

Evaluation of the Effects of Pressure Gradients on Four Brazilian Freshwater Fish Species

Paulo dos Santos Pompeu^{1*}, Luiz Felipe Mascarenhas Horta² and Carlos Barreira Martinez²

¹*Departamento de Biologia; Universidade Federal de Lavras; 37200-000; Lavras - MG - Brasil.* ²*Centro de Pesquisas Hidráulicas; Universidade Federal de Minas Gerais; Av. Antônio Carlos, 6627; 31270-901; Belo Horizonte - MG - Brasil*

ABSTRACT

*This work aimed to experimentally evaluate the behavior of Brazilian freshwater fish species when submitted to a gradual increase in pressure, as well as sudden decompression's effects simulating the passage through a hydroelectric turbine. Four species from the São Francisco river basin were tested: *Astyanax bimaculatus*, *Hypostomus* sp., *Leporinus reinhardti* and *Prochilodus costatus*. For all of them mortality rates due to decompression were extremely low. However, the symptoms related to decompression, such as bulged eyes and hemorrhage, were not observed only in *Hypostomus* sp., and were more frequent the larger the pressure values were, considering the values from which decompression was performed. All these symptoms decreased significantly after 24 h of observation. With the increase in pressure inside the apparatus, the four tested species moved towards the upper levels. This behavior could make possible the implementation of bypass downstream fish passages in dams constructed in Brazil.*

Key words: downstream fish passage, dams, experimental apparatus, fish mortality, pressure effects on fish

INTRODUCTION

Many fresh water fish species perform complex movements during their life cycle, known as migration. Although only a small fraction of Brazilian species are migratory (Petrere Jr., 1985; Godinho and Godinho, 1994), due to their abundance and larger size (Northcote, 1978), they are the most important for fisheries (Goulding, 1979; Bittencourt and Cox-Fernandes, 1990; Godinho, 1993).

For the Paraná and São Francisco rivers, the migratory movements can be described according to the models presented by Petrere Jr. (1985) and Godinho and Pompeu (2003). Seasonally, the adults migrate from the feeding areas to reproduction sites, in a process known in Brazil as the *piracema*. Although the *piracema* is the most evident migratory movement, other movements include the carrying of eggs and larvae down the river, towards the floodplains, the return of adults to the feeding areas and the movements of youths towards the river or small streams.

* Author for correspondence: pompeu@ufla.br

On many rivers around the world, the reduction of fish stocks has been detected, due to, among other factors, failure on the recruitment by the interruption of fish migration (Godinho and Godinho, 1994). Among the undertakings that affect directly the movements of migratory species, dams are, in Brazil, the most important, especially the ones faded to form the reservoirs of hydroelectric power plants.

Among the strategies used to eliminate the blockage by dams on the fish migration, is the construction of fish passages (Clay, 1995). In Brazil, projects of these mechanisms have the main goal of allowing the upstream passage of adult fishes, during the *piracema*. Following this objective, fish ladders and lifts have been implemented as a way of attending the current valid state legislations (Fernandez, et al., 2004; Agostinho et al., 2007; Pompeu and Martinez, 2007).

Although the number of fish passage mechanisms implemented in Brazil is growing, very little attention has been given to the problems related to keeping the downstream movements. Currently, in North America and Europe, this has been one of the main subjects related to the conservation of the ichthyofauna, considering the fact that several types of damage, or even the mortality of almost the total of individuals, can be caused during the fish passage through spillways and turbines (Larinier and Travade, 2002). During the passage through the turbines, sudden pressure variations are one of the main causes of injury and death among the migratory fishes (Cada, 2001).

In order to avoid fish entrance in the turbine's intake line, mechanisms for downstream passage have been installed in North America and Europe, guiding the fishes towards a bypass system, which directs them safely downstream the dam (Larinier and Travade, 2002). However, these mechanisms are based on the knowledge of the local ichthyofauna's behavior, especially when submitted to a gradual increase of pressure.

This work had the objective of experimental evaluation of the behavior of four Brazilian species when submitted to a gradual increase in pressure, as well as sudden decompression's

effects, simulating the passage through a hydroelectric turbine.

MATERIALS AND METHODS

Numerically, both in number of species and individuals, the Brazilian fish fauna is dominated by the Characiformes and Siluriformes Orders (Lowe-McConnell, 1975), which include most of the Brazilian migratory species (Petreire Jr., 1985). Four species of fishes, three Characiformes (*Astyanax bimaculatus*, *Leporinus reinhardti*, and *Prochilodus costatus*) and one Siluriforme (*Hypostomus* sp. from Britski et al., 1988) from the São Francisco Basin were used. These species were chosen according to differences in size of individuals available for testing, their availability, since they had been used in other experiments in CPH (Hydraulic Research Center) of the Federal University of Minas Gerais, and also because they belonged to genera widely distributed in the South America (Table 1).

All tests were conducted in an apparatus specially developed for them, which was divided in five vertical levels (Fig. 1).

The main frame of the structure was represented by a PVC tube, 30mm thick and 3000mm high. Along the tube, fourteen acrylic windows, 16mm thick, were installed. They were divided and positioned in three lines: two of them with five windows, which had the objective of visualization of the fishes, and the third line, with four windows, which allowed the intern illumination of the structure through the optional connection of light bulbs.

On both ends of the tube, the covers allowed the fishes introduction and removal through installed gate valves (100 mm in diameter). These covers were machined in Nylon and screwed onto the main body of the apparatus. The lower cover presented a conical intern format, which avoided the fishes' imprisonment during their removal. On the upper cover, besides the valve, three copper tubes connected the main structure with a control panel.

Table 1 - Common name of species and size of individuals tested (*Migratory behavior according Lamas, 1993).

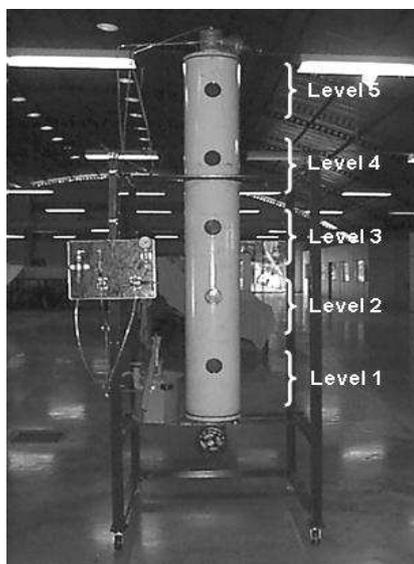
Species	Common name	Migratory Behavior*	Standard length (cm)	
			Mean	Standard deviation
<i>Astyanax bimaculatus</i>	Lambari	no	7.1	0.9
<i>Hypostomus</i> sp.	Cascudo	no	19.9	4.9
<i>Leporinus reinhardti</i>	Piau-três-pintas	yes	12.4	1.8
<i>Prochilodus costatus</i>	Curimatá-pioa	yes	27.9	1.7

The apparatus's control panel basically involved three circuits, connected to the upper nylon cover, with the following ends: determination of intern pressure values, through a manometer; decompression through a ball valve and pressurization of the apparatus through a manual pump connected to the circuit, in which a safety valve and ball valves were installed in order to avoid pressure drop. On each test, one to ten individuals were inserted in the apparatus,

depending on the species, and pressure levels reached ten, twenty or fifty meters in water column (m_{H_2O}). The number of individuals and compression levels changed according to the species (Table 2). For *Hypostomus* sp. and *P. costatus*, species of largest size, only 50 m_{H_2O} tests were performed, due to the low number of individuals available and the limitations in the number of individuals in the apparatus in each test.

Table 2 - Number of individuals tested by species of fish and compression level.

Species	Compression levels (m_{H_2O})		
	10	20	50
<i>A. bimaculatus</i>	30	30	30
<i>Hypostomus</i> sp.	-	-	20
<i>L. reinhardti</i>	22	24	34
<i>P. costatus</i>	-	-	20

**Figure 1** – Experimental apparatus indicating the considered vertical levels.

However, for each test performed, the following procedures were adopted: selection of maximum of ten individuals; insertion of individuals; observation of distribution of individuals along the apparatus; pressurization up to the desired level;

observation of the new distribution of individuals along the apparatus; decompression test and removal of individuals.

The condition of the fishes was checked immediately before and after the pressures

changes. After the removal, the fishes were isolated in a tank, and were checked after 1 and 24 h. Observations included the number of dead and external signs of trauma.

Significant differences in the vertical distribution along the apparatus, before and after the compression, were verified for each species using the Mann-Whitney test. This same test was used to compare, for each species, the proportion of individuals with any symptom caused by the decompression, after the experiment and 24 h past. A Kruskal Wallis test was utilized to verify significant differences between the total injury rates presented by *A. bimaculatus* and *L. reinhardti*, when submitted to different levels of decompression, and between the total injury rates presented by the four species submitted to a 50 m_{H2O} decompression.

RESULTS

When inserted in the apparatus, all *Hypostomus* sp. individuals and most of the *P. costatus* and *L. reinhardti* moved to the lower level. However, for the *A. bimaculatus* individuals, this initial distribution occurred in a more homogeneous way along all levels. But when submitted to a 50 m_{H2O} compression, a significant re-distribution of the individuals towards the upper levels was observed (Fig. 2). This movement towards the upper levels

began immediately after the start of the compression process. Hemorrhage in the head and bulged eyes were the symptoms more often shown by *A. bimaculatus* and *L. reinhardti*, when submitted to different levels of pressure, respectively. However, the number of affected individuals reduced gradually within 24 h of observation (Fig. 3 and 4). Although the rates of occurrence of these symptoms rose with the increase in levels of decompression, no significant differences was observed between the total injury rates presented by *A. bimaculatus* ($H = 4.270$; $p = 0.118$) and *L. reinhardti* ($H = 2.641$; $p = 0.267$) after the tests, when compared to those different levels. Only one individual of each of these two species died during the tests.

Hemorrhage was the only symptom presented by *P. costatus*, when submitted to decompression from 50 m_{H2O}. However, this species was the one which presented the greatest mortality rate (20%) during the tests (Fig. 5).

The *Hypostomus* sp. presented hemorrhaged or pale individuals in a small proportion, though all the individuals recovered after 24 h of observation, with no death occurrences (Fig. 5).

When the four species were compared, considering the proportion of individuals with any type of injury after decompression from 50 m_{H2O}, no significant differences were found ($H = 6.644$; $p = 0.084$).

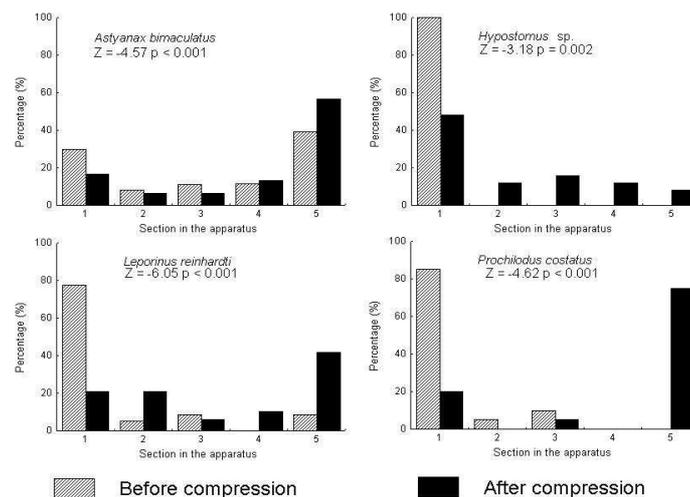


Figure 2 - Distribution of individuals of the tested species in the experimental apparatus, before and after the compression level of 50 m_{H2O}.

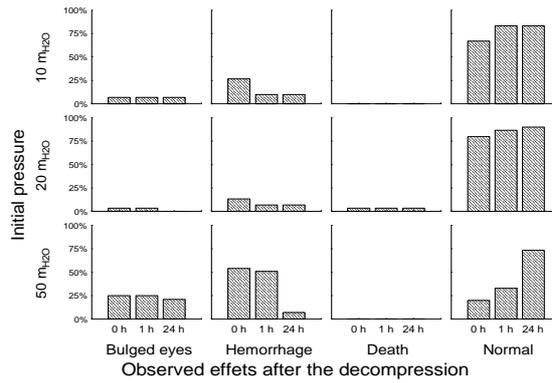


Figure 3 – Observed effects for *Astyanax bimaculatus* immediately after decompression, after one and 24 hours, when submitted to three different initial pressures.

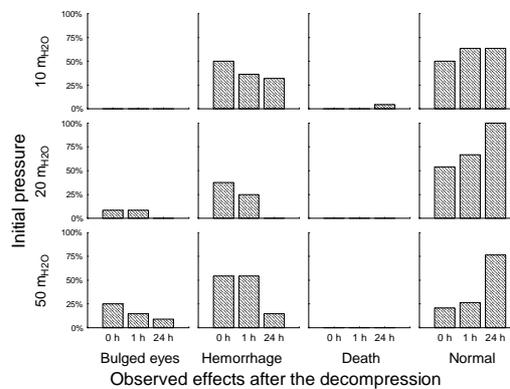


Figure 4 - Observed effects for *Leporinus reinhardti* immediately after decompression, after one and 24 hours, when submitted to three different initial pressures.

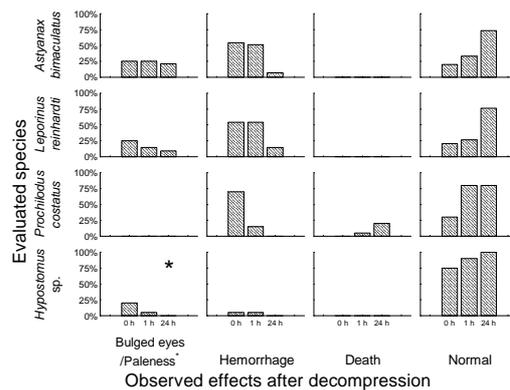


Figure 5 - Observed effects for the evaluated species immediately after decompression, after one and 24 hours, when submitted to 50 m_{H2O} of initial pressures.

When only the three tested Characiformes were compared, these differences were not significant ($H = 0.609$; $p = 0.738$). However, when *Hypostomus sp.*, the only Siluriforme tested, was

compared with the other species, significant differences were observed for *L. reinhardti* ($H = 4.183$; $p = 0.041$) and *P. costatus* ($H = 4.397$; $p = 0.036$), but *A. bimaculatus* ($H = 3.240$; $p = 0.072$).

A significant reduction in the proportion of individuals with any type of symptom was observed after the 24 h' observation, for the four tested species: *A. bimaculatus* ($Z = 2.023$; $p = 0.043$); *L. reinhardti* ($Z = 2.205$; $p = 0.028$) e *P. costatus* ($Z = 2.352$; $p = 0.019$) and *Hypostomus* sp. ($Z = 2.000$; $p = 0.046$).

DISCUSSION

In reservoirs of the dams, the heavy flow in the water intake attracts the fishes to the turbines, despite the water velocity is low (< 1.0 m/s). The physical damage that often occurs to the fishes, as they pass through the hydropower turbines, is a major source of mortality for many fish populations in the vicinity of hydropower projects (Cada et al., 1997).

Studies with Salmonids have been indicating that the fish mortality rates vary from 0% to 100% for Francis turbines, rarely reaching rates below 10% (Eicher et al., 1987), and from 0% to 20% for Kaplan turbines (Therrien and Bourgeois, 2000). There is no studies concerning the fishes passage through Pelton turbines, but it can be considered impossible.

Sudden pressure variations, shocks and compression against the blades and disorientation due to high turbulence on the draft tube are the main causes of death among the migratory fishes which pass the dam through the turbines (Cada, 2001), and the relative importance of these structures depends on the species, size, and life stage of the organisms performing the passage (Cada et al., 1997).

The four fish species tested visibly presented different sensitivity to fast decompression. The highest levels of injury in *P. costatus* is an important issue. Shoals of *Prochilodus* genera fish are the most important for fisheries, considering the relative biomass, in many South America rivers (Welcomme, 1985).

The highest differences in mortality rates between Kaplan and Francis turbines indicate that, in most cases, mechanical injuries must perform a fundamental role in this mortality, knowing that for each type of turbine, differences in the pressure variations are small, while the shapes of the blades of each type are completely distinct. However, despite not representing the most important factor concerning fish mortality when passing through the turbines, pressure variation, to which the fish is

submitted, represents an adverse situation, considering that under natural conditions, fishes are submitted to pressures close to atmospheric values, with slight variations relative to changes in position in the water column. Damage due to pressure is dependent on the amount and rate of change of pressure experienced by the fish, which is proportional to the total head of the dam, as well as the type of fish. Physostomous fish, such as the tested species, have a pneumatic duct that connects the swim bladder to the esophagus, which is used, along with the mouth, to rapidly take in or vent gas (Lagler et al. 1962). Physoclistous fish, such as the Perciformes, do not have a pneumatic duct and must adjust their body's gas content by diffusion into the blood. Because this diffusion process may take hours, these fish are more susceptible to damage due to rapid pressure decrease. This is probably the main reason for a large number of corvinas (*Pachyurus* spp.) have been found dead by decompression, downstream dams in the São Francisco Basin (Obs. Pers).

For all the tested species, mortality rates due to decompression were extremely low, indicating that the mechanical damage is probably a main factor of death among Brazilian fishes when passing through the turbines. However, it must be taken into account that disorientation of the fishes when they leave the draft tube, make them severely vulnerable to predation by aquatic predators and birds (Rieman et al., 1991), situation in which any type of injury, like the observed ones, can contribute to weaken the fishes, making the predation rates rise.

The use of structures to minimize the damages in the fishes when passing through the turbines is relatively new, with the first reports dating around fifty years (Therrien and Bourgeois, 2000). However, only during the last decades, their use has become popular in North America. In Brazil, there are no such structures installed yet.

Among the main apparatus faded to facilitate the fish passage downstream, physical barriers, which avoid fish entrance in the turbines, behavioral barriers, which guide the fish (attract or repel) through some stimulus towards the spillways or specific systems for downstream passage, such as the bypass, installed in the turbines' intake can be included (Larinier and Travade, 2002). The latter has been used in several large-scale projects in North America (Columbia river and its tributaries), with turbine intake flows between 300 and 600 m³/s (Williams, 1990). Screens up to twelve

meters long are installed in the upper section of the turbines' water intake in order to detour fish to a bypass system, which directs them towards the tailrace, or to a mechanism of transportation. This system is based on the principle that, with the increase in pressure along the intake, fish will swim towards the surface. This behavior was observed for all the four tested species and make possible the implementation of similar structures in dams constructed in Brazil. Particularly relevant were the results presented by the tested migratory species (*P. costatus* and *L. reinhardti*), due to the importance of the downstream movements of adults and juveniles (Godinho and Pompeu, 1993). However, none of the downstream passage systems have shown 100% efficiency. Even the well designed grate system and the bypass system protect only a small portion of the fishes (Ferguson, 1992). For this reason, additional alternatives have been proposed, such as the construction of friendly turbines (Cada, 2001; Neitzel et al., 2004) and the priority setting on the downstream passage through the spillways, which are considered a more benign means of fish passage. However, gas supersaturation generated by spill at the dams may represent additional source of mortality the development of gas bubble disease (Backman and Evans, 2002).

Kaplan turbine adaptations have been suggested and implemented efficiently in North America, representing a good alternative in the future (Cada, 2001). At the Wanapum Dam on the Columbia river in the state of Washington, U.S, they replaced an old Kaplan turbine with a new Minimum Gap Runner (MGR) turbine designed by Voith Siemens Hydro (Cada, G. pers. comm., 2007). The new turbine is a refinement of the old Kaplan. They did index testing and fish survival testing in February-May of 2005. At turbine flows ranging from 9,000 to 17,000 cubic feet per second, efficiency of the new turbine ranged from 91.36 to 93.80 %. Efficiency of the old Kaplan ranged from 89.00 to 89.37 %. The new turbine produced more electricity, and fish-passage survival (Chinook salmon smolts) was about the same for the two turbines, averaging 97 %. The utility is replacing the rest of their Kaplan turbines with the new MGR design.

Controlled spilling has been pointed as an additional alternative, although its success is directly proportional to the spill flow, relative to the river's flow (Coutant and Whitney, 2000). In Brazil, few studies focused on this matter. In the

Santa Clara Dam, operating on the Mucuri River, studies indicated that, despite its high height (60m), individuals of various species were able to go down the spillway with no apparent external damage, although in a small proportion, mainly during high flows (Pompeu *et. al.*, 2004). Thus, for the dams with surface spillway, an alternative would be to reduce the number of fish that enters the turbines, through the installation of grates and the directioning of them towards the spillways.

The use of some of these alternatives could contribute significantly to reduce the impacts of the dams over the downstream migrants, representing an additional approach for South America fish population conservation.

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RESUMO

Este trabalho teve como objetivo avaliar experimentalmente o comportamento de espécies brasileiras quando submetidas a um aumento gradual na pressão, bem como os efeitos de uma descompressão rápida simulando a passagem por uma turbina hidrelétrica. Quatro espécies da bacia do rio São Francisco foram testadas: *Astyanax bimaculatus*, *Hypostomus* sp., *Leporinus reinhardti* e *Prochilodus costatus*. Para todas elas as taxas de mortalidade devido à descompressão foram extremamente baixas. No entanto, sintomas relacionados à descompressão, como exoftalmia e hemorragia só não foram observados em *Hypostomus* sp., sendo mais frequentes quanto maior o valor de pressão a partir do qual realizou-se a descompressão. Todos estes sintomas diminuíram significativamente após 24 horas de observação. Com o aumento da pressão no aparato, as espécies testadas se movimentaram em direção aos níveis superiores. Este comportamento sugere a possibilidade de se utilizar passagens de peixes para jusante do tipo *bypass* em barragens a serem implantadas no Brasil.

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