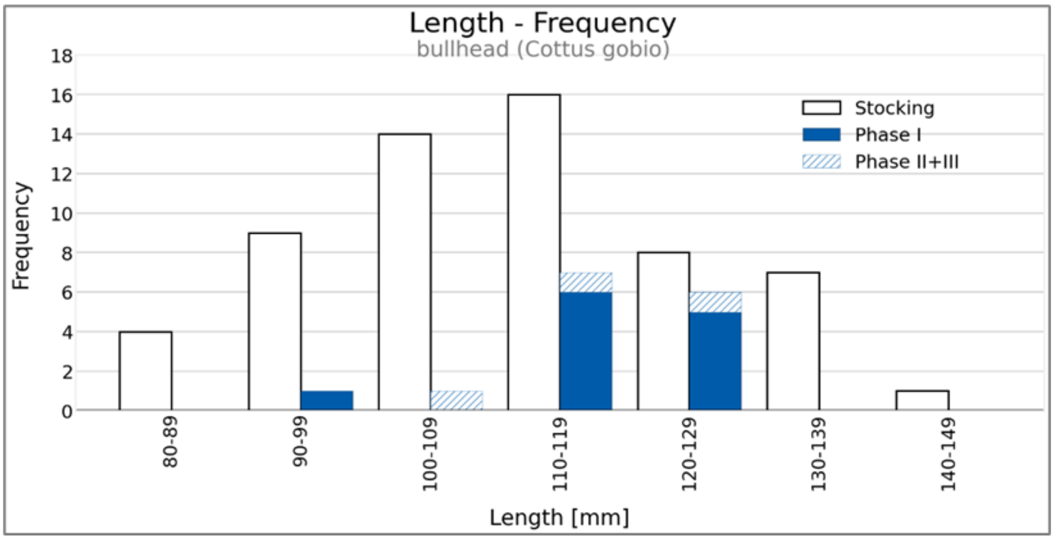

Figure 12. Length frequencies of the bullhead: stocking, ascent in the test (Phase I), and ascents in subsequent monitoring (Phases II and III).

Apart from the monitored ascents, bullheads could be observed visually within the MDF several times when the water supply was reduced to count the fish in the collecting pool (Figure 13). This indicates that this small riverbed-dwelling fish does not necessarily pass through the system in one single uninterrupted go, but that it is able to take breaks within the fishway during the ascent. This observation is also supported by Tudorache et al. [32], whose experiments on bullheads with a respirometer could not determine the critical swimming speed because these fish can brace themselves against the flow using their strong pectoral fins and can thus withstand even high flow velocities without making any swimming movements. Similar observations were made by Schwalme et al. [34] with cyprinids of small sizes in a standard Denil fishway, where these fish used the areas behind the baffles to rest during the ascent.

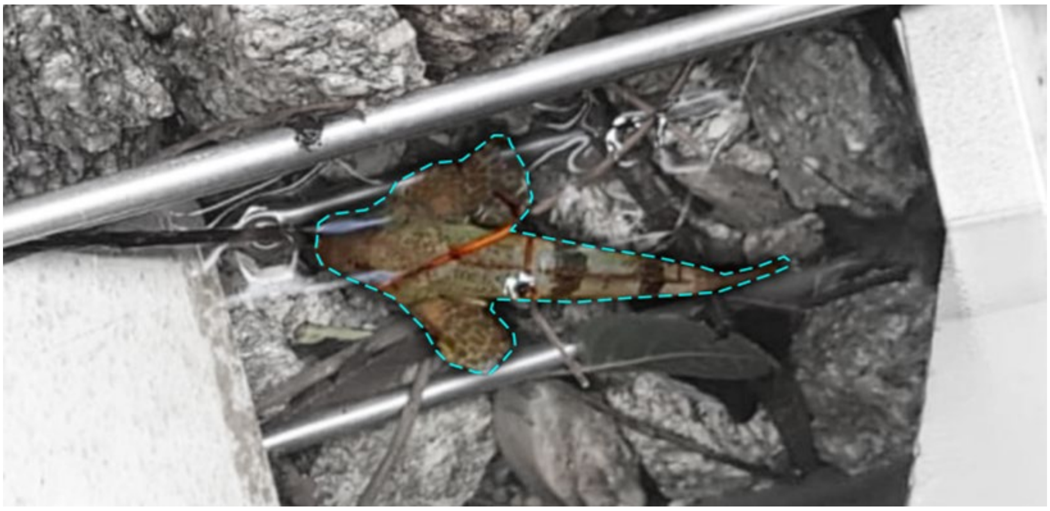

Figure 13. Bullhead beside the centred gabion, between two baffles, in the modified Denil fishway (MDF) during emptying.

3.2.2. Qualitative and Quantitative Upstream Migration of Brown Trout in the Monitoring Phases (Phases II and III)

During the investigation period, the complete range of fish sizes from the tailwater habitat could almost be observed in both types of fishways at the controlling pool (14, 15). The ascent rates showed similar results for both fishways and in both phases, ranging from 0 to 18 individuals a day.

Table 2 provides an overview of the observed ascent rates and fish lengths of brown trout in the two types of fishways. Furthermore, the two phases, II and III, are compared with each other. The two systems yield similar results when comparing the total number of ascended individuals (MDF: 49 and PWF: 46), as well as when comparing the two phases (II: 46 and III: 49). The daily rates of ascent in the two systems vary between 0 and 18 individuals. The mean daily ascent rate was higher in Phase III, at five individuals/day, than in Phase II, where four individuals/day were observed. A negative influence of the daily change in the sampled types in Phase II can, therefore, most likely be excluded. The different duration of the observation intervals in the two phases should not have any considerable influence on the results. Both fish ladders show an average daily ascent rate of four individuals, with a similar degree of dispersion. The standard deviation (SD) of the daily ascent rate of the MDF is about 3.3, which is comparable to the standard deviation of the PWF with a value of 4.5. A similar result is gained in the context of fish lengths, although during the testing, smaller fish sizes migrated through the MDF than in the PWF.

Table 2. Comparison of daily ascents.

Fishway	Brown Trout				
	Σ	Individuals/day			
		Min	Mean	Max	SD
Denil	49	0	4	9	3.3
Pool and weir	46	0	4	18	4.5
Phase II	46	0	4	9.0	3.1
Phase III	49	0	5	18.0	4.9
Fishway	**Σ**	**Fork Length (mm)**			
		Min	**Mean**	**Max**	**SD**
Denil	49	95	166	320	54.6
Pool and weir	46	100	183	380	42.8

The number of adults among the ascending fish was notably higher than in the tailwater. In addition to this, significantly larger individuals were detected during monitoring compared to those in the tailwater (Figures 14 and 15). Thus, the passage of brown trout whose body lengths exceeded those of the size-determining fish species (brown trout, 300 mm) was detected in both fish passage types. Juvenile fish, however, were recorded in lower numbers, with the two lower size classes of 80–89 mm and 90–99 mm remaining unobserved at the PWF and the size class of 80–89 mm remaining unobserved at the MDF. This can be explained, on the one hand, by the beginning of the spawning season, leading to the biggest fish swimming upstream and ascending from the Feistritz River. On the other hand, bigger brown trout show higher migratory activity than small fish and also migrate outside the spawning season [35]. Apart from that, the passage of small individuals (<90 mm) through the perforated board with 10 mm hole diameters cannot be excluded.

In summary, the MDF showed no deficits when compared to a PWF in the context of quantitative upstream migration with respect to ascent rates (individuals/day).

Comparing the length frequencies (Figure 15), the MDF shows a higher percentage of fish of smaller size classes. For medium-sized and adult fish, similar results were obtained compared to those of the pool and weir fishway. The two-tailed Wilcoxon test ($W = 1377$, $z = -1.533$, and $p = 0.0621$) showed that no significant difference could be found in the length distribution of the ascended individuals in the two investigated systems. The assumption that the ascended individuals in the PWF were smaller than those in the MDF was tested by means of a one-tailed Wilcoxon test (W = 1377, z = 1.870, and $p = 0.969$) and could be disproved. Therefore, any degree of size selectivity in the MDF can also be excluded.

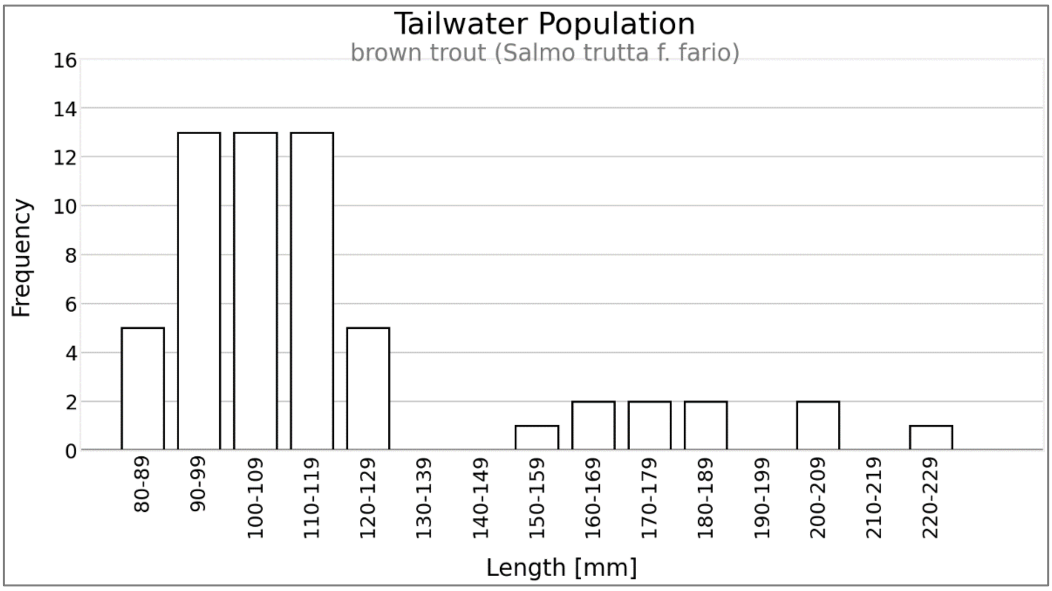

Figure 14. Length frequency of the tailwater population of brown trout.

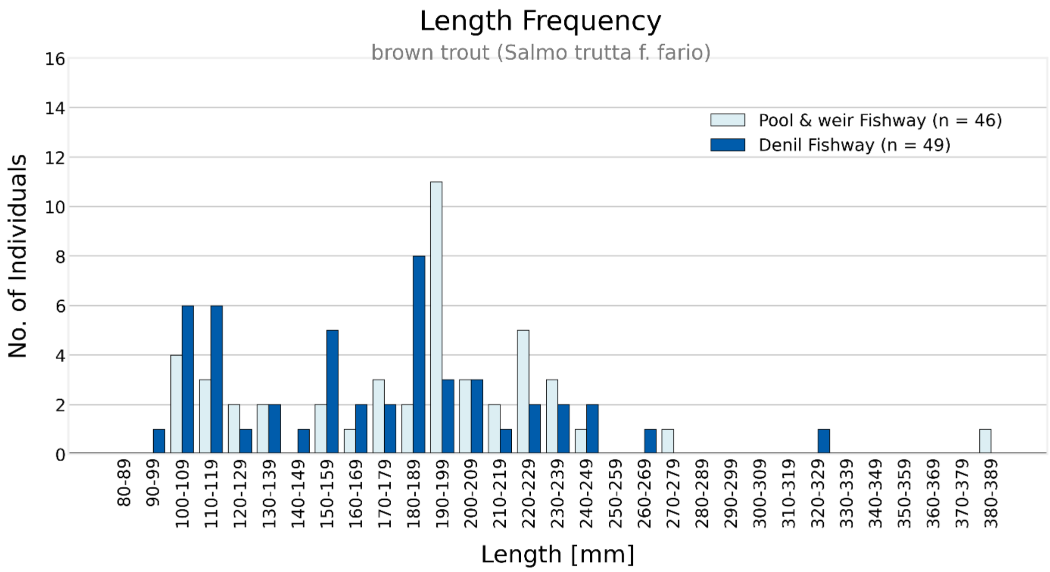

Figure 15. Length frequencies of brown trout in monitoring (left: modified Denil fishway; right: pool and weir fishway).

The number of ascents amounted to 53 individuals (49 brown trout, 1 rainbow trout, and 3 bullheads) in the MDF and 46 brown trout in the PWF during observation periods of 12 days each. The following figure, Figure 16, illustrates the daily ascents during the monitoring process (Phases II and III). While only the ascent of brown trout could be observed in the pool and weir fishway, the monitoring of the MDF recorded one additional rainbow trout (*Oncorhynchus mykiss*) with a length of 310 mm and three bullheads with lengths ranging between 100 and 130 mm.

Apart from one flood event, during which the monitoring was suspended for two days, the discharge during the observation period was always below the mean flow (see

Table 1). In each case, the largest proportion of the residual water was released via the fish ladders. As a result, the fish in both fishways displayed high findability during the entire observation period. During the monitoring, water temperatures stayed between 8 and 13 °C, representing uniform conditions over the study period. The salmonid activity begins at temperatures of 4–6 °C, with an optimum temperature for the migration activities of brown trout being observed at water temperatures between 10 and 14 °C [35,36], indicating that conditions were favourable during the investigation.

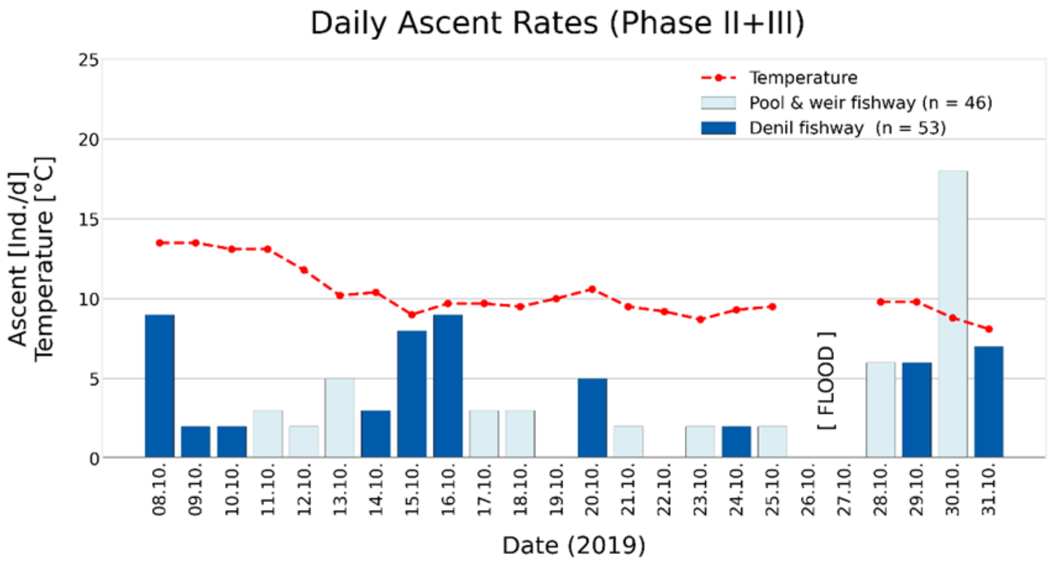

Figure 16. Daily ascent rates in monitoring (Phases II and III) and water temperature.

The correlations show no influence of the water temperature on the ascent rates during the observation period (rho = −0.03 and $p = 0.89$). It can thus be stated that both systems were tested under comparable environmental conditions.

The Hirschbach River is currently the habitat of only one of the two autochthonous species, the brown trout. This was also proved by fishing in the tailwater. Hence, the recorded ascents of bullheads during the monitoring period can, with a high degree of probability, be traced back to the use of stocked fish.

The MDF is a promising alternative to conventional types of fishways and, at low costs and with little land consumption, is supposed to make the passability in the trout and grayling region possible in the future. Further studies, mainly for bottom-dwelling bullheads, will be carried out to consolidate the data of the passage efficiency of this system.

4. Patents

eco² Fishpass, Austria Patent No. 51150/2018; pending patent applications: Germany No. 2018 251 767.3, Romania No. A 2019 00037, Switzerland No. 00007/19, and EU No. EP3214225A1.

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