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EFFICIENCY OF FISH LADDERS FOR NEOTROPICAL ICHTHYOFAUNA

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ABSTRACT

The reproductive strategies of potamodromous fish of the Plata basin involve upstream migration and passive downstream movements of eggs and larvae for dozens of kilometres. At the end of the downstream movements, the fry need marginal lagoons or bays in order for their development to be successful. The construction of reservoirs, often in series, has interrupted the movements, and is perhaps the main factor in the decrease in the abundance of migratory fish in the basin. In an attempt to lessen the impact on the upstream migrations, fish passages (floodgates, elevators and mainly ladders) have been constructed and, despite limitations, they have functioned with relative success. Some studies show the continuity of the migration of individuals captured downstream and released into the reservoir. However, downstream migration of adult migratory species is made difficult by the fact that they are, in this phase, generally reophylic (live in running water) and occupy only the upper stretches of reservoirs (fluvial and transitional zones). It would be feasible only in short reservoirs and with a very short residence time. The fact that reservoirs present calm waters, more transparency and contain a large number of small fish could delay the passive drift of eggs and larvae, exposing them to intense predation and/or promoting their settling toward deeper water, where the conditions of oxygenation are generally critical. In the remote event that the larvae reach the dam, most of them cannot be attracted to ladders (elevators are conceived only for upstream movements) or driven away from the reservoir vicinities, in as much as they have passive movements and would therefore suffer great mortality if they passed through turbines or a spillway. In reservoirs with large free stretches upstream and endowed with ample natural floodplain areas, transposition can be an useful instrument in the maintenance of genetic heterogeneity since the number of transposed specimens does not compromise the stocks of the lower stretch. These limitations, connected to the strategy of neotropical fishes, make fish passages in most situations an inadequate instrument for preservational management. Copyright © 2002 John Wiley & Sons, Ltd.

KEY WORDS: fish ladder; migratory fish; neotropical fish; fish management

INTRODUCTION

Beginning in the 1960s there was an increase in the construction of reservoirs in Brazil, whose function was mainly the generation of electricity. These reservoirs currently generate around 95% of Brazil's electrical energy (Sugunan, 1997). Most of the dams occur in the southern and southeastern regions, especially in the Paraná River. There are around 130 dams higher than 10 m in this basin, of which 26 possess areas greater than 100 km^2. In addition to this, many reservoirs were constructed in series.

One of the most obvious impacts of the successive dams constructed in the Paraná River basin is on the migratory fish population. The interruption of the migratory routes of these species, separating the environment of initial development, spawning and growth is, in large part, responsible for the virtual disappearance of large migrators in the upper stretches of the Paraná River basin (Agostinho and Julio, 1999).

Attempts to lessen the impacts or their consequences on fishing consisted of stocking, control of fishing activity and construction of structures that facilitated fish passing the dams, but all have considerable ambiguities in the principles and operation. In this paper we discuss fish ladders and their efficiency as a measure of conservation, management or mitigation for the neotropical region.

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LEGAL BASES AND PRIOR STUDIES

Fish ladders have a long history, dating back at least 300 years (Clay, 1995). The first fish ladder in Brazil was constructed in 1911 at the Itaipava Dam, in the Pardo River (upper Paraná River). That ladder is 7 m high and it was considered successful in the passage of fish (Godoy, 1985). At the beginning of the 1920s, a second ladder was constructed at the Cachoeira das Emas Dam, in the Mogi Guaçu River. Although only 3 m high, it was badly proportioned and began to function only when it was modified in 1942 (Godoy, 1985).

The construction of fish ladders gained force, however, starting from 1927, when their installation became a legal requirement (Law no. 2250/SP, of 12/28/1927; Decree no. 4390, of 03/14/1928). The legislation prescribed that 'all those who, for any purpose, dam the waters of rivers, streams and brooks are obliged to construct ladders that allow the free ascent of fishes'. After this law, construction of fish ladders became widespread but failed to take into account the interactions between their technical characteristics (type, slope, flow, position in relation to the axis of the dam, etc.) and the nature of the ichthyofauna present.

The above law was relaxed by the first federal fishing code (Decree Law 794, of 19 October 1938) which in its article 68 prescribed facilities for fish passes or hatcheries (stocking) as an obligatory complement to dams, according to the evaluation of the Hunting and Fishing Service. The legal documents that followed made the construction of ladders the object of analyses, initially by the former SUDEPE, the Federal Agency for the Development of Fisheries (Decree Law 221 of 28 February 1967), and by the Environmental Agency (IBAMA) such as a piece of the environmental impact report (Decree Law 88351/83 and 99274/90).

Recently, as a result of public pressure, ladders and other passage facilities are again being discussed, along with the controversy surrounding the efficiency of these structures. However, even with innumerable opportunities to evaluate the efficiency of these facilities, they were rarely monitored.

MANAGEMENT CONTEXT

Various kinds of structure and mechanism—mainly ladders, elevators and floodgates of various types—are constructed worldwide to facilitate the transposition of fish upstream and downstream of dams. Floodgates (Salto Grande, Uruguay River) and elevators (Yacyreta, Paraná River, Argentina-Paraguay) are operated with relative success in the Plata basin. Except for the elevators in implementation in the Porto Primavera Dam (São Paulo-Mato Grosso do Sul, Brazil), the construction of these facilities is restricted to ladders in small rivers.

Given the mistakes committed even now, it is advisable that the decision-making process in the construction of the facility, whatever it may be, should be preceded by a broad survey in the basin, identifying spawning areas, growth and initial development of the species of interest and their position in relation to the axis of the dam.

The type of strategy of the local fish species and the position of the critical areas may advise the undertaking or determine the characteristics of the ladder. In addition to this, the decision should contemplate not only the ladder, but also different aspects related to the management process. Thus, the ladder should be seen only as a management tool. However, other aspects such as the appropriateness of the design, continuity of the reproductive migration, and finally descending migration and passage through the dam should be considered.

EFFICIENCY OF UPSTREAM TRANSPOSITION

The design of the fish pass is highly relevant to the efficiency of its functioning, affecting its use by fish and selecting species. The literature shows an ample range of designs that should be tested for certain species and which, provided that some limitations are respected, do not constitute a fundamental problem for the passage of fish.

The principal limitation in fish passes seems to be the fish attraction mechanisms at the beginning (entrance) of the ladder. If the entrance is not readily recognized, the fish may stay in their vicinity for a prolonged time, delaying migration and compromising spawning, or they may never even access it.

The dam itself already constitutes a source of stress for the fish, which for centuries have reached their spawning areas without this type of obstacle. Added to this source of stress are the physical and chemical conditions of the water downstream (temperature, velocity, water quality, etc.). Thus, the entrance to the fish pass should be recognized in the shortest time possible so that the migratory process has continuity. Due to the fact that the attractions are of a hydraulic nature, their operation should be sufficiently flexible to make them more effective than the water flows of the spillways and outlet tunnel. As this operation involves the 'loss' of water for generation, its functioning can conflict with the hydroelectric use of the reservoir, particularly in plants that have limitations in flow. The fact that the ascending migrations occur, in general, in periods of rising flow, reduces this conflict.

Another aspect to be considered refers to the location of the transposition structure, which should be compatible with the fish admission facility and the position of the rest of the components of the dam, especially the spillway and water entrance for the turbines. Its functioning can be compromised by the relative position of the ladder, in as much as the transposed fish may be taken by the water capture and returned to the initial point, passing through the turbines or spillways and being subjected to intense mortality.

An additional complication in relation to the exit of fish from the transposition structure is the water level fluctuation in a reservoir. This is a great challenge, especially in reservoirs intended to regulate flow, for which level fluctuations are implicit in their functioning.

The available data in the literature about the efficiency of ladders in the transposition of fish lack details and a more systematized study. As in other undertakings or actions connected to the management of fishing resources in reservoirs, most of the fish ladders were never monitored, despite the high investments and efforts involved.

Data obtained by the Environmental Department at the Itaipu Binacional on the experimental ladder below Itaipu Dam (height, 27.3 m; length, 155 m; velocity, 2.2 m/s) reveal that 28 of the 68 species registered downstream of the dam ascend the ladder to some extent.

Among the migratory species of medium to large size, the curimba (*Prochilodus lineatus*), the mandi (*Pimelodus maculatus*) and the piapara (*Leporinus elongatus*) stand out (Figure 1). The frequency of the other large migrators, such as the dourado (*Salminus maxillosus*), the pintado (*Pseudoplatystoma corruscans*) and the piracanjuba (*Brycon orbignyanus*), on the ladder was very low. Other species, such as the pacu (*Piaractus mesopotamicus*) and the jaú (*Paulicea luetkeni*), present in the downstream area, were never registered in this apparatus. Restrictions imposed on the size (or height) of the fish by the dimensions of the superficial and

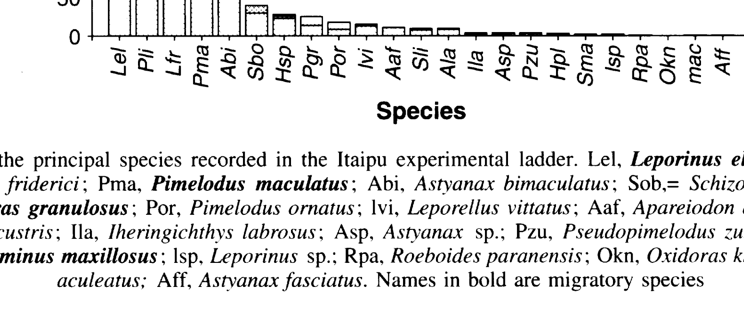

Figure 1. Frequency of the principal species recorded in the Itaipu experimental ladder. Lel, ***Leporinus elongatus***; Pli, ***Prochilodus lineatus***; Lfr, *Leporinus friderici*; Pma, ***Pimelodus maculatus***; Abi, *Astyanax bimaculatus*; Sob,= *Schizodon borellii*; Hsp, *Hypostomus* sp.; Pgr, ***Pterodoras granulosus***; Por, *Pimelodus ornatus*; Ivi, *Leporellus vittatus*; Aaf, *Apareiodon affinis*; Sli, ***Sorubim lima***; Ala, *Acestrorhynchus lacustris*; Ila, *Iheringichthys labrosus*; Asp, *Astyanax* sp.; Pzu, *Pseudopimelodus zungaro*; Hpl, ***Hemisorubim platyrhynchos***; Sma, ***Salminus maxillosus***; Isp, *Leporinus* sp.; Rpa, *Roeboides paranensis*; Okn, *Oxidoras knerii*; mac, *Megalancistrus aculeatus*; Aff, *Astyanax fasciatus*. Names in bold are migratory species

Table I. Evaluation of the efficiency of fish transposition on some fish ladders in Brazilian reservoirs (Quirós, 1988)

River/Dam	Difference in level (m)	Functioning	Source
Pardo/Itaipava	7	+	Godoy (1985)
Mogi Guaçu/Cachoeira Emas	5	+	Godoy (1985)
Sorocaba/Faz. Cachoeira	6	+	Godoy (1985)
Tibagi/Salto Mauá	6	+	Godoy (1985)
Mogi Guaçu/Cach. de Cima	3	−	Castello (1982)
Paranapanema/Piraju	16	+	Godoy (1985)
Tijuco/Salto do Moraes	10.5	−	Godinho *et al.* (1991)
Jacuí/Amarópolis	5	+	Godoy (1985)
Jacuí/Anel de Dom Marco	5	+	Godoy (1985)
Jacuí/Fandango	5	+	Godoy (1985)
Taquari/Bom Retiro do Sul	9	+	Godoy (1985)
Itapocu/Graramirim	2	−	Godoy (1985)
Poço do Barro/P. Barro	15	+	Godoy (1985)

bottom openings of the crossbeams that separate the tanks on the experimental ladder have been mentioned by Borghetti *et al.* (1994).

Reophylic species not considered large migrators and juvenile forms of large species were registered far from the ladder. Borghetti *et al.* (1994), in previous studies performed on the same ladder, relate that the motivation of the fish in ascending it was of a reproductive nature, based on the elevated frequency of individuals in advanced maturation. The data obtained later, however, do not allow consideration of reproduction as the principal motive of the ascent, given the large number of juvenile and other individuals recorded that were unprepared to spawn (Fernandez and Oro, 1996).

The evaluation made by Godoy (1985) and other authors (Table I) suggests that at least for dams lower than 16 m, ladders are efficient means of transposition. Errors in the design show that even those ladders whose purpose was to overcome small differences in level do not function. It is known, however, that ladders are, in general, selective. This aspect is superficially broached in existing studies.

In addition to fish ladders, other kinds of facilities for the passage of fish in dams were constructed in South America. Borland-type floodgates and fish elevators stand out. In the case of the fish floodgate of the Salto Grande Reservoir (Uruguay River), Quirós (1988) reports that although some species ascend it, functional deficiencies related to the attraction of fish, flow adjustments and hydrologic cycle are present.

The Yacyretá (Paraná River) fish elevators, on the other hand, have had satisfactory efficiency in the transposition of migratory fishes (CONVÊNIO SECYT, 1996). In the period January 1995 to July 1996, the transposition involved 36 species, or 44% of the species registered in the stretch immediately downstream. It is estimated that in the year 1995, 1 767 000 individuals had been transferred, corresponding to a biomass of approximately 252 tons. The most successful species in the transposition by these elevators were the mandi (*Pimelodus maculatus*; = *P. clarias*), with 72% of the total, followed by the armado (*Pterodoras granulosus*), with 12%. Other large migratory species, including those that were not registered on the Itaipu Binacional experimental ladder, were transposed.

THE CONTINUITY OF REPRODUCTIVE MIGRATION

A doubt that permeated the discussions about the efficiency of fish ladders until a short time ago was the capacity of a fish in migration against the current, once through the dam, to continue migrating in the lentic environment of the more internal areas of the reservoirs. Tagging and recapture studies conducted in the Itaipu Reservoir seem to clarify the matter (Fuem.Nupelia/Itaipu Binacional, 1990; Agostinho *et al.*, 1993).

Curimbas (*P. lineatus*) and armados (*P. granulosus*), originating from the stretch immediately downstream of the Itaipu Dam, were tagged and released upstream and captured above the reservoir, about 180 km from

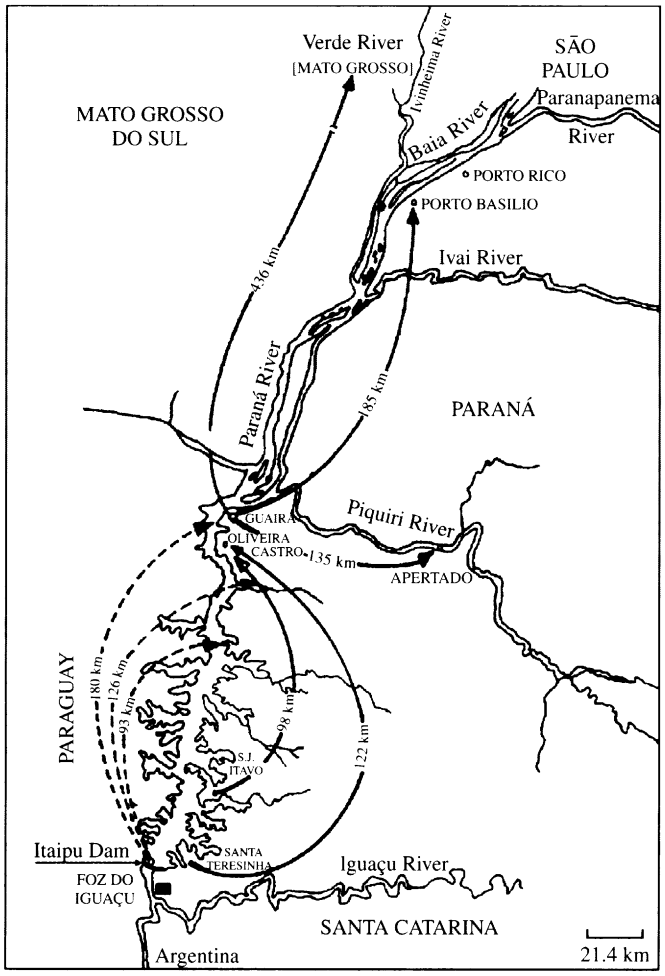

Figure 2. Ascending movements of *P. lineatus* starting from the Itaipu Reservoir. Individuals captured downstream from the Itaipu Dam (dashed line) and released in the reservoir were recaptured 180 km above it

the release site (Figure 2). The movement of these fish in the body of the reservoir was slower than that of the others released directly into the river (Agostinho *et al*., 1993). However, the average velocity and distance travelled by the individuals caught downstream and released upstream were greater (seven of the nine individuals with greater moving/velocity (7855 tagged individuals; 315 recaptured) belonged to this category) than for those captured just above the dam and released at the same site (Agostinho *et al*., 1994). The results suggest that the orientation of the fish in the body of the reservoir does not constitute a limitation on the efforts of fish transposition upstream.

DESCENDING MIGRATION AND PASSAGE THROUGH THE DAM

A relevant aspect in the decision about fish ladder construction is the recruitment of fish for the population strata located downstream. In order that the transposition system has significance in the maintenance of populations or stocks of fish, it is necessary that the spawning results extend to the lower stretches. This theme is as critical or more critical than the ascent of the fish to the upper stretches and has been systematically ignored in the planning of the means of transposition (Quirós, 1988; Clay, 1995).

In this context, two aspects are critical to neotropical ichthyofauna: (i) the larvae and juveniles should cross the entire body of the reservoir up to the dam; and (ii) they should pass through the dam with minimum mortality. In relation to the first, it is opportune to remember that neotropical migratory fishes, especially those of the Plata basin, spawn in upper areas of the basin, in periods of increasing water levels (beginning of floods), high or elevated temperatures and turbid waters (that reduce the preying on eggs and larvae by visual predators). Eggs and larvae migrate passively with the current for tens of kilometres while they develop (Agostinho and Gomes, 1997; Nakatani *et al.*, 1997; Agostinho *et al.*, 2000). The larvae are taken by the floods to lateral lagoons and bays (nurseries), where they stay for various periods of time (up to two years, depending on the species). But later the juveniles disperse, integrating the adult stocks, generally downstream (Agostinho *et al.*, 2000).

The degree of interference of a reservoir in this process depends basically on its position in relation to the critical areas of the fish life cycle (spawning area, natural nurseries and feeding area).

If the upstream stretch of the reservoir is extensive, contains unchanged spawning sites and presents extensive flood areas, it is expected that the migratory species, which remain upstream, would maintain their stocks, with losses in genetic diversity over time. In this case, the transposition would have as its objective only the maintenance of genetic diversity, with possible damage to the stocks downstream of the dam.

In another scenario, the upstream stretch would be short and contain spawning sites without relevant flood areas. In this case, the stock of large migrators would be drastically reduced, with the possibility of being eliminated from the upstream area after some years. Transposition, in this way, could allow spawning in upstream areas. Eggs and larvae would, however, be conveyed to a reservoir whose waters present low velocity and high transparency, allowing intense predation. Eggs and larvae, even of large migratory species, such as the pintado (*P. corruscans*) or the dourado (*S. maxillosus*), are naturally preyed on by fish with other feeding habits, including foraging species, such as insectivores or planktophages (Agostinho and Gomes, 1997). Although there is not any information in the specialized literature, it is improbable that the eggs and larvae reach the dam before being totally decimated by the abundant populations of foraging fish that dominate the reservoirs, whose waters are very transparent, especially in the more internal areas. The construction of fish passages in the latter case represents an additional source of impact to the success of the reproduction of individuals with the chance of spawning in segments lower than the dam.

A different situation occurs among the salmonoids, fish of the northern hemisphere, on which the concept of transposition, in Brazil, was based. Their migration towards the sea is active and occurs in very large sizes (smolt or yearling = 10 to 15 cm), drastically reducing predation.

In the event, here considered remote, of the larvae that originate from high points in the basin reaching the dam, their transposition downstream is another aspect that makes the transposition structures a questionable instrument of preservation of the stocks of fish in the basin.

The losses in the passage through the dam vary in accordance with the route taken by the fish. In general, the losses through the spillway are different from those of the turbines (Clay, 1995). In the spillway, mortality depends on its height and design, varying from 0.2% to 99%. However, other factors related to the exit mechanism are related to the slaughter, such as the abrasion against the surface, sudden changes of pressure, rapid changes in current direction (shearing effect) and supersaturation (Ruggles, 1980). These factors can, however, be minimized by the spillway design.

Mortality in the turbines, a difficult problem to solve, results from (i) mechanical damage due to contact with fixed or mobile equipment, (ii) damage induced by rapid pressure changes and exposure to conditions of low pressure, (iii) damage by amputation, resulting from extreme turbulence, and (iv) damage by cavitation resulting from exposure to areas with a partial vacuum. In general, the damage occurs in a combined form.

The type of turbine used is also related to the cause and intensity of the losses in fish passage. In general, Francis-type turbines cause greater mortality from mechanical damage than the Kaplan type (Clay, 1995), which has greater space between the blades and is operated at a lower velocity. The Kaplan type, however, has greater problems with the other types of damage. Both can cause all types of damage if operated with less than maximum efficiency.

Various techniques applicable to fish in descending migration, aiming at removing them from the water capture of the turbines or the spillway area of influence, have been developed. Among these, behavioural barriers stand out, as do curtains of air bubbles, sloping currents and lights of various types, sound barriers, electricity and screens. These resources were, however, developed for the salmonoids, which are active swimmers and can be repelled by adverse artificial conditions. The same is not probable for the larvae, which descend passively with the water.

A physical barrier to avoid larvae entrance presents the problem of the accumulation of residues and debris, demanding intense maintenance work. In some way, it requires an alternative route for the passage of fish downstream (by pass). It involves, generally, the use of mesh screens sufficiently small to impede the passage of large fish and not block the circulation of water. It is difficult to imagine the installation of mesh screens sufficiently small to keep back larvae some millimetres in diameter. In any case, if kept back, the current against the wall of the screen could crush them.

Studies of eggs and larvae distribution conducted by Nupélia/Universidade Estadual de Maringá in the first kilometre below the Itaipu Reservoir demonstrate that: (i) the larvae registered originated from the reservoir, as demonstrated by the fact that they belonged to essentially two species that reproduce in this environment (*Hypophthalmus edentatus* with 90% of the total and *Plagioscion squamosissimus* with 8.5%), with their adult forms and those in reproduction absent from the stretch below the dam; (ii) the rate of damaged larvae (mutilated and crushed) reached values more than 30% of the total, suggesting high mortality, in as much as those fragmented were not kept back by the ichthyoplankton net; and (iii) no large migrator larvae were recorded. The results, although demonstrating that many larvae can reach downstream of the dam (through the turbines or spillway), suggest that the occasional larvae that penetrate the reservoir starting from the lateral tributaries do not get to breach the more internal areas of the reservoir.

DISCUSSION AND EVALUATION

It appears that fish ladders at the beginning were constructed without the necessary technical or scientific knowledge of the undertaking or of the fish, increasing the risk of failure and waste of resources, efforts and opportunities. For example, as a result of legislation, fish ladders were constructed just above a naturally uncrossable waterfall (70 m), such as in the Negros Creek (São Carlos–São Paulo), or in streams where the ichthyofauna was composed of only sedentary species (Ihering, 1930; Charlier, 1957).

However, some studies in the literature have reached different conclusions in relation to the efficiency of the passages. Thus, Godoy (1957, 1975) gives an account of the great efficiency of the 3 m high fish ladder constructed in Cachoeira das Emas (Pirassununga–São Paulo) that was the object of many studies. Borghetti *et al.* (1993, 1994) and Fernandez and Oro (1996) relate that a great number of characiform and siluriform species ascend an experimental ladder (approximately 27.3 m high) located just below the Itaipu Dam. Godinho *et al.* (1991), on the other hand, confirms the low efficiency of the ladder (10.8 m high) installed near the dam of the Salto Morais Reservoir, in the Tijuco River. Godoy (1985) reports that between the years 1957 and 1980, 23 dams with ladders were constructed in northeastern Brazil, all with satisfactory functioning in the ascent of fish. The studies report, however, only the efficiency in allowing the fish to pass the dams or the capacity of different species to ascend ladders. They do not deal with the effectiveness of the passage in preserving the stocks in the basin.

Thus, lessons related to fish passages have not yet been learned. For example, the fish passages recently constructed in large Brazilian dams are still generating controversy. Most of the reservoir has its backwater close to another dam and does not have relevant nursery areas. Probably, the fish ladder (under construction) and elevator (functioning) at Porto Primavera Dam (CESP, 2000) will generate a large impact on the downstream recruitment of fish fauna and fisheries. Large amounts of fish, that could be reproducing in the free stretch below (six out of ten main species in the Itaipu fishery use this area to spawn and grow; Agostinho and Zalewski, 1996), are passing upstream where spawning and nursery areas are restricted. A similar situation could be occurring with the fish ladder located in Canoas I Dam, in the Paranapanema River (a tributary of the Paraná River), operated by the Duke Company.

Despite scarce and incomplete knowledge, the results published to date indicate that South American experience of fish passages, based on the North American models for salmonoids, was not profitable. Money and effort were lost, as well as opportunities to study. Besides this, it is possible that those facilities could be responsible for additional impacts. Thus, considering the high investment needed for the construction of fish passages, the decision on their construction should be preceded by a broad evaluation of their efficiency in the maintenance of stocks, including possible negative impacts downstream from where they are. Decision-makers should consider not only the efficiency of the passage, but additionally the existence of spawning habitats and nurseries upstream and the effect of removing fish from downstream.

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