fishes

Conference Report

Performance of a Pool and Weir Fishway for Iberian Cyprinids Migration: A Case Study

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Received: 28 March 2019; Accepted: 13 August 2019; Published: 16 August 2019

Abstract: One of the movement barriers that fish populations must overcome for migration success in the upper basin of Tormes river (Salamanca, Spain) is a 20 m high dam. The design of its pool and weir fishway for potamodromous fishes (mostly Iberian barbel—*Luciobarbus bocagei*—and Northern straight-mouth nase—*Pseudochondrostoma duriense*) to overcome the obstacle was improved in 2013. The aim of this study was to assess the efficiency of the fishway using FDX passive integrated transponder (PIT)-Tags inserted into the fish and PIT-Tag detection antennas at the fishway. During several sampling events, 7113 barbel and nase individuals were tagged and released at the point of capture along the basin (2538 and 4575 of which were tagged downstream and upstream, respectively). PIT-Tag Detection Antennas close to the top and bottom of the fishway monitored tagged fish continuously for 10 months (from March to December 2017), to analyze the performance of the fishway. Upstream passage efficiency was greater for barbel (60% and 25% for barbel and nase, respectively). Differences in passage efficiency between species may be due to differences in their size. Mean length for barbels attempting to pass was 336 mm (±47 mm) while for nases was 143 mm (±26 mm). Moreover, both the number of attempts to pass and ascend time for nases were higher than for barbels. Entrance efficiency was low (3.5% and 10.8% for barbel and nase, respectively), although 2017 was a very dry year, thus these results are most likely influenced by flow rates. Therefore, the fishway has proved to be functional but is actually poor for efficiency purposes, especially for small fish.

Keywords: PIT tag; ecological flow; *Luciobarbus bocagei*; *Pseudochondrostoma duriense*

1. Introduction

Fragmentation of rivers is one of the major threats for European freshwater fish [1], particularly for threatened species such as Iberian endemic species [2]. In the Spanish portion of the Duero basin, more than 3500 barriers to movement were inventoried [3]. This number of obstacles has a negative effect on viability of fish populations in the medium and long term as movement is restricted to short-length free river segments, reducing carrying capacity and gene flow [4–6].

The upper basin of the Tormes river, one of the most important tributaries of the Duero river (Salamanca and Ávila, Spain), has a high conservation interest because of its Iberian ichthyofauna diversity. The entire basin is included in the Natura 2000 network (ZEC ES4150085 and ZEC ES4110002). It is one of the few remaining streams in the Iberain peninsula without invasive alien species (such as carp, pike, largemouth bass, or common bleak) and presents a well-preserved community of fishes, composed primarily of endemic Iberian fishes, most of them included in the Directive 92/43/EEC [7]. Potamodromous species, those that undertake migrations wholly within freshwater, in the basin are common; brown trout (*Salmo trutta*), Iberian barbel (*Luciobarbus bocagei*), bermejuela (*Achondrostoma arcasii*), Northern straight mouth nase (*Pseudochondrostoma duriense*), Iberian chub (*Squalius carolitertii*), and calandino (*Squalius alburnoides*). However, the strong fragmentation of the basin has led to a decline in cyprinid stocks, especially for those with strong migratory requirements, such as barbel or nase.

In 2011, the Duero Basin Authority started a program to recover longitudinal connectivity in the upper basin of Tormes river including the removal and/or permeation of fish movement barriers. Monitoring in the medium to long term is a fundamental part of river restoration projects, since changes in the fluvial dynamics do not manifest immediately [8]. However, there are few studies in this regard, particularly for Iberian cyprinids under natural conditions [9].

One of the obstacles to consider in the upper basin of the Tormes River is a dam about 20 m high from the base, owned by a hydroelectric power station. The dam has a pool and weir fishway redesigned and rebuilt in 2013 to improve its operation. The fishway was hydraulically evaluated following the AEPS methodology [10], concluding that it meets the functionality objectives required for these types of structures [11]. However, monitoring upstream of the dam indicates that there are connectivity issues in this section of the study area (Wildlife Service of Castilla y León, pers. comm.).

To guarantee longitudinal connectivity of the river, a well-designed fishway must enable safe passage, reduce delay in migrations, and ultimately be effective at enabling fish to pass the obstacle [12]. It is necessary to study target species' migration patterns in order to meet these three requirements, since passage performance depends on many factors including hydraulics [13–17], fish behavior [18–20], swimming capabilities [13,21–23], and environmental parameters [24,25]. The aim of this study was to evaluate the efficiency of the pool and weir fishpass of a large dam (Salamanca, Spain) from an ichthyological point of view. The study will allow to obtain information on the critical points, such as downstream migration or natural obstacles influenced by the operation of the power station, that still need to be solved regarding this passage obstacle for the migration of the current species.

2. Results and Discussion

The dam is in the distributional limit for brown trout population (note that only six individuals were captured and tagged downstream of the dam) and the Iberian chub population is scarce along the basin. Consequently, this study was focused on Iberian barbel (*Luciobarbus bocagei*) and Northern straight mouth nase (*Pseudochondrostoma duriense*) because, although one detection of brown trout and Iberian chub were obtained, the results cannot be inferred for their populations.

Significant differences were obtained for size of barbel and nase tagged fish (H = 357.715, d.f. = 1, $p < 0.0001$). The average size of barbel tagged downstream of the dam was 336 ± 47 mm, and all of them were sexually mature [26]. On average, the size of tagged nase was 143 ± 26 mm. Although the literature describes maximum lengths of 500 mm for this species [26], captured nase in the Tormes river basin do not exceed 250 mm in length. However, most of them were also sexually mature individuals.

The fishway was monitored from late spring 2016, as this dam is among different control points in the study of fish migration at the upper basin of Tormes river. The results for efficiency refer only to records obtained in 2017; primarily because an entire migration period was analyzed, and also because two antenna systems (one at the top and another at the bottom of the fishway) were set up in 2017.

2.1. Performance of the Fish Ladder

During 2017, 145 fishes were recorded at the fishway, 57.9% of which were nase (Table 1). Total ascending passage efficiency was 40.1%, which is within the range of this kind of fishway for non-salmonid species [27]. However, barbel presented a higher passage efficiency than nase (60.6% and 25.0%, respectively; H = 18.590, d.f. = 1, $p < 0.0001$), that could be attributed to their different swimming capacity and size, but also to the characteristics of the fishway and its hydraulic conditions [16]. Relative critical swimming capacity for nase has been estimated to be 15% higher than for barbel [21,22]. However, differences in species body length entail inverted absolute swimming capacities, and therefore, barbel would have a greater ability to negotiate the fishway.

Table 1. Number of fishes recorded at the fishway.

	L. bocagei	*P. duriense*
Entries by different fish	61	84
Entries from downstream tagged fish	55	84
Entries from 100–150 m downstream 2017 event tagged fish	2	30
Successful ascents	37	21

The factors involved in the performance of a fishway, including length, slope, water velocity, and turbulent energy, all combine to influence passage efficiency [14–17,27]. Successive pool-weir fish ladders evaluated in the literature presented slopes around 8% [27,28], which is half the slope of the fishway studied. Although structural characteristics of the fishway does not seem to represent a problem for 60% of the barbels, it would be a significant difficulty for small fishes (Figure 1a).

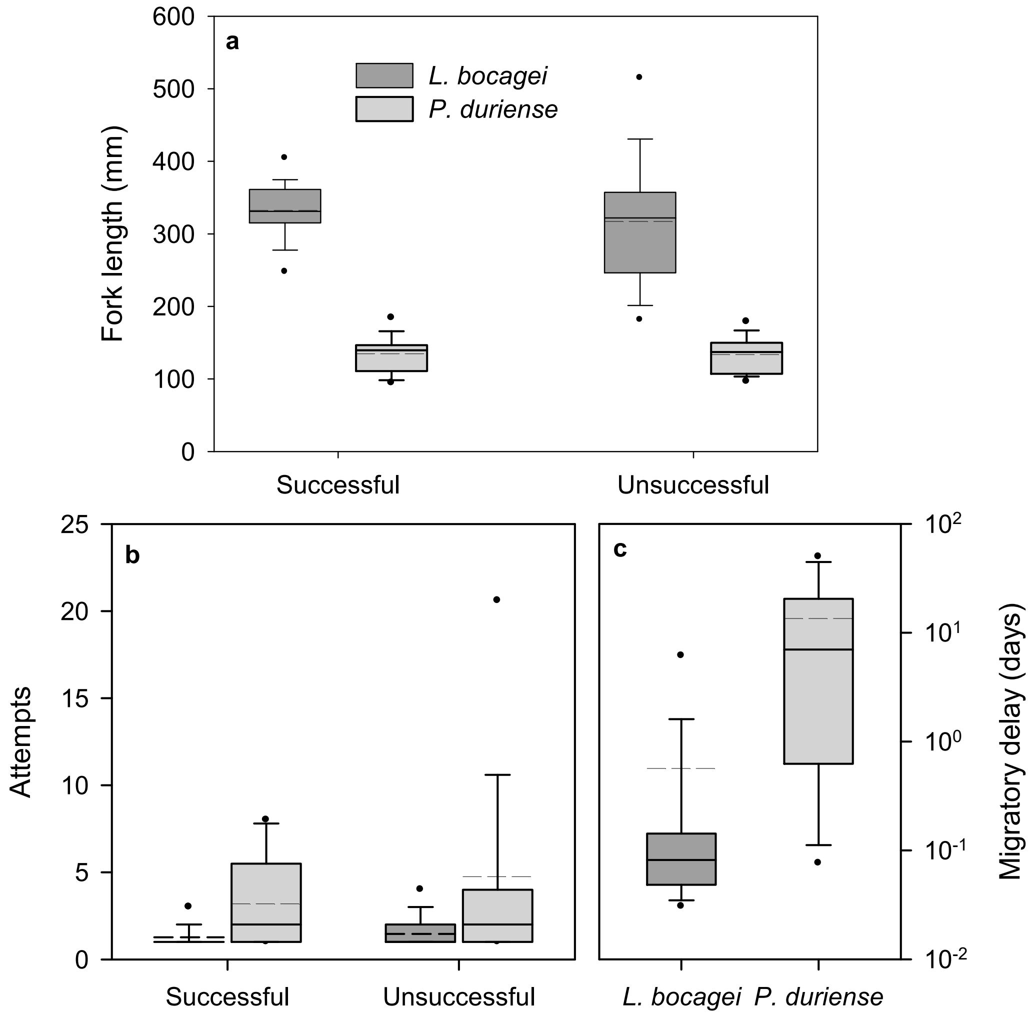

Figure 1. (**a**) Size of fish recorded at the antennas system; (**b**) number of attempts, and (**c**) and migratory delay (calculated as the time between first record at bottom antenna and the last record at the top antenna). Box represents the 50% of data (from 25th to 75th percentiles), whisker caps represent 10th and 90th percentiles, and points represents 5th and 95th percentiles. The short dashed line represents the mean.

Binomial generalized linear models (GLMs) carried out to model success or failure passage seem to suggest that fish length is the best predictor (based on Akaike Information Criterion (AIC)) of fish passage (Table 2). Species explains as much as a global model (species, length, and flow), and the model considering species, length, and its interaction. While both species and length explain the results, it is difficult to state there is a length effect within species, likely because of small sample size to describe very complex fish behavior.

Table 2. Summary of the results for different binomial generalized linear models (GLMs) carried out.

Predictors	AIC	Chi-Square	*p*-Value
Flow	197.10	0.0061	0.9379
Species	176.41	20.70	<0.0001
Species, fish length, flow	175.62	25.49	<0.0001
Species, fish length, species × fish length	175.45	25.66	<0.0001
Fish length	171.79	25.32	<0.0001

Passability for all species with migratory requirements in the basin and all size classes should be the objective in order to improve the performance of the fish ladder [29]. Nevertheless, according to the influence of fish body length in passage efficiency and taking into account that both species could reach sexual maturity with lengths less than 100 mm [26], it can be concluded that the fishway represents an obstacle for small fish upstream migration. Moreover, Iberian barbel and Northern straight mouth nase are obligate migrators in the basin and their optimal spawning habitat, with shallow current water areas and gravel bed [26], is located upstream of the dam considered. For that, it is essential to know migration patterns of target species which will require more monitoring [18].

The differences in the ability to overcome the fishway were also reflected in other parameters, such as number of attempts or delay at the fishway. Number of attempts for nase was, on average, four-fold higher than for barbel (H = 18.024, d.f. = 1, $p < 0.0001$; Figure 1b). For passage time, successful barbel needed 3.5 ± 2.9 h to travel the distance between both antennas whereas nase took 41.8 ± 51.4 h (H = 20.233, d.f. = 1, $p < 0.0001$). Taking into account the time needed to overcome the fishway from the first time of detection, nase exceeded by two orders of magnitude the time to overcome the fishway and to reach the reservoir with regard to barbel (H = 25.075, d.f. = 1, $p < 0.0001$). This time provides information on the migration delay, which can affect reproduction, and therefore, the viability of fish populations [19,30]. The fastest barbel spent 40 min ascending the fishway compared to 6 days for the slowest one; while for nase, delay varied between 106 min and 50 days (Figure 1c).

Moreover, differences in migration timing during the study year between species were observed. For barbel, movements were concentrated in May and June. For nase, the migration period extended until November, although since August no records have been detected at the top antenna (Figure 2). Upstream spawning migration of cyprinids typically occurs in spring, while downstream migration occurs in autumn [31]. However, tag detections in autumn did not correspond to downstream movements. Other researchers have also highlighted movement of Iberian cyprinids outside of the spawning season [20]. Thus, motivation to move upstream, which has been proposed as a key factor for passage efficiency [9], seemed to be more prolonged for nase. Nevertheless, hydraulics combined with physiological status of fish in autumn could hinder successful passage for this species [32]. In any case, longer monitoring time is needed in order to confirm those migration patterns and to find out if motivation is due to spawning or habitat exploration reasons.

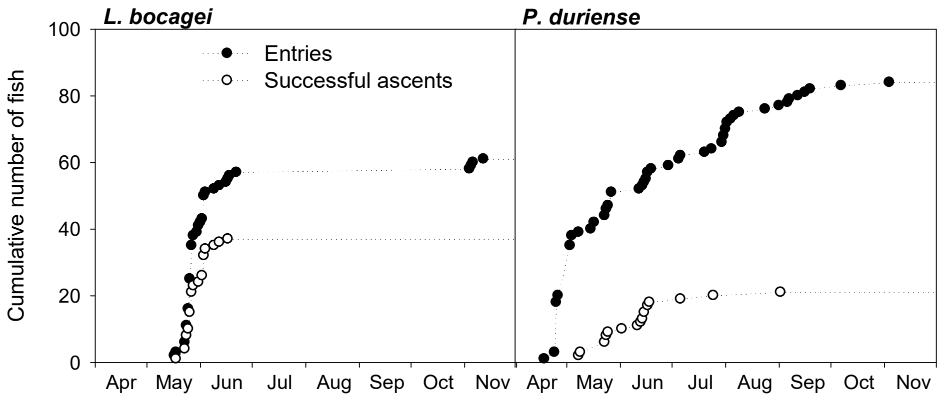

Figure 2. Cumulative number of different fish entering the fish ladder and successful ascents. First record for entries and last record for successful ascents were plotted.

The lack of tag detections of individuals attempting to move downstream suggests that fish do not use the fishway for downstream passage. Furthermore, six individuals tagged upstream of the dam were recorded at the fishway antennas for the first time ascending the fish ladder. Consequently, they used other ways to move downstream. It remains to be determined which of three possible pathways are used by fish moving downstream. These pathways include (1) the fish ladder, unlikely according to the results; (2) the spillway of the dam, which involves a free fall of, at least, 10 m; or (3) the power canal and passage through the turbines. We hypothesize the difficulty in identifying the entrance from the reservoir makes the fishway non functional for downstream migration.

Entrance efficiency was calculated according to movement of tagged fish just downstream from the dam (100–150 m) in 2017 (Table 1). It was 3.5% and 10.8% for barbel and nase, respectively, which was extraordinarily low, particularly because attraction efficiencies are usually higher than passage efficiencies [28]. Even though entrance efficiency would be related to attraction efficiency, to calculate the attraction of the fishway, an antenna should be placed before the entrance of the fish ladder (the exit of water) to detect those individuals approaching the fishway. However, recorded fish had already begun to ascend. Those results indicate a problem at the entrance of the fishway, either low attraction efficiency or a problem accessing the fish ladder. We hypothesize that flow regime would be related to low entrance efficiencies. River flow from April to November 2017 was, on average, 80% less than the previous year ($p < 0.0001$) and in 2017, 60% fewer individuals were detected at the top antenna, which may potentially be attributed to lower flows registered that year (Figure 3).

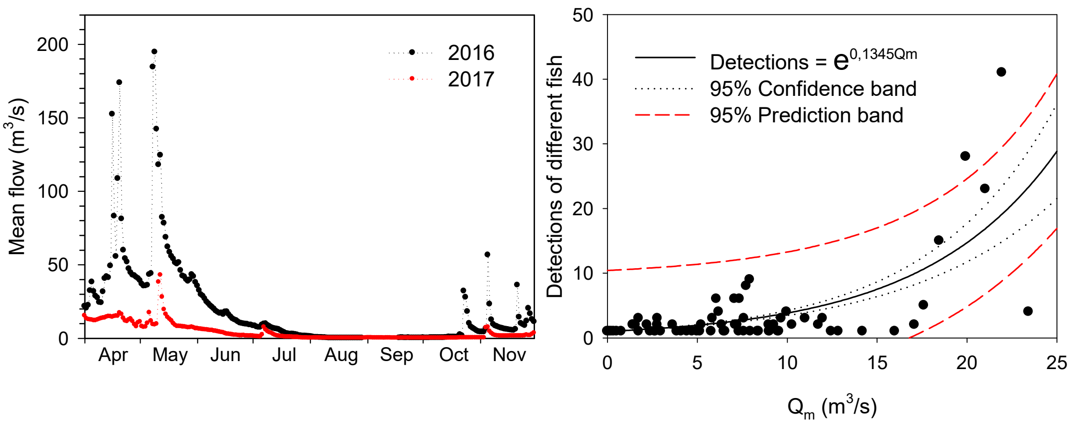

Figure 3. Daily mean river flow in 2016 and 2017 (left) and relationship between daily mean flow rate and top antenna detections (right). Flow was measured in a gauging station 5 km upstream from the dam.

2.2. Ecological Flow and Its Relevance Downstream of the Dam

General performance of the fish ladder seems to be positively correlated with flow rates (Figure 3). Note that, during the same period, 133 vs. 53 individuals were recorded at the top antenna in 2016 and 2017, respectively. At a location 200 m downstream of the fishway and between the dam and the hydroelectric power plant outlet, there is a natural waterfall that constitutes an obstacle for fish migration depending on the river flow (Figure 4). During tagging events, an unexpected decrease was observed from 2016 to 2017 in the Iberian barbel population. In spring 2016, 743 barbels were captured and tagged whereas in spring and summer 2017, only 57 individuals were caught and tagged between the fish ladder and the waterfall. Furthermore, several individuals had recent abrasion wounds, attributed to the passage through the waterfall.

Figure 4. Waterfall downstream of the dam. On the left, a photograph taken on 30 May 2017 with a mean flow rate of 2.59 ± 0.17 m^3/s. On the right, 30 August 2017 with a flow rate upstream of the dam of 0.021 m^3/s.

Set ecological flow during spawning migration (May and June), which is strictly fulfilled by the power station, is 2.5 m^3/s, while minimum flow must be 1.05 m^3/s the rest of the year. Discharge at the waterfall in May 2017 was, on average, 6.7 m^3/s. With these poor conditions, fish face serious difficulties negotiating the obstacle.

Nonetheless, this hypothesis should be tested with future monitoring. The next step should be focused on determining the minimum water flow necessary to ensure connectivity at the waterfall.

3. Materials and Methods

3.1. Study Site Overview

The study site is at a large dam located in the upper basin of the Tormes River (Salamanca, Spain). The Tormes river at the upper basin drains a watershed of 1853 km^2 and has mean annual discharge of 19.64 m^3/s. The regime is mainly pluvio-nival with a low waters period of three months (July to September). Only in years with high snow precipitations the regime changes to nivo-pluvial. Due to the geology of the basin, granitic rocks, heavy rains, and storms produce discharge peaks over 600 m^3/s for short periods (less than one week). The shape of the river is a succession of canyons with rapids, riffles, and pools and small open areas of run and glide waters.

The dam belongs to a hydroelectric power station, which has a turbine concession of 30 m^3/s and includes a concrete pool and weir fish ladder, which was enlarged in 2013. Between the dam and water discharge after the turbines there is an old gauging station (not operational) and a natural waterfall (Figure 5).

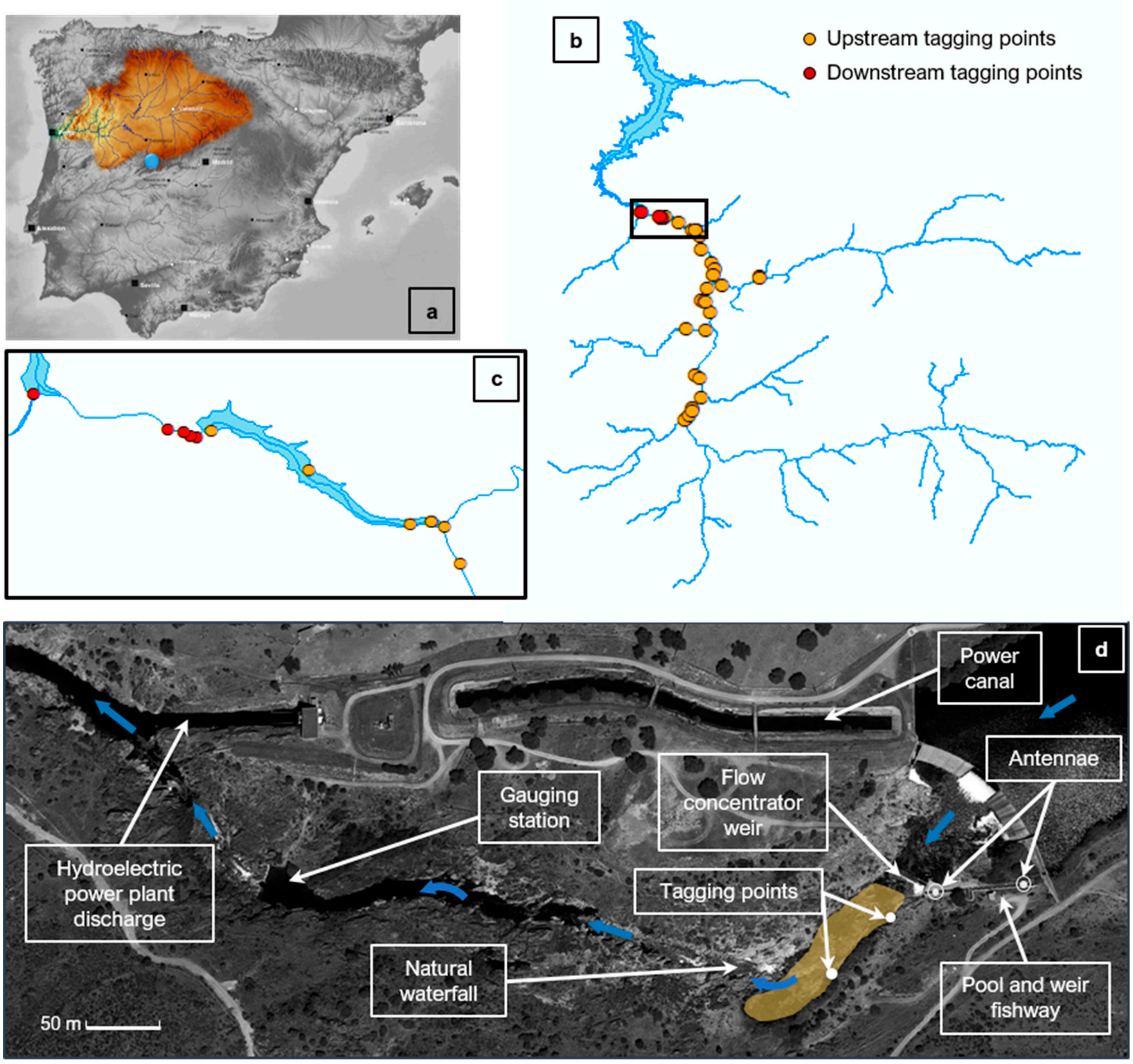

Figure 5. General view of the study area. (**a**) Location of Duero basin and Tormes river in the Iberian Peninsula (adapted from Port(u*o)s [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)]); (**b**) location of tagging points in the basin; (**c**) location of tagging points in the vicinity of the dam, and (**d**) satellite view of the study site. Blue arrows indicate flow river direction; yellow area indicates the electrofishing area just downstream the fishway.

The power station's fishway is a pool and weir fish ladder with successive pools connected by free (at the original ladder) and submerged notches (at the enlarged new ladder) and bottom offset orifices. Currently, it consists of 46 pools and the entrance from downstream of the fishway is located adjacent to a weir, which was constructed to concentrate flow and attract fish.

The height to overcome is 13.4 m with an average slope of 16.3% and a power dissipation of 160 W/m^3. Circulating flow in the fish ladder is 0.14 m^3/s and water drop between pools is 0.25–0.30 m. A detailed description of the fishway can be found in C.H.D. et al. [11].

3.2. Monitoring Study

Within the monitoring program of the upper Tormes basin, brown trout (*Salmo trutta*), Iberian barbel (*Luciobarbus bocagei*), Northern straight mouth nase (*Pseudochondrostoma duriense*), and Iberian chub (*Squalius carolitertii*) were captured by electrofishing along the main river and tributaries during several sampling events, annually from 2015 (May–June 2015 and May–June and September–October in 2016 and 2017) and tagged with 12-mm passive integrated transponder (PIT) tags (Biomark® FDX

HPT12). Fishes were sedated with MS-222 (10 mg/L) to avoid management stress. After tagging, fishes were released after anesthesia recovering within 25 m around of capture point. According to the size of the PITs, individuals larger than 80 mm were tagged. Tags were implanted in the abdominal cavity of individuals less than 150 mm fork length while sub-epidermal tagging was carried out on the larger-sized specimens. For each individual, species, fork length, and sex, when possible, were recorded. Currently, there are more than 8000 individuals tagged in the entire river basin (Table 3), although for this study only barbel and nase were considered since they are the most active species at the study site (note that 53% of all barbel and 25% of all nase were tagged downstream of the dam).

Table 3. Number of fishes tagged at the upper Tormes basin until December 2017. Downstream and upstream refers to the dam considered.

	S. trutta	*L. bocagei*	*P. duriense*	*S. carolitertii*
Total downstream tagged fish	6	1405	1133	3
Total upstream tagged fish	571	1228	3347	358
Downstream 2017 event tagged fish	2	71	418	1
Upstream 2017 event tagged fish	226	210	1376	106
100–150 m downstream 2017 event tagged fish	2	57	277	1

Pass-through antennas (Biomark®, Boise, ID, USA) were placed at the 3rd and 39th pools where the water exits the fishway in order to analyze passage efficiency and entrance efficiency of the ladder. The placement of the antennas was chosen regarding the lack of interferences by metallic structures at the top of the fishway and avoiding missing detections during high flow events due to overflooding of the bottom fishway. Although the fishway was monitored from June 2016 (by the top antenna), the 3rd pool antenna began operations in March 2017; therefore, only detections from March to December 2017 were considered for estimates of efficiency.

Passage efficiency was calculated as the percentage of fishes entering the fishway that passed successfully, while entrance efficiency was estimated as the percentage of fishes tagged and released 100–150 m downstream from the fish ladder during the 2017 tagging events that reached the first antenna. Only those tagged fish were considered for entrance efficiency because we are certain that these fish were in the vicinity of the fishway.

Migratory delay was calculated as the time between the first detection until the last one for successful passage individuals, whereas passage time was estimated as the time between the last detection at one antenna and the first detection at the other. To calculate the number of attempts it is necessary to define what an attempt is. A new attempt was deemed to have occurred when the difference between two detections was twice the mean time for a successful passage of each species had lapsed.

3.3. Statistical Analyses

Results were statistically evaluated using SPSS 25 package (IBM corp., Armonk, NY, USA). Data normality and homoscedasticity were checked with a Shapiro–Wilk W test and a Levene test, respectively. Intraspecific and interspecific comparisons for individual length, passage time, migratory delay, and number of attempts were performed with non-parametric Kruskall–Wallis test. Generalized linear models (GLM) were performed to assess passage success or failure according to species, length, and flow, using a binomial approach with logistic regression. Relationship between mean river flow and antenna detections was made fitting the curve to an exponential growth equation using Sigmaplot for Windows version 10.0 (Systat Software Inc., San Jose, CA, USA). Statistics were considered significant at $p < 0.05$.

4. Conclusions

During the conditions evaluated, the passage efficiency of the pool and weir fish ladder was 40% with differences among species (barbel 60%; nase 25%). Nase and small barbel appear to have problems overcoming the fishway. Available data suggest that the fish ladder is not sufficient or suitable for downstream migration, probably due to the placement of the entrance from the reservoir. Most likely, fish use freefall over the dam or enter the canal, passing through the power station turbines. Very poor fish entrance was estimated in 2017 (less than 10%). However, the low flow rates during the spawning season in 2017, especially between the dam and the power station outlet, could negatively affect both attraction of the fishway and fish behavior. A longer time series of data will allow the calculation of performance efficiencies under different conditions. Environmental flows set for the power station are not sufficient to solve problems that natural obstacles downstream of the dam create for fish migration, especially for years as dry as 2017.

Author Contributions: Conceptualization, G.G.; Data curation, A.P., R.A., G.G.; Formal Analysis, A.P.; Funding Acquisition, C.M.; Investigation, A.P., R.A., G.G.; Methodology, A.P., R.A., G.G.; Project Administration, C.M., G.G.; Supervision, C.M., G.G.; Validation, A.P., G.G.; Visualization, A.P.; Writing—Original Draft Preparation, A.P.; Writing—Review and Editing, A.P., G.G.

Funding: This work was funded by Confederación Hidrográfica del Duero (Programa de mejora de cauces).

Acknowledgments: The authors acknowledge Salto de San Fernando S.L. their cooperation to facilitate this study. Special thanks to Peter MacKinnon and Gary Thiede for their suggestions reviewing the manuscript and to Nick Bouwes for his significant ($p < 0.0001$) statistics help.

Conflicts of Interest: The authors declare no conflict of interest.

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