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MIGRATORY FISHES OF BRAZIL: LIFE HISTORY AND FISH PASSAGE NEEDS

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ABSTRACT

Many of the most important commercial and recreational species of the megadiverse Brazilian freshwater fishes migrate in rivers among essential habitats during all life stages. These movements, however, have been severely blocked by hundreds of hydroelectric dams and reservoirs and they will be even more obstructed due to hundreds of new developments. Fishways have been used in many countries to allow fish to pass around dams. Fishway construction is booming in Brazil, but poor understanding of migrations by Brazilian fishes has led legislators, scientists, and the public to several misconceptions about the rules of fishways in fisheries conservation. First, is a belief that fishways are only needed to facilitate upstream spawning migrations. Also, it has been suggested that upstream passage for Neotropical migrant fishes is not useful if there is no large free-flowing stretch upstream of a dam that contains spawning habitat and has a large natural floodplain (nursery habitat). In this paper, we discuss that, in addition to providing passage for pre-spawning migrants, upstream fishways also provide passage for other fish migrations (e.g. foraging), and that all up- and downstream migrations during life history need to be addressed at dams to conserve fish resources. We also argue that an upstream fishway is important even if the upstream reach does not have spawning or nursery habitats. In addition, we discuss the need for protection of downstream migrant fish, and the importance of fish behaviourists and engineers working together on fishway design and operation to solve fish passage issues.

KEY WORDS: fishway; fish migration; life history; fish behavior; Neotropical fishes; fish conservation

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INTRODUCTION

Freshwater fishes are one of the marvels of Brazil's natural resources. With 2481 known species (Buckup *et al*., 2007), Brazil has the greatest diversity of freshwater fish of any country on Earth (McAllister *et al*., 1997). Many species of this megadiverse freshwater fishes are migratory but the actual number of species is unknown. These species migrate during all life stages along their river using habitats essential to their life cycle. Most migratory fishes are potamodromous, locally known as 'piracema' fishes, and only some are diadromous. Piracema fishes normally grow to a large size, are more abundant in undammed rivers, and are the most important commercial and recreational fishes in Brazil. The large aggressive dourados (*Salminus* spp.), the abundant curimbatás (*Prochilodus* spp.), and the highly prized food catfishes surubim (*Pseudoplatystoma corruscans*) and dourada (*Brachyplatystoma rousseauxii*) are few examples from the large group of piracema fishes.

Brazil has one of the largest amounts of surface freshwater in the world, with almost all the available water in rivers. River dams provide 95% of all the electrical power consumed in the country (ANEEL, 2002). The Brazilian hydropower potential is 260 GW, but only 23% of this potential has been developed (ANEEL, 2002). By the early 2000s, 433 hydropower dams had been built in Brazil (ANEEL, 2002). Thus, hundreds of new plants are yet to be constructed.

Damming of rivers negatively impacts the aquatic biota in many ways and is one of the main causes for the reduction of fish abundance and species diversity worldwide (Welcomme, 1989; Godinho and Godinho, 1994; Northcote, 1998; FAO/DVWK, 2002). Blocking the migrations of migratory fish species is one of the most obvious impacts of dams. Therefore, fishways have been used in many countries to pass fish around dams and is part of the

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technical arsenal for fisheries restoration in dammed rivers (Stanford *et al*., 1996). Two of the richest Brazilian states passed laws in the mid 1990' requiring the building of an upstream fishway at dams. Some fishways were also constructed in other Brazilian states.

In Brazil, ordinary people, legislators, and even some fisheries scientists believe that fishways are only needed to facilitate upstream spawning migrations. Also, Agostinho *et al.* (2002) suggested that fishways are an inadequate tool for conserving Neotropical fishes in most situations, but they can be useful if there is a large free-flowing stretch upstream of a dam that contains spawning habitat and has large natural floodplain areas (nursery habitat). In this paper, we discuss that, in addition to providing passage for pre-spawning migrants, upstream fishways also provide passage for other fish migrations (e.g. foraging), and that all up- and downstream migrations during life history need to be addressed at dams to conserve fish resources. We also argue that an upstream fishway is important even if the upstream reach does not have spawning or nursery habitats. In addition, we discuss the need for protection of downstream migrant fish, and the importance of fish behaviourists and engineers working together on fishway design and operation to solve fish passage issues.

Fish migrations and fishways

To properly appreciate the need and importance of a fishway for a species, understanding migrations of all life stages of target species is essential (e.g. Kynard, 1993; Kynard and Horgan, 2002; Kynard, in press; Kynard *et al*., in press-a,b). Although the piracema fishes are the most important freshwater fisheries resources in Brazil, their migrations are still very poorly known (Petrere, 1985; Carolsfeld *et al*., 2003). Migration of few species was discovered using mark-recapture methods. The first biotelemetry studies to reveal details of migrations started less than 10 years ago and only few species have been tracked so far using this technique. Nevertheless, Godinho and Pompeu (2003) proposed a general conceptual model of migrations for the piracema fishes of the São Francisco River Basin (Figure 1). With some modifications, this model can likely be applied to the other piracema fishes (Figure 2). The model indicates a complex migration pattern for all life stages of piracema fishes. They migrate (or disperse) along rivers during all life stages. Eggs and larvae disperse only downstream and, at some stage, juveniles migrate upstream. Although this upstream migration is poorly studied, juveniles likely home to natal reaches used by parents, and some may stray into non-natal waters. Juveniles of some species may also migrate downstream. Pre-spawning, post-spawning, and foraging adults may migrate both up- and downstream like zulega (*Prochilodus*

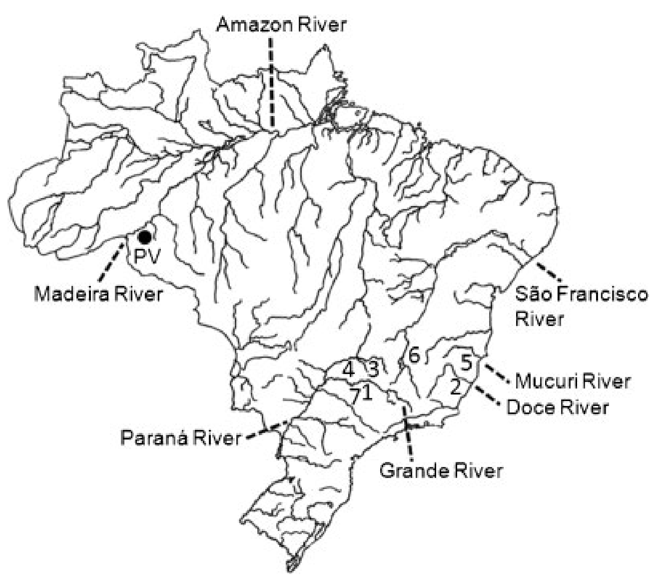

Figure 1. Map of Brazil showing location of rivers, dams (1, Igarapava Dam; 2, Mascarenhas Dam; 3, Miranda Dam; 4, Salto do Morais Dam; 5, Santa Clara Dam; 6, Três Marias Dam; 7, Volta Grande Dam) and city (PV = Porto Velho) cited in the text

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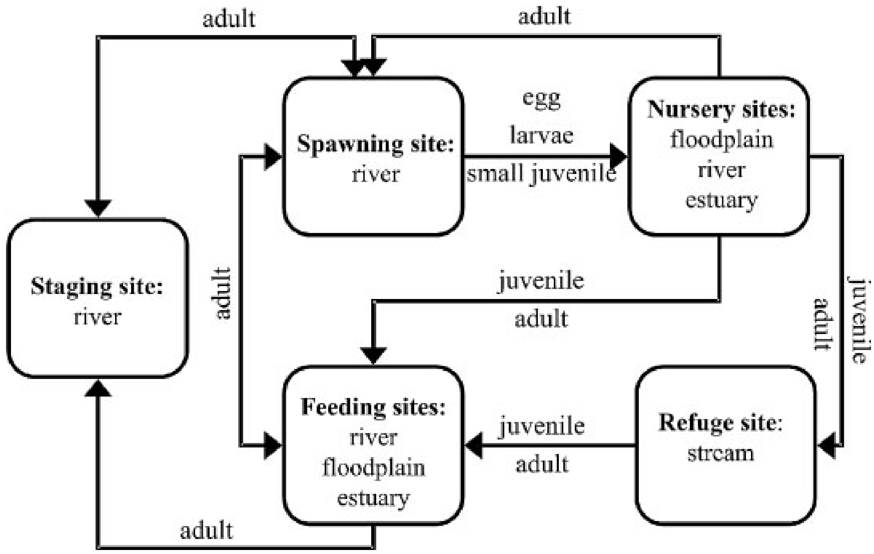

Figure 2. General model of migration of freshwater Brazilian fishes (modified from Godinho and Pompeu, 2003)

argenteus) and surubim in the São Francisco River (Godinho and Kynard, 2006; Godinho *et al*., 2007a). An upstream migration is the most common pre-spawning movement yet found in piracema fishes.

In an ideal scenario, a river dam needs to have fishways that allow all life stages to safely pass it whether the fish is moving up- or downstream. Fish ladders, fish lifts, and fish locks are classic solutions for passing fishes upstream at dams. However, none of these fishways is effective at passing downstream migrant fish (Clay, 1995; Kynard, 2004; Kynard, in press), although in special cases, fish ladders may provide a small amount of downstream fish passage. Data on downstream migration of Brazilian fishes at dams are very limited and this is an important knowledge gap. Downstream migrants of non-Brazilian fishes that have been studied so far prefer to remain in the dominant flow of the channel (Kynard, 1993; Clay, 1995; Kynard *et al*., 2003). This behavioural habitat preference takes fish directly over natural rapids or dam spillways (if there is spillage), or into the penstock and through a turbine if there is little or no spillage (Kynard *et al*., 1999). Fish mortality during turbine passage is complicated and depends on generation factors like turbine type, operation efficiency, cavitation, etc (Stone and Webster Environmental Service, 1992; Bell and Kynard, 1985) and on fish-related factors like species, size, and life stage (Coutant and Whitney, 2000). Turbine-induced mortality ranges widely with 100% of large fish dying in many cases (Davies, 1988; Kynard *et al*., in press-a). While much has been learned about protecting downstream migrant fishes that are near the water's surface, only recently has research begun to investigate methods for protecting benthic species (Kynard *et al*., 2005). Reducing mortality on downstream migrants is critical to enable migratory fishes free access to essential habitats to complete their life history. Providing protection for downstream migrants is one of the greatest challenges for fish passage biologists and engineers.

Two fundamental migration patterns found in many northern hemisphere fishes, including anadromous and potamodromous species, are also found in many piracema fishes. These patterns are: first, adults migrate upstream from foraging areas to spawning grounds; and second, adults migrate downriver from spawning to feeding grounds. An upstream spawning migration and a downstream feeding migration may also be the dominant pattern among piracema fishes, but several exceptions have been found and will be discussed later.

An important trait of piracema fishes is the timing of the first migration. This occurs when they are tiny eggs and larvae that are carried by the river flow because their parents broadcast semi-buoyant, non-adhesive eggs. Larvae hatch in <24 h and active swimming begins several days after hatching (Godinho *et al*., 2003b). Eggs and larvae drift downriver during this time. They can likely drift for hundreds of kilometers or even more than a thousand of kilometers.

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All available information suggests that the eggs and larvae should encounter low mortality due to turbine passage, if the turbine has no cavitation (Cada, 1990). However, if eggs and larvae move downstream and enter the headwaters of a reservoir, the reservoir becomes a migratory barrier (Godinho *et al*., 2007b) and a source of failed recruitment (Kynard *et al*., in press-c). Protection of eggs and larvae that can drift into a reservoir and die is a major challenge for Brazilian scientists that is even more difficult than providing safe downstream passage at dams for juveniles and adults. Protection of dispersing small Salmonidae in most situations is often not needed because their dispersal is short and in small tributaries where screens can prevent entrainment into water diversions (Kynard, 2004).

Although it is not yet possible to assure safe downstream passage for all life stages of piracema fishes, an upstream fishway can be beneficial to fish populations. Some examples of this situation follow.

Upstream fish passage is not only for spawning migrations

Data from various Brazilian River basins show that upstream migration is common for spawning adults (Carolsfeld *et al*., 2003; Godinho and Kynard, 2006). However, adult upstream migration may also be for other purposes than spawning. Thus, an upstream fishway would also provide a migratory route for non-spawning migrations. For example, in the São Francisco River downstream of Três Marias Dam (TMD), a post-spawning upstream migration was one of the most frequent migrations by surubim (Godinho *et al*., 2007a). Also, zulega and surubim make upstream migrations during the non-spawning season (Godinho and Kynard, 2006; Godinho *et al*., 2007a). Many curimbatás (*Prochilodus lineatus*) that spawn in a tributary of the Grande River migrated downriver after spawning, and then migrated upstream into the main stem (Godoy, 1975). Dams in the Grande River now block the upstream post-spawning migration of this species and curimbatás have severely declined there.

Fishes migrate upstream in the fishway at Igarapava Dam, Grande River, every month of the year. Almost all of the 11+ native species that use the fishway in the spawning season also use it in the non-spawning season (Bizzotto, 2006). The number of fish that use the fishway in the non-spawning season is 14% of all fish that pass upstream in 1 year. Thus, a significant number of species and individuals are using the Igarapava fishway for non-spawning upstream migrations.

Some Brazilian fishes, like the important robalo (*Centropomus* spp.), are diadromous and migrate from the ocean into freshwater to feed (McDowall, 1988). River dams without a fishway block the feeding migration of these fish. This is a perfect example of where an upstream fishway is needed for non-spawning migrants. The most important fish-related factors for fishway design is not whether fish are migrating to spawn or forage, but several biological criteria: size and swimming ability, behaviour, and body energetics.

Without an upstream fishway, diadromous fishes can be extirpated from river stretches upstream of dams. Such problems are common in North America (Clay, 1995; Kynard, 2004) and have also happened in the Doce River (Southeast Brazil) where the Mascarenhas Dam eliminated robalo and three other diadromous fishes from the upper segments of the river (Alves *et al*., 2007). At the fishway of the Santa Clara Dam, Mucuri River, Southeast Brazil, three diadromous species are among the 11 species most frequently passed (Pompeu and Martinez, 2006).

Upstream fishway for young fish

Upstream fishways in North America are focused on passing pre-spawning adults (with a large body size) upstream to spawning habitat (Clay, 1995). However, a growing body of evidence from many rivers in North America, Europe, and Australia finds that migratory fish species have evolved up- and downstream migrations by juveniles and non-spawning adults (Mallen-Cooper, 1999; Lucas and Baras, 2001; Kynard *et al*., in press-a,b). We provide some examples to show that some Brazilian fishes have also evolved similar life history migration patterns.

Young zulega migration in the São Francisco River. The TMD was built in the early 1960s in the upper section of the São Francisco River. There is no dam for 1090 km downstream of TMD. Zulega is one of the most important commercial and recreational fish in the basin that grows to 15 kg (Franco de Camargo and petrere, 2001; Godinho *et al*., 2003a).

Young zulegas, mostly young-of-the-year, migrate upstream, aggregate in the TMD tailrace, and search for an upstream passage route past the dam for days (Godinho and Kynard, 2006). Because TMD does not have an upstream fishway, the young zulegas stay downstream. Every year, a new batch of young zulegas reaches the

DOI: 10.1002/rra

dam tailrace. An unknown fraction of these young recruits to the zulega population that lives just downstream of TMD. Many juveniles must recruit there because that is the population that supports the most important zulega fisheries known in the São Francisco River. Adult zulega of the Três Marias population do not migrate downstream but remain at and just downstream of the dam and seem to require upstream passage (Godinho and Kynard, 2006). Spawning by these adults is limited because the cold hypolimnion discharge at TMD does not have the appropriate triggers for spawning (Godinho and Kynard, 2006). Spawning of zulegas downstream of TMD only occurs in populations that inhabit the river at or downstream of the first major tributary, located 30 km downstream from the dam where adults receive the appropriate cues to spawn. The spawning of these populations downstream of TMD are triggered by floods in the tributaries; they do not have an upstream migration drive to move upstream of TMD.

The lack of an upstream fishway at TMD increases density of the downstream zulega population and attracts large migratory piscivorous fishes (Godinho *et al*., 2007a), increasing fishing yield. The high density of zulegas at TMD could be the proximate factor that explains why many post-spawning predatory surubims (Godinho *et al*., 2007a) and dourados (*Salminus franciscanus*, personal data) migrate upstream to the dam. These are the two largest piscivorous fishes in the São Francisco River. Together with zulega, they are the most important commercial riverine fishes in the TMD region, which is the most productive fishing region in the São Francisco River. Local fishers have better equipment and dedicate more intensity to fishing than other fishers nearby (Franco de Camargo and petrere, 2001). Clearly, there is an income concentration in the fishers of the TMD region and this is likely due to the young zulega migrants that are forced to stays downstream of the TMD and grow to maturity there.

Young dourada migration in the Amazon River. Two run-of-the-river dams are proposed for construction in the upper stretch of the Madeira River (the largest Amazon River tributary), just upstream of Porto Velho city. These two dams will block migrations of all migratory fish species, including the large dourada, a catfish that grows to 192 cm. Dourada is ranked first in the catfishes landings of the Amazon River Basin (Petrere *et al*., 2004) and is one of the main commercial fish in the Porto Velho region (Goulding, 1979). Also, dourada is exported outside the Amazon River Basin as a food fish.

Douradas migrate from the nursery ground at the freshwater zone of the Amazon River estuary to tributaries in the upper basin, like the Madeira River (Barthem and Goulding, 1997). They leave the estuary as large juveniles and are believed to spend 1–2 years feeding in the central Amazon River before migrating farther upstream to adult habitat. Douradas are still juveniles when they pass Porto Velho during the upstream migration towards the spawning grounds in the upper basin (Goulding, 1979). After growing into adults and spawning, douradas remain upstream and do not return downstream. Early-life stages of douradas move to nursery grounds at the freshwater zone of the Amazon River estuary where they grow into large juveniles and migrate upstream.

The conceptual model of dourada migration of Barthem and Goulding (1997) shows that dourada early-life stages must pass Porto Velho during their downstream migration to the estuary. This likely occurs when they are eggs or larvae. With the damming of the Madeira River, we expect that high mortality of dourada eggs and larvae will occur when they drift from the river into the headwaters of the reservoir. This mortality could be 100% and, if so, the stock of dourada spawning in the upper Madeira River Basin will decline because the life history chain has been broken by the dam and reservoir. This situation may be common after river damming and creation of a long reservoir (Kynard *et al*., in press-d).

Even if damming results in zero offspring surviving to spawn from the dourada stock in the upper Madeira River Basin, some straying juvenile douradas from other Amazon River tributaries may annually migrate upstream into the Madeira River. The number of migratory juveniles that will eventually migrate upstream into the Madeira River will be directly proportional to the frequency of straying from their natal rivers. This straying frequency is difficult to estimate in species like dourada that have early-life stages that disperse very early from the natal grounds (Lucas and Baras, 2001). Although homing is normally the dominant mechanism by which offspring return to their natal spawning grounds (Lucas and Baras, 2001), straying has an important adaptative significance (McDowall, 2001). It likely occurs in dourada, like it does in the well-studied Salmonidae and in many other highly migratory families of fish (Lucas and Baras, 2001; Jonsson *et al*., 2003). Also, dourada seem to be composed of a single genetic stock along the main stem (Batista *et al*., 2004), which is the situation expected when the frequency of straying is high (Mork, 1994; Bohonak, 1999).

Douradas that stray or home and enter the tailrace of the Madeira River dams will need to be passed upstream. Only this action will likely prevent the extinction of dourada in the upper portions of the basin, where the spawning

DOI: 10.1002/rra

grounds are located. Depending on the number of dourada that annually reach each tailrace, fishways may eventually be able to pass enough fish to sustain some fisheries upstream of the dams. Fishways will also prevent accumulation of douradas at the dam's tailrace, which would favour local fishers to the detriment of upstream fishers.

Passing dourada upstream at Madeira River dams will likely require innovative fishway entrance design. Fishway entrances are typically located at the water's surface, which cannot be easily found by bottom-oriented fishes like sturgeons (Kynard, 1998) or catfishes (Oldani and Baigún, 2002). Nature-like and technical fishways are the two types of fishways under study for dourada at Madeira River dams. Nature-like fishways reproduce as closely as possible the natural stream geomorphology, while technical fishways are constructed in a technically utilitarian way (FAO/DVWK, 2002). The entrance to a nature-like fishway needs to be located several km downstream of each dam where the Madeira River is 1+ km wide and 10–20 m deep. In this situation, most douradas will likely not find the entrance and the fishway will not attract and pass them successfully. The entrance of a technical fishway, on the other hand, can be located in the dam's tailrace where most dourada will concentrate to search for upstream passage; thus, placing fish near the entrance location and increasing the chance some fish will find the entrance. However, most dourada, like most sturgeons, will not easily find a surface entrance (Kynard, 1998). A bottom entrance could greatly improve attraction in passing benthic fishes, but no design is presently available and research is needed to design such an entrance. Another possibility that does not require the uncertainty of a bottom entrance is to add a side-ramp attraction stream to one side of the tailrace at the dam to attract benthic fish into a technical fishway.

Floodplain access is not necessarily required prior to building an upstream fishway

We disagree with the suggestion of Agostinho *et al.* (2002) that fish passage is an inadequate conservation tool if there is no large natural floodplain area (nursery ground) upstream of a dam. Many Brazilian rivers have floodplains that are very important nursery grounds for migratory fishes (Carolsfeld *et al*., 2003). Also, the larger the floodplain the higher the fishing yield (Welcomme and Hagborg, 1977; Petrere, 1983). However, the absence of a floodplain in large rivers does not mean that piracema fishes cannot complete their life cycle. For example, in the Uruguay River in southern Brazil, fishes rely on in-river habitats for rearing of larvae and juveniles because there are no floodplains (Zaniboni Filho and Schulz, 2003). A further example that migratory fishes use other nursery habitats besides the floodplain is the establishment of introduced piracema fishes in rivers without floodplains. This is the case of dourado (*Salminus brasiliensis*) and pioa (*Prochilodus costatus*) in the Doce River (Alves *et al*., 2007). Even in rivers with large floodplains, the use of in-river habitats for early-life stage rearing of migratory fishes has been already suggested (Barthem and Goulding, 1997; Godinho and Pompeu, 2003; Godinho *et al*., 2007b). The ability of migratory fishes to rear in the main stem becomes very important for their future survival in rivers subjected to damming and flow regulation. In this situation the frequency of natural floods that carry early life stages into floodplains for rearing will be reduced and early life stages will be forced to stay in the main stem.

Avoiding local extinction and conserving fisheries resources

Upstream fishways can prevent local extinctions of fish and provide fisheries resources to reservoirs that are sink habitats (reaches not connected to upstream spawning or to high-quality nursery grounds) if the downstream population is in a source habitat (where recruitment exceeds mortality). Igarapava and Miranda dams were built in the late 1990s in the Paraná River Basin. Both reservoirs are run-of-the-river, have surface areas on the same order of magnitude (Igarapava Reservoir = 36.5 km^2, Miranda Reservoir = 53.0 km^2), and are just downstream from another dam. In both areas, feeding habitat for adult piracema fishes includes the reservoir and a short (5–8 km) river reach at the head of the reservoir. Some small streams run into each reservoir, but they are either too short or inaccessible to migratory fishes due to impassible waterfalls. Spawning and/or high-quality nursery grounds are not available for migratory fishes in these stretches. For example, the mandi (*Pimelodus maculatus*) apparently spawns in the Igarapava Reservoir catchment, but reproductive success is null (Maia *et al*., 2007).

The mandi is a migratory species that occurs in Igarapava and Miranda reservoirs. Seven years after impoundment, the presence or absence of an upstream fishway likely resulted in a very different fate for the mandi populations in the two reservoirs (V. Vono & A.L. Godinho unpublished work). In Miranda Reservoir, which had no

DOI: 10.1002/rra

fishway connecting the reservoir to the downstream source riverine habitat, the minimum and mean length of mandi increased with reservoir age, showing mandi had no recruitment and no immigration of juveniles and will go extinct in the near future. In the Igarapava Reservoir, on the other hand, mandi is not endangered. Mandi was the most common species passed upstream in the fish ladder at Igarapava Dam (Bizzotto, 2006). Also, after leaving the fishway, most mandi stayed in the reservoir (Silva, 2004), while others continued to migrate through the reservoir to the short remnant reach of river at the reservoir headwaters. For mandi, the upstream immigration of new individuals avoided increasing the minimum and mean length of fish with reservoir ageing, and also, resulted in this species being the most important commercial fish in the reservoir. Thus, the Igarapava fishway made possible the formation of a source and sink system that has avoided extinction of migratory fish in the sink Igarapava Reservoir. As noted by Reed (2004), dispersal among segmented populations in fragmented landscapes partially alleviates the effect of fragmentation on extinction rate. The case of mandi in the Igarapava Reservoir also indicates that an upstream fishway maybe useful even if a large free-flowing stretch upstream of a reservoir and large natural floodplain areas are not present. Nevertheless, if certain fisheries are ecologically or economic important, or both, it seems critical to build dams and reservoirs in a way that retains a remnant reach of river at the head of reservoirs, which will be used for spawning by some migratory species.

A large proportion of the species that use fishways in Brazil has been classified as sedentary. For example, most of the species passing the fishway of the Salto do Morais Dam, Paraná River Basin, and the Igarapava fishway were classified as sedentary (Godinho *et al*., 1991; Bizzoto, 2006). Because moving upstream in these fishways requires strong migratory behaviour, this movement by many species calls into question the present classification as sedentary species. Clearly, these migrants have strong migratory behaviour to move upstream to complete their life history activities, and without the fishway, this behavioural drive could not be expressed. Fish that are not thought to be migratory, but which enter and pass upstream in newly constructed fishways force a rethinking of the sedentary characterization. This situation is well documented in Europe where 80% of the riverine fishes are typically migratory (Lucas and Baras, 2001), and this situation is beginning to be documented in North America (Kynard, in press). In North America, state and federal fisheries agencies are beginning to require up- and downstream fishways to include these potamodromous migrant species.

The migrations of mis-classified sedentary fishes are not likely any less important for completion of their life history than the migrations of piracema fishes. The consequences of dam barriers on the pre-spawning migration of piracema fishes is clear, the consequences on blocking migrations of the other migratory fishes are poorly understood. There is a great need to identify these migrations, determine the life history consequences of preventing the migrations, and determine the significance of restoring the river connectivity on populations segmented by a dam. The actual knowledge of migrations by most Brazilian fishes is still insufficient for a sound classification of most species as migratory or sedentary.

Reduction of downstream fish stock

One might argue that an upstream fishway is not justified if a downstream protection system (bypass system or downstream fishway) is not also present to prevent downstream migrants from entering turbine intakes by way of the reservoir. For certain species and places, a downstream fishway may not be required. For example, there is a school of a few hundred adult migratory curimbatá, which inhabit the tailrace of the Volta Grande Dam, Grande River. This school has a remarkable small home range (i.e. only the dam's tailrace and 3 km downstream of the dam), that was likely caused by damming. Because of the small number of fish in this school, there are no great fisheries or ecological goal to be gained from passing these fish around the dam. However, the migratory behaviour of these fish provides an example of a situation where a downstream fishway is not likely needed. Individuals of this group, which were radio-tagged and displaced upstream of the dam into the Volta Grande Reservoir, migrated upstream and did not return downstream in the two years they were tracked (Silva, 2004; A.L. Godinho unpublished work). If these adults were spawned upstream of the dam and were attempting to return to their natal reach, then their movements in the reservoir suggest that after upstream migrants pass the dam, they do not need a downstream fishway (at least within 2 years).

Other examples where downstream fishways are not needed are provided by zulega and douradas. The conceptual model of zulega migration predicts that juveniles that migrate upstream to the tailrace at TMD may not

DOI: 10.1002/rra

return downstream if they are passed upstream of the dam because they will rear and spawn upstream of the dam. The conceptual model of dourada migration also indicates that downstream migration is not expected for adult douradas in the Madeira River. However, the predictions for these specific situations need to be studied further because sufficient data are not available for a sound management decision on the need for downstream fishways. For example, the two year study of migration of the long-lived curimbatá in the Volta Grande Reservoir does not give assurance that adults will never return downstream during their entire life cycle. It took 15 years of continuous yearly study of adults and juveniles of Connecticut River shortnose sturgeon (*Acipenser brevirostrum*) to understand their up- and downstream migration patterns during their life, which is 25–30 years (Kynard *et al*., in press-a).

Safe downstream passage is likely necessary for many species at many dams, but more study is needed to identify downstream migrations during life history of migratory species. If mortality of fish during passage through turbines is high, then a bypass or protection system is needed. Mortality of fish during downstream migration at Brazilian dams is poorly understood and we are aware of only limited data on this subject. Silva (2004) detected downstream migration of three radio-tagged mandis through a bulb turbine at Igarapava Dam. Tracking indicated that one, maybe two, mandis died during passage. Tests with bulb turbines found them to be the most fish-friendly turbine (Pavlov *et al*., 2002), and therefore, fish mortality at Igarapava turbines should be low.

Most dams in Brazil have either Kaplan or Francis turbines, which cause unacceptable mortalities and are not fish-friendly, like bulb turbines (Pavlov *et al*., 2002). Therefore, studies are needed to determine turbine-related mortality during downstream migration of Brazilian fishes. Adults of many Brazilian fishes likely regularly migrate downstream and are entrained into turbine intakes as they pass downstream of the dam. Their fate is unknown and few dead fish may be seen in the tailrace of just downstream of a dam because most fish killed by turbines continue to drift downstream unobserved (Bell and Kynard, 1985).

Downstream fish passage is a major gap in the knowledge of effective fish passage worldwide (Coutant and Whitney, 2000; Pavlov *et al*., 2002; Kynard, 2004). Research on downstream fishways has focused on Salmonidae and a few other surface-oriented species (Clay, 1995; Ferguson *et al*., 1998) and research on a system for bottom-oriented species has just begun (Kynard *et al*., 2005). In North America, fish management agencies use many methods to protect downstream migrant fish (Odeh and Orvis, 1998). Downstream passage development for fish in the U.S.A. has been slow, particularly for benthic fishes (Kynard, 2004). It will take many years of research and trial and error tests at dams until this problem is solved. Meanwhile, poor understanding of downstream migration of Brazilian fishes is not an excuse for not building upstream fishway because an upstream fishway alone can contribute to conservation of valuable fisheries resources as shown by the previous examples. If a downstream fishway is needed, but not provided, screening of the turbine water intake may be necessary to prevent fish from being entrained into the turbines. This is a common and effective method of protecting fish from entrainment in many countries (Clay, 1995; Coutant and Whitney, 2000; Kynard, 2004).

The loss of fish passed upstream in a dam–reservoir system without a downstream bypass can be controlled by fisheries managers, if necessary, by limiting the number of fish passed upstream of the dam. In this situation, management of up- and downstream subpopulations of fish must be done under the theory of source and sink (Pulliam, 1988; Priyanga, 2004). An effective upstream fish passage counting system is required to implement this theory for fish passage. A good counting system like the one at the Igarapava fishway provides a model to improve fish counting at Brazilian fishways. Details on the counting system are provided by Bizzotto (2006).

Fishway design and operation is also important for a successful passage

Much of the success of an up- or downstream fishway depends on creating a strong attraction flow that fish find and on operating the artificial system to create an environment that fish accept and do not avoid (Kynard, 1993). To do this efficiently, requires understanding of how fish response to the physical environment, particularly to water velocity and structure. Many years of experience and failure of fishways has led to the conclusion that fish passage development is most efficient when engineers work with fish biologists that know about fish behaviour in both natural and artificial environments. Delaying construction until research is done on critical fish responses is also important to prevent costly mistakes (Kynard *et al*., 2005; Kynard *et al*., in press-c). Knowledge about fish behaviour is the critical fish-related element that should guide fishway design and operation (Kynard, 1993;

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Kynard, 2004). While there are several upstream designs that work for many species (Clay, 1995), there is still the need for innovative upstream fishway designs that pass a diverse fish community (Kynard *et al*., in press-d). Brazil has experienced a boom in fishway construction in the last decade but fish behaviour was clearly not taken into consideration during the design of most. An inappropriately designed fishway has a high probability of not being efficient at attracting, passing fish, or both.

Even the best designed fishway will not pass fish efficiently if it is not operated correctly. A major problem in many North American fishways is that operation is left to the dam operator without any or only periodic monitoring or inspection by regulatory agencies. There are also no clear penalties for the dam operator that fails to operate a fishway as designed. This often leads to an inappropriate water discharge being used to attract fish to the fishway entrance, a critical step in fish passage. Unfortunately, a similar situation exists at fishways in Brazil.

CONCLUSION

A fishway has the immediate objective of allowing fishes to complete their migrations in rivers. Understanding migrations by the various life stages is the basic information needed to plan and develop fish passage. Only by understanding the complete pattern of up- and downstream migrations will we be able to correctly interpret the life history significance of such migrations by juveniles and adults at a dam and the consequences of not providing fish passage. In North America, the crucial test of fisheries agencies for the need for an upstream fishway is the presence of a sufficient number of upstream migrants that are blocked by a dam. If the number is great enough, as determined by management agencies, this triggers planning for upstream passage at the dam. The same process is used in determining the need for a downstream fishway. Inadequate conservation and management actions are almost certain to occur if essential basic knowledge of migration of target species is not available to assist decision making by managers.

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