RIVER RESEARCH AND APPLICATIONS

River Res. Applic. **28**: 504–512 (2012)

Published online 18 July 2011 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/rra.1557

EXISTING AND FUTURE CHALLENGES: THE CONCEPT OF SUCCESSFUL FISH PASSAGE IN SOUTH AMERICA

P. S. POMPEU,[a]* A. A. AGOSTINHO[b] and F. M. PELICICE[c]

[a] *Department of Biology, Federal University of Lavras, Lavras, Minas Gerais, Brazil*
[b] *Department of Biology/NUPELIA, Maringá State University, Maringá, Paraná, Brazil*
[c] *NEAMB, Federal University of Tocantins, Porto Nacional, Tocantins, Brazil*

ABSTRACT

Most of the large rivers of South America are impounded mainly for hydropower production. The construction of fish passes has been one of the strategies adopted by Brazilian authorities and the energy sector to diminish the effects of these barriers on migratory fish communities. Despite the high investments and efforts involved, most facilities have been considered ineffective for conservation purposes. Decades of poor monitoring and the lack of specific studies have limited our knowledge on the real role of fish passes. Efficiency has been frequently defined as the proportion of fish that ascend a fish passage facility, compared to the shoal size that reaches the dam. Inspired by the notion that fishes accumulated below the dam need to migrate upstream, the quantity of fish passed upstream historically indicated successful management, as generally inferred by the fish abundance inside the fish pass. We propose a new concept for estimating fish pass efficiency for South American rivers, based on the capability of the fish pass to maintain viable populations. This broader approach is necessary because knowledge of fish habitats below and above the pass, plus the feasibility of downstream movements of eggs, larvae and adults through the reservoir and past the dam, is needed for assessing whether a fish pass is working as a conservation tool. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: conservation tool; fish migration; fishway; neotropical fishes

Received 14 September 2010; Revised 1 April 2011; Accepted 2 June 2011

INTRODUCTION

Fisheries management in South American reservoirs has been based on stocking, fisheries' harvest limits and construction of fish passes. The experience of Brazil, where most of this information originated, illustrates this scenario. Until the 1950s, the main purpose of Brazilian management programmes was to ensure the movement of migratory fish through dams by constructing fish ladders, mostly in small rivers. Since the 1960s, the companies have been obliged to protect threatened fish species either by incorporating fish ladders in the dam design for facilitating migration or by creating breeding facilities to produce fingerlings of the affected native species to be stocked in the reservoir (Sugunan, 1997; Agostinho *et al*., 2010).

Although these actions have been performed throughout the country for years, we lack rigorous studies that evaluate their efficiency in recuperating species and threatened populations, sustaining fish populations and cost–benefit analyses (Vieira and Pompeu, 2001). The low fishery yield, the precarious conservation status of native population in southern and south-eastern Brazil reservoirs and the significant reduction of migratory species (Agostinho *et al*., 1994; Cesp, 1996) clearly indicate that this strategy is not satisfactory (Agostinho *et al*., 2002, 2004).

The construction of fish passes was the oldest management strategy adopted by the Brazilian energy sector to diminish the effects of barriers on fish communities, especially migratory species. The first fish ladder in Brazil was constructed in 1911, at the Itaipava Dam, in the Pardo River, upper Paraná Basin (Godoy, 1985). In 1927, the construction of fish ladders became a legal requirement in São Paulo State (Agostinho *et al*., 2002). With the increasing number of hydropower dams in the 1960s, fish passes became required by the legislation of other states. As a result, dozens of Brazilian dams have been equipped with ladders and other such facilities (Agostinho *et al*., 2008).

Despite the substantial fiscal investments and engineering efforts, the ecological effectiveness of most fish passes in South America was never assessed (Agostinho *et al*., 2002). Some fish passes have been considered ineffective to conserve migratory species (Godinho *et al*., 1991; Oldani *et al*., 2007), and others are reported to be promoting regional fishery collapses (Lopes *et al*., 2007; Pelicice and Agostinho, 2008). Decades of poor monitoring and the lack of specific studies have limited our knowledge on the real

*Correspondence to: P. S. Pompeu, Department of Biology, Federal University of Lavras, 37200-000, Lavras, Minas Gerais, Brazil.
E-mail: pompeu@ufla.br

role of fish passes. The studies performed in South America mainly concentrated on the selectivity of individual fish ladders on the ascending fish (Fontenele, 1961; Godoy, 1987; Godinho *et al*., 1991; Agostinho *et al*., 2002, 2007b, 2007c; Fernandez *et al*., 2004; Alves, 2007; Makrakis *et al*., 2007b; Bizzotto *et al*., 2009), focusing on their selectivity concerning the ascending fish. In addition, efficiency has been frequently defined as the proportion of fish that ascend a fish passage facility compared to the school size immediately below the dam (Novak *et al*., 2003; Agostinho *et al*., 2007c) and was evaluated for at least two fish lifts (Oldani and Baigun, 2002; Pompeu and Martinez, 2007). Inspired by the notion that fishes need to migrate upstream, the quantity of fish passed upstream, whatever the species, historically indicated successful management. As a consequence, the role of passes in aiding population recruitment and completion of life cycles has been largely neglected.

In this paper, we propose a new concept for evaluating fish pass efficiency in South America, based on the potential of the fish pass to maintain viable populations regionally, meant by a positive trend in abundance. This broader approach is necessary, because the current criterion (successful upstream passage) does not assure fish conservation (Kraabøl *et al*., 2009). Expanding on Fausch *et al*. (2002), we emphasize that fish habitat components below and above the pass, as well as the feasibility of downstream movements of eggs, larvae and adults, must be included in evaluating fish pass effectiveness as conservation tools. Although this manuscript mainly considers fish passage in South America, it could also have applications worldwide, because many biases in fish passage research that occur globally have been highlighted (Roscoe and Hinch, 2010).

THE LIFE CYCLE OF SOUTH AMERICAN MIGRATORY SPECIES

Although few South American species migrate long distances (Petrere, 1985; Godinho and Godinho, 1994; Carolsfeld *et al*., 2003), they are the most important species for commercial (Goulding, 1979; Bittencourt and Cox-Fernandes, 1990; Godinho, 1993) and artisanal fisheries because of their larger size, abundance and market value (Northcote, 1978; Hoeinghaus *et al*., 2009). Migration occurs in a wide range of South American taxa, although the most conspicuous migrations are principally associated with Characiformes and Siluriformes. Nonetheless, short-distance migrations and fish movements over ecological time are critical components of meta-population dynamics, evolution and speciation (Fausch *et al*., 2002).

A general pattern for reproductive migration includes breeder displacement to the upper areas of the basin (>1000 km, Godoy, 1975) during the beginning of the wet season, a period of high temperatures and turbid waters (that reduce predation on eggs and larvae by visual predators). Spawning occurs in flowing waters (e.g. the main stem and upper tributaries), where eggs drift downstream for kilometres while they develop and hatch (Nakatani *et al*., 2001; Agostinho *et al*., 2002). Floods take larvae to nursery grounds in floodplains (Agostinho *et al*., 2003) or tributary mouths flooded by high waters in the main river channel (Zaniboni Filho and Schultz, 2003). After spawning, spent adults migrate downstream, followed by the downstream drift of larvae and fry (Petrere, 1985). Adults also enter flooded areas, where they feed and improve their condition (Gomes and Agostinho, 1997). Some of these species remain in floodplain lakes for 1 or 2 years (Agostinho *et al*., 1993), returning to the river in subsequent flood seasons. Although this pattern may be dominant, there are several variations, including basins where migratory fish complete their life cycles using in-river habitats, where floodplain is absent (Godinho and Kynard, 2009), such as the Uruguay River (Zaniboni Filho and Schultz, 2003). The most complex movements are observed in the Amazon region, involving adult migration upstream and downstream for spawning or feeding, in tributaries and in the main channel (Carolsfeld *et al*., 2003).

Migratory dynamics also include estuarine and marine environments. Some large Amazonian catfishes run more than 3000 km between estuaries in Belém-Pará and headwaters in upper tributaries (Barthem and Goulding, 1997). The dourada *Brachyplatystoma rousseuaxii*, for example, reaches the upper courses of white water rivers to spawn, showing a remarkable spatial variation in population structure in the Amazon basin (Barletta *et al*., 2010). Juveniles (6 cm TL) drift to the Amazon estuary and flooded forest lakes (nursery areas), located in downstream reaches. Juveniles dominate the population up to 1200 km from the estuary, whereas adults compose at least 70% of the population above 1800 km. Only adults can be found 3000 km from the estuary (Alonso and Picker, 2005). Diadromous species (mainly galaxiids) are confined to the more austral part of South America (Moyle and Cech, 1988), where they have an amphidromous behaviour (i.e. reproduction in fresh water, larvae migrate to the sea and juveniles return to fresh water) (*stricto sensu*, McDowall, 2007). However, some species, found mainly in the Brazilian coastal basins, can also be considered amphidromous (*lato sensu*), migrating from the sea to the rivers for feeding purposes (Pompeu and Martinez, 2006).

In short, migration involves complex behaviours that are still not fully understood for many species, but research has shown that specific habitats for spawning, nursery and feeding are a common need among migratory fish species. Migration is perhaps the evolutionary solution

DOI: 10.1002/rra

that maximized population persistence, by allowing the use of appropriate habitats according to the demands of different stages of species life histories. If populations are impeded access to these habitats, individual fitness and reproduction success are predicted to decrease. In the context of dams and reservoirs that fragment habitats along rivers, a successful fish pass should restore access to such critical habitats (Pelicice and Agostinho, 2008) that are biologically meaningful and enable the population to maintain itself.

EVALUATION OF SOUTH AMERICAN FISH PASSES

There is little information concerning the efficiency of South American fish passes. The vast majority of fish passes were never monitored, or if they were monitored, the monitoring was not based on valid protocols, or the study designs and results were unavailable.

We reviewed the literature and located information concerning the ability of facilities at 16 locations for providing fish passage, including ladders, lifts, locks and trap and truck systems (Table I; Figure 1). Selectiveness and dominance in ascension were the most common aspects evaluated. Most studies reported a negative selectivity <40%, meaning that >60% of the species found downstream of the dam were observed using the pass at some time. On the other hand, a high dominance was observed in all passes, because few species (3–5) usually represent >80% of the passed individuals.

The negative selectiveness of six fish passes was evaluated. This selectiveness corresponded to the per cent of species entering the passes but not reaching the reservoir. In the lifts and trap and truck systems, we may consider that all the species entering the system are successfully passed. However, the pass may cause mortality from contact with the moving structures and confinement in the fish chamber. In the Santa Clara case, the percentage of dead or injured fish was estimated as 0.5% and 0.8% for the total fauna and for the migratory group, respectively (Pompeu and Martinez, 2007). There is variation between fish ladders, but in general, approximately half the fauna that enters the mechanism does not reach the exit or even the reservoir (Table I). The selectiveness tends to be slightly lower for highly migratory species, probably because of their greater swimming capabilities.

In South America, quantitative estimates of the upstream efficiency of fish passes are available only for the Santa Clara trap and truck system and the Yaceretá fish lift. Both indicate that a small proportion of the downstream fish are passed. Quantitative estimates require tagging and recapture programs or detection at another fish pass downstream, where the number of passed individuals are estimated. Such estimates can be used as target population size information. Even in North America, where monitoring is more frequent, such studies are scarce. For a database of 213 projects with at least one published paper concerning fish passage, information on the number of fish using the mechanism was available for only eight, and only three provided sufficient data for quantitative efficiency estimates (Novak *et al.*, 2003). In South America, indirect inferences of the efficiency of upstream passage were obtained for the fish ladder at Igarapé, where a minimum of 14% of the individuals marked downstream were recaptured upstream, and for the ladders at Canoas I and II, where a high upstream passage is presumed due to the decline of downstream populations.

Upstream fish pass selectivity has a complex origin. It depends largely on the behaviour and ability of each species in locating and accessing the facility, together with hydraulic aspects, structural design and operation (Larinier, 2002a; Knaepkens *et al.*, 2006; Lundqvist *et al.*, 2008; Godinho and Kynard, 2009; Roscoe and Hinch, 2010). To improve fish ascension, different behaviours, needs and local dynamics must be considered, which is a great challenge in neotropical rivers, given the rich diversity of fish species. Engineers and biologists, however, have achieved considerable progress in improving upstream passage (Larinier, 2002b; Mallen-Cooper and Brand, 2007; Mallen-Cooper and Stuart, 2007; Stuart *et al.*, 2008a, 2008b), and the knowledge of the swimming performance of neotropical fishes has markedly increased (Santos *et al.*, 2007, 2008, 2009; Castro *et al.*, 2010), aiding further improvements.

Evaluations of downstream passage in South America are scarce. Adult downstream passage was evaluated in only four reservoirs (see Table I), indicating that such an event is null or extremely reduced. There are several reasons that could explain this pattern. Lack of attractiveness and problems with site location probably occurs, but the rheophilic behaviour of South American fish likely plays a major role. Attraction to lotic habitats induces fish to avoid areas with lentic characteristics, especially large reservoirs. Mark–recapture and tagging studies indicate the following behaviours. Fish released in areas influenced by large dams tended to avoid the lentic environment, migrating to upper lotic reaches or tributaries (Antonio *et al.*, 2007; Makrakis *et al.*, 2007a). Fish passed upstream are able to migrate through the impounded area (Antonio *et al.*, 2007), but once in lotic upper sites, it is likely that there is little incentive to return downstream. Even if fish sought to migrate downriver, they would have to travel across huge lentic environments, where flows are low or nonexistent. Fish, therefore, remain in upper lotic stretches of the impoundment (Agostinho *et al.*, 2007b) and do not reach the dam, where they could access the fish pass, assuming that it could effectively pass fish downriver. In other words, rheophilic behaviour likely precludes downstream migration through large dams and their reservoirs.

DOI: 10.1002/rra

Table I. Some functioning aspects evaluated in fish passes installed in South America, such as selectivity (% of species not registered in the fishway, based on fish surveys in the region), selectivity along the passage (% of species passed to the reservoir or that reached upper parts of the pass, based on the number of species registered in the fish way), upstream passage efficiency (% of fish passed upstream, based on the number of fish recorded below the dam), and downstream passage (qualitative/quantitative indications of downstream passage)

Hydropower dam (height)	Fish passage type (length)	Basin	Reservoir area, km^2	Local situation (Figure)	Selectivity (dominance?)	Selectivity along the passage: Total fauna	Selectivity along the passage: Migratory	Upstream passage efficiency: Total fauna	Upstream passage efficiency: Migratory	Downstream passage: Adults	Downstream passage: Eggs/larvae	References
Canoa Quebrada (25 m)	Ladder (400 m)	Amazon	11.7	?	– (yes)	–	–	–	–	–	–	Junho *et al.* (2007)
Peixe Angical (39 m)	Ladder (575 m)	Tocantins	294	A	59% (yes)	53%	38%	–	–	–	Unlikely	Freitas *et al.* (2009)
Lageado (37 m)	Ladder (874 m)	Tocantins	630	A	37% (yes)	48%	53%	–	–	Unlikely	Unlikely	Agostinho *et al.* (2007b, 2007c)
Igarapé (6 m)	Ladder (?)	São Francisco	<1	A	? (?)	–	–	–	14%	–	–	Alves (2007)
Risoleta Neves (49 m)	Trap and Truck	Doce	3.5	A	71% (yes)	–	–	–	–	–	–	Braga *et al.* (2007)
Santa Clara (60 m)	Trap and Truck	Mucuri	7.5	D	3% (yes)	0.5%	0.8%	3.1%	7.0%	Very reduced	Possible	Pompeu (2005), Pompeu and Martinez (2007)
Salto Moraes (11 m)	Ladder (78 m)	Paraná	–	?	17% (yes)	98%	–	–	–	–	–	Godinho *et al.* (1991)
Funil (45 m)	Fish lift	Paraná	33.5	E	8% (yes)	–	–	–	–	–	Unlikely	Pereira and Pompeu (2010), Suzuki (2009)
Igarapava (18 m)	Ladder (282 m)	Paraná	36	B	44% (yes)	–	–	–	–	–	–	Bizzotto *et al.* (2009), Casali *et al.* (2010)
Canoas I (29 m)	Ladder (210 m)	Paraná	30	B	21% (yes)	–	–	Probably high	Probably high	No	Reproduction areas absent	Britto and Sirol (2005), Hoffmann *et al.* (2005), Lopes *et al.* (2007)
Canoas II (25 m)	Ladder (228 m)	Paraná	22	F	28% (yes)	–	–	Probably high	Probably high	No	Reproduction areas absent	Britto and Sirol (2005), Hoffmann *et al.* (2005), Lopes *et al.* (2007)
Porto Primavera (22 m)	Ladder (520 m)	Paraná	2250	B	54% (yes)	–	22%	–	–	–	Reproduction areas absent	Makrakis *et al.* (2007a)
Itaipú (196 m)	Ladder (155 m)	Paraná	1350	A	59% (yes)	15%	11%	–	–	–	–	Fernandez *et al.* (2004)
Itaipú (196 m)	Channel (10 km)	Paraná	1350	A	10% (yes)	58%	41%	–	–	–	–	Makrakis *et al.* (2007b), Okada *et al.* (2005)
Yaceretá (21 m)	Fish lift	Paraná	1600	?	32% (yes)	–	–	1.88%	0.68%	–	–	Oldani and Baigun (2002), Oldani *et al.* (2007)
Salto Grande (30 m)	Fish locks	Uruguay	800	?	25% (yes)	–	–	–	–	–	–	Oldani *et al.* (2007)

Aspects that were not investigated are marked with '–'.
Local situation = see Figure for code explanation (A–F). Categorization is based on present author's judgement.
Dominance = a few species (3–5) summing more than 70% of captures.

DOI: 10.1002/rra

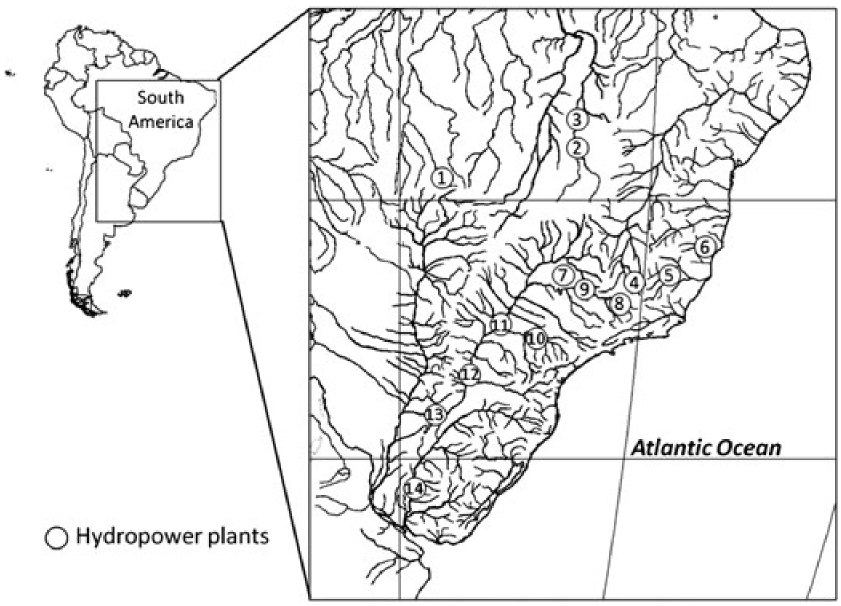

Figure 1. Location in South America of the evaluated fish passes (1—Canoa Quebrada; 2—Peixe Angical; 3—Lageado; 4—Igarapé; 5—Risoleta neves; 6—Santa Clara; 7—Salto Moraes; 8—Funil; 9—Igarapava; 10—Canoas I and Canoas II; 11—Porto Primavera; 12—Itaipú; 13—Yaceretá; 14—Salto Grande)

Downstream passage of young fish (eggs and larvae) must be considered also. Recent studies indicate, however, that the spatial distribution of young is markedly affected by dams (Agostinho *et al*., 2007b; Freitas *et al*., 2009), especially when large reservoirs are created, with evidence that drifting eggs and larvae disappear in the lentic areas of the impoundment, and do not reach the dam. However, selected ichthyoplankton species are capable of crossing small reservoirs, such as Santa Clara (7.5 km^2), contributing to downstream recruitment (Pompeu, 2005).

There is consensus that fish passes built to promote upstream passage cannot provide downstream passage (Larinier and Travade, 2002). However, these movements are necessary to avoid the depletion of downstream stocks. Therefore, besides upstream passage concerns (e.g. selectivity along passage and quantitative efficiency), the necessity of downstream passage must be considered, because available evidence suggests that selectiveness and mortality are even higher than that occurring during fish ascension (Table I).

THE OBJECTIVES OF A FISH PASS

According to Therrien and Bougeois (2000), considerations about fish passage efficiency must include all the species of interest, the number of obstacles in the river and their location and the biological and conservation objectives of the fish pass. For migratory species, depending on the dam location, it is essential that the obstacles are passed and that the fish reach the spawning area at the right time for successful recruitment. For resident species with trophic migrations or short reproductive migrations, the major biological objective should be to avoid population fragmentation. In this case, a fish passage mechanism is considered efficient if it is successfully used by a substantial number of individuals but not necessarily by the entire population (Larinier, 1998). To conserve long-distance migratory species, it is important for the fish to be able to locate the entrance of the mechanism and pass the dam and to evaluate the effectiveness of the pass in maintaining the migratory species populations, an aspect rarely evaluated (Cada and Francfort, 1995; Agostinho *et al*., 2004). Upstream passage alone is not indicative of population recruitment and conservation of stocks, because fish may ascend the pass but recruitment may not occur.

Therefore, the objectives of a fish pass should be directly related to the spatial distribution of critical habitats, such as reproduction sites and nursery areas downstream or upstream. The distribution of these habitats must be previously evaluated to help understand the possible role and relevance of a pass in maintaining the recruitment of wild stocks or if it is applied to secondary objectives (e.g. genetic exchange, artificial stocking). Studies of selectiveness and efficiency (upstream and downstream) must complement the understanding of the potential of the passage as a management tool.

Considering the location of these critical habitats for maintaining the life cycle of migratory species, at least six situations occur (Figure 2). Most fish passes studied were placed in dams included in group A (Table I), where large lotic reaches occur upstream and downstream and include

DOI: 10.1002/rra

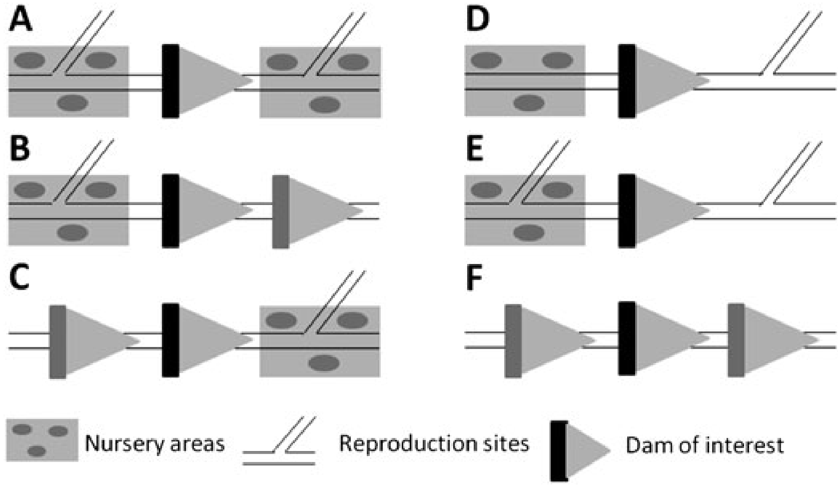

Figure 2. Six possible locations of critical habitats (reproduction sites and nursery areas) in relation to a dam with a fish pass installed. A) Conditions for spawning (e.g. lotic reaches and tributaries) and recruitment (e.g. floodplains and lateral habitats) exist upstream and downstream of the dam. B) Such conditions only occur downstream or upstream (C). D) Reproduction sites are located only upstream and nurseries only downstream. E) Migratory fish spawn upstream and downstream, but the nursery areas are located only downstream. F) Critical habitats are completely absent in the reach

floodplains. Because the populations may become self sustaining in the long term in both regions, these passes would become questionable or justified only for the maintenance of the genetic flow between the populations. Reduced success of downstream movements of fish could result in decreased downstream fish stocks (Lopes *et al*., 2007), which justifies performing stock-strength evaluations. However, the efficiency of passage upstream was not evaluated in any of the cases and effective downstream movements of adults, eggs and larvae seem improbable in all reservoirs where this aspect was evaluated (Table I).

Some fish passes were installed immediately downstream of other dams. In this case, the conditions for reproduction and recruitment are found only further downstream (situation B). Passes operating in these conditions may function as ecologic traps (Pelicice and Agostinho, 2008), because they remove the fish from healthy environments and transport them to sites with no critical habitats. The Igarapava ladder has been justified by the maintenance of fish stocks in the reservoir for fishing (artificial stocking), functioning as a source-sink system (Godinho and Kynard, 2009). The implementation of a pass in this case would not help the recruitment dynamics, because the fish are transported to areas of lower environmental quality. If any purpose different from the conservation of natural stocks justifies the construction of a mechanism, fish passage must be controlled and rigorously monitored.

No studied fish passes were located at dams where the conditions for recruitment of migratory species are found only upstream of the dam (situation C). Although a device in this case is not necessary, it could represent a chance to return individuals of migratory species accidentally carried downstream, or imprisoned downstream by the damming, to areas where they could reproduce. The populations of migratory species would not be able to maintain self-sustainable populations downstream of the dam, which means that these species would be more likely to disappear from the reach.

Among the studied fish passes, only the trap and truck system at Santa Clara represents the condition where migratory species spawn upstream and rear downstream of the dam. (situation D). This is the only case study where maintenance of connectivity between areas upstream and downstream is crucial for maintaining migratory species populations. The situation at the Funil fish lift is very similar, although spawning sites may also be found downstream (situation E). In both situations, the fish pass is appropriate if upstream migration is equivalent to downstream fish movement. If the descendent migration does not happen, the pass loses its value to recruitment conservation. In this case, alternative measures are more appropriate (e.g. rehabilitation of spawning habitats downstream and development areas upstream). Therefore, if there is high selectiveness, management may be difficult and expensive. A dam that fragments or separates spawning and development areas causes severe impacts, especially when it creates a huge reservoir. To avoid this situation, the distribution of critical habitats should be thoroughly evaluated during the inventory of the hydroelectric potential of the reach.

There are extreme cases where critical habitats are absent downstream and upstream of the dam. This is common in rivers having a series of dams in sequence, such as the large tributaries of the Paraná River. Even in this case, where there are no lotic reaches downstream or

DOI: 10.1002/rra

upstream (situation F), fish passage facilities have been installed, such as the fish ladders at Canoas II dam. Passes aiming to maintain recruitment are irrational in this situation if they do not reconnect critical fish habitats in the river by incorporating passes at all the dams. If passes were built, selectiveness studies would be necessary at each dam, because the fish moving upstream must return to lower reaches at some portion of their life cycles. If these aspects are neglected, the construction of a fish pass may jeopardize the conservation status of the fish.

Among all the configurations presented in Figure 2, there are very few cases where the passes aid recruitment dynamics, despite their objective to conserve migratory fish. The lack of attention to the distribution of critical habitats causes some inconsistencies between the potential of the management action and its objectives, with a huge chance of failure or even generation of further negative impacts. This can be observed in the ladders installed in the Paranapanema River. Information on selectiveness and efficiency is crucial to show the functioning and limitations of the device; ignoring such flaws leads to failure of this management strategy, even in cases where passage may seem opportune.

THE FUTURE OF FISH PASSES IN SOUTH AMERICA AND THE EFFICIENCY CONCEPT

The few studies evaluating fish passes in South America have indicated problems related to their functioning, such as selectivity in providing upstream passage, and the virtual absence of downstream migration. In addition, passes have been installed without considering the distribution of critical habitats. As a consequence, most passes fail to aid recruitment of migratory species. Such observations conflict with the usual approach, which considers the number of ascending fish as a measure of management success. This concept of successful management demands a fundamental revision; a broader approach is needed, and the concept of 'maintaining viable populations' must replace the concept of 'successful fish ascension'.

Survival through fish pass systems needs to be included in a discussion of success but is rarely considered. Independent of dam location relative to critical habitats, failures in downstream passage represent the major obstacle to the success of fish passes as management and conservation tools. The lack of downstream migration is worrisome because it causes additional impacts on the fish fauna. If fish passes fail to reconnect sites fragmented by the dam, and free movements are not restored, facilities will work as one-way migratory routes—allowing only ascension. In this case, stocks may be redistributed along the river, causing population imbalances or the subtraction of stocks from downstream, as observed at the Canoas dams on Paranapanema River (Agostinho *et al*., 2007a; Lopes *et al*., 2007).

Depending on the spatial distribution of critical spawning and rearing habitats, severe impacts are likely in the form of source-sink dynamics (Godinho and Kynard, 2009) or ecological traps (Pelicice and Agostinho, 2008). Because most large rivers in South America are serially impounded, there is substantial risk of confining populations within short reaches lacking critical fish habitats. The probability of creating ecological traps and other impacts is much more likely than usually expected. Managers and the general public must understand that passes that fragment connection among critical habitats will have little significance for management and conservation and instead will be detrimental to fish at considerable economic expense.

However, the aspects of fragmented critical habitats and precluded downstream movement have been frequently neglected, even where fish passes pass tons of fish annually. Downstream fish passage is a major knowledge gap concerning effective fish passage worldwide (Pavlov *et al*., 2002), and post-departure monitoring is required to assess the fitness consequences of passage (Roscoe and Hinch, 2010). However, the needs of passing larvae and eggs in South America are an additional challenge, because depending on the reservoir area, they cannot reach the dam region, and downstream bypasses would be ineffective. Serious management programs, which employ fish passes to restore natural recruitment in basins impaired by large dams, must consider that downstream passage is as important as upstream migration, and the desired numbers of fish passed upstream must depend on the downstream passage feasibility.

We propose that 'maintaining viable populations' is the only ecologically rational concept for fish passage efficiency appropriate for South American rivers, because passes installed in different hydropower dams will have different goals. This concept means that populations are self-maintained in the wild, with the aid of the passes (e.g. recruitment, genetic exchange, demographic inputs). We repeat that most fish passes were never monitored, most of the limited number of studies were incomplete, primary ecological information concerning fish migration and life histories is lacking, and we are aware of no long-term studies on migratory fish populations both upstream of a reservoir and downstream of its dam. Such information is needed to determine if some fish passes allow migratory fishes to complete their life cycles, thereby working as a valuable conservation tool.

ACKNOWLEDGEMENTS

We thank Robert M. Hughes for the English review and suggestions on the manuscript. The manuscript was also benefited by two anonymous referees.

DOI: 10.1002/rra

REFERENCES

Agostinho AA, Vazzoler AEAM, Gomes LC, Okada EK. 1993. Estratificación espacial y comportamiento de Prochilodus scrofa en distintas fase del ciclo de vida, en la planície de inundación del alto rio Paraná y embalse de Itaipu, Parana, Brasil. *Revue D'Hydrobiologie Tropicale* **26**: 79–90.

Agostinho AA, Júlio HF Jr, Petrere M Jr 1994. Itaipu reservoir (Brazil): impacts of the impoundment on the fish fauna and fisheries. In *Rehabilitation of Freshwater Fisheries*. Cowx IG (ed.). Fishing News Books: Oxford, UK; 171–184.

Agostinho AA, Gomes LC, Fernandes DR, Suzuki HI. 2002. Efficiency of fish ladders for neotropical ichthyofauna. *River Research and Applications* **18**: 299–306.

Agostinho AA, Gomes LC, Suzuki HI, Júlio HF Jr 2003. Migratory fish from the upper Parana River basin, Brazil. In *Migratory Fishes of South America: Biology, Social Importance and Conservation Status*, Carolsfeld J, Harvey B, Ross C, Baer A (eds). World Fisheries Trust, The World Bank and The International Development Research Centre: Victoria; 19–98.

Agostinho AA, Gomes LC, Latini JD. 2004. Fisheries management in Brazilian reservoirs: lessons from/for South America. *Interciencia* **29**: 334–338.

Agostinho AA, Gomes LC, Pelicice FM. 2007a. *Ecologia e Manejo de Recursos Pesqueiros em Reservatórios do Brasil*. EDUEM: Maringá, Paraná; 501 p.

Agostinho AA, Marques EE, Agostinho CS, de Almeida DA, de Oliveira RJ, Melo JRB. 2007b. Fish ladder of Lajeado Dam: migrations on one-way routes? *Neotropical Ichthyology* **5**: 121–130.

Agostinho CS, Agostinho AA, Pelicice FM, Almeida DA, Marques EE. 2007c. Selectivity of fish ladders: a bottleneck in Neotropical fish movement. *Neotropical Ichthyology* **5**: 205–213.

Agostinho AA, Pelicice FM, Gomes LC. 2008. Dams and the fish fauna of the Neotropical region: impacts and management related to diversity and fisheries. *Brazilian Journal of Biology* **68**: 1119–1132.

Agostinho AA, Pelicice FM, Gomes, LC, Júlio Junior HF. 2010. Reservoir fish stocking: when one plus one may be less than two. *Natureza & Conservação* **08**: 103–111.

Alonso JC, Picker L. 2005. Dinâmica populacional e estado atual de exploração de piramutaba e dourada. In *O manejo da pesca dos grandes bagres migradores: piramutaba e dourada no eixo Solimões-Amazonas*, Fabré NN, Barthem RB (eds). ProVárzea/IBAMA: Maringá; 21–28.

Alves CBM. 2007. Evaluation of fish passage through the Igarape Dam fish ladder (rio Paraopeba, Brazil), using marking and recapture. *Neotropical Ichthyology* **5**: 233–236.

Antonio RR, Agostinho AA, Pelicice FM, Bailly D, Okada EK, Dias JHP. 2007 Blockage of migration routes by dam construction: can migratory fish find alternative routes? *Neotropical Ichthyology* **5**: 177–184.

Barletta M, Jaureguizar AJ, Baigun C, Fontoura NF, Agostinho AA, Almeida-Val VMF, Val AL, Torres RA, Jimenes-Segura LF, Giarrizzo T, Fabré NN, Batista VS, Lasso C, Taphorn DC, Costa MF, Chaves PT, Vieira JP, Corrêa MFM. 2010. Fish and aquatic habitat conservation in South America: a continental overview with emphasis on neotropical systems. *Journal of Fish Biology* **76**: 2118–2176.

Barthem R, Goulding M. 1997. *Os bagres balizadores: ecologia, migração e conservação de peixes amazônicos*. Sociedade Civil Mamirauá: Tefé.

Bittencourt MM, Cox-Fernandes C. 1990. Peixes migradores sustentam pesca comercial. *Ciência Hoje* **11**: 20–24.

Bizzotto PM, Godinho AL, Vono V, Kynard B, Godinho HP. 2009. Influence of seasonal, diel, lunar, and other environmental factors on upstream fish passage in the Igarapava Fish Ladder, Brazil. *Ecology of Freshwater Fish* **18**: 461–472.

Braga ALC, Silva MOB, Hojo RES, Resende GF. 2007. Fish passage through the fishway system on Risoleta Neves Dam Power Plant in Doce River, MG. In *Proceedings of the International Symposium on Fish Passages in South America*, Pompeu PS, Santos HA, Alves CBM (eds). UFLA: Lavras; 91–96.

Britto SGC, Sirol RN. 2005. Transposição de peixes como forma de manejo: as escadas do Complexo Canoas, médio rio Paranapanema, bacia do Alto Rio Paraná. In *Ecologia de Reservatórios: Impactos Potenciais, Ações de Manejo e Sistemas em Cascata*, Nogueira MG, Henry R, Jorcin A (eds). Rima: São Carlos; 285–304, 459 p.

Cada GF, Francfort JE. 1995. Examining the benefits and costs of fish passage and protection measures. *Hydro Review* **14**: 47–55.

Carolsfeld J, Harvey B, Ross C, Baer A. 2003. *Migratory Fishes of South America: Biology, Social Importance and Conservation Status*. IDRC/World Bank: Victoria, Canada.

Casali RCV, Vono V, Godinho HP, Luz RK, Bazzoli N. 2010. Passage and reproductive activity of fishes in the Igarapava fish ladder, Grande River, southeastern Brazil. *Rivers Research and Applications* **26**: 157–165.

Castro MA, Santos HA, Sampaio FAC, Pompeu PS. 2010. Swimming Performance of the Small-Sized Characin Bryconamericus stramineus (Characiformes: Characidae). *Zoologia* **27**: 939–944.

Cesp. 1996. *Aspectos Limnológicos, Ictiológicos e Pesqueiros de Reservatórios da CESP no período de 1986 a 1994*. Companhia de Energia do Estado de São Paulo: São Paulo; 81 p.

Fausch KD, Torgersen CE, Baxter CV, Hiram WL. 2002. Landscapes to riverscapes: bridging the gap between research and conservation of stream fishes. *Bioscience* **52**: 483–498.

Fernandez DR, Agostinho AA, Bini LM. 2004. Selection of an experimental fish ladder located at the dam of the Itaipu Binacional, Paraná River, Brazil. *Brazilian Archives of Biology and Technology* **47**: 579–586.

Fontenele O. 1961. Escadas de Peixes nos Açudes do Nordeste Brasileiro. *Boletim da Sociedade Cearense de Agronomia* **2**: 11–21.

Freitas IS, Marques EE, Melo JRB, Araújo ES, Pinto MDS. 2009. Composição e abundância do ictioplâncton na escada de Peixe Angical e suas imediações. In *Reservatório de Peixe Angical: bases ecológicas para o manejo da ictiofauna*, Agostinho AA, Pelicice FM, Marques EE (eds). RiMa: São Carlos; 159–164.

Godinho AL. 1993. E os peixes de Minas em 2010? *Ciência Hoje* **16**: 44–49.

Godinho HP, Godinho AL. 1994. Ecology and conservation of fish in southeastern Brazilian river basins submitted to hydroelectric impoundments. *Acta Limnologica Brasiliensia* **5**: 187–197.

Godinho AL, Kynard B. 2009. Migratory fishes of Brazil: life history and fish passage needs. *Rivers Research and Applications* **25**: 702–712.

Godinho HP, Godinho AL, Formagio PS, Torquato VC. 1991. Fish ladder efficiency in a southeastern Brazilian river. *Ciencia e Cultura* **43**: 63–67.

Godoy MP. 1975. Peixes do Brasil. Subordem Characoidei : bacia do rio Mogi Guassu. Editora Franciscana: Piracicaba-SP. 4 v.

Godoy MP. 1985. *Aquicultura—Atividade Multidisciplinar, Escadas e Outras Facilidades para Passagens de Peixes, Estações de Piscicultura*. Eletrosul—Centrais Elétricas do Sul do Brasil S.A.: Florianópolis.

Godoy MP. 1987. A Escada de Peixes de Cachoeira de Emas, Rio Mogi Guassu, Estado de São Paulo, Brasil. *Com. Mus. Ciênc. PUCRS* **43**: 139–151.

Gomes LC, Agostinho, AA. 1997. Influence of the flooding regime on the nutritional state and juvenile recruitment of the curimba, *Prochilodus scrofa*, Steindachner, in upper Paraná River, Brazil. *Fisheries Management and Ecology* **4**: 263–274.

Goulding M. 1979. *Ecologia da pesca do rio Madeira*. CNPq/INPA: Manaus; 172 p.

Hoeinghaus DJ, Agostinho AA, Gomes LC, Pelicice FM, Okada EK, Latini JD, Kashiwaqui EAL, Winemiller KO. 2009. Effects of river impoundment on ecosystem services of large tropical rivers: embodied energy and market value of artisanal fisheries. *Conservation Biology* **23**: 1222–1231.

DOI: 10.1002/rra

Hoffmann AC, Orsi ML, Shibatta OA. 2005. Diversidade de peixes do reservatório da UHE Escola Engenharia Mackenzie (Capivara), Rio Paranapanema, bacia do alto rio Paraná, Brasil, e a importância dos grandes tributários na sua manutenção. *Iheringia, Série Zoologia* **95**: 319 – 325.

Junho RAC, Ferreira FAM, Vono V, Assis A. 2007. Vertical slot fishway at Canoa Quebrada small hydroelectric powerplant in central Brazil. In *Proceedings of the International Symposium on Fish Passages in South America*, Pompeu PS, Santos HA, Alves CBM (eds). UFLA: Lavras; 20 – 26.

Knaepkens G, Baekelandt K, Eens M. 2006. Fish pass effectiveness for bullhead (*Cottus gobio*), perch (*Perca fluviatilis*) and roach (*Rutilus rutilus*) in a regulated lowland river. *Ecology of Freshwater Fish* **15**: 20 – 29.

Kraabøl M, Johnsen SI, Museth J, Sandlund OT. 2009. Conserving iteroparous fish stocks in regulated rivers: the need for a broader perspective! *Fisheries Management and Ecology* **16**: 337 – 340.

Larinier M 1998. Upstream and downstream fish passage experience in France, fish migration and fish bypasses. In *Proceedings from the Symposium on Fish Migration and Fish Bypasses Channels*. University of Agricultural Sciences: Vienna.

Larinier M. 2002a. Location of fishways. *Bulletin Français de la Pêche et de la Pisciculture* **364**: 39 – 53.

Larinier M. 2002b. Pool fishways, pre-barrage and natural bypass channels. *Bulletin Français de la Peche et de la Pisciculture* **364**: 54 – 82.

Larinier M, Travade F. 2002. Downstream migration: problems and facilities. *Bulletin Français de la Pêche et de la Pisciculture* **364**: 181 – 201.

Lopes CM, Almeida FS, Orsi ML, Britto SGC, Sirol RN, Sodré LMK. 2007. Fish passage ladders from Canoas Complex—Paranapanema River: evaluation of genetic structure maintenance of *Salminus brasiliensis* (Teleostei: Characiformes). *Neotropical Ichthyology* **5**: 131 – 138.

Lundqvist H, Rivinoja P, Leonardsson K, McKinnel S. 2008. Upstream passage problems for wild Atlantic salmon (*Salmo salar* L.) in a regulated river and its effect on the population. *Hydrobiologia* **602**: 111 – 127.

Makrakis S, Makrakis MC, Wagner RL, Dias JHP, Gomes LC. 2007a. Utilization of the fish ladder at the Engenheiro Sergio Motta Dam, Brazil, by long distance migrating potamodromous species. *Neotropical Ichthyology* **5**: 197 – 204.

Makrakis MC, Miranda LE, Makrakis S, Xavier AMM, Fontes HM, Morlis WG. 2007b. Migratory movements of pacu, *Piaractus mesopotamicus*, in the highly impounded Paraná River. *Journal of Applied Ichthyology* **23**: 700 – 704.

Mallen-Cooper M, Brand DA. 2007. Non-salmonids in a salmonid fishway: what do 50 years of data tell us about past and future fish passage? *Fisheries Management and Ecology* **14**: 319 – 332.

Mallen-Cooper M, Stuart IG. 2007. Optimising Denil fishways for passage of small and large fishes. *Fisheries Management and Ecology* **14**: 61 – 71.

McDowall RM. 2007. On amphidromy, a distinct form of diadromy in aquatic organism. *Fish and Fisheries* **8**: 1 – 13.

Moyle PB, Cech JJ Jr 1988. *Fishes: An Introduction to Ichthyology*. Prentice Hall: New Jersey.

Nakatani K, Agostinho AA, Baumgartner G, Bialetzki A, Sanches PV, Makrakis MC, Pavanelli, CS. 2001. *Ovos e larvas de peixes de água doce: desenvolvimento e manual de identificação*. EDUEM: Maringá-PR.

Northcote TG. 1978. Migratory strategies in production in freshwater fishes. In *Ecology of Freshwater Fish Production*, Gerking SD (ed.). Blackwell Scientific Publications: Oxford; 326 – 359, 520 p.

Novak J, Loar J, Cada G. 2003. Evaluation of mitigation effectiveness at hydropower projects: fish passage, draft report. Division of Hydropower Administration and Compliance Office of Energy Projects Federal Energy Regulatory Commission. Technical report. 64 p.

Okada EK, Agostinho AA, Gomes LC. 2005. Spatial and temporal gradients in artisanal fisheries of a large Neotropical reservoir, the Itaipu Reservoir, Brazil. *Canadian Journal of Fisheries and Aquatic Sciences* **62**: 714 – 724.

Oldani NO, Baigun CRM. 2002. Performance of a fishway system in a major South American dam on the Parana River (Argentina–Paraguay). *River Research and Applications* **18**: 171 – 183.

Oldani NO, Baigun CRM, Nestler JM, Goodwin RA. 2007. Is fish passage technology saving fish resources in the lower La Plata River basin? *Neotropical Ichthyology* **5**: 89 – 102.

Pavlov DS, Lupandin AI, Kostin VV. 2002. *Downstream Migration of Fish through Dams of Hydroelectric Power Plants*. Oak Ridge National Laboratory: Oak Ridge.

Pelicice FM, Agostinho AA. 2008. Fish-passage facilities as ecological traps in large neotropical rivers. *Conservation Biology* **22**: 180 – 188

Pereira GJM, Pompeu PS. 2010. *Relatório consolidado do programa de monitoramento da UHE Funil*. Consórcio AHE Funil: Lavras; 27 p.

Petrere M Jr 1985. Migraciones de peces de agua dulce en America Latina: algunos comentarios. *COPESCAL Documento Ocasional* **1**: 17.

Pompeu PS. 2005. Estudo da regra operativa e avaliação de um mecanismo de transposição de peixes do tipo elevador com caminhão-tanque. Unpublished Ph.D. Dissertation. Federal University of Minas Gerais, Belo Horizonte, 190 p.

Pompeu PS; Martinez CB. 2006. Variações temporais na passagem de peixes pelo elevador da Usina Hidrelétrica de Santa Clara, rio Mucuri, leste brasileiro. *Revista Brasileira de Zoologia* **23**: 340 – 349.

Pompeu PS, Martinez CB. 2007. Efficiency and selectivity of a trap and truck fish passage system in Brazil. *Neotropical Ichthyology* **5**: 169 – 176.

Roscoe DW, Hinch SG. 2010. Effectiveness monitoring of fish passage facilities: historical trends, geographic patterns and future directions. *Fish and Fisheries* **11**: 12 – 33.

Santos HA, Pompeu PS, Martinez CB. 2007. Swimming performance of the migratory neotropical fish *Leporninus reinhardti* (Characiformes: Anostomidae). *Neotropical Ichthyology* **5**: 139 – 146.

Santos HA, Pompeu PS, Vicentini GS, Martinez CB. 2008. Swimming performance of the freshwater neotropical fish: *Pimelodus maculatus* Lacepède, 1803. *Brazilian Journal of Biology* **68**: 433 – 439.

Santos HA, Pompeu PS, Toledo CAM, Martinez CB. 2009. Estabelecimento de parâmetros hidráulicos para escadas de peixes do tipo ranhura vertical, baseados em características de espécies neotropicais. *Revista Brasileira de Recursos Hídricos* **14**: 99 – 112.

Stuart IG, Baumgartner LJ, Zampatti BP. 2008a. Lock gates improve passage of small-bodied fish and crustaceans in a low gradient vertical-slot fishway. *Fisheries Management and Ecology* **15**: 241 – 248.

Stuart IG, Zampatti BP, Baumgartner LJ. 2008b. Can a low-gradient vertical-slot fishway provide passage for a lowland river fish community? *Marine and Freshwater Research* **59**: 332 – 346.

Sugunan VV. 1997. Fisheries management of small water bodies in seven countries in Africa, Asia and Latin America. *FAO Fisheries Circular* **933**: 1 – 149.

Suzuki FM. 2009. Dinâmica de ovos e larvas de peixes da bacia do rio Grande, a montante do reservatório de Furnas, Minas Gerais, Brasil. Unpublished Master's Thesis. Federal University of Lavras, Lavras, 114 p.

Therrien J, Bougeois G. 2000. Fish passage at small hydro sites. Report by Genivar Consulting Group for CANMET Energy Technology Centre, Ottawa.

Vieira F, Pompeu PS. 2001. Peixamentos: uma alternativa eficiente? *Ciência Hoje* **30**: 28 – 33.

Zaniboni Filho E, Schultz, UH. 2003. Migratory fishes of the Uruguay River. In *Migratory Fishes of South America: Biology, Social Importance and Conservation Status*, Carolsfeld J, Harvey B, Ross C, Baer A (eds). World Fisheries Trust, The World Bank and The International Development Research Centre: Victoria; 157 – 194.

DOI: 10.1002/rra