SÉRIE PEIXE VIVO

RISK ASSESSMENT OF FISH DEATH AT HYDROPOWER PLANTS IN SOUTHEASTERN BRAZIL

PROGRAMA PeixeVivo
CEMIG
A natureza em boa companhia.

COMPANHIA ENERGÉTICA DE MINAS GERAIS – CEMIG

RISK ASSESSMENT OF FISH DEATH AT HYDROPOWER PLANTS IN SOUTHEASTERN BRAZIL

BELO HORIZONTE

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CONTENTS

PREFACE

"Ministério Público [Attorney General] to investigate the death of fish in São Francisco"

"For fishers, fish kill in Três Marias was an environmental crime"

These were headlines found in newspapers of Minas Gerais, and from other states, reporting occurrences of fish deaths in different rivers, which were often associated with hydropower plants. These plants have operated for a long time without protocols establishing rules of coexistence with ichthyofauna, and accidents were frequent. Cemig, the power company in Minas Gerais, also managed accidents with fish deaths resulting from the operation of its hydropower plants. Over time, the Company developed methods to evaluate the presence of fish near hydropower plants in order to estimate possible impacts from their operation that, in addition to causing environmental damage, affected its image. After an accident involving the death of fish at Três Marias Dam on São Francisco River in 2007, the upper Administration of Cemig realized the need to implement more effective measures for the conservation of the ichthyofauna in rivers where the Company had hydropower plants. The Peixe Vivo Program then emerged, with the mission of *minimizing the impact on ichthyofauna by seeking solutions and management technologies that integrate Cemig's electricity generation with the conservation of native fish species, promoting community involvement.*

This mission is a great challenge! The Cemig Group possesses a generation park of more than 60 hydropower plants, most of which are distributed among several river basins of Minas Gerais, but with others outside of the State. Some of these plants are concessions of consortia or group companies and possess structural peculiarities and their own environmental and operational procedures. So, where to begin?

To understand the problem of fish deaths during the maintenance and operation of hydropower plants, partnerships were established with universities and research centers. The first partnership was with the Federal University of Minas Gerais, with the collaboration of professor Alexandre Godinho, who managed the project "Risk Assessment of Fish Death at Hydropower Plants", starting in 2009. This year represented a great milestone for Peixe Vivo Program because the Company made its largest financial investment to date to seek solutions for mitigating impacts to fish, associated with the process of electric power generation, and for fish conservation. With this project, the Peixe Vivo Program team gained great reinforcement with committed and dedicated biologists who work day by day to increase our knowledge of the biology, ecology, and behavior of the native species of our ichthyofauna.

The constant exchange of experience between the University team and the Company's technical teams, including those of the areas of environment, energy planning, and maintenance and operation of the hydropower plants, facilitated the development of methodologies for evaluating the risk of fish death and the creation of internal instruments that establish controls for fish protection during power generation. From then on, several unprecedented results were obtained with tailrace monitoring and accompanied operational procedures in the hydropower plants, which can be found in the chapters of this book.

The concessionaires of hydropower plants in Brazil have been learning to deal with minimizing the risks of fish deaths caused by the operation of their plants, and has in the Peixe Vivo Program a reference of good practices. The adoption of certain procedures in operation and environmental monitoring has created effective protocols to reduce the impacts on fish and the economic damage that results from fines and lawsuits, as well as the negative affect to the image of the hydropower companies. We have built this book thinking about that. We aim to share experiences and show society that we are not oblivious to the impacts caused by energy generation and we are always seeking best practices for understanding and mitigating them. In sharing, we hope to help others in similar situations. This book should further motivate all segments involved with this issue, in particular the energy concessionaires, environmental authorities, and the affected population, to recognize and face this reality that cannot be relieved. This book is also important for those who are not directly connected to the area and wish to understand the generation process and its direct impacts on fish. Good ideas and assertive treatments come from a good diagnosis and an understanding of the problem.

This work was built gradually by several hands that were united by a cause. In the midst of the drainages, monitoring, reporting, and meetings, all authors and coauthors devoted their time to preparing quality material on their experience in the hydropower plants and what could be learned so far.

Despite all the positive results we have achieved so far, we know that our mission has not yet been fulfilled. The task of mitigating impacts on fish, seeking solutions that integrate the generation of electric power with the conservation of species, must continue as long as there are generator units operating in our rivers.

Today's newspaper headlines already feature a new and auspicious perspective:

"Company promotes initiative to prevent the death of fish caused by hydropower plants"

"With Peixe Vivo Program, Cemig is a reference in sustainable management"

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FOREWORD

Injuries or deaths of fish downstream of dams are recurrent events in Brazilian rivers, and the causes have rarely been well understood. Although the operations of generation and maintenance of the components of hydropower plants have a central role in these events, the high number of variables, and the interactions between them and the ichthyofauna, make the identification of *causa mortis* a complex task. This may explain the limited knowledge we have about the details of operations with deleterious potential to fish, a fact that constrains the efficiency of preventing these accidents. A considerable part of this ignorance is due to the enormous media interest that fish mortalities arouse in sectors of society, mobilizing environmental agencies, prosecutors, environmentalists, and riverine peoples. Feeling intimidated by the potential of receiving catastrophic fines, and a marred image, from being associated with these events, the hydropower concessionaires seek to clarify such events in a superficial and, sometimes, arrogant way. This causes mortalities to be surrounded by a climate of secrecy and concealment, which in no way contribute to their understanding. This posture also impairs the conduction of scientific studies, since the deaths are ephemeral in most cases and, when they manifest, their causes are no longer present.

This scenario, however, is changing. The present work, sponsored by Cemig, brings together a set of scientific information on the subject, and represents a fundamental step towards understanding the problem and proposing solid paths for its study. In it, risk and mortality events at dams are analyzed in a clear, objective manner and in the light of good science, signaling that the union between concessionaires and researchers is essential for the generation of knowledge and solutions. Different themes are investigated in its 13 chapters, including protocols for risk assessment, operational procedures with potential to promote mortality, interference in biotic and abiotic conditions in downstream stretches, ichthyocenosis concentrating on the dam area, biology of the most susceptible species, chronic and acute events of mortality, as well as prevention strategies. It is therefore an extremely timely initiative that demonstrates the sensitivity of the authors and supporters to an urgent demand from society, especially from hydropower concessionaires and environmental protection agencies.

Finally, it is worth highlighting the important role that Cemig has been playing, through its Peixe Vivo (Live Fish) Program, in the search for solutions to mitigate impacts arising from the construction of dams. It is also worth mentioning that the advances are not limited to the reservoirs under its concession, and can be applied throughout the hydropower sector. In this sense, it is commendable that, in addition to associating with universities and research centers to seek scientific solutions to problems, Cemig values the dissemination of research through the Peixe Vivo Series. This initiative allows the results to be appreciated, discussed, and applied by all those interested in the subject. The publication of this volume, by its pioneering character, has enormous historical significance.

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SÉRIE
PEIXE VIVO

FISH AND
HYDROPOWER PLANTS

CHAPTER 1

RISK OF FISH DEATH AT BRAZILIAN HYDROPOWER PLANTS

ALEXANDRE LIMA GODINHO &
RAQUEL COELHO LOURES

Godinho A.L. & Loures R.C. (2017) Risk of fish death at Brazilian hydropower plants. In: R.C. Loures & A.L. Godinho (eds.) *Risk assessment of fish death at hydropower plants in southeastern Brazil.* Belo Horizonte: Companhia Energética de Minas Gerais, pp. 19-36 (Série Peixe Vivo, 6).

1 – BRAZILIAN HYDROPOWER PLANTS

The system of power generation and transmission in Brazil is hydrothermal, with a strong predominance of hydropower plants with multiple concessionaires (ONS 2015). The electricity installed capacity for Brazil was 142.6 GW at the end of the first quarter of 2016 (Aneel 2016), with most of the energy being of hydropower origin (Figure 1) and produced by 1,216 hydropower plants. Almost all of this hydropower (97%) was generated by 203 large hydropower plants, which are those with an installed capacity greater than 30 MW or with a reservoir larger than 3 km^2. Most of the remaining hydropower came from small hydropower plants, which, by definition, have an installed capacity between 1 and 30 MW and a reservoir of up to 3 km^2 (Aneel 1998). Large hydropower plants are present in the large river basins of all regions of the country and in many of the small and medium-sized basins.

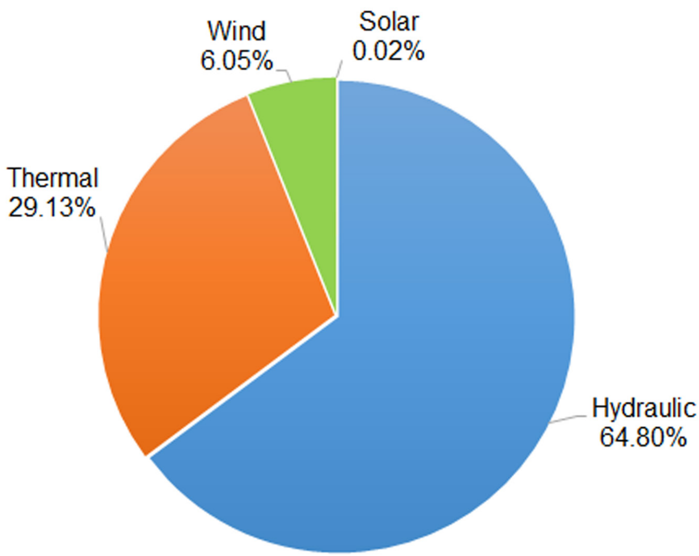


FIGURE 1 – The contribution of energy sources to the total installed capacity of 142.6 GW of Brazil as of March 2016 (Source: Aneel 2016).

The first hydropower plant in Brazil came into operation in 1883 in the Inferno Creek, Diamantina, Minas Gerais State, with the purpose of moving pumps for the extraction of gravel from diamond terrain. The first hydropower plant in Latin America for public and private lighting was Marmelos, built in 1889 on the Paraibuna River, Juiz de Fora, Minas Gerais State, with an installed capacity of 4 MW (Cachapuz 2006). The beginning of the 1960's marks the expansion of hydropower exploration in Brazil with the inauguration of the first two hydropower plants with reservoirs of more than 1,000 km^2, the Furnas (Grande River) and Três Marias (São Francisco River) dams, both in Minas Gerais State. Together, the installed capacity of these two hydropower plants was 1.6 GW, 35% of the existing installed capacity at the time (Spiller & Martorell 1996). Many other large plants were constructed thereafter. Today, Furnas and Três Marias dams represent just a little more than 1% of the installed capacity of Brazil.

The hydropower capacity of Brazil reached 246.7 GW in November 2014 (Eletrobras 2015). According to this source, the river basins with the greatest hydropower potential were the Amazonas (38.8% of the total), Paraná-Uruguai (30.3%), Tocantins (10.8%), and São Francisco (9.2%). On the other hand, the river basins with the greatest installed capacity were the Paraná (66.0% of the hydropower potential used), São Francisco (47.5%) and Tocantins (49.9%). In the Amazonas River basin, only 9% of the potential hydropower was being exploited at the time, although some hydropower plants were under construction and several have been designed for this basin.

To reduce the risk of power outage, the Brazilian power system is interconnected by transmission lines, which allow energy to be exchanged among different regions of the country. The Sistema Interligado Nacional (SIN, National Interconnected System) comprises hydropower plants in all regions of the country (Figure 2). Only 1.7% of the energy produced in Brazil is not from hydropower plants in the SIN and is produced by small isolated plants mainly in the Amazon region (ONS 2015). The SIN allows a permanent flow of power among regions, ensuring that areas with better conditions for energy generation (*i.e.*, higher river flow and greater water storage in reservoirs) send energy to areas with poorer conditions.

The Operador Nacional do Sistema (ONS, National System Operator) ensures the proper functioning of the SIN. It coordinates and controls both the operation of the hydropower plants and the power transmission throughout the SIN, under supervision and regulation by Aneel, the Brazilian electricity regulatory agency (ONS 2015). Thus, the operation of hydropower plants in Brazil is in the hands of the ONS. The concessionaries do not have the autonomy to decide when and how much power to produce in their plants. In addition, electromechanical, electrical, civil, social, and environmental restrictions to power generation, as well as the multiple uses of reservoirs and the control of floods, are analyzed by the concessionaire of a particular plant together with regulatory agencies (Cavallari 2009).

The lack of autonomy of the concessionaires is important for fish conservation and management, as it makes the challenge of operating hydropower plants with minimal impact to fish even more difficult. Knowing the biology of fish that occur near hydropower plants alone is not enough to define the best operational procedures. It is also necessary to consider several other restrictions imposed by the ONS and to obtain their approval in order to alter power generation.

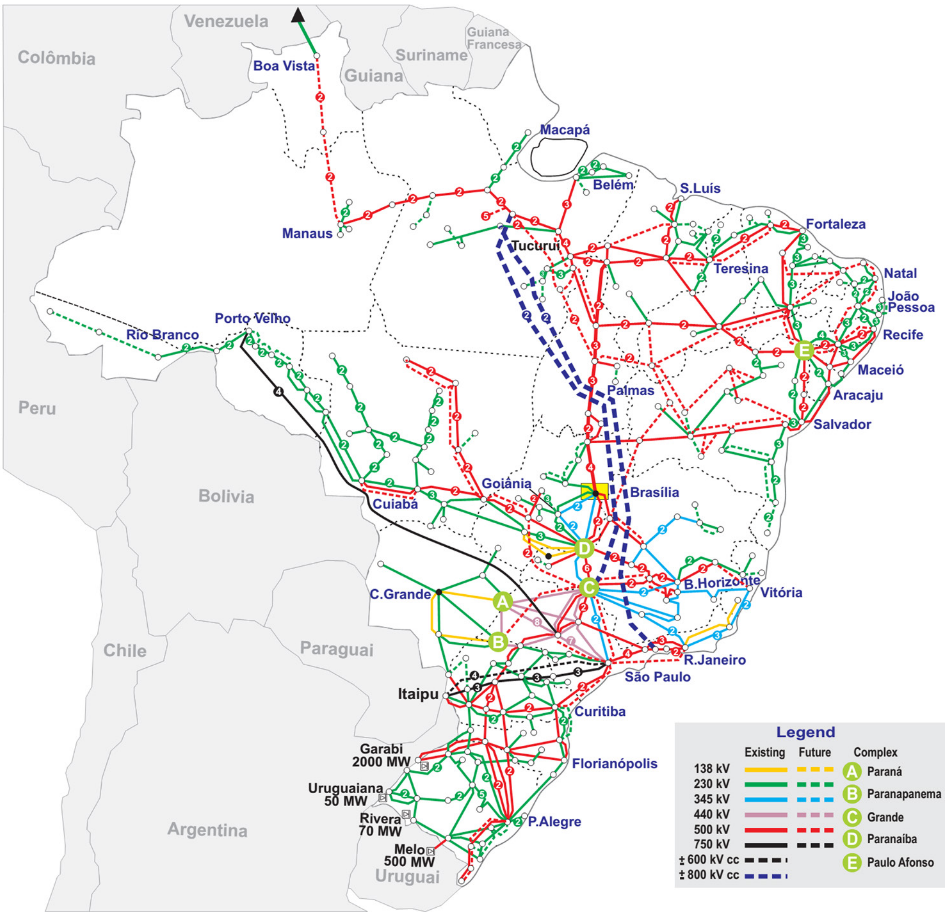


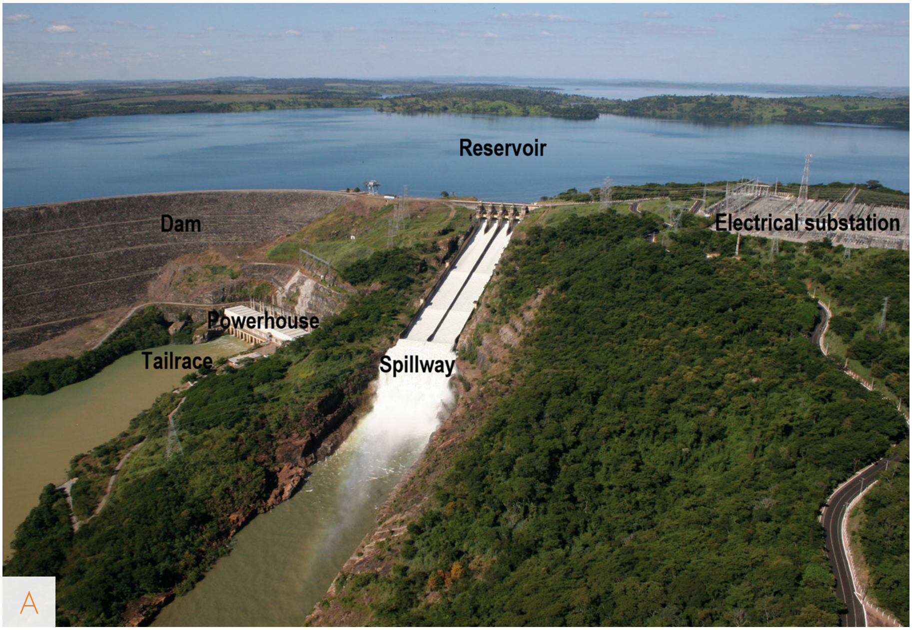
FIGURE 2 – Electroenergetic map of the Sistema Interligado Nacional (SIN, National Interconnected System) in Brazil (Source: ONS 2014).

2 – HYDROPOWER PLANTS

Hydropower plants generate power using the hydraulic potential of a river. Hydropower comes from the potential energy of water stored in a reservoir being transformed into kinetic energy that rotates a turbine (mechanical energy). The generator, which is connected to the turbine, transforms this mechanical energy into electrical energy.

Hydropower plants comprise a reservoir, dam, spillway, powerhouse, and tailrace (Figure 3). There are two main types of reservoirs: run-of-the-river and storage. In the first, the outflow discharge (the flow that passes through the turbines and spillway) is practically equal to the inflow discharge (the flow that arrives to the reservoir) in the short term (hours to days). Thus, the water level of the reservoir does not vary or varies very little, generally less than 1 m. On the other hand, storage reservoir accumulates water during peaks of inflow discharge, and releases it when inflow discharge is low. Therefore, the water level of a storage reservoir varies many meters throughout the year because the outflow and inflow discharges are not equal.

The reservoir water used to produce power in the powerhouse passes through the water intake screen, penstock, spiral case, and distributor before reaching the turbine blades (Figure 3). The water exits the turbine through the draft tube, returning to the river downstream through the tailrace. The generator, turbine, and associated equipment that convert potential energy into electrical energy compose a generator unit. Water not used to produce energy is released through the spillway and into the river downstream.



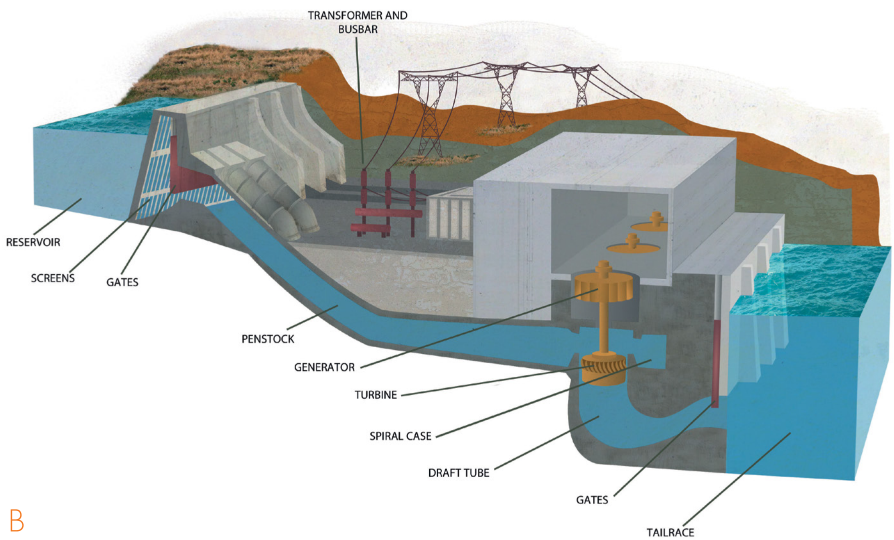


FIGURE 3 – External parts (A) and internal structures (B) of a hydropower plant.

3 – IMPACT OF HYDROPOWER PLANTS ON FISH

Among human activities, hydropower production has one of the greatest impacts on the life of river fishes. Various other human activities, like farming, deforestation, pollution, fishing, and the introduction of exotic aquatic organisms, also impact river fishes by contributing, with varying intensities, to reduced fish abundance.

From construction to operation, hydropower plants impact fish in a variety of ways. By transforming the river's running water (lotic) into the standing water (lentic) of a reservoir, hydropower plants can eliminate habitats that are vital for fish, such as spawning and nursery grounds. Some species of fish prefer lotic over lentic environments, and thus avoid inhabiting reservoirs. Fish that live downstream from dams are also affected by hydropower plants. The quality and quantity of the outflow discharge of a hydropower plant can differ from that present in the river prior to a dam, and have a negative affect on spawning and offspring survival of fishes. The outflow discharge could be colder or warmer, has less oxygen, or be less turbid than prior to the dam. Additionally, floods may be less intense and of longer duration than in the pre-dam period. These factors together may decrease the abundance of fish in the river downstream of hydropower plants.

Many species of fish agglomerate near hydropower plants, particularly in the tailrace. Several of these species are migratory. They migrate upstream and downstream, during different life cycle stages, between different habitats used for spawning, nursery, refuge, and feeding (Godinho & Kynard 2009). When fish encounter a dam while moving upstream, they may remain near the dam for days, weeks, months or even years, giving rise to agglomerations. Fishers like to fish near hydropower plants because of such agglomerations.

Fish near hydropower plants are at risk of death. Several hydropower plant operations can affect fish directly, as described in Andrade *et al.* (2012) and Chapter 3 of this book. One of the most common operational procedures is turbine stop, which is followed by startup or dewatering. Turbine stop-startup is commonly done when there is variation in power demand, and thus occurs for a short duration of time (hours to days). Sporadically, turbines need periodic maintenance or review. In these cases, the turbine is dewatered by the withdrawal of the water in its hydraulic circuit. During turbine stop, its discharge is reduced to zero. Tailrace fish can then enter the draft tube, sometimes in tons. When the turbine is then started again, the fish in the draft tube can suffer injury or even death from physical shock of the blades or walls of the draft tube. Deaths or injuries are also common due to barotraumas, such as exophthalmos (eyeball projection out of the orbit), stomach eversion, and rupture of the swim bladder, caused by sudden variation in pressure inside the turbine. In turbine dewatering, fish trapped in the spiral case, draft tube, and dewater sump need to be recovered. When there are many, recovery is complex, time consuming, and with increased risk of death.

To improve the environmental safety of hydropower plants, it is crucial to understand how they affect fish so that mitigation actions can be implemented. From this understanding, constructive solutions and new operational rules can, and have been, implemented to reduce fish entrapment and death during turbine operations and maintenance procedures that pose risks to fish. Understanding will only be achieved with the development of specific studies. In addition to assuring their conservation, protecting fish will help reduce monetary losses by the power sector concessionaires due to fines and temporary interdiction in power generation as a result of their deaths.

4 – REDUCTION OF FISH DEATH IN THE OPERATION OF HYDROPOWER PLANTS

After the environmental accident at Três Marias Dam, in 2007, that killed about 7 tons of fish, Cemig (the hydropower company of the state of Minas Gerais) made efforts to find solutions and best practices to protect fish during the operation and maintenance of its plants. As a result, Cemig created the Peixe Vivo (Live Fish) Program with the objectives of minimizing fish death and improving fish conservation and management programs. The guidelines and objectives of the program were defined in conjunction with researchers, fishers, civil society, and NGOs.

The project Risk Assessment of Fish Death at Hydropower Plants, one of the priorities of the Peixe Vivo Program, took place from 2008 to 2013 in partnership with the Federal University of Minas Gerais. Results of the project are explored in this book. Its main objectives were to: (i) identify the hydropower plant operational procedures that pose the greatest risk for fish death; (ii) reduce the risk of fish death during these operational procedures; and (iii) monitor the operational procedures that pose the greatest risk in order to ensure environmental safety.

The following specific objectives were established:

- Standardize methods for gathering data to assess the risk of fish death during turbine procedures, taking into account the particularities of each hydropower plant;
- Monitor fish abundance and environmental conditions continually in locations of the basins that are under the influence of the hydropower plants of the Cemig Group;
- Quantify the amount of fish recovered in turbine dewatering;
- Evaluate, and propose improvements to, the methods used to recovery fish from the draft tube of turbines during dewatering;
- Study aspects of the biology (such as reproduction, feeding, distribution, etc.) of the fish species most affected by turbine procedures;

- Build a database to support corrective and procedural actions related to fish death in the operation of hydropower plants of the Cemig Group; and
- Train specialized personnel in risk assessment and how to implement measures to protect fishes.

Several significant results have already been achieved by the project. Some of these are presented below, while others are addressed in other chapters of this book.

5 – ACCOMPLISHED RESULTS

Mandi (*Pimelodus maculatus*) is the most common species of fish trapped during turbine dewatering at the hydropower plants of Cemig Group. In Amador Aguiar II and Três Marias dams, the abundance of mandi in the tailrace can be used to predict, with a certain degree of accuracy, the amount of mandi trapped in the turbine during dewatering (Chapter 3). Prior to dewatering, such a prediction is made and reported to environmental analysts, operators, and Cemig management staff. Using this methodology, several dewaterings were postponed when large quantities of mandi where present in the tailrace, resulting in the prediction of greater environmental risk.

In addition to the abundance of fish in the tailrace, the amount of fish recovered from the draft tube depends on the turbine discharge immediately prior to closing the draft tube with a stoplog. This was a conclusion reached by the study undertaken at Três Marias Dam by Andrade *et al.* (2012), who suggested that turbine discharge should be maximal prior to initiating dewatering in order to reduce the amount of fish trapped in the draft tube.

Andrade *et al.* (2012) also evaluated the effectiveness of the divert fish operation. Used in many hydropower plants across the country, this procedure is performed to reduce the amount of fish trapped in the draft tube during dewatering. It consists of opening the spillway and/or stopping the turbine adjacent to the one to be dewatered. The procedure assumes that fish near the draft tube exit of the turbine that will be drained will be attracted away from it. Tests performed at Três Marias Dam suggest that the desired effect of the divert fish procedure may not occur (Andrade *et al.* 2012). At Amador Aguiar II Dam, the results on the capacity of the spillway discharge to attract fish from the draft tube were inconclusive (Chapter 8). Further testing is needed to determine the efficiency of the divert fish procedure.

The use of a fish screen at the exit of the draft tube of Três Marias Dam significantly reduced the amount of fish killed in turbine stop-startup. Andrade *et al.* (2012) obtained data from 385 turbine stop-startups (159 without fish screen, 226 with fish screen). The biomass of dead or dying fish collected in the tailrace after turbine startup without fish screen was 0 to 120 kg per startup, for a total of 828 kg of fish collected. With the use of a fish screen, the biomass of dead or dying fish collected ranged from 0 to 8 kg, and the total biomass was only 23 kg. The success of using a fish screen at Três Marias Dam stimulated their installation at the Funil (Grande River) and Retiro Baixo (Paraopeba River) dams, both in the state of Minas Gerais.

Fishing on the São Francisco River downstream of Três Marias Dam is sustained by migratory fishes (Godinho & Kynard 2009). Thousands of people depend on these fishes for their livelihoods. The abundance of migratory fishes, in turn, depends on river flooding, because their main nurseries are floodplain lakes. Early life stages of migratory fishes are only able to reach floodplain lakes during floods. The study on agglomeration of young fish at Três Marias Dam found that agglomerations of greater intensity occur only after two consecutive years of large floods (Chapter 12). This finding is fundamental for the prevention of fish deaths at Três Marias Dam during more intense agglomerations, and for planning artificial floods for restoration and maintenance of the São Francisco River fishery.

Every year, mainly from October to April, carcasses of dead fish are found floating in the first few kilometers of the Paranaíba River downstream from São Simão Dam (Chapter 7). A 10-km stretch of the river was surveyed twice a day during these months at the end of 2009 and early 2012, with all carcasses observed being collected. Mandi (*Pimelodus maculatus*) was the most common species, with 56% of the carcasses and 25 % of the biomass collected. Most of the mandi carcasses were adults and in the initial stages of decomposition. These fish had injuries from barotrauma and mechanical shock, which occurred in the turbines of the hydropower plant. During some years, the number of carcasses drifting in the river was related to the number of turbine startups. Mark-and-recapture experiments with mandi carcasses recovered just 1.7% of the marked carcasses, indicating that only a small fraction of the drifting carcasses of mandi were collected in the surveys and that many carcasses drift without being observed.

Another significant result was the discovery, on the Paranaíba River downstream of the São Simão Dam, of the largest population of the threatened jaú (*Zungaro jahu*) catfish known in the state of Minas Gerais. Reaching more than 1 m in length and more than 100 kg, jaú is one of the largest migratory fish in Brazil. The species likely occurred throughout nearly the entire extents of Grande and Paranaíba rivers (Godinho 1998). Common in the past, the species is rare today. Consequently, jaú is critically endangered in Minas Gerais (Drummond *et al.* 2008). The most current records of its occurrence in the state include a few localities in the Paranaíba and Grande rivers (Godinho 1998). In addition, one or more individuals have been recorded near the Igarapava, Funil, Marimbondo, and Porto Colômbia dams. In the spillway plunge pool of São Simão Dam, a surprising 43 jaús (standard lengths of 48–108 cm, body weights of 2.3–23.0 kg) were captured in only four days of sampling. The capture of jaús in the Paranaíba River downstream of São Simão Dam, as in other places of its occurrence, is an occasional event. In order to capture a significant amount of jaús, Araújo *et al.* (2015) used the knowledge of local fishers, and caught them with gillnets set immediately after the closure of the spillway gates. The spillway discharge, therefore, attracts jaú to the spillway plunge pool. The discovery of this population, and an effective technique for capturing jaú, offer great prospects for studying this species, which remains poorly-known. In addition, this finding creates an immediate need to implement conservation actions for jaú.

6 – IMPORTANCE TO CEMIG AND THE ELECTRICITY SECTOR

Given the scenario of expensive environmental fines and the interdiction of turbine operation due to environmental accidents with fish, proper risk assessment and the adoption of effective protection measures after 2007 reduced the economic and environmental costs to Cemig, as well as the damage to its image, that it had suffered in previous years.

The use of the **Risk Assessment of Fish Death (RAFID)** methodology, described in detail in Chapter 2, reduced fish death at hydropower plants. The affected biomass, an indicator created within Cemig for indicating the sum of weight of dead fish in the operation of its plants, reduced by 77% since the beginning of RAFID (Figure 4). The main reason for this reduction was the employment of protective actions for fish in the planning and execution of turbine maintenance in conjunction with Cemig's engineering team.

Among the Cemig Group's hydropower plants, from 2001 to 2007 the operational procedures that affected fish the most were turbine dewatering and startup, which were responsible for 53.2% and 20.7% of all affected biomass during the period, respectively (Figure 5). Starting in 2008, after the establishment of RAFID and the implementation of protective actions for fish, the scenario changed. The biomass affected by turbine dewaterings decreased to nearly zero, placing it at fifth place among the operational procedures with the greatest risk for fish death. Turbine startup took first place with 39.5% of the affected biomass, followed by normal operation (26.9%). The implementation of more effective environmental safety actions for these two causes of fish death are still a challenge for the Cemig Group, which continues to work to minimize fish deaths in the operation of its hydropower plants.

The results achieved by RAFID indicate a positive return on the investment by the Cemig Group. Its application resulted in a significant reduction in the risk of fish death and, consequently, fines, and the disruption of the generation of energy. The experience gained from the implementation of RAFID has brought recognition to the Peixe Vivo Program, which now shares information about its procedures with other companies in the electricity sector, environmental agencies, and society in general.

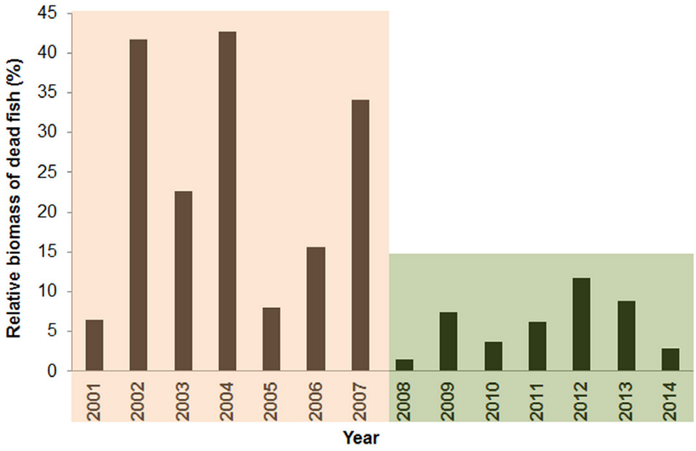


FIGURE 4 – Relative biomass of dead fish recorded in 44 hydropower plants of the Cemig Group from 2001 to 2014. The period prior to (2001–2007) and after (2008–2014) the implementation of the Risk Assessment of Fish Death methodology is indicated. Fish death reduced by 77%.

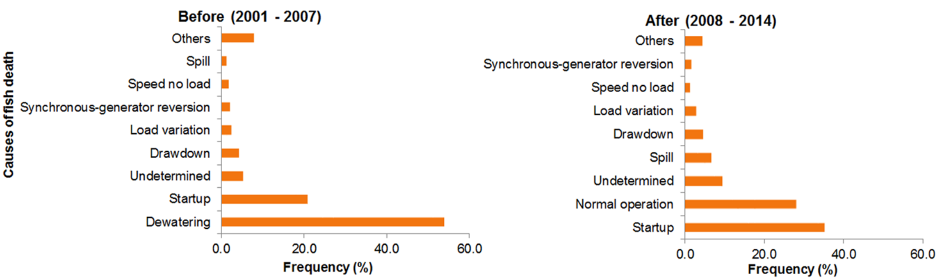


FIGURE 5 – Relative frequency of biomass of dead fish per cause of death at hydropower plants of Cemig Group before and after the implementation of the Risk Assessment of Fish Death methodology.

Despite all the advances made so far, the challenges of mitigating the direct impacts of the operation and maintenance of hydropower plants have yet to be exhausted, and will hardly be so in the short term. Certainly, the company-university partnership is a solid path towards addressing these challenges. Therefore, this partnership must continue for the development of new research. Accordingly, the Risk Assessment of Fish Death at Hydropower Plants project, concluded in early 2013, was continued with new objectives and new hypotheses as the Validation of Protocols for Protection of Fish in Hydropower Plants project. Thus, the challenges that still remain, and others that will appear, will be studied in the search for the best way to reconcile the operation and maintenance of hydropower plants with fish conservation.

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CHAPTER 2

METHODOLOGY FOR RISK ASSESSMENT OF FISH DEATH AT HYDROPOWER PLANTS

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Loures R.C., Godinho A.L., Silva R.J., Andrade F.R., Rêgo A.C.L, Carvalho M.M. *et al.* (2017) Methodology for risk assessment of fish death at hydropower plants. In: R.C. Loures & A.L. Godinho (eds.) *Risk assessment of fish death at hydropower plants in southeastern Brazil.* Belo Horizonte: Companhia Energética de Minas Gerais, pp. 37 – 70 (Série Peixe Vivo, 6).

1 – INTRODUCTION

Nuclei of human settlement have formed along rivers since the dawn of humanity, and fish have served as food presumably from the earliest stages of human occupation of river valleys (Welcomme 1985). The socioeconomic transformations of the 20th century led to a dramatic increase in the global human population, along with its economic activities and demand for natural resources (Dugan *et al.* 2010). The result has been increased impacts to rivers due to industrial and domestic dumping, and the construction of dams for water and energy supply, with severe consequences for the aquatic organisms therein, mainly fish.

The occurrences of fish kills have a special impact on people because they always associate these events with a decrease in the availability of fish for fishing and consumption. The causes of fish kills can, and should, be determined so that corrective measures can be taken to prevent future losses. However, determining the cause(s) of such events can be difficult and requires careful observation, accurate data collection, and appropriate sampling procedures (Meyer & Barclay 1990). Since fish can die from a wide variety of causes, caution should be taken before making any premature conclusions. Fish can die from a number of natural (*e.g.*, infectious diseases, parasitic infestations, oxygen depletion, increased temperature, and toxic algal blooms) or anthropic (*e.g.*, pollution and contamination by toxic substances, and the operation of hydropower plants) causes, and both can cause large-scale losses (Meyer & Barclay 1990).

The damming of a river for energy production interrupts the free transit of fish, which then often concentrate immediately downstream of dams where they have access to the draft tube of the turbines (Figure 1). These fish are subject to direct impacts from the hydropower plants, whose operations can produce injuries and death. Thus, Brazilian hydropower concessionaires must deal with the sporadic occurrence of fish deaths by, first, reducing death and minimizing environmental impacts, and, second, decreasing economic losses, from fines and lawsuits, and damage to their image.

FIGURE 1 – Concentration of fish in the tailrace of Três Marias Dam, São Francisco River, Minas Gerais, in March 2007.

In order to establish preventive measures against fish death, and to increase environmental safety at is hydropower plants, Cemig (the power company of the state of Minas Gerais), through the Peixe Vivo (Live Fish) Program in partnership with the Federal University of Minas Gerais (UFMG), developed the **Risk Assessment of Fish Death (RAFID)** methodology for the operation and maintenance of their hydropower plants. The methodology was developed through a research project (Chapter 1), and permits the identification of the main operational procedures that cause fish death, as well as the means to reduce it, during the operation and maintenance of hydropower plants. The project assesses the risk of operational procedures to fish through a priori monitoring of their abundance near hydropower plants and the environmental conditions downstream. In addition to forming a database, this information supports preventive actions related to the environmental safety of operating hydropower plants. The biology of the fish species most affected by the operational procedures of hydropower plants are also investigated in order to help understand the reasons why these species congregate near the plants and their relationships with this environment.

This chapter presents the process of developing RAFID, and details the steps taken by Cemig, from the identification of the main risks to the definition of protocols used to evaluate the risk of fish deaths, at their hydropower plants. The chapter ends with the description of sampling methods and an analysis of their efficiency.

2 – DEVELOPMENT OF RAFID

The Cemig Group, which includes wholly-owned subsidiaries and associated companies, is the third largest power generator in Brazil with 84 hydropower plants, 23 wind farms, and 3 thermopower plants in operation, totaling 7.8 GW of installed capacity, almost all of which is located in the state of Minas Gerais. Due to the large number of hydropower plants, and their location in practically all of the hydrographic basins in the state, criteria for prioritizing the inclusion of hydropower plants in the study were established following the five steps shown in Figure 2.

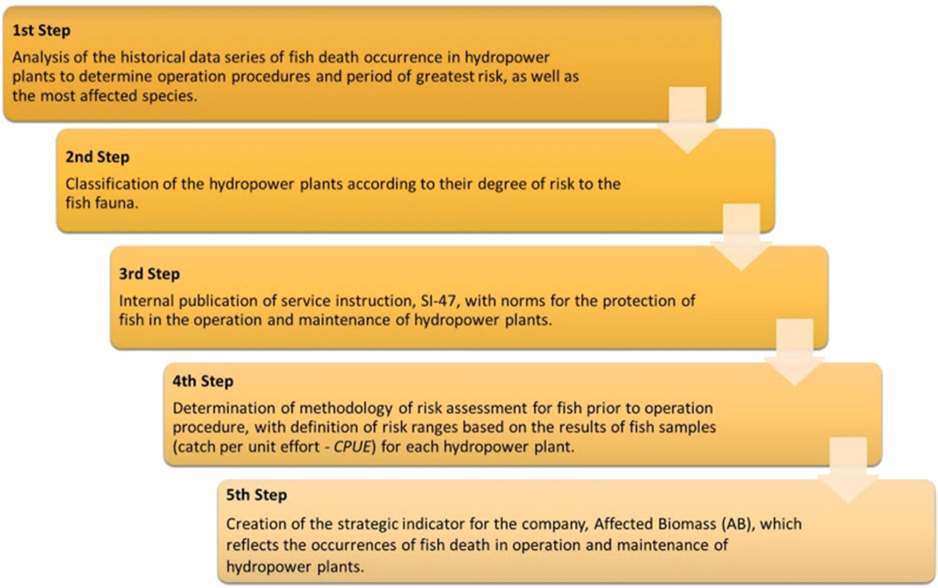

FIGURE 2 – Steps in creating the Risk Assessment of Fish Death (RAFID) methodology in the operation and maintenance of hydropower plants.

Step 1

The first step in the development of RAFID was to analyze historical series data on the occurrence of fish deaths for Cemig Group hydropower plants. With the publication of the Brazilian Environmental Crimes Law, in 1998, Cemig established an internal procedure for recording environmental occurrences in order to control them and take corrective measures. For RAFID, records from 2001 to 2007 were analyzed with information on hydropower plant, date, species, quantity of biomass affected (dead fish biomass), and probable cause of occurrence. These data were used to determine the operational procedures in the operation and maintenance of hydropower plants that caused the most fish deaths (detailed description in Chapter 3), the plants with the highest number of occurrences, the period of the year with the greatest frequency of occurrence and the fish species most affected.

High-risk operational procedures. The identification of operational procedures that have the greatest impact on fish (having higher risk) is crucial for understanding the factors involved in the occurrence of fish deaths and in determining the specific corrective and preventive measures to be taken. The analysis of historical series data showed that turbine dewatering and turbine startup were the two operational procedures that produced the most dead fish biomass, with 52.5% and 20.8% of all dead fish biomass, respectively (Figure 3). Turbine dewatering was the operation that produced the greatest amount of biomass of dead fish, but the fourth in the number of occurrences. Thus, although dewatering occurs sporadically, it is a high-risk operation. Turbine startup was the operation with the greatest number of fish death events, accounting for 39.9% of all records.

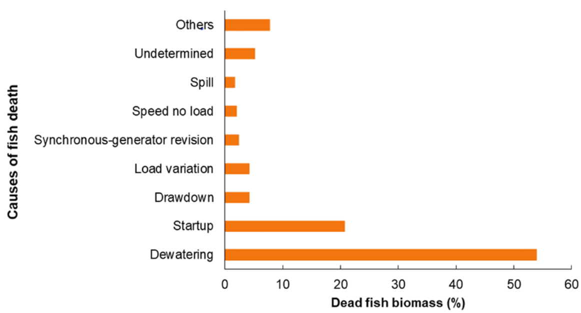

FIGURE 3 – Percentage of dead fish biomass per cause of death at hydropower plants of the Cemig Group from 2001 to 2007.

Period of greatest risk. The period of November to April encompasses the months with the highest risk of fish death because they had the greatest biomass of dead fish (Figure 4). The greater risk during this period is likely due to the fact that it is when there is the greatest concentration of fish immediately downstream from dams (Chapters 4, 6, 9, 10, and 11), and so operational procedures should be avoided during this time.

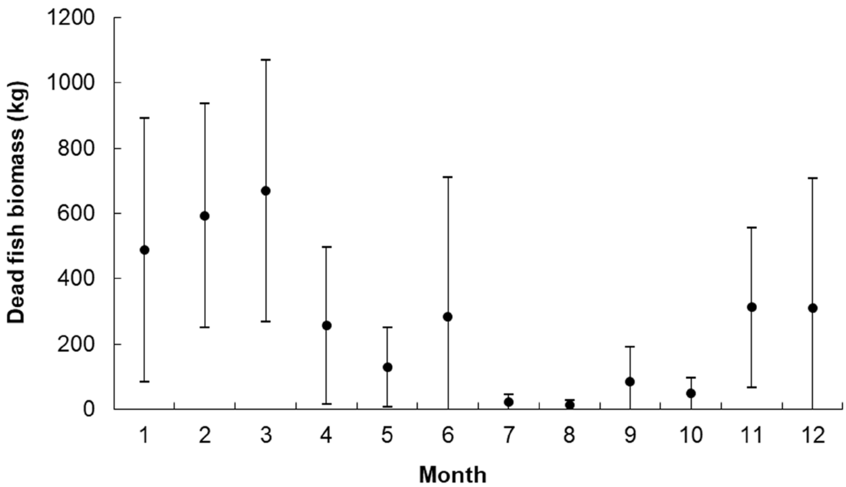

FIGURE 4 – Monthly mean of dead fish biomass from operation and maintenance of Cemig Group hydropower plants from 2001 to 2007, with the 95% confidence interval.

Most impacted species. The fishes most affected by the operation and maintenance of hydropower plants are those of the genus *Pimelodus* (mandi), which were present in 65% of the fish death occurrences, followed by the genus *Prochilodus*, present in 23%, and *Plagioscion squamosissimus* (corvina), present in 16%. The occurrences with *Pimelodus* seem to be mostly related to turbine dewatering, while *Prochilodus* and corvina appear to be more affected by turbine startup and commissioning. These data served to guide the development of a methodology for monitoring prior to operational procedures with risk to fish (4th step) and the subsequent analysis of the efficiency of the risk prediction methodology by considering the capture of the most affected fishes.

Step 2

The hydropower plants were analyzed to determine the frequency of occurrence of events of fish death over the years. This analysis lead to the classification of Cemig Group plants according to their degree of risk to fish (Table 1; Figure 5).

TABLE 1 – Category of risk for Cemig Group hydropower plants.

INCREASING RISKS

CATEGORY	DESCRIPTION	HYDROPOWER PLANT*
A	Large and small hydropower plants that have high potential risk (defined by high abundance of fish downstream) and/or that have already had a significant environmental accident with fish.	Amador Aguiar II (ASD), Emborcação (EMD), Funil (FUD), Itutinga (ITD), Pai Joaquim (PJD), São Simão (SSD), and Três Marias (TMD) dams.
B	Large and small hydropower plants of medium to low potential risk (defined by medium to low abundance of fish downstream) and/or have not had a significant environmental accident involving fish.	Amador Aguiar I (AFD), Baguari (BGD), Camargos (CMD), Irapé (IRD), Jaguara (JGD), Miranda (MRD), Nova Ponte (NPD), Porto Estrela (PED), Queimado (QMD), Rosal (ROD), Volta Grande (VGD), Aimorés, Cajuru, Igarapava, and Salto Grande dams.
C	Small hydropower plants that discharge at the bottom.[1]	Sá Carvalho (SCD), Anil, Bom Jesus do Galho, Jacutinga, Joasal, Luiz Dias, Marmelos, Martins, Paciência, Paraúna, Piau, Poquim, Salto Morais, Santa Marta, and Sumidouro dams.
D	Small hydropower plants that do not discharge at the bottom.	Cachoeirão, Gafanhoto, Lages, Machado Mineiro, Paraopeba, Peti, Pipoca, Pissarrão, Poço Fundo, Rio de Pedras, São Bernardo, Santa Luzia, Salto Passo Velho, Salto Voltão, Tronqueiras, and Xicão dams.

* Acronyms indicate plants studied for RAFID; technical information for each plant can be found in Appendix B.

1 Bottom discharge is an operational procedure in which the plant is totally shutdown to allow the removal of sediment from the bottom of the reservoir by draining the water through bottom gate(s). In the operation, the turbine is stopped, the gateway of the adductor channel is closed, and the bottom duct(s) is/are opened. When the effect of the bottom discharge is completed, the bottom gate(s) is/are closed and the adductor channel gate is opened, ending the bottom discharge. This operational procedure must be done in a controlled manner with constant monitoring of water quality (mainly turbidity and dissolved oxygen). A minimal outflow discharge must be maintained to avoid environmental damage and/or negative impacts downstream of the dam.

FIGURE 5 – Map of the hydropower plants of the Cemig Group categorized according to risk of fish death.

Step 3

The next step was to create and implement a specific Service Instruction (SI) for the Cemig Group. For each of the categories of risk, specific actions were proposed for risk assessment and impact mitigation according to the potential for an environmental occurrence and the operational procedure being performed.

The development of the SI, titled “SI-47: Ichthyofauna Protection During Operation and Maintenance of Hydropower Plants”, was carried out by a multidisciplinary group with representatives from different areas of the Cemig Group. Its main objective was to define the precautions to be taken for fish protection during the operational procedures of hydropower plants of the Cemig Group. This instruction came into effect in October 2007, guiding the operation, maintenance, and environmental teams while carrying out their activities during operational procedures with risk to fish, according to the categories described in Step 2. Here, we highlight some important points of SI-47:

a. Formalizes the risk categories of Cemig Group hydropower plants according to the potential risk of impacting fish;

b. Defines authorities and responsibilities for before, during, and after operational procedures;

c. Creates systematic planning for operational procedures, considering not only engineering but also the environment;

d. Creates an environmental safety index, which is a checklist of provisions and procedures to be applied prior to operational procedures;

e. Determines specific controls for each hydropower plant according to its risk category;

f. Determines the communication to be made to the responsible environmental agency prior to performing operational procedures;

g. Determines the implementation of fish monitoring by a specialized team of biologists prior to performing an operational procedure with risk to fish.

Step 4

Among the requirements of SI-47 is that monitoring is to be performed in order to assess the risks to fish prior to the implementation of any operational procedure (prior monitoring). The methodology of this monitoring was developed under the assumption that the risk of fish death during an operational procedure is proportional to the amount of fish downstream from the hydropower plant at the moment that the operational procedure is implemented. Considering the logistics of sampling, monitoring is to be performed about three days prior to the scheduled operation by a team of biologists. For this purpose, five teams of biologist were established throughout Minas Gerais, one in each of the five regions of the state: West, North, South, East, and Triângulo Mineiro.

As each hydropower plant has its own particularities with regard to outflow discharge, civil structure, and downstream fish fauna, the methodology was adapted to attend to risk assessment, yet respect logistic limitations and, especially, the safety of the team near dangerous areas. The methodology was, however, standardized for each hydropower plant to allow comparisons to be made among data overtime. In addition, various sampling techniques were tested to determine those most suitable for fish sampling as close to the hydropower plants as possible, especially for the target (most affected) species. After sampling, the team is to generate a report evaluating the degree of risk to fish by the proposed operational procedure. Based on the degree of risk, the team indicates whether or not the operational procedure is to be performed.

In addition to prior monitoring, periodic monitoring was also established at each hydropower plant using the same methodology. The purpose of periodic monitoring was to obtain sufficient samples so that other aspects of the biology of fish downstream from the hydropower plants could be investigated.

Step 5

The last step was to consolidate RAFID by developing a strategic indicator. This indicator, called Affected Biomass (AB), corresponds to all the dead fish biomass (in kg) produced by the operation and maintenance of a given hydropower plant. This indicator, like others, is subject to periodic audits and allows the results to be assessed relative to goals and monitoring compliance. The AB is determined every month for a hydropower plant, and is disclosed to the Cemig Group, along with an analysis of the performance of the plant with regard to the occurrence of fish deaths. This indicator was found to increase the motivation of the teams involved in the process of power generation, from those responsible for planning operational procedures to those who executed them, to reduce impacts to fish.

3 – PROTOCOLS FOR RISK ASSESSMENT

Standardized sampling protocols help maintain data quality by ensuring that data are collected consistently over time and space (Kwan & Peterson 2007). The sampling design for prior and periodic monitoring at the hydropower plants, as well as the definition of a procedure to follow turbine dewatering, were important in reducing fish death. Protocols describing the materials and methods to be adopted in these monitoring and operational procedure follow-ups have been developed to guide the staff performing such activities, particularly hydropower plants in SI-47 category A and CMD, which is in category B (see Table 1 for the hydropower plants acronyms).

In the following items, we present the general methods that have been standardized and applied in prior and periodic monitoring. Some of the results obtained from these monitoring efforts and follow-ups of operational procedures are presented in other chapters of this book.

3.1 Definitions of fishing gear

Fish species are heterogeneous in relation to several parameters, such as preferential habitat, size, body shape, ages of individuals, sex, and nutritional status. Consequently, species differ as to their vulnerability to a particular capture method (Hamley 1975). Thus, the selectivity of the different fishing gear should be taken into account when studying fishes.

Selectivity depends on the sampling method and the species, size, or gender of the fish. Selectivity is responsible, for example, for the capture of a particular species in a proportion different from the proportion it represents, in relation to the other species, at the sampling site. The same can happen with regard to size and sex. Researchers can use this selectivity to their advantage when focusing on a particular species or size of fish. Fishing gear efficiency refers to the amount of effort employed to capture a certain number of fish of the target species. Maximizing the efficiency of a particular fishing gear saves time and resources in more targeted assessments (Hubert *et al.* 2012).

The first step in the development of RAFID was the identification of the species with the greatest number of deaths at the hydropower plants. Mandi (*Pimelodus maculatus*), a catfish important for artisanal fishing and common near the dams, was, by far, the most frequent species involved in environmental accidents. Thus, mandi was identified as the target species for prior monitoring. Much is known about the ecology and biology of mandi in reservoirs and natural environments, but studies on mandi living immediately downstream from hydropower plants are rare.

The fishing gear selected for the study were: gillnets, cast nets and hook-and-line (Table 2). It was not possible to use all three types of fishing gear at all hydropower plants due to safety issues and the absence of suitable places to set gillnets. The data obtained from the sampling with this gear were used to support decisions on the performance of operational procedures, to evaluate the spatiotemporal abundance of fish at the hydropower plants, and to evaluate the efficiency of the different types of gear for capturing the target species.

In the first year of the project, gillnets with stretched meshes of 3, 4, 5, 6, 7, 8, 10, 12, 14, and 16 cm were used. After this period, the size (standard length) of the fish recovered during turbine dewatering was compared with those captured in the monitoring downstream from the hydropower plants. The size of recovered mandi ranged from 9 to 33 cm, with 95% being between 9 and 25 cm. Gillnets of stretched mesh sizes of 3 to 8 cm captured 93% of the mandi from 9 to 25 cm, so sampling after the first year was carried out only with gillnets of these mesh sizes. Gillnets with a mesh size of 5 cm were also excluded after the first year because the size of the fish they captured overlapped with the size of the fish caught by gillnets with a mesh size of 6 cm.

Particularities

At PJD, all three types of fishing gear were used in the first four sampling campaigns, but from the fifth sampling campaign on only hook-and-line was used.

The efficiency of all three types of fishing gear was notably influenced by variation in depth, water velocity, and/or quantity of woody debris in the sampling area due to changes in outflow discharge, although hook-and-line was the least influenced. Hook-and-line was also the most efficient and selective gear for catching mandi, the most important species for the operation of PJD.

At TMD, as will be discussed further in this chapter, gillnets (stretched mesh from 3 to 16 cm) and cast net (stretched mesh 5.5 cm) showed similar results in the number and species of fish captured in the region just downstream from the hydropower plant. Thus, cast nets were chosen for use at TMD because it was easier to implement and allowed the fish to be released in better physical condition.

At ITD, hook-and-line and cast nets were used for fish monitoring because they were better suited to the local conditions than gillnets. With these two types of fishing gear it was possible to sample the more turbulent water near the tailrace where conditions were unsuitable for gillnets. Hook-and-line was used to catch fish at sites of greater depth, while cast nets were used in shallower places.

3.2 Prior monitoring protocol

The objective of prior monitoring is to evaluate the abundance of fish as close as possible to the downstream side of the hydropower plant (Figure 6), a few days before an operational procedure, in order to analyze the risk of fish death and to make a decision about the operation. The data generated by prior monitoring supports corrective and operational actions related to the death of fish, thereby increasing the environmental safety of the operation of hydropower plant.

Periodicity

Prior monitoring is performed no more than three days prior to an operational procedure. If the operational procedure occurs immediately after a weekend or holiday, or in exceptional situations, the sampling date is determined in consultation with the environmental representative of the hydropower plant during the planning meeting. Ideally, prior monitoring should be done as close as possible to the date of the operational procedure.

Operational and limnological data

During prior monitoring, operational data (spillway discharge, turbine discharge, outflow discharge, and reservoir volume) and limnological data (dissolved oxygen, water temperature, and water transparency) are obtained. The operational data are acquired from the Telemetry and Hydrometeorological Monitoring System of Cemig. Dissolved oxygen (*DO*) and water temperature are measured with mutliparameter probes. Transparency is measured using a Secchi disk in a place with no visible water flow and in the sun (Esteves 2011). The location of the limnological sampling site at each hydropower plant are shown in Figure 6.

Sampling gear and catch effort

For capturing fish, gillnets, cast nets and/or hook-and-line are used (Table 2). Gillnets are set late in the afternoon on one day and removed the next morning for a total netting period of about 14 h. Three batteries of gillnets are set with each battery having one net each of the following stretched mesh sizes: 3, 4, 6, 7, and 8 cm. The nets are about 1.7 m high and 10 m (mesh 3 and 4 cm) or 20 m (other mesh sizes) long, totaling 408 m^2 of gillnet. Fishing with cast nets is performed by professional fishers. Half of the casts are made in the morning and the other half in the evening. The mesh size of the cast net can vary according to the hydropower plant, and corresponds to the size used by local fishers to catch mandi. Fishing with hook-and-line is carried out for 6–8 h on a single day during the daytime by a fisher or in half the time with two fishers.

TABLE 2 – Fishing gear and effort employed for sampling during per prior or periodic monitoring at hydropower plants of Cemig Group.

DAM	GEAR			CATCH EFFORT			BAIT
	Gillnet (mesh*)	Cast net (mesh*)	Hook (n°)	Gillnet (m^2)	Cast net (cast)	Hook (h/fisher)	
Amador Aguiar II	3, 4, 6, 7, 8	5	8	408	40	6	Earthworm
Camargos	3, 4, 6, 7, 8	8	4	408	50	8	Earthworm
Emborcação	3, 4, 6, 7, 8	5	8	408	40	6	Earthworm
Funil	3, 4, 6, 7, 8	8	4	408	50	8	Cow heart
Itutinga	-	8	4	-	50	8	Earthworm
Pai Joaquim	-	-	8	-	-	6	Earthworm
São Simão	3, 4, 6, 7, 8	5.5	8	408	72	6	Earthworm
Três Marias	-	5.5	-	-	60 to 100	-	-

* stretched mesh size in centimeters

Biometry

All captured fish are identified and the total *(TL)* and standard *(SL)* lengths and body weight *(BW)* determined. All mandi caught in gillnets, the first 50 mandi captured in cast nets and the first 30 mandi caught with hook-and-line are fixed in 10% formaldehyde, as are dead fish of other species. Additional live fish are returned to the river.

Data analysis

For hook-and-line, the catch per unit effort ($CPUE_h$) in number of individuals is calculated by the formula:

$$CPUE_h = \frac{N_h}{EP_h}$$

Where:

N_h= number of fish captured by hook-and-line;

EP_h= hook-and-line fishing effort (number of fishers multiplied by hours of fishing).

For gillnetting, the following formula is used to calculate $CPUE_g$:

$$CPUE_g = \sum_{i=1}^{3} \left(\frac{N_i}{E_i} \right)$$

Where:
N_i = number of fish captured by gillnet battery i;
E_i = fishing effort (in 100 m^2) for gillnet battery i.

For fish captured by cast net, the $CPUE_c$ is calculated by the formula:

$$CPUE_c = \frac{N_c}{E_c}$$

Where:
N_c = number of fish captured by cast net;
E_c = cast net fishing effort (number of casts).

Risk level categories

For each hydropower plant, the risk level categories (low, medium, high, and very high) was determined for turbine dewatering. Risk level categories were defined by comparing *CPUE* of prior monitoring with fish biomass (alive and dead) recovered from turbine dewatering. This comparison showed that recovered biomass tends to increase with increasing *CPUE* of prior monitoring. Therefore, the biomass to be recovered during turbine dewatering can be predicted a priori with a certain level of accuracy. The higher the predicted biomass to be recovered the greater the risk for fish death. For the determining risk level category, prior monitoring is performed, the *CPUE* calculated, and its value compared to the minimum and maximum *CPUE* values for each risk level category. The greater the amount of *CPUE* data from prior monitoring and recovering fish biomass, the more precise will be the boundaries of the risk level categories, and the safer the prediction.

The recommendations and measurements for each risk level category are:

- Low risk: the operational procedure is recommended;

- Medium risk: the operational procedure is recommended, but it is suggested that the Contingency Plan be carefully evaluated;
- High risk: the operational procedure is recommended only if it cannot be delayed (according to engineering evaluation). It is suggested that the Contingency Plan be carefully evaluated and that two environmental teams be present to monitor the operational procedure and to recovery fish in case of prolongation of activities;
- Very high risk: The operational procedure is not recommended and should only be carried out if it is urgent and cannot be delayed.

Issuance of report

In order to make a decision regarding the implementation of turbine dewatering, a memo is sent by e-mail to related areas of the Company containing the *CPUE*, risk level category, and recommendation regarding undertaking the operational procedure. The information is to be sent on the workday immediately prior to the performance of the operational procedure. Subsequent to the memo, a report is prepared containing data from prior monitoring and information about the fish to be recovered as a result of the turbine dewatering. This report is also sent to representatives of the areas of the hydropower plant that will be involved in carrying out the operational procedure.

3.3 Periodic monitoring protocol

The protocol for periodic monitoring is the same as that for prior monitoring, with the exception of sampling frequency. The frequency of periodic monitoring sampling is every two months and is not associated with an operational procedure, as is prior monitoring. The periodic monitoring of TMD is an exception, with it occurring every 10 days. Periodic monitoring aims to determine temporal variation in the community structure and abundance of fish, especially mandi, and their relationship with limnological and hydropower plant operational factors. The data collected also forms a database for analyses that support corrective and operational actions related to fish deaths, thus increasing the environmental safety of the operation of hydropower plants.

FIGURE 6 – Sampling points at hydropower plants of Cemig Group. Letters indicate the fishing gear used (C = cast net, G = gillnet, and H = hook-and-line) or sites for sampling limnological data (L).

3.4 Monitoring protocol for turbine dewatering with fish recovery

Turbine dewatering has historically presented the highest risk for fish death, mainly due to stress and hypoxia (Figure 3). The operational procedure is performed when there is a need to access the structures and components of the turbine that are usually submerged, or to undertake some particular maintenance procedure. During turbine dewatering, the upstream and downstream floodgates are closed, isolating the turbine from the external environment. Prior to the downstream gate being closed, fish in the tailrace may enter the draft tube, likely facilitated by the reduced turbine discharge, and become trapped in there and/or in the spiral case and dewater sump (Figure 7). The trapped fish need to be recovered and returned uninjured to the river. However, depending on the quantity of trapped fish in the turbine, there is a risk of *DO* depletion before they can be recovered, which can lead to stress and even death by hypoxia. The quantity of trapped fish, the concentration of *DO* in the water, and the time required to perform the turbine dewatering determine the severity of the situation (Chapter 3). Since *DO* consumption will be proportional to the quantity of fish trapped, procedures are necessary to measure *DO* during turbine dewatering and fish recovery (Loures 2009).

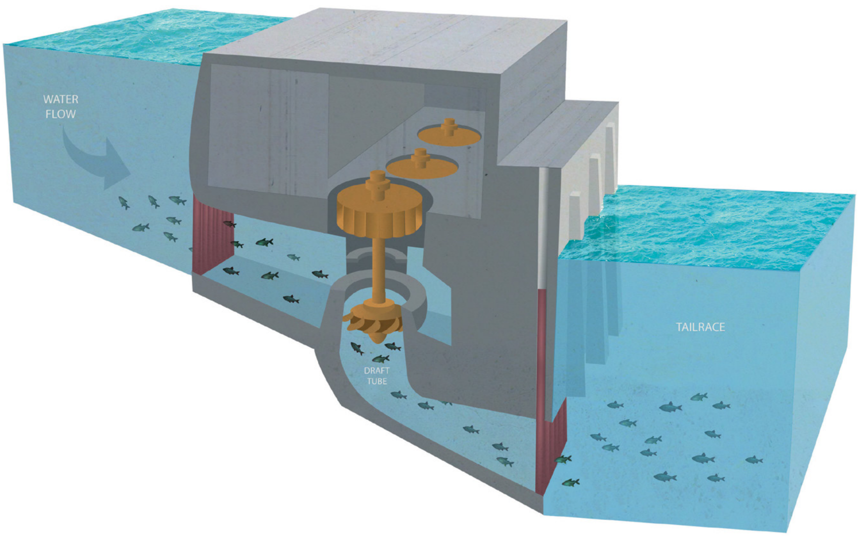

FIGURE 7 – Scheme showing fish inside the draft tube, which become trapped during turbine dewatering.

Turbine dewatering mobilizes a significant contingent of material and people in various synchronized functions. In this way, monitoring becomes essential to avoid accidents involving the environment and people. Thus, a monitoring protocol for turbine dewatering with fish recovery was designed to guide the professionals involved with the operation. The protocol provides the procedures that should be adopted in the planning and monitoring of turbine dewatering with fish recovery from the draft tube, spiral case, and dewater sump. Its objectives are to:

- Properly plan the operational procedure;
- Determine procedures for monitoring *DO* and water temperature;
- Determine procedures for fish recovery, including packing and transportation;
- Quantify the biomass and number of fish (dead and alive) recovered from the dewatering;
- Establish a post-dewatering procedure;
- Establish procedures for evaluating the operational procedure.

Planning meeting:

To be carried out at least seven days prior the turbine dewatering, when the schedule of the operational procedure and Contingency Plan are presented, the environmental safety form is completed and the minutes written.

Communication with environmental agencies

Prior to the execution of the dewatering, communication is made with the relevant environmental agencies to inform them about the planned turbine dewatering, as provisioned in SI-47.

Provisioning

Necessary materials are provisioned in advance according to the determinations of the planning meeting.

Prior monitoring

As provisioned in SI-47, prior monitoring is to be performed according to the procedures described in the Prior Monitoring Protocol.

Monitoring temperature and dissolved oxygen

During turbine dewatering, temperature and *DO* of the water are monitored. The *DO* is an indirect indicator of the quantity of fish trapped in the turbine and a parameter of water quality crucial to fish survival. To measure *DO*, water is sampled from the spiral case, draft tube, and dewater sump. Preferably, a bucket with a fast-coupling type of connection near the bottom should be used (Figure 8). This apparatus avoids increasing *DO* by water falling into the bucket, which could occur if the tip of the sampling hose was placed in mouth of the bucket. The bucket must be fully filled for accurate measurement.

FIGURE 8 – Metal bucket, with a bottom valve that connects a hose to another valve in the draft tube hatch (A), for measuring dissolved oxygen and water temperature (B).

In general, *DO* can vary depending on the characteristics of the reservoir drainage basin and time of year. Each hydropower plant has reference *DO* values and, therefore, it is important to measure *DO* prior to the isolation of the turbine to provide a reference. Measurements should be performed periodically (*e.g.*, every 30 min), recorded, and analyzed. It is important to check the rate of *DO* decrease, because rapid decreases may indicate that many fish are trapped. In such a case, the interval between measurements should be reduced. The possibility of aborting the operational procedure should also be discussed with those responsible.

When possible, and according to the particularities of each hydropower plant, the Contingency Plan should include minimum *DO* limits that guarantee environmental safety of the operational procedure. The plan must predict risk categories and the respective actions to be taken for continuing the operation or even its cancellation. Among the actions that can be taken to improve *DO* are industrial air injection and water renewal in the draft tube.

Estimating the quantity of live and dead fish

Fish are withdrawn from the spiral case, draft tube, and dewater sump in containers with water. Fish from at least one container in every three are transferred to a basket for species identification, counting, and weighing (Figure 9A-E). These data will allow estimation of the number and biomass of fish recovered per species. Adaptations to this estimation method can be made to suit the civil structure of a particular hydropower plant or the number of fish recovered (*e.g.*, if there are few recovered fish all can be identified, counted, and weighed). Dead fish are also identified, counted, and weighed.

Destination of recovered fish

Fish withdrawn from the turbine are placed in a transportation box with aerated water to be released in a previously determined location (Figure 9F). Those that die are disposed appropriately. In case a large number of live fish is recovered, 50 individuals of the target species (mandi) are randomly selected, euthanatized, and fixed in 10% formaldehyde for later laboratory analysis.

Reporting

A report is issued at the end of each dewatering with data from prior monitoring and the operational procedure, and sent to representatives of the areas of the hydropower plant involved in the operational procedure.

FIGURE 9 – Basket for draining water from the transportation box used to remove fish from the draft tube (A and B). Weighing (C and D), sorting for identification and counting (E) and releasing (F) fish.

4 – ANALYSIS OF FISHING GEAR EFFICIENCY

Fishing gear is selective and possesses practical restrictions to its use (Siqueira *et al.* 2009). This section presents the analyses of the fish samples made using gillnets, cast nets, and hook-and-line in order to determine the most efficient gear for each hydropower plant, particularly for the target species mandi. The results can be used to refine prior and periodic monitoring protocols, improve the risk assessment of fish death prior to an operational procedure with risk, and optimize time and resources.

4.1 Data analysis

Data used for the analysis of fishing gear efficiency was collected from June 2010 to June 2012 at ASD, CMD, EMD, FUD, ITD, and SSD. Species richness (*S*), Shannon diversity index (*H*'), evenness (*J*'), and dominance (*D*) of the fish caught by each type of fishing gear were analyzed according to the following equations (Kwak & Peterson 2007):

Shannon diversity index:

$$H' = -\sum_{i=1}^{S} p_i \, In \, p_i$$

S = number of species
p_i = proportion of the total sample represented by the *i*th species

Evenness:

$$J' = \frac{H'}{H'_{max}} = \frac{H'}{In\, S}$$

H'_{max} = = maximum possible value of *H*'
S = number of species

Dominance:

$$D = \sum_{i=1}^{S} p_i^2$$

S = number of species
p_i = proportion of the total sample represented by the ith species

For mandi, we determined Spearman's correlation among fishing gear type (Zar 1999). We tested for normality of the data using the Shapiro-Wilk test.

4.2 Results and Discussion

Gillnets were the most suitable fishing gear for sampling the fish community and target species at four of the six hydropower plants studied. In addition to having captured the greatest number of individuals, gillnets generally produced *S*, *H'*, and *J'* values much higher than those of other types of gear (Table 3). For these reasons, gillnets are routinely used in monitoring programs and have been recommended by standardized sampling protocols (Siqueira *et al.* 2009; Hubert *et al.* 2012). Further information regarding the species caught is available in other chapters of this book.

TABLE 3 – Abundance (*N*), richness (*S*), Shannon diversity index (*H'*), evenness (*J'*), and dominance (*D*) by fishing gear at hydropower plants of the Cemig Group.

Variable	Fishing gear	Hydropower plant					
		Amador Aguiar II	Camargos	Emborcação	Funil	Itutinga	São Simão
N	Gillnet	4655	437	3038	1208	-	3629
	Cast net	745	87	548	172	244	483
	Hook	265	7	203	86	60	275
S	Gillnet	29	13	35	25	-	41
	Cast net	6	2	6	7	6	19
	Hook	6	8	9	9	8	20
H'	Gillnet	1.7	1.3	1.6	2.3	-	2.3
	Cast net	0.5	0.4	0.9	1.5	1.5	2.2
	Hook	0.2	1.3	1.1	1.1	0.5	2.1
J'	Gillnet	0.5	0.5	0.5	0.7	-	0.6
	Cast net	0.3	0.6	0.5	0.8	0.8	0.7
	Hook	0.1	0.6	0.5	0.5	0.3	0.7
D	Gillnet	0.3	0.4	0.3	0.1	-	0.2
	Cast net	0.7	0.8	0.6	0.3	0.3	0.2
	Hook	0.9	0.4	0.5	0.5	0.8	0.2

Amador Aguiar II Dam

Mandi represented 41% of the total number of individuals caught by gillnet, 85% by cast net, and 96% by hook-and-line at ASD. Temporal variation in the number of mandi captured by cast net and hook-and-line followed that for gillnet. Consequently, there was a positive correlation in the number of mandi caught between the types of fishing gear (Table 4). The greatest captures of mandi were in the rainy season for all three types of fishing gear (Figure 10). Cast net only captured mandi in the two months of the greatest capture of mandi with gillnet and hook-and-line, indicating that mandi are only captured by cast net when their density is greater in the sampled area. Therefore, the cast net was found to be the worst fishing gear for determining the presence of the target species.

Camargos Dam

Gillnet was the fishing gear that captured the most individuals and species at CMD (Table 3). No mandi were captured with cast net, and the high D of this gear was the result of the, almost exclusive, capture of curimba (*Prochilodus lineatus*). There was no correlation between the number of mandi caught by gillnet and hook-and-line (Table 4). Hook-and-line was more specific to the capture of mandi, being responsible for 90% of all mandi sampled. Very few mandi were captured in the dry season (Figure 11). Unlike at other hydropower plants, mandi was not the most captured species at CMD, ranking third in abundance. Nevertheless, mandi is the most important species for the operational procedures of CMD.

Emborcação Dam

Mandi accounted for 49% of the number of the fish caught by gillnet, 73% by cast net, and 64% by hook-and-line. Independent of fishing gear type, more mandi were sampled in the rainy season (Figure 10). In this season, mandi accounted for 47 to 90% of all fish caught by gillnet. The cast net only captured mandi in the rainy season, when water transparency was lower, suggesting that higher turbidity increases the susceptibility of mandi to this fishing gear. Therefore, the cast net was the worst sampling method for determining the presence of mandi at EMD. The number of mandi caught by hook-and-line exhibited temporal variation similar to that for the number of mandi caught by gillnet and cast net. Therefore, there was a positive correlation in the number of mandi caught between gillnet and hook-and-line, and between cast net and hook-and-line; there was no correlation between gillnet and cast net (Table 4).

Funil Dam

Gillnet was responsible for catching the most fish (82%) at FUD. It also generated the highest *S* and *H'*. Mandi accounted for 62% of the number of fish captured by gillnet and 37% by hook-and-line. Only three mandi were sampled by cast net, all in a single sample. The number of mandi caught exhibited seasonal variation, with higher captures in the rainy season (Figure 10). There were no correlations in the number of mandi caught between fishing gear types (Table 4). As in CMD, mandi was not the most captured species at FUD, but still the most important species for the operation of FUD.

Itutinga Dam

Mandi was the most captured species at ITD, but it was only captured by hook-and-line. It represented 68% of all fish caught by this fishing gear. The number of mandi captured varied seasonally with most (67%) being captured in the rainy season (Figure 11). Although more species were caught with hook-and-line than with cast net, the *D* for hook-and-line was greater due to the predominance of mandi (Table 3).

São Simão Dam

Mandi represented 10% of the number of individuals caught by gillnet, 5% by cast net, and 22% by hook-and-line. Gillnet captured the largest number of mandi, followed by hook-and-line. These two were the most adequate fishing gear for sampling mandi, with hook-and-line being more specific than gillnet. Cast netting was not suitable for capturing mandi because it caught them in only 2 of the 26 sampling campaigns. The cast net sampling points were likely inappropriate for catching mandi, but they were the only sites that allowed throwing the cast net. Thus, cast net was the worst fishing gear type for mandi. More mandi were captured in the rainy season, both with gillnet and hook-and-line (Figure 10); however, these two fishing gear types did not show similar patterns of temporal variation in the number of fish captured. There were no correlations in the number of mandi between fishing gear types (Table 4).

TABLE 4 – Correlations between fishing gear types in the number of mandi caught at five hydropower plants of Cemig Group. Significant values are highlighted in bold.

HYDROPOWER PLANT	GILLNET X CAST NET		GILLNET X HOOK		CAST NET X HOOK	
	r	*P*	*r*	*P*	*r*	*P*
Amador Aguiar II	**0.78**	**<0.01**	**0.91**	**<0.01**	**0.69**	**0.01**
Camargos	-	-	0.53	0.14	-	-
Emborcação	0.21	0.51	**0.75**	**0.01**	**0.68**	**0.01**
Funil	0.41	0.36	0.40	0.33	0.45	0.31
São Simão	0.69	0.08	-0.14	0.49	0.44	0.16

Particularities

Pai Joaquim Dam

In the first four sampling campaigns, when all three types of fishing gear were used, mandi was the most captured species. Gillnet captured the greatest number of species and the second largest number of individuals. Mandi represented only 3% of fish caught by gillnet, 14% by cast nets, and 44% by hook-and-line. Gillnet also experienced the most interference from water level variation, which prevented its use in a standardized way. Cast net captured only 4% of all individuals, followed by 37% by gillnet, and 59% by hook-and-line. Thus, cast net was the worst gear for fish sampling at PJD. As in other hydropower plants, more mandi were captured in the rainy season (Figure 11). Hook-and-line was the method selected for sampling at this hydropower plant due to its greater efficiency and selectivity for mandi, the most important species to the operation of PJD.

Três Marias Dam

At TMD, monitoring was carried out only with cast net. As in other hydropower plants, mandi was captured more frequently in the rainy season (Figure 11). During periodic monitoring, another study using gillnets at TMD was funded by Peixe Vivo Program (Loures & Pompeu 2012). This study made it possible to compare fish composition and abundance between gillnet and cast net. No significant difference was found in species composition (ANOSIM, $P > 0.05$), and the two gears exhibited a strong correlation in *CPUE* ($r = 0.85$, $P < 0.05$; Prado *et al.* 2015). These results indicate that the efficiency of both types of gear is similar. Thus, the choice of gear can be made according to the purpose of the sampling and the particularities of each sampling gear. At TMD, we chose to use cast net since it allows the release of fish after gathering the necessary data. Furthermore, since cast net is selective for mandi, using it to monitor TMD will help build a database for future comparisons of patterns of occurrence, permanence, and dominance of mandi, the fish species present in most of the environmental occurrences at TMD. In addition, such data will help indicate years with 'arribação' (Chapter 12), an event that occurs during a discrete period of time.

5 – FINAL CONSIDERATIONS

Mandi was the most captured species in all but two hydropower plants. Its high trophic and reproductive plasticity apparently allows it to be abundant near hydropower plants (*e.g.* Dei Tos *et al.* 2002; Maia *et al.* 2007). It was present throughout the year, but more were captured in the rainy season, as was also found by Dei Tos *et al.* (2002) and Buisson *et al.* (2007). Chapter 6 of this volume treats mandi biology in more detail. It also analyzes temporal variation in mandi abundance at the hydropower plants and its relationship with abiotic factors. Chapters 9, 10, 11, and 12 provide information on the factors that influence the capture of mandi at São Simão and Três Marias dams.

Based on the findings presented here regarding the efficiency of fishing gear types at various hydropower plants, monitoring protocols were adapted to improve risk assessment of fish death prior to operational procedures, to optimize time in the field, and to improve safety during fish sampling. Thus, it was determined that gillnet and hook-and-line would be used at CMD and FUD, gillnets at ASD, EMD, and SSD, hook-and-line at ITD and PJD, and cast nets at TMD.

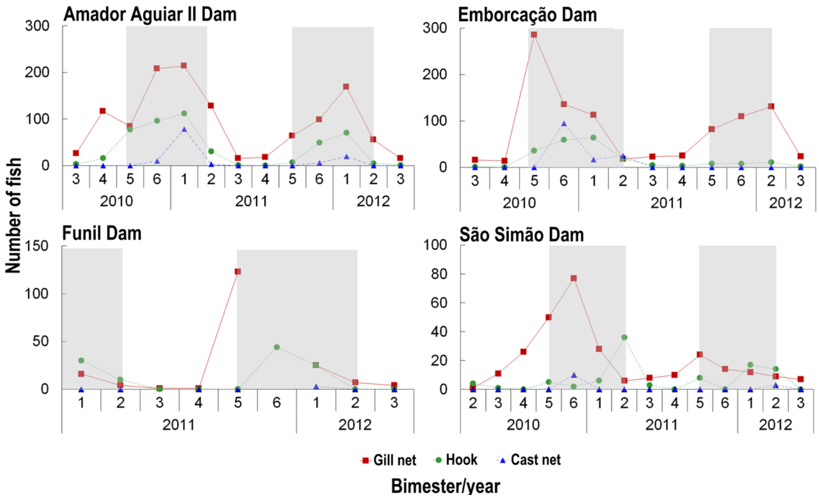

FIGURE 10 – Bimester variation in the number of mandi caught by gillnet, hook-and-line, and cast net at hydropower plants of the Cemig Group. The shaded area corresponds to the months of the rainy season (October to March).

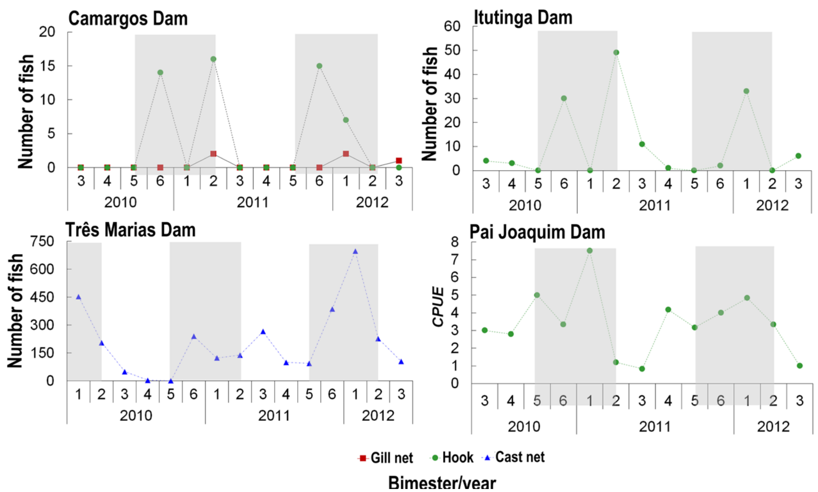

FIGURE 11 – Bimester variation in the number of mandi caught by one or two fishing gear types at hydropower plants of the Cemig Group. The shaded area corresponds to the months of the rainy season (October to March).

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CHAPTER 3

FISH AFFECTED BY OPERATIONAL PROCEDURES OF HYDROPOWER PLANTS IN SOUTHEASTERN BRAZIL

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1 – INTRODUCTION

The construction of hydropower plants is responsible for profound and irreversible changes to waterways, with decisive implications for the fishes therein (Agostinho *et al.* 2007). Among the several impacts to the fish fauna, the concentration of fish just downstream of dams (Agostinho *et al.* 2007) and fish deaths due to the operation and maintenance of turbines (Andrade *et al.* 2012) are among the most frequent and severe problems for hydropower plants. Such fish deaths may hurt the company's image and lead to fines and stoppage of power generation.

Fish are at risk of injury and death by entrapment, mechanical shock, decompression, hypoxia, and desiccation during operational procedures of hydropower plants. The main turbine operational procedures that generate these risks are dewatering, load variation, speed no load, startup, synchronous-generator reversion, and blackstart. Non-turbine operational procedures risky to fish are drawdown and spill. Descriptions of each of these operational procedures, with the associated risks to fish, are provided in Table 1, while a schematic of a turbine showing its components can be seen in Chapter 1 of this book.

In this chapter, we present data from 186 operational procedures that occurred from 2009 to 2012 in 19 hydropower plants of the Cemig Group. We, then, discuss the impact of these operational procedures on fish and evaluate the measures taken to mitigate their effects. The 19 hydropower plants included in this study are located in seven river basins in southeastern Brazil (Figure 1, Table 2).

TABLE 1 – Description of the principal operational procedures of hydropower plants that affect fish (in alphabetical order except for blackstart).

OPERATIONAL PROCEDURE	DESCRIPTION	MAIN RISKS TO FISH
Dewatering	Deployment of upstream and downstream floodgates and/or stoplogs to isolate the turbine hydraulic circuit. Dewatering provide access to the interior of the turbine in order to perform maintenance of its structures.	Before turbine isolation is completed, tailrace fish can enter and become trapped in the draft tube. In dewatering, dissolved oxygen (*DO*) reduction may drop to a lethal level. Stress and injury can occur to fish trapped in the turbine and being recovered.
Drawdown	Lowering of the reservoir water level to reduce the load of the sediments in the reservoir or to perform service to the dam or to the reservoir. It is an unusual operation in large hydropower plants.	During drawdown, fish may be trapped upstream. They may die due to desiccation or lack of *DO*. Changes in physical and chemical parameters of water (*e.g.*, turbidity, pH, and *DO*) can affect fish upstream and downstream.
Load variation	The amount of power generated (load) in the hydropower plants depends on the energy demand. The higher the demand, the higher the load and the higher the turbine discharge. Significant variations in load in a hydropower plant can cause significant oscillations in the downstream water level.	The risk level depends on the downstream river morphology and the amplitude of the water level variation. Fish may be trapped and suffer hypoxia or desiccation in puddles and hollows formed by variation in water level. In addition, fish near the draft tube may be affected by sudden increase in pressure and turbulence due to greater discharge.
Speed no load	In speed no load, the turbine discharge is reduced to about 10–15% of its maximum capacity. The turbine rotates without power production until reaching its rated speed, a precondition to input charge in the turbine. Speed no load is also done to evaluate the mechanical condition of the turbine.	The reduction in turbine discharge allows fish to approach the turbine rotor where there is risk of decompression and collision with the turbine blades. This may produce barotrauma (*e.g.*, exophthalmia and stomach eversion) and physical injuries.

OPERATIONAL PROCEDURE	DESCRIPTION	MAIN RISKS TO FISH
Spill	The spill of reservoir water to downstream is for various demands, like dam safety during floods, downstream minimum flow, navigation, and creating a waiting volume.	During spill, fish upstream may descend and suffer physical injury in the spillway. Fish downstream may suffer gas bubble disease due to water supersaturated with gas. When the floodgates close, fish may become trapped in the spillway or in downstream puddles and hollows with risk of hypoxia and desiccation.
Startup	Turbine startup begins with the release of water flow through the wicket gates and with the initiation of turbine rotation. Discharge increases until the turbine reaches its rated speed.	While the turbine is stopped, fish can enter the draft tube. During the startup, they may suffer physical injuries, due to barotrauma and collision with the turbine blades and draft tube wall, making them more vulnerable to predation by fish and birds.
Synchronous-generator reversion	Occurs when the turbine returns to generate energy after running as synchronous condenser. During synchronous condenser, the wicket gates blades are closed and the water level of the draft tube is lowered by air injection into the turbine. In this condition, the turbine rotor rotates freely without contact with the water and without producing energy. Synchronous-generator reversion is done by opening the wicket gates blades. The incoming water expels the air down the draft tube. This operational procedure provides greater stability to the electrical system through voltage control.	The same of the startup.
Blackstart	In this test, which is carried out periodically, all turbines of a hydropower plant are stopped to measure the time needed to reestablish generation.	Same as those for startup, but on a larger scale because it involves starting larger number turbines.

FIGURE 1 – Locations of the studied hydropower plants in southeastern Brazil.

TABLE 2 – Studied hydropower plants by watershed.

WATERSHED	RIVER	HYDROPOWER PLANTS[1]
Araguari	Araguari	Pai Joaquim (PJD), Nova Ponte (NPD), Miranda (MRD), Amador Aguiar I (AFD), and Amador Aguiar II (ASD)
Doce	Doce	Baguari (BGD)
	Santo Antônio	Porto Estrela (PED)
	Piracicaba	Sá Carvalho (SCD)
Grande	Grande	Camargos (CMD), Itutinga (ITD), Funil (FUD), Jaguara (JGD), and Volta Grande (VGD)
Itabapoana	Itabapoana	Rosal (ROD)
Jequitinhonha	Jequitinhonha	Irapé (IRD)
Paranaíba	Paranaíba	Emborcação (EMD) and São Simão (SSD)
São Francisco	São Francisco	Três Marias (TMD)
	Preto	Queimado (QMD)

[1] Ordered from upstream to downstream by river.

2 – METHODS

We obtained data on 186 hydropower plant operational procedures from internal reports of Cemig. Hydropower plant environmental staff and/or a biologist of the project 'Risk Assessment of Fish Death at the Hydropower Plants' were present at all these operational procedures. The data obtained were from a fraction of the total number of operational procedures performed at the hydropower plants, primarily at hydropower plants and from operational procedures of greater risk to fish according to the Cemig's Service Instruction 47 (SI-47). The SI-47, described in detail in Chapter 2, grouped hydropower plants according their potential risk to fish as measured by the amount of fish historically affected by their operational procedures.

For each operational procedure, we obtained the following data: plant where it took place, recovered species, and recovered biomass of dead fish. For dewatering, we also obtained the season of the year, recovered biomass of live fish, dewatering duration, fish recovery duration, and *DO* measurements during dewatering.

Specifically for ASD (the hydropower plant with the greatest amount of data available for analysis), we used data of fish samples taken downstream of the hydropower plant with gillnets prior to dewatering and the number of recovered mandi (*Pimelodus maculatus*) from the draft tube.

2.1 Quantification of recovered live fish

We quantified the number and/or biomass of live fish recovered during dewatering, drawdown, and after spillway discharge.

During dewaterings, the fish trapped in the spiral case, draft tube, and dewater sump were recovered with dip and seine nets (Figure 2A and 2B). We identified, counted, and weighed the fish (Figure 2C). When large quantities of fish were trapped, we sampled aliquots to estimate the total number and biomass of trapped fish, as well as the number of species (richness). The fish were released upstream and/or downstream from the dams.

In drawdown, after the lowering of the reservoir water level, inspections were performed near the dam. Any fish trapped in puddles were recovered with sieves, dip nets, and cast nets. The fish were identified and returned to the water upstream of the dam.

After spillway discharge, the area immediately downstream of the spillway or the reduced flow reach was inspected to recover fish trapped in puddles. The fish were recovered manually and/or with the aid of dip and seine nets (Figure 2D). The fish were identified and returned to the watercourses downstream of the dam.

FIGURE 2 – Fish recovery in the draft tube of São Simão Dam during turbine dewatering (A and B). Weighing of fish recovered during turbine dewatering in Pai Joaquim Dam (C). Recovery of trapped fish immediately downstream of São Simão Dam after closing the spillway gates (D). Photos: Átila Rodrigues Araújo (A, B, and D) and Dine Romero Rodrigues (C).

2.2 Quantification of recovered dead fish

Immediately after the operational procedures of blackstart, load variation, speed no load, startup, and synchronous-generator reversion, we inspected by boat sections of the watercourse 500–2,000 m downstream from the hydropower plants and recovered the dead fish sighted floating on the surface (Figure 3). Dead fish found during dewaterings, drawdown, and after spillway discharge were also recovered. All recovered fish were identified, weighed and discarded. Dead fish also included moribund fish.

FIGURE 3 – Recovery of dead fish downstream of São Simão Dam after turbine startup. Photo: Mateus Moreira de Carvalho.

2.3 Sampling of fish prior to dewatering

We collected fish just downstream of ASD. We used three batteries of gillnets, each battery with stretched mesh of 6, 7, and 8 cm, and about 1.7 m in height and 20 m in length (Figure 4). We set the nets late in the afternoon of one day and took them out the following morning. We performed the samplings up to five days prior to dewatering.

We calculated catch per unit effort (*CPUE*) of mandi using the formula:

$$CPUE = \sum_{i=1}^{3} \left(100\, N_i\, F_i^{-1}\right)$$

where:

N_i = number of fish captured by gillnet battery *i*;

F_i = fishing effort (in m^2) of the gillnet battery *i*.

FIGURE 4 – Sampling with gillnets just downstream of Amador Aguiar II Dam.

2.4 Dissolved oxygen during dewatering

We determined the *DO* of the draft tube water during dewaterings, after the isolation of the turbine hydraulic circuit (Figure 5). We measured *DO* until water of the draft tube reached the level of the hatch sill, generally at intervals of 30 min.

FIGURE 5 – Measuring dissolved oxygen of the draft tube water during turbine dewatering at Amador Aguiar I Dam. Photo: Átila Rodrigues Araújo.

2.5 Analyses

We determined the percentage of occurrence of each type of operational procedure. We evaluated seasonal variation (dry vs rainy) in the number of dewaterings, considering the dry season to be from April to September and the rainy season from October to March.

We quantified the number of recovered species during operational procedures, and determined the number of species per order and the main families among the fish recovered live and dead. We calculated the frequency of operational procedures with the presence of the main species recovered live and dead.

We determined the frequency of biomass of dead fish per operational procedure considering the accumulated value and the mean biomass of dead fish per operational procedure.

For dewatering, we determined the number per hydropower plant, the total biomass (alive and dead) and species richness of recovered fish. We tested correlations between these variables.

We test for differences between recovered biomass of live fish and recovered biomass of dead fish in dewaterings of hydropower plants of different age classes and risk categories with the Kruskal-Wallis test. For this, we classified the hydropower plants into the age classes 1 (≤ 10 years), 2 (11 to 30 years), or 3 (≥ 31 years), from the year operation began (Appendix B) until 2012, and into the risk categories A (high), B (medium), and C (low) based on SI-47 (Table 1 of Chapter 2).

We calculated the mean dewatering duration for each hydropower plant when these data were available. We considered dewatering duration to be the time to drain the water plus the time to recover fish (recovery duration). We used Spearman nonparametric correlation to test for the existence of correlation between (i) mean recovered total biomass and mean recovery duration and (ii) mean recovered biomass of dead fish and mean dewatering duration. In the first correlation, we used data from the following hydropower plants: AFD, ASD, EMD, FUD, IRD, ITD, JGD, MRD, NPD, PED, SSD, and TMD. In the second, we used data from ASD, CMD, EMD, FUD, ITD, JGD, MRD, NPD, ROD, and SSD.

We used linear regression to develop a predictive model for the number of mandi trapped in the draft tube as a function of its *CPUE* in the tailrace of ASD.

We determined the mean values of *DO* in dewatering for each hydropower plant. We used this mean to analyze *DO* of the hydropower plants grouped by watershed according to Table 2. For hydropower plants with at least six dewaterings (ASD, EMD, QMD, SSD, and TMD), we tested the correlation between mean *DO* of the draft tube water and recovered total biomass in the draft tube and dewater sump.

We used Statistica 7.0 for all statistical analyses with a significance level (α) of 0.05.

3 – RESULTS AND DISCUSSION

3.1 Frequency of operational procedures and seasonal variation in dewaterings

The most frequent operational procedures undertaken by hydropower plants were dewaterings and startups (Figure 6). The hydropower plants with the highest number of dewaterings were ASD (13.6%), TMD (12.3%), and SSD (8.6%). The latter two also had the highest number of startups (74.7% and 17.3%, respectively). The majority of dewaterings (75.3%) occurred in the dry season.

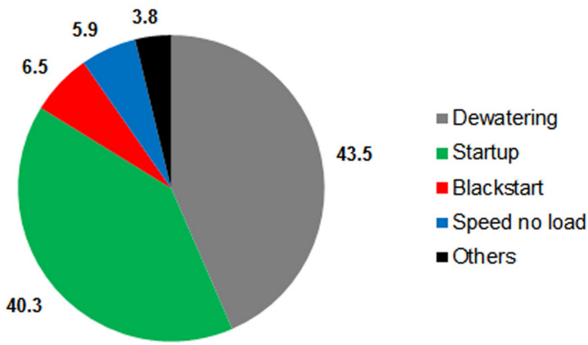

FIGURE 6 – Percentage of occurrence of operational procedures.

Hydropower plants periodically perform turbine maintenance, both in a scheduled manner and as an emergency measure. During maintenance, the presence of fish in the tailrace represents a potential risk of an environmental accident. This risk depends on the species and, above all, on the amount of fish that enter the draft tube of the stopped turbine. Fish accumulated in the tailrace may enter in turbines under maintenance and be exposed to risks such as mechanical shock or entrapment (Andrade *et al.* 2012).

The quantity of fish in the tailrace varies throughout the year. Operational procedures performed in the rainy season represent a greater risk to fish since this is when *piracema* (upstream reproductive migration of fish) occurs (Godinho & Kynard 2009). Migrating fish tend to accumulate downstream of hydropower plants (Agostinho *et al.* 2007, Lopes & Silva 2012). For example, Loures & Pompeu (2012) observed more fish in the tailrace of TMD in the rainy season. We do not recommend turbine maintenance during the rainy season because the risk is higher at this time of the year. However, it is not always possible to do turbine maintenance in the dry season due to the dynamics with scheduling activities and the occurrence of emergency demands. Most dewatering in the studied hydropower plants occurred in the dry season. This was partially due to more effective institutional control so that the occurrence of this operational procedure was in a period of lower risk to fish.

3.2 Fish species present during operational procedures

From all the operational procedures studied, we recorded 83 species among the recovered fish. The orders with the largest number of species were Characiformes, Siluriformes, and Perciformes (Figure 7). Within these orders, the families Anostomidae, Characidae, Cichlidae, and Pimelodidae accounted for more than 60% of the species. Characidae had the highest frequency of live recovered species, while Pimelodidade had the highest frequency of dead recovered species. Mandi was the species with the greatest occurrence during the operational procedures (Figure 8), and is one of the species most impacted by the operation and maintenance of turbines in Brazilian hydropower plants (Andrade *et al.* 2012).

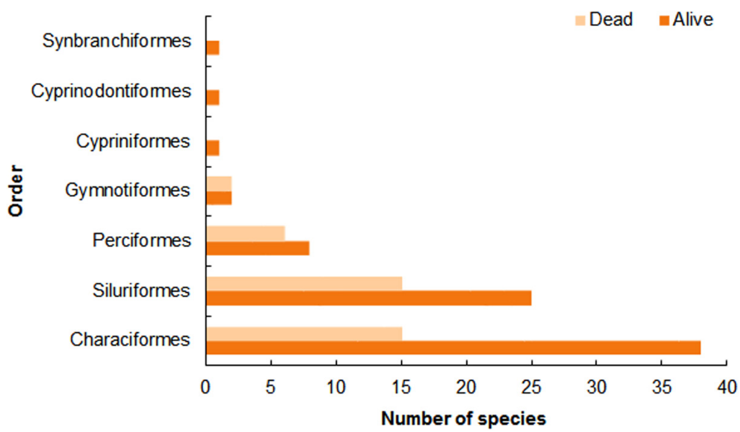

FIGURE 7 – Number of species by order among the live and dead fish recovered during operational procedures of hydropower plants in southeastern Brazil between January 2009 and December 2012.

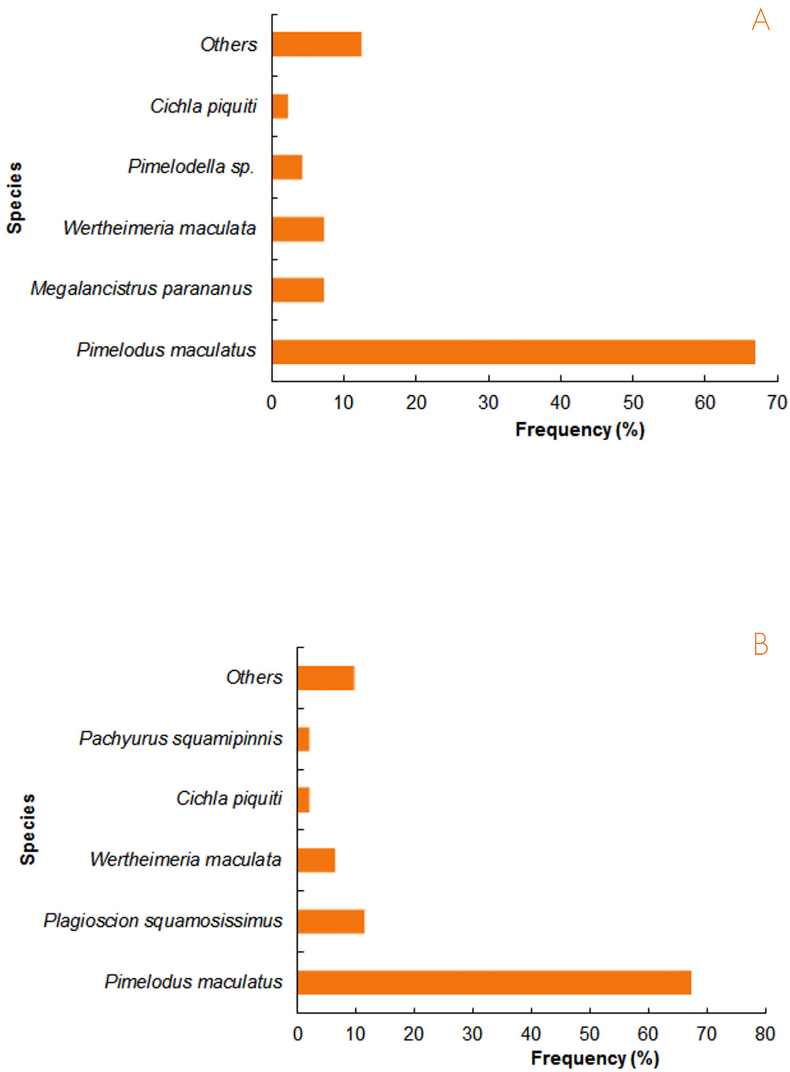

FIGURE 8 – Frequency of operational procedures with the occurrence of the main species of recovered live (A) and dead (B) fish at hydropower plants in southeastern Brazil between January 2009 and December 2012.

3.3 Biomass of dead fish during operational procedures

The operational procedures with the highest accumulated percentages of biomass of dead fish in the evaluated period were dewatering (61.5%) and startups (26.6%), but synchronous-generator reversion was the operational procedure with the highest mean percentage of biomass of dead fish (Figure 9).

The risks to fish in dewaterings are associated with stress, hypoxia, and physical injury (Portz *et al*. 2006), given the time they are trapped in the draft tube after turbine isolation. Dewatering is the riskiest operational procedure for fish, both because of recovery difficulty, even with improvements made in recent years, and because of the number of individuals that can potentially be trapped (Andrade *et al*. 2012). The high values recorded for biomass of dead fish in this study confirm the risks of this operational procedure.

In startups, deaths are mainly caused by physical injury and barotrauma. The affected biomass by startup was generally not elevated (1.9 kg on mean), but since this is the most frequent operational procedure in the hydropower plants, its potential risk to fish is elevated. Turbine startups are frequent in hydropower plants because the need to meet energy demand varies over time and among different regions of the country. In addition, turbine stop for preventive and periodic maintenance is also recurrent.

Synchronous-generator reversion was the operational procedure with the highest mean biomass of dead fish, even though it did not exhibit a high value for accumulated biomass of dead fish. Fish can suffer physical injuries and barotrauma while the air in the draft tube is expelled by the operational procedure. Synchronous-generator reversion occurs only at certain hydropower plants (*e.g.*, EMD, ITD, NPD, and PED), but may be frequent. We did not gather data for all the hydropower plants that use synchronous-generator reversion, but based on data from EMD, we suspect this operational procedure is responsible for high fish mortality.

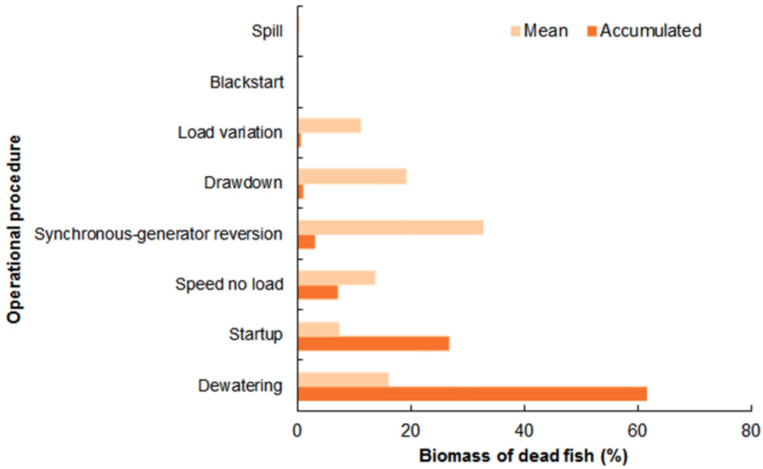

FIGURE 9 – Percentage of biomass of dead fish (mean and accumulated) in operational procedures at hydropower plants in southeastern Brazil between January 2009 and December 2012.

3.4 Dewaterings

The number of dewaterings was correlated with recovered total biomass and recovered species richness (Figure 10). There was also a correlation between recovered total biomass and species richness. There was no significant difference in mean recovered biomass of live and dead fish in dewaterings among hydropower plants of three age classes and three categories of risk (Kruskal-Wallis test: $P > 0.05$). We believe that this lack of difference could be related to improvements in the operational procedures implemented since the SI-47, such as fish risk evaluation with prior dewatering monitoring, presence of biologist in the dewatering, scheduling dewatering for periods of lower fish concentrations at the hydropower plants, structural improvements in the hydropower plants, and enhancement in fish recovery techniques. Without these implementations, a larger recovered biomass of live and dead fish would occur in dewaterings at hydropower plants at greater risk of fish death. Greater biomass would also be expected at newer hydropower plants since, in general, the abundance of fish downstream from them is greater. For this reason, procedures for risk mitigation are often used in newer, as well as higher risk, hydropower plants.

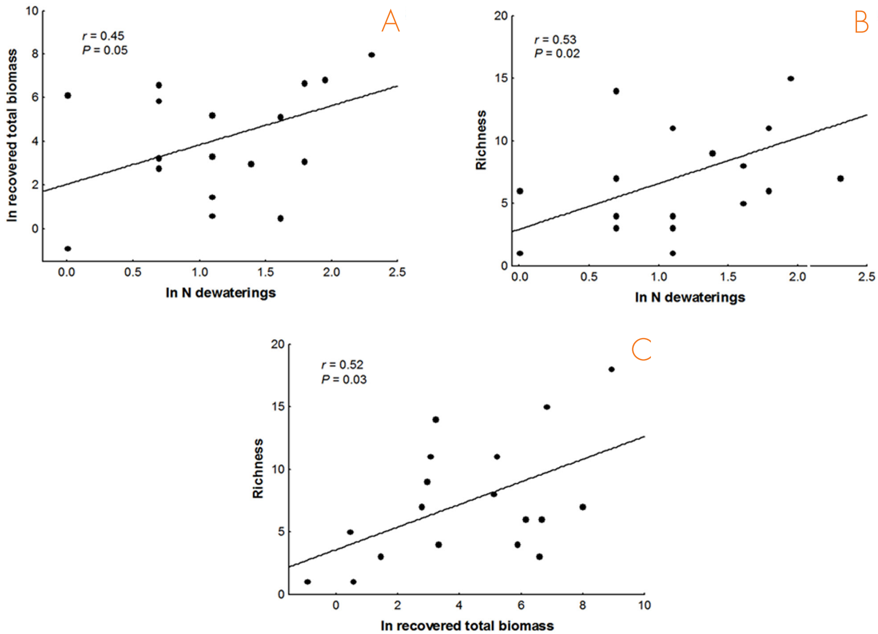

FIGURE 10 – Recovered total biomass (kg) and number of accompanied dewaterings (A); recovered species richness and number of dewaterings (B); recovered species richness and recovered total biomass (C) of hydropower plants in southeastern Brazil between January 2009 and December 2012. Each point corresponds to one hydropower plant.

3.4.1 Dewatering duration

Mean dewatering duration ranged from 1h33min to 16h57min, and mean fish recovery duration correlated with mean recovered total biomass (Figure 11). There was also a correlation between mean recovered biomass of dead fish and mean dewatering duration (Figure 12).

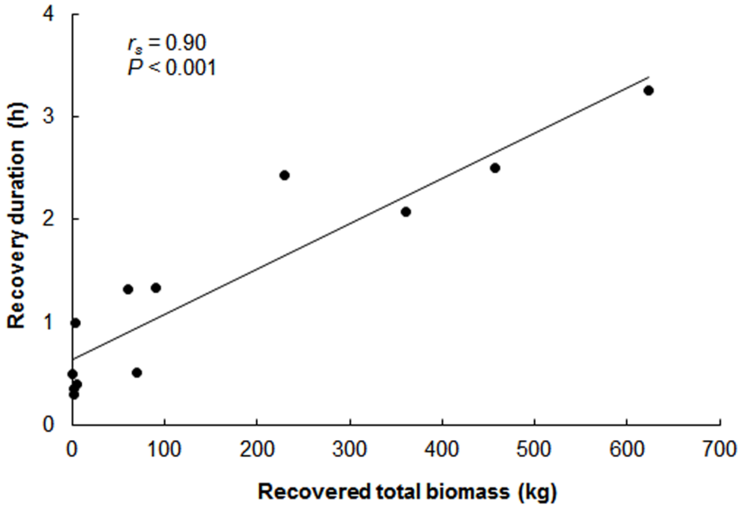

FIGURE 11 – Fish recovery duration and recovered total biomass during turbine dewaterings of hydropower plants in southeastern Brazil between January 2009 and December 2012. Each point corresponds to the mean for one hydropower plant.

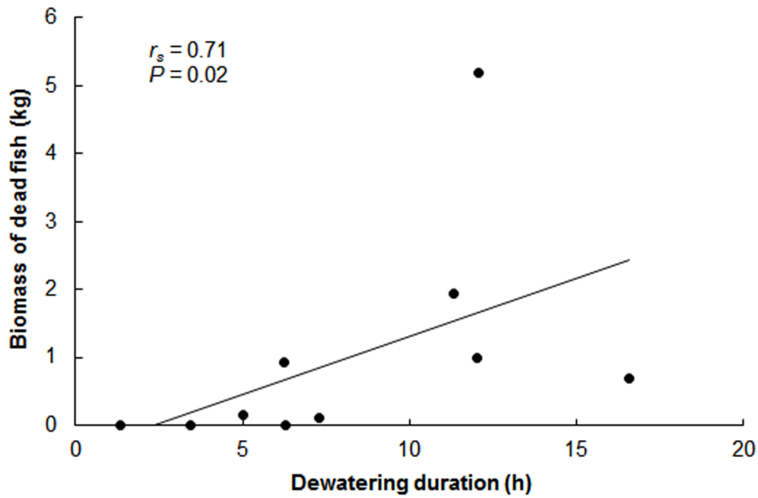

FIGURE 12 – Recovered biomass of dead fish and dewatering duration of turbines of hydropower plants in southeastern Brazil between January 2009 and December 2012. Each point corresponds to the mean for one hydropower plant.

We found that the greater the amount of biomass to be recovered, the longer the recovery duration. Because confinement time influences fish stress, prolonging this activity may increase the risk of fish death. We also observed that the longer the operational procedure, the greater the biomass of dead fish. The stress generated by turbine dewatering, associated with increased density and progressive decrease of *DO* during dewatering, were likely responsible for this relationship. In addition, during confinement, capture, and transport, fish may injure each other. Fish with injuries are vulnerable to fungal and bacterial infection that can cause death later. Since the increased risk of turbine dewatering is related to its duration, scheduling and preparation for dewatering should be carried out with the greatest possible caution.

3.4.2 Predictive model for the number of mandi trapped in the draft tube

For ASD, we established a model to predict the number of mandi trapped in the draft tube (dependent variable) as a function of the *CPUE* of mandi in the tailrace (independent variable). The dependent variable had a non-linear relationship with the independent variable, and so linearization was accomplished by logarithmic transformation (Figure 13). The prediction model was significant (regression coefficient $\neq 0$) and the equation obtained for this hydropower plant was $Y = 5.692 + 0.552\ X$ ($r^2 = 0.60$; $P = 0.02$), where Y = ln of the number of mandi trapped and $X = \ln(CPUE + 1)$. For TMD, the formula of the predictive model was $Y = 17.1 + 65.4\ X$ (Andrade *et al.* 2012).

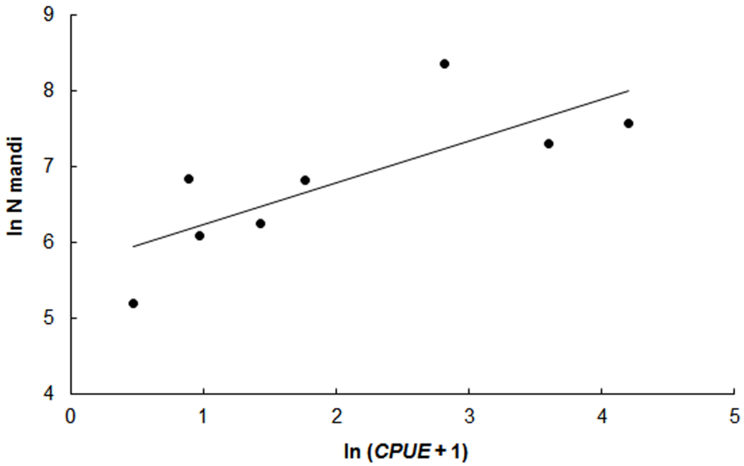

FIGURE 13 – Number of mandi trapped during turbine dewaterings of Amador Aguiar II Dam and the capture per unit effort (*CPUE*) of mandi in the tailrace.

The development of a model to use *CPUE* to predict the number of trapped fish during a turbine dewatering is a significant advance for the mitigation of impacts caused by hydropower plants. The equations presented for ASD and TMD can predict the risk associated with future dewaterings. This tool is essential for making decisions with regard to whether to undertake a dewatering or not, and for determining the adequate supply of materials and people. The addition of new data from more dewaterings will be fundamental for the refinement of these models. Such predictive models should also be developed for other hydropower plants and operational procedures, when there is enough data.

3.4.3 Dissolved oxygen during dewaterings

The *DO* values for turbine dewaterings performed from January 2009 to December 2012 varied among the hydropower plants of the different watersheds (Figure 14). The lowest *DO* occurred in the hydropower plants of the Jequitinhonha (IRD) and São Francisco (TMD and QMD) rivers. Thermal stratification occurs in the reservoirs of these hydropower plants (Esteves *et al.*

1985, Supram 2010) and the water intake of their turbines is in the hypolimnion, which tends to anoxia. Therefore, there is lower *DO* in the water of the draft tube of these hydropower plants. In the hydropower plants of other watersheds, *DO* values were higher and similar. These reservoirs may or may not stratify, but the turbine water intakes of most of these hydropower plants are closer to the surface or above the hypolimnion. The EMD, situated on the Paranaíba River, is an exception because it had low *DO* values in some dewaterings, possibly because the turbine water intakes can be in the hypolimnion, depending on the reservoir water level and whether or not the reservoir is stratified.

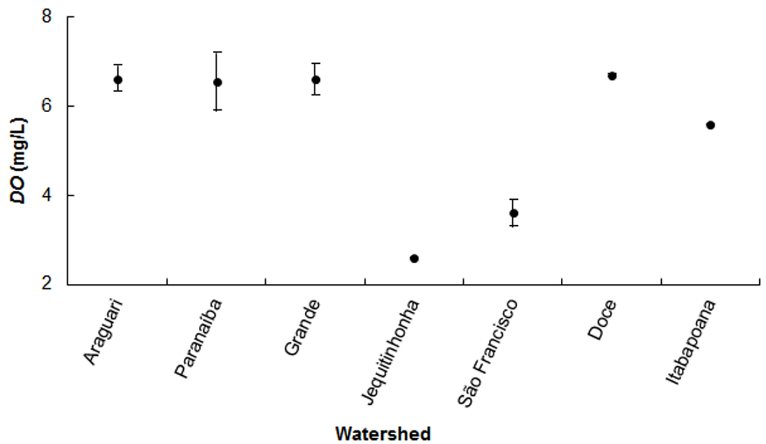

FIGURE 14 – Mean and standard error of dissolved oxygen (DO) in the draft tube water during turbine dewaterings of hydropower plants in watersheds of southeastern Brazil.

In ASD, but not in the other hydropower plants with available data, there was a negative correlation between mean *DO* of the draft tube water and recovered total biomass (Figure 15). Thus, the larger the fish biomass trapped in the draft tube in dewatering, the greater the *DO* consumption. The depletion of *DO* increases fish stress and the risk of death during dewatering, so greater fish biomass is related to greater risk of death. Thus, monitoring the *DO* during dewatering is an important indication of the trapped biomass and, eventually, whether or not to abort an operational procedure in the case of large biomass of trapped fish.

The lack of a correlation between mean *DO* of the draft tube water and recovered total biomass at the other analyzed hydropower plants (EMD, QMD, SSD, and TMD) may have been because of insufficient data to document the interference of seasonality and the stratification of reservoirs in the *DO* on the draft tube water. There are yet other factors that can change *DO* during dewatering, such the operational procedure duration and water and oil leaks within the turbine.

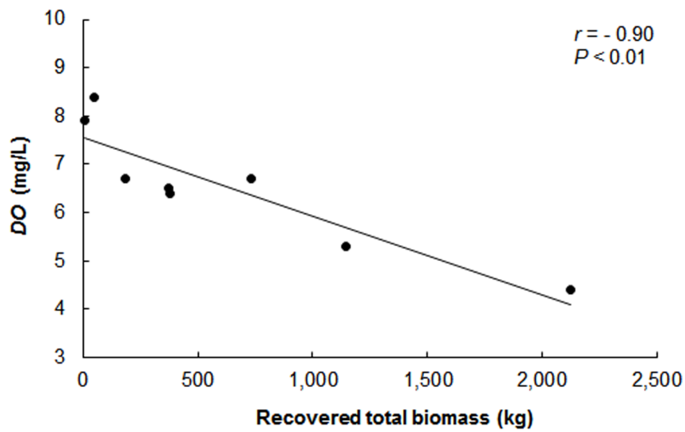

FIGURE 15 – Mean dissolved oxygen (*DO*) in the draft tube water and the recovered total biomass in turbine dewaterings of Amador Aguiar II Dam between January 2009 and December 2012.

4 – FINAL CONSIDERATIONS

Risks to fish in the operation and maintenance of hydropower plants are an integral part of the power generation process. Studying these activities in order to find patterns and develop risk mitigation processes is a practice that should be common throughout the entire power sector. We believe that the consolidated results presented here should be taken into account in the operation and maintenance of hydropower plants. In addition, these findings indicate the importance of continued research in search of new solutions to other problems that have not yet been properly investigated.

5 – ACKNOWLEDGMENTS

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CHAPTER 4

FISH DIVERSITY DOWNSTREAM OF HYDROPOWER PLANTS OF THE UPPER PARANÁ RIVER BASIN, BRAZIL

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1 – INTRODUCTION

The Neotropical region harbors the greatest freshwater fish diversity in the world with about 4,475 species (Reis *et al.* 2003). Estimates indicate that the richness of the upper Paraná River basin alone is around 310 species, although the discovery of new species in this basin is still increasing exponentially (Langeani *et al.* 2007).

The construction of hydropower plants is fundamental for a country's development, but it generates social and environmental impacts that are difficult to mitigate or compensate (Fearnside 1999). Impacts occur both upstream and downstream of the dams. Upstream, the transformation of the river into a lake changes drastically the composition of fishes that inhabit the region (Agostinho *et al.* 2007). Awareness of these modifications has already been widely reported scientifically. Agostinho *et al.* (2007), for example, found a mean richness of 30 fish species for 77 reservoirs throughout Brazil, a number considered low for the size of the reservoirs and the high fish diversity in the rivers pre-impoundment. Nonetheless, this knowledge helps to implement more effective measures for mitigating the impacts of hydropower plants.

On the other hand, the main downstream impacts generated by hydropower plants are related to the regulation of natural river flow, with changes in flood intensity, magnitude, duration, and frequency (McCartney *et al.* 2001). Since floodplains are considered primary factors in the regulation of several local biological phenomena (Lowe-McConnell 1987), downstream impacts may be even greater than those upstream (Agostinho *et al.* 2008), and may extend for hundreds of kilometers (McCartney *et al.* 2001). For ichthyofauna, alterations in reproduction, recruitment and migration are among the most significant downstream impacts (Agostinho *et al.* 2008).

Knowledge regarding fish assemblages in the region immediately downstream of hydropower plants is not as vast as it is for reservoirs (Agostinho *et al.* 2008). Therefore, determining the ecological patterns of the fish assemblages present in this region is fundamental for implementing actions for their conservation and mitigating impacts caused by hydropower plant construction and operation. Thus, the objective of this chapter is to evaluate the ecological characteristics related to richness and diversity of the fish assemblages immediately downstream of hydropower plants on the upper Paraná River, and to determine how these characteristics are influenced by hydropower plants and other abiotic factors of the habitat.

2 – METHODS

We sampled fish from 12 hydropower plants in the Grande and Paranaíba River basins located in the upper Paraná River basin (henceforth Upper Paraná) from 2009 to 2012. The hydropower plants sampled were: Amador Aguiar I (AFD), Amador Aguiar II (ASD), Camargos (CMD), Emborcação (EMD), Funil (FUD), Itutinga (ITD), Jaguara (JGD), Miranda (MRD), Nova Ponte (NPD), Pai Joaquim (PJD), São Simão (SSD), and Volta Grande (VGD) dams. We sampled fish following the methods described in Chapter 2 of this book.

For each hydropower plant, we determined total richness (S_t), richness of migratory fishes (S_m), total number of individuals sampled (N_t), number of individuals of migratory species (N_m), the Shannon diversity index (H'), the equitability index of Pielou (J'), and the dominance index of Berger-Parker (d) following Pielou (1966) and Berger & Parker (1970). For richness, we considered the species of cascudo (*Hypostomus*) that could be identified, and considered those that could not be easily differentiated as *Hypostomus* spp. (Langeani & Rêgo, 2014). The classification of migratory species followed Agostinho *et al.* (2007). The constancy of occurrence of each taxon among hydropower plants was determined by the formula of Bodenheimer (1938): $C = P.100.N^{-1}$, where P = number of hydropower plants containing the species, and N = number of sampled hydropower plants. The species were classified as constant (present in more than 50% of the hydropower plants), accessory (present in 25% to 50% of the hydropower plants) or accidental (present in less than 25% of the hydropower plants).

For each hydropower plant, we constructed a rarefaction curve based on the number of individuals sampled and 100 randomizations without replacement to evaluate if sampling efforts were sufficient to collect all species that could be captured by the fishing gear employed. We also determined the Spearman correlation (r_s) of S_t with N_t and the number of samples.

We determined the number of fish sampled in the wet (October to March) and dry (April to September) seasons for each hydropower plant, and tested for differences in these values using the Kruskal-Wallis test. We also examined variation in the number of fish sampled among years for ASD and EMD, the two hydropower plants with the highest number of fish sampled.

We used generalized linear models (GLM) to verify the influence of abiotic variables on S_t, S_m, N_m, and H'. Initially, the model contained the following variables: presence of a lotic stretch downstream of the hydropower plant, number of tributaries (4th order or higher) in that lotic stretch, hydropower plant age, turbine discharge, spillway discharge, and river basin (Table 1). For turbine discharge we used the daily average. Due to the large amplitude of turbine discharge among hydropower plants, we standardized it by dividing by mean turbine discharge calculated for all hydropower plants. We did the same for spillway discharge. We treated the river basin as a categorical variable to capture any historical differences in the use and occupation of the two basins. We tested the model against the null model (response variable explained by chance) using *deviance* analysis and the chi-square test for S_t and S_m, and F for N_m and H' (Crowley 2007). If the model was non-significant, we concluded that the abiotic variables have no influence on the response variables. If the model was significant, we then simplified it using *deviance* analysis to remove the least significant variables (highest P value) one by one until only the most significant variables remained in the model. We analyzed the suitability of the model graphically by the probability envelope of the residuals in relation to the chosen probability distribution (Poisson distribution for S_t and normal distribution for H'), and by residual *deviance* analysis (Crowley 2007).

We used the Bray-Curtis similarity index to construct a similarity matrix and then performed non-metric multidimensional scaling (nMDS) to characterize the similarity of the assemblages among hydropower plants. We used logarithmic transformation to reduce the effect of the most abundant species. We performed PERMANOVA to test differences between groups formed by nMDS. The stress assessment was based on Kruskal's rule (1964). We performed SIMPER analysis on the transformed similarity matrix to identify the species that contributed the most to the differentiation of the groups formed by the nMDS.

TABLE 1 – Characteristics of the 12 hydropower plants sampled in the upper Paraná River basin, Brazil (*TL* = downstream lotic stretch present (P) or absent (A); *NT* = number of tributaries (4th order or higher) in the lotic stretch downstream; *PA* = hydropower plant age; Q_t = turbine discharge; Q_s = spillway discharge; *NS* = number of samples).

Hydropower plant	Acronym	River basin	*TL*	*NT*	*PA* (years)	Q_t (m^3/s)	Q_s (m^3/s)	*NS*
Amador Aguiar I	AFD	Paranaíba	A	0	5	21.8	316.8	7
Amador Aguiar II	ASD	Paranaíba	P	1	5	36.9	282.3	29
Camargos	CMD	Grande	A	0	51	17.6	103.4	18
Emborcação	EMD	Paranaíba	P	3	29	10.0	425.3	20
Funil	FUD	Grande	P	2	10	41.9	242.7	12
Itutinga	ITD	Grande	P	0	56	12.1	99.7	20
Jaguara	JGD	Grande	A	0	40	120.6	749.0	6
Miranda	MRD	Paranaíba	A	0	13	7.6	302.7	6
Nova Ponte	NPD	Paranaíba	A	1	17	5.5	244.8	5
Pai Joaquim	PJD	Paranaíba	A	1	70	0.0	15.2	19
São Simão	SSD	Paranaíba	P	3	33	298.1	2.113.5	34
Volta Grande	VGD	Grande	A	1	37	64.2	926.9	7

3 – RESULTS AND DISCUSSION

This work is one of the first to analyze fish assemblages immediately downstream of Neotropical hydropower plants, and is particularly novel in covering such a significant number of hydropower plants (12) widely distributed spatially in two basins (Grande and Paranaíba rivers). Although downstream impacts of hydropower plants are very intense, and potentially even greater than those upstream, few studies have attempted to understand the ecological patterns present in them (Pringle *et al.* 2000; Agostinho *et al.* 2008), such as Loures & Pompeu (2015) who evaluated variation in richness and abundance of fish downstream of the Três Marias Dam (TMD) on the São Francisco River. Most of the work in the Neotropical region has been related to changes in reproductive dynamics caused by altered flood regimes (*e.g.*, Agostinho *et al.* 2004) or on the importance of downstream tributaries for the maintenance of populations of migratory species (*e.g.*, Agostinho *et al.* 2004, Sato *et al.* 2005).

3.1 Richness and abundance

We captured 18,297 fish of at least 87 taxa from the 12 sampled hydropower plants. The number of individuals sampled per hydropower plant ranged from 73 to 5,694; ASD had the greatest number of individuals (5,694) followed by SSD with 4,391. The four hydropower plants with the most fish captured, ASD, EMD, FUD, and SSD, accounted for 83.8% of all the fish collected. The highest S_t was for SSD (59), followed by EMD (45) and ASD (39). The species list and occurrence per hydropower plant are in Appendix A.

The fish sampled represented four orders (Characiformes, Gymnotiformes, Perciformes, and Siluriformes). Together, Characiformes and Siluriformes contributed 91.6% of all the fish captured. Characiformes possessed the greatest richness with 48 species. On the other hand, Siluriformes, with 10,310 fish, was the most numerous order (56.4% of the total), leveraged by the extensive capture of mandi and cascudo. Characiformes and Siluriformes are the richest and most abundant orders in the Neotropical region (Lowe-McConnel 1987), and represent about 80% of all fish species in the Upper Paraná (Langeani *et al.* 2007).

The species rarefaction curves allowed the separation of hydropower plants into two groups: those with a curve close to the asymptote (Figure 1), and those with a sloping ascending curve (Figure 2). In the first group are the hydropower plants with the greatest number of samplings, where we probably captured most of the species of fish likely to be caught by the fishing gear used. The second group contains hydropower plants with the lowest number of samplings. The more steeply inclined slopes of the rarefaction curves of these hydropower plants indicate subsampling of S_t. Therefore, these hydropower plants need more sampling so that the rarefaction curve approaches asymptote. For all hydropower plants, the use of other fishing gear would allow the collection of more species, particularly small-sized species; however, that was not our goal. The results presented show the limitations imposed by the selectivity of the fishing gear used, and can be used as an example for studies that seek to carry out a complete inventory of the fish assemblage of a given region.

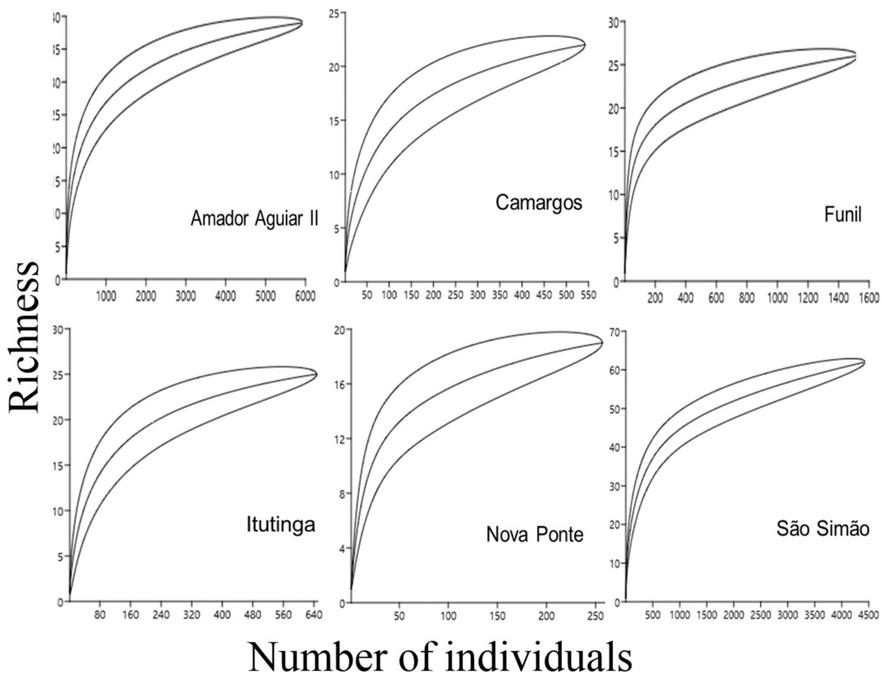

FIGURE 1 – Rarefaction curve with 95% confidence interval for fish species richness immediately downstream of six hydropower plants of the upper Paraná River basin, Brazil, that got close to an asymptote.

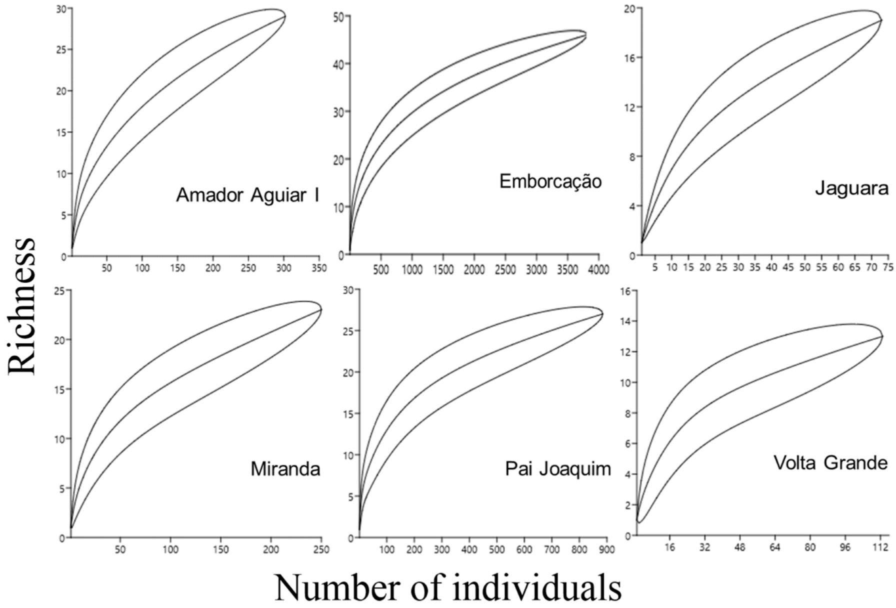

FIGURE 2 – Rarefaction curve with 95% confidence interval for fish species richness immediately downstream of six hydropower plants of the upper Paraná River basin, Brazil, that did not get close to an asymptote.

A high positive correlation occurred between S_t and N_t ($r_s = 0.88$, $P < 0.05$) and number of samples ($r_s = 0.78$, $P < 0.05$) for the studied hydropower plants (Figure 3). Both S_t and N_t are related to sampling effort and the type of equipment used in the sampling (Magurran 2004).

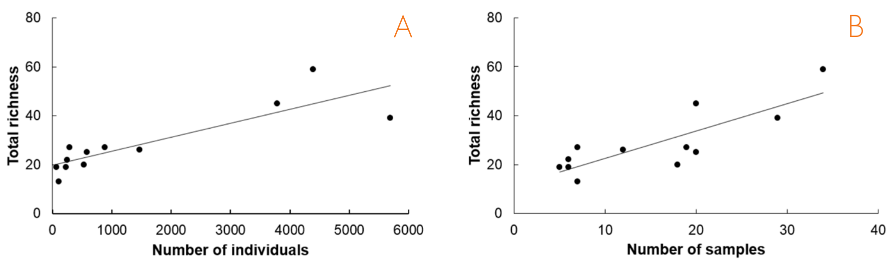

FIGURE 3 – Relationship of total species richness and number of individuals sampled (A) and number of samples (B) of 12 hydropower plants of the upper Paraná River basin, Brazil.

Variation in S_t was explained by the presence of a downstream lotic stretch, number of tributaries in the downstream stretch, and basin of the hydropower plant (Table 2). The presence of a lotic stretch downstream of hydropower plants and the number of tributaries likely provide more fish habitats and, consequently, more species, than at hydropower plants with a downstream stretch that is drowned by a reservoir or that do not have downstream tributaries. In addition, downstream lotic stretches and tributaries provide refuge for rheophilic fish with low tolerance to lentic environments.

The main impacts caused by hydropower plants to the river downstream are related to flow control (Ligon *et al.* 1995, MacCartey *et al.* 2001). This control generates alterations in the morphology of the river (Ligon *et al.* 1995), in the quality and quantity of the water (Agostinho *et al.* 2001), and in the release of sediments and nutrients (Barbosa *et al.* 1999). Although such impacts can extend for many kilometers from the hydropower plant, the further away they are, the smaller are their effects (McCartney *et al.* 2001). Our data showed that fish richness was higher in the hydropower plants with a downstream lotic stretch (Figure 4), likely because of the presence of habitat for rheophilic fish. In addition, Neotropical ichthyofauna is better adapted to lotic environments, given the virtual absence of natural lentic environments (Lowe-McConnell 1987).

Another aspect that influenced S_t was the basin of the hydropower plant. Those located in the Paranaíba River basin exhibited greater richness than the ones in the Grande River basin independent of the presence of a downstream lotic stretch. These two basins experienced intense land occupation by agriculture, livestock, and increasing human populations (Scolforo *et al.* 2008, IMB 2012, CPLA 2015). However, hydropower plants in the Grande River basin are located in the main stem, which has become a reservoir cascade (Chapter 2). In the Paranaíba River basin, there are nine hydropower plants but five are in Araguari River and four in the main channel. The transformation of a river into a reservoir cascade has been documented as a determining factor for decreased species richness and homogenization of assemblages in the remaining stretches (Petesse & Petrere 2012).

We did not find any relationships between S_t and the operational variables. The analysis encompassing the operational variables and the different manner in which each hydropower plant must operate to meet the Operador Nacional do Sistema (ONS; National System Operator) did not demonstrate the reality for each of them separately. However, Loures & Pompeu (2015) demonstrated that richness downstream of TMD is related to outflow discharge and rainfall.

TABLE 2 – Estimation of parameters and analysis of variance of the GLM of total species richness as a function of the presence or absence of a lotic stretch downstream of the hydropower plant, the number of tributaries in that stretch, and river basin. Null model with deviance of 59.49 and 11 degrees of freedom. (DF = degrees of freedom; *P* = *P*-value).

PARAMETER	*Deviance*	DF	*Deviance*	GL residual	*P*
Lotic stretch	6.38	1	12.94	8	0.01
Number of tributaries	40.17	2	19.32	9	<0.001
Basin	7.61	1	5.34	7	0.005

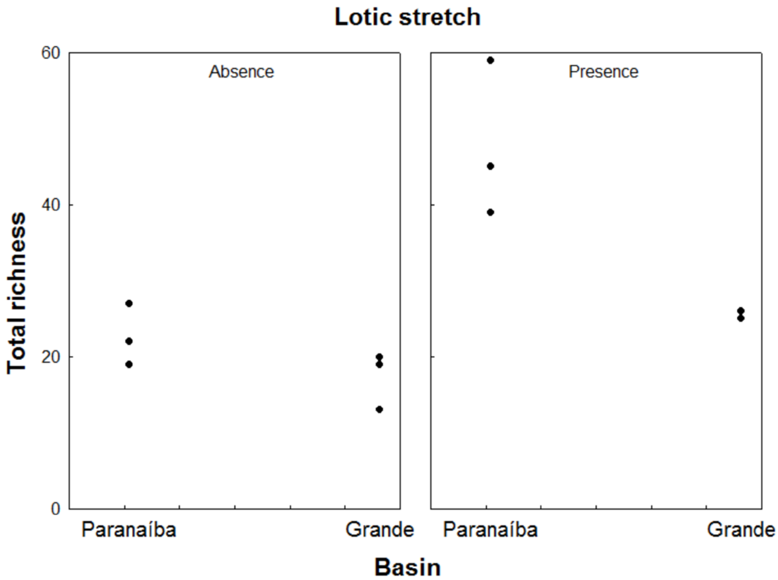

FIGURE 4 – Total richness of fish species at hydropower plants of the Paranaíba and Grande river basins discriminated by the presence or absence of a lotic stretch downstream.

Mandi (*Pimelodus maculatus*) was the most captured species with 6,402 fish, followed by cascudo (*Hypostomus* spp., 2,410), piau-três-pintas (*Leporinus friderici*, 1,332), and corvina (*Plagioscion squamosissimus*, 1,045). Images of these four fishes are in Figure 5. Mandi was one of the three dominant fish taxa in all but two of the studied hydropower plants (Figure 6).

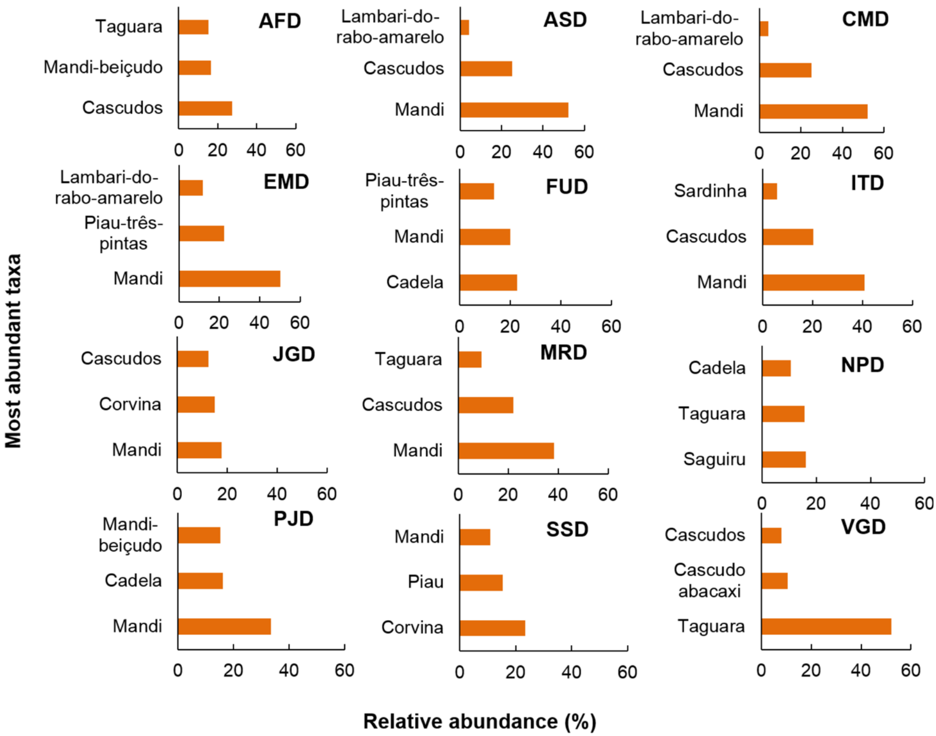

FIGURE 5 – Relative abundance of the three most dominant fish taxa sampled at 12 hydropower plants of upper Paraná River basin, Brazil.

FIGURE 6 – Photographs of the most abundant species: (A) mandi, (B) piau-três-pintas, (C) cascudo and (D) corvina. Photo: Alexandre Peressin (A).

Piau-três-pintas seems to prefer lotic habitats. Classified as migratory species by some authors (*e.g.,* Agostinho *et al.* 2007), there is evidence that piau-três-pintas spawns in lentic and semi-lentic environments (Vazzoler *et al.* 1997). Cascudo is rheophilic, and so its habitat is reduced by reservoirs. We captured almost 60% of all cascudo at ASD, Araguari River. The great abundance of cascudo in the Araguari River was previously documented by Vono (2002). The rocky bottom of the lotic stretch downstream from ASD likely favors cascudo abundance. In addition, cascudo, as well piau-três-pintas, may benefit from the greater water transparency downstream of dams. At the sampled hydropower plants, cascudo is herbivorous and piau-três-pintas is omnivorous with a tendency to herbivory (Chapter 5). The greater water transparency increases the photic zone, increasing the availability of food of vegetal origin for these taxa. Likewise, corvina, a visually oriented predator, may experience an increase in predation efficiency with higher water transparency. It is noteworthy that almost all sampled corvina (99%) were from SSD.

Although we have grouped several species of cascudo into a single taxon (*Hypostomus* spp.), species of Loricariidae generally have highly specialized morphology, and most of their morphological, trophic, and functional characteristics are related to the use of the lotic habitats in which they live (Pinna 1998, Casatti & Castro 2006). For a discussion about the abundance of mandi, see Chapter 6.

A total of 5,694 individuals were collected at ASD in 4 years. The year with the greatest number of individuals collected was 2011 with 3,218 fish (Figure 7A). The most captured species was mandi with 2,968 individuals, most of which were caught in 2011. A total of 3,791 individuals were collected at EMD with 2012 being the year with the greatest number of fish collected (Figure 7B). Mandi was also the most collected species at this hydropower plant, with 1,905 individuals. The greatest number of mandi (681) was sampled in 2010.

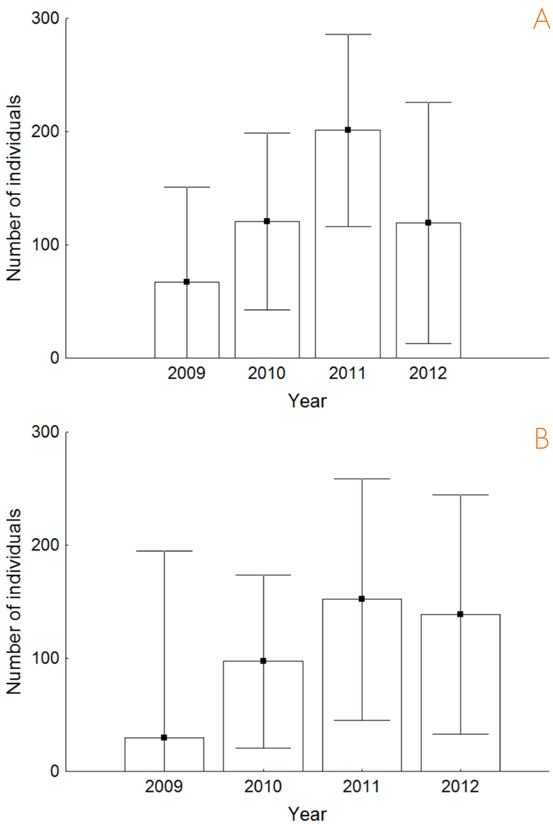

FIGURE 7 – Annual variation in the mean and 95% confidence interval for the number of individuals sampled at Amador Aguiar II (A) and Emborcação (B) dams.

There was a significant difference in the number of individuals sampled between wet and dry seasons (Wilcoxon test: $Z = 277$; $P < 0.01$; Figure 8). This difference was also observed for each hydropower plant (Chapters 9 and 10). This seasonal difference is already well known in natural environments (Lowe-McConnell 1987), with greater abundance in the rainy season due to influences of water level. This seasonality is mainly associated with food availability and trophic relationships (predation and food competition) among fish species. The water level of the habitats we sampled is under the control of the hydropower plants, but this control did not eliminate the seasonal dynamics of abundance. In undammed rivers, seasonal differences in fish abundance are likely more pronounced.

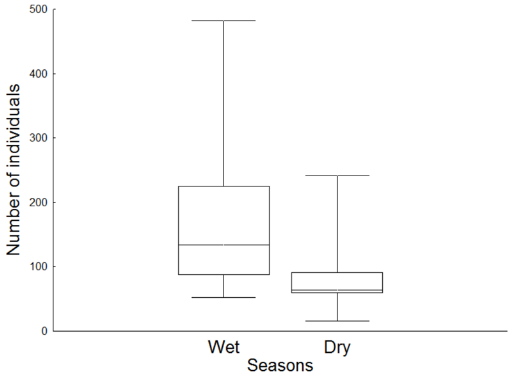

FIGURE 8 – Boxplot (median, interquartile range, and range) of the number of fish sampled in the wet and dry seasons at 12 hydropower plants of the upper Paraná River basin, Brazil.

It is worth mentioning that our results were influenced by the type of fishing gear used, which was biased towards mandi (Chapter 2). We used fishing gear (gillnet) that captured mandi more efficiently because the major goal of this book was to reduce the risk of fish death, mainly of mandi. Gillnet is one of the least selective types of fishing gear, but the abundance of some species other than mandi may be underestimated by the mesh sizes used. On the other hand, the fishes most affect by the operation of hydropower plant tend to be those that are more abundant near the plant. Mandi is the species most affect by various hydropower plants of the Upper Paraná (Chapter 3) and, thus, one the most abundant fish at those plants, but likely in proportions different from those we found.

3.2 Diversity, equitability, dominance, and occurrence

The value of *H'* ranged from 1.62 to 2.64 (Table 3). Some hydropower plants with greater S_t, like ASD and EMD, exhibited lower *H'*. This result is explained by the dominance of a few species, especially mandi, which represented more than 50% of the number of fish sampled at these two hydropower plants. Consequently, these sites had the lowest J'. On the other hand, some hydropower plants with lower S_t (*e.g.*, JGD and NPD) had higher H' due to a higher J'. These hydropower plants, however, were sampled only a few times, which has a direct influence on N_t and S_t, both components of H' and J'.

TABLE 3 – Ecological attributes of the fish fauna sampled at 12 hydropower plants of upper Paraná River basin, Brazil (N_t = total number of fish sampled, N_m = number of migratory fish sampled, S_t = total fish species richness, S_m = richness of migratory fish, H' = Shannon diversity index, J' = Pielou equitability index, d = Berger-Parker dominance index). Acronyms of hydropower plants according to Table 1.

Hydropower plant	N_t	N_m	S_t	S_m	H'	J'	d
AFD	287	89	27	4	2.32	0.70	0.27
ASD	5,694	3,318	39	9	1.62	0.44	0.52
CMD	533	129	20	6	1.91	0.64	0.32
EMD	3,791	2,873	45	10	1.65	0.43	0.50
FUD	1,467	811	26	7	2.38	0.73	0.22
ITD	579	333	25	8	2.07	0.64	0.41
JGD	73	29	19	4	2.52	0.86	0.18
MRD	250	140	22	5	2.03	0.66	0.38
NPD	235	61	19	3	2.51	0.85	0.16
PJD	884	333	27	7	2.01	0.61	0.33
SSD	4,391	990	59	12	2.64	0.65	0.23
VGD	113	60	13	2	1.71	0.67	0.52

Differing from S_t, none of the abiotic variables analyzed explained variation in *H'*. This may have been due to the higher *J'* of hydropower plants with greater S_t. Similarly, Agostinho *et al.* (2001) observed that *H'* was little influenced by the change in flow during the flood season of the Paraná River downstream from Porto Primavera Dam, although it had a more pronounced influence on S_t. Apparently, none of the abiotic variables explained *H'* likely because hydropower plants with low S_t had high *H'*. In addition, hydropower plants without a downstream lotic stretch had fewer species, but their diversity was higher due to lower dominance. It is possible that the non-influence of abiotic variables on *H'* can be modified with the addition of new species if more samplings are carried out at the hydropower plants whose rarefaction curves were still ascending.

Regarding constancy of occurrence, almost half of the taxa (44.8%) was classified as accidental, 36.8% as accessory, and 18.4% as constant (Table 4). Among the 41 taxa classified as accidental, 25 occurred at only one hydropower plant, such as jurupoca (*Hemisorubim plathyrhynchos*), bagre (*Megalonema platanum*), and pacu-caranha (*Piaractus mesopotamicus*). More migratory fishes were classified as accidental taxa, which are directly affected by dams causing their populations decline and, in some cases, to local extinction, thereby explaining their rarity in sampling (Barbosa *et al.* 1999, Pelicice *et al.* 2014), especially in rivers with successive dams. Among the constant taxa, only lambari-do-rabo-amarelo (*Astyanax altiparanae*), cascudo, and taguara (*Schizodon nasutus*) occurred in all of the hydropower plants analyzed. These three taxa are small/medium-sized fish and widely distributed throughout the Upper Paraná.

Excluding cascudo, only 12 fish species were among the three species most abundant at the sampled hydropower plants. Mandi was the most abundant specie in six of them (Figure 6). The plants ASD and VGD were the plants with the highest *d,* with mandi and taguara being the most abundant species, respectively (Table 3). Our results showed, therefore, that a limited number of fish species became common in the fish assemblages downstream of the studied hydropower plants in the Upper Paraná. Ecosystems impacted by anthropic actions tend to possess simplified biological communities in relation to communities in preserved environments (Odum 1988, Villéger *et al.* 2010).

TABLE 4 – Categorization of constancy of taxa sampled downstream of 12 hydropower plants of the upper Paraná River basin, Brazil.

Constancy of occurrence	Taxa
Constant	*Astyanax altiparanae, Astyanax fasciatus, Eigenmannia virescens, Galeocharax knerii, Hoplias intermedius, Hoplias malabaricus, Hypostomus spp., Iheringichthys labrosus, Leporinus friderici, Leporinus obtusidens, Leporinus octofasciatus, Pimelodus maculatus, Pimelodus microstoma, Schizodon nasutus, Steindachnerina insculpta*
Acessory	*Acestrorhynchus lacustris, Apareiodon piracicabae, Brycon orbignyanus, Cichla kelberi, Cichla piquiti, Cichla sp., Crenicichla jaguarensis, Cyphocharax gillii, Cyphocharax modestus, Geophagus brasiliensis, Leporellus vittatus, Leporinus geminis, Leporinus macrocephalus, Leporinus piavussu, Leporinus striatus, Megalancistrus parananus, Metynnis maculatus, Oligosarcus paranensis, Oreochromis niloticus, Pimelodella avanhandavae, Pimelodus paranaensis, Pinirampus pirinampu, Plagioscion squamosissimus, Pseudopimelodus mangurus, Pseudoplatystoma corruscans, Rhamdia quelen, Rhinodoras dorbignyi, Satanoperca pappaterra, Serrasalmus maculatus, Serrasalmus marginatus, Trachelyopterus galeatus, Triportheus nematurus*
Accidental	*Apareiodon affinis, Astyanax schubarti, Bryconamericus exodon, Bryconamericus stramineus, Crenicichla haroldoi, Crenicichla sp., Cyphocharax nagelii, Geophagus proximus, Gymnotus sylvius, Hemisorubim platyrhynchos, Hoplosternum littorale, Hypostomus affinis, Hypostomus commersoni, Hypostomus margaritifer, Leporinus amblyrhynchus, Leporinus lacustris, Leporinus paranensis, Leporinus sp., Leporinus tigrinus, Loricaria lentiginosa, Loricaria sp., Megalonema platanum, Metynnis lippincottianus, Moenkhausia intermedia, Myloplus tiete, Piaractus mesopotamicus, Pimelodus argenteus, Porotergus ellisi, Pterygoplichthys anisitsi, Pygocentrus nattereri, Rhaphiodon vulpinus, Rineloricaria sp., Roeboides descalvadensis, Salminus brasiliensis, Salminus hilarii, Schizodon intermedius, Serrasalmus sp., Steindachnerina brevipinna, Tilapia rendalli*

3.3 Similarity

The nMDS, created with the Bray-Curtis similarity index using abundance data, allow us to identify three groups of hydropower plants: Group 1 composed of ASD, EMD, and SSD; Group 2 composed of AFD, CMD, FUD, ITD, MRD, NPD, and PJD; and Group 3 composed of JGD and VGD (Figure 9). The hydropower plants were grouped first by their geographic proximity. Although Group 2 contains hydropower plants from two basins, those from the same basin (*e.g.*, CMD, FUD and ITD) were closer (Figure 9).

The separation of the hydropower plants into three groups was corroborated by PERMANOVA (*Pseudo-F* = 3.61 and $P = 0.001$). In addition, the SIMPER analysis indicated dissimilarities of 60.7% between Groups 1 and 2, 63.2% between Groups 2 and 3, and 77.2% between Groups 1 and 3. Mandi was also responsible for the separation of the hydropower plants within each group. A possible cause for the differentiation of Group 3 was the lower number of individuals sampled, as a consequence of the lower number of samplings in the hydropower plants of this group.

In a previous analysis, the fish assemblage at Três Marias Dam (TMD), in the São Francisco River, was also included in the model. Although TMD is in a different basin, it was included in the group of hydropower plants of the Paranaiba River basin (Group 1) because of the contribution of mandi to the similarity. This finding demonstrated the importance of mandi to structuring the fish assemblages at the studied dams.

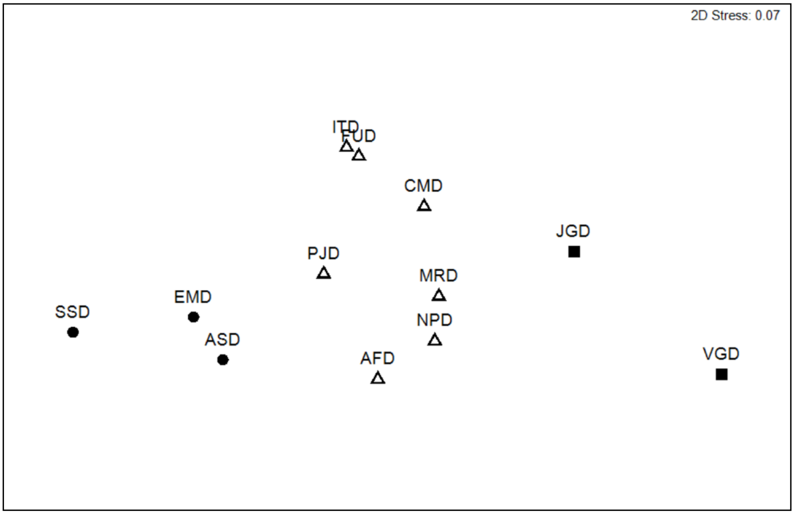

FIGURE 9 – Similarity in the fish species composition at 12 hydropower plants of the upper Paraná River basin, Brazil, with the formation of three groups: Group 1 (circle), Group 2 (triangle) and Group 3 (square). Acronyms of hydropower plants according to Table 1.

3.4 Introduced species

Introduced species were present at all hydropower plants sampled with the exception of ITD. We recorded 16 introduced species, with corvina was the most common one (1,045 fish sampled at JGD, SSD, and VGD), followed by cará (*Geophagus proximus*; 231 individuals sampled at SSD), and piaba-facão (*Triphorteus nematurus*; 105 individuals sampled at ASD, EMD, and SSD). Tucunaré-amarelo (*Cichla kelberi*) and tucunaré-azul (*Cichla piquiti*), found in six hydropower plants each, were the introduced fishes present at the largest number of plants.

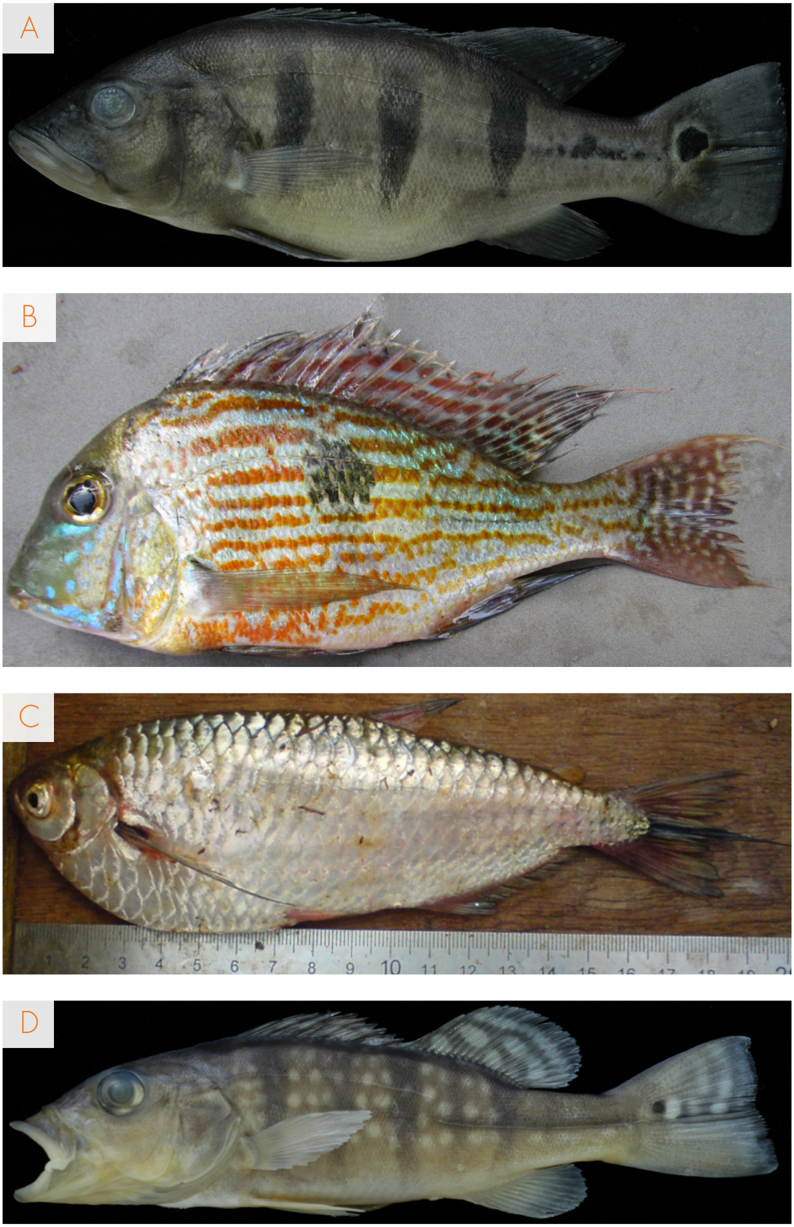

FIGURE 10 – Photographs of some of the introduced species sampled at hydropower plants of the upper Paraná River basin, Brasil: (A) tucunaré-amarelo, (B) cará, (C) piaba-facão, and (D) tucunaré-azul. Photos: Francisco Langeani (A and D).

Tucunaré and the corvina are classic examples of introduced species that were successful in the Upper Paraná. Originally from the Amazon River basin, they are now widely distributed in the Upper Paraná and are usually well adapted to their environments (Agostinho & Júlio 1996, Smith *et al.* 2005). The introduction of species is a major cause of the loss of native species worldwide (Vitousek *et al.* 1996, Simberloff 2003, Simberloff *et al.* 2013), yet the impacts of introduced species are not easy to measure, especially in the Neotropical region where there are complex networks of interactions between species and with the environment (Lodge 1993). However, some studies have already advanced towards understanding the mechanisms responsible for the loss of biodiversity caused by the introduction of species in the Upper Paraná. Examples are: overlapping of feeding and reproductive habits and alteration of water characteristics by dams (*e.g.,* cará; Gois *et al.* 2015), and aggressiveness and demographic dynamics of the introduced species (*e.g.*, tucunaré-amarelo; Pelicice *et al.* 2015).

In Brazil, the main cause of fish introduction is aquaculture, mainly due to the rupture and overflow of fish tanks during floods (Orsi & Agostinho 1999). In the Upper Paraná, the suppression of Sete Quedas Falls by the Itaipu Reservoir allowed several species to invade the Upper Paraná (Agostinho *et al.* 2007). We sampled some of these, such as pacu-CD (*Metynnis maculatus*), piaba-facão, and saguiru (*Cyphocharax gillii*), in our study.

3.5 Migratory species

Migratory species are particularly important in freshwater environments since they are usually of larger size and cover several trophic levels (Carolsfeld *et al.* 2003). In the Upper Paraná, most of the migratory species are under severe threat and are experiencing notable population declines due to, among other causes, intense fragmentation caused by dams (Carolsfeld *et al.* 2003). We captured 9,166 individuals of 17 migratory species, some of which are shown in Figure 11. The most captured species was mandi with 6,402 individuals (69.8% of all migratory species), followed by piau-três-pintas with 1,332 individuals (14.5%).

The richness of migratory species was explained by the presence of a lotic stretch downstream (Table 5). The abundance of these species, in turn, was explained by the presence of the stretch downstream and by the number of tributaries in this section (Table 6). Migratory species require free-flowing rivers to move between functional habitats to complete their reproductive cycle (Lucas *et al.* 2001, Carolsfeld *et al.* 2003). In this way, the presence of lotic stretches provisions possible spawning, development, and feeding areas, as well as the presence of downstream tributaries that can serve as alternative routes for migration (Antonio *et al.* 2007) or provide the spawning triggers eliminated by dams (Godinho & Kynard 2006). These characteristics can guarantee the presence of viable populations of migratory species even in systems where long stretches free of dams are no longer present. Mandi is able to spawn in short stretches of rivers (Agostinho *et al.* 2003), and so, compared to other migratory species, it is considered a short-distance migrator. Despite the large proportion of mandis in the total number of migratory fish caught in this study, it was also influenced by the presence of a lotic stretch and tributaries downstream of the hydropower plants, even though it is a short distance migrant.

TABLE 5 – Estimation of parameters and analysis of variance of GLM for richness of migratory fish as a function of the presence of a lotic stretch downstream the hydropower plant, number of tributaries in that stretch, and river basin. Null model with *deviance* of 15.87 and 11 degrees of freedom. (DF = degrees of freedom; *P* = *P*-value).

PARAMETER	*Deviance*	DF	*Deviance* residual	DF residual	*P*
Presence of a lotic stretch	10.16	1	5.71	10	0.001

TABLE 6 – Estimation of parameters and analysis of variance of GLM for number of individuals of species of migratory fish as a function of the presence of a lotic stretch downstream the hydropower plant, number of tributaries in that stretch, and river basin. Null model with *deviance* of 57.44 and 11 degrees of freedom. (DF = degrees of freedom; *P* = *P*-value).

PARAMETER	*Deviance*	DF	*Deviance* residual	DF residual	*P*
Presence of a lotic stretch	18.96	1	12.82	8	<0.001
Number of tributaries	25.66	2	31.78	9	<0.001

With the exception of the two most abundant migratory species (mandi and piau-três-pintas), the other migratory species were captured in small numbers and at few hydropower plants. This was the case for piracanjuba (*Brycon orbignyanus*), whose nine individuals were collected only at CMD and ITD. This distribution of the migratory fishes, with many species with few individuals distributed among few hydropower plants, may have influenced the effect of the model variables.

FIGURE 11 – Photographs of some migratory species sampled in hydropower plants of the upper Paraná River basin, Brazil: (A) dourado (*Salminus brasiliensis*), (B) piracanjuba, (C) tabarana (*Salminus hilarii*) and (D) pacu-caranha. Photos: Alexandre Peressin (A, B and C).

In conclusion, the data presented in this chapter demonstrate the importance of mandi in the river immediately downstream of hydropower plants. This species is the one that experiences the most deaths during operation and maintenance of hydropower plants in southeastern Brazil (Chapter 3). Mandi is likely one of the species that experiences the most deaths at other hydropower plants in the country as well. The occurrence of fish kills in hydropower plants has led to the creation of Cemig's Peixe Vivo Program, which has been studying these impacts and creating tools to mitigate them, with remarkable results, since 2007 (Chapter 1).

The present study presented unpublished data on ecological attributes of the ichthyofauna downstream of hydropower plants and their relationship with abiotic factors. More sampling, particularly in the less-sampled hydropower plants, will help to better elucidate these relationships and allow more inferences to be made about them. Despite this, we highlight the importance of lotic stretches downstream of dams for the conservation of fish biodiversity, as was done by Agostinho *et al.* (2007), reinforcing the need to avoid the formation of reservoir cascades.

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SÉRIE
PEIXE VIVO

FISH AND
HYDROPOWER PLANTS

CHAPTER 5

DIET AND TROPHIC STRUCTURE OF THE FISHES AT HYDROPOWER PLANTS OF THE UPPER PARANÁ RIVER BASIN, BRAZIL

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1 – INTRODUCTION

The hydrological cycle plays a significant role in the lives of fishes (Agostinho *et al.* 2004), including their diet (Gandini *et al.* 2014). In the Neotropical region, this cycle is responsible for producing conditions important for the maintenance of the aquatic biota, such as increasing food availability for fish (Lowe-McConnell 1999). Increased food availability is a consequence of flooding of the riparian vegetation and the transport of living organisms (Junk 1980). Flooding also enriches river water with the nutrients present in the organic and inorganic flooded matter (Luz-Agostinho *et al.* 2009).

In the Paraná River basin, the regulation of flow has seriously impacted stretches downstream of hydropower plants due to changes in the intensity, duration, and timing of floods (Agostinho *et al.* 2004). Graf (2006) reported a reduction in flooding by up to 90% downstream of dams with a seven-fold decrease in the area of the inundated floodplain. The changes in flow caused by hydropower plants and the retention of nutrients in the reservoir modify the input of organic matter downstream of dams (Poff *et al.* 1997), changing the availability of food for fish. Doi *et al.* (2008) demonstrated that algal drift from reservoirs alters the trophic chain downstream of dams for about 10 km, with a pronounced influence in the first 200 m.

The study of feeding and trophic ecology of fish is important for understanding their relationship with the environment and provides valuable insight for their management (Hahn *et al.* 1997). Although fish feeding in reservoirs is reasonably well known (Hahn & Fugi 2007), little is known about the effects of dams on the diet of fish downstream (*e.g.,* Gandini *et al.* 2012).

Considering that the operation of hydropower dams alters the availability of food for fish downstream, species with different feeding habits may show distinct feeding responses to the artificial hydrological cycle. Thus, we sampled fishes downstream of 12 hydropower plants of the upper Paraná River basin with the following objectives: (i) identify the main food items ingested, (ii) define the trophic guilds of the fishes, (iii) describe the trophic structure, and (iv) determine the abiotic and operational factors of the hydropower plants that influence trophic structure.

2 – METHODS

We collected fish downstream from the following 12 hydropower plants: Amador Aguiar I (AFD), Amador Aguiar II (ASD), Miranda (MRD), Nova Ponte (NPD), Pai Joaquim (PJD), Emborcação (EMD), São Simão (SSD), Camargos (CMD), Funil (FUD), Itutinga (ITD), Jaguara (JGD), and Volta Grande (VGD) dams. The first five are on the Araguari River, a tributary of the Paranaíba River, the next two are on the Paranaíba River, and the last five are on the Grande River.

We sampled fish using gillnets, cast nets and hook-and-line from February 2009 to June 2012. The periodicity, effort, and sampling method used at each plant are described in Chapter 2 of this book. We also used fish recovered in turbine dewaterings at NPD (June 2009), ASD (March, April, June, August, and December 2009), CMD (October 2009 and April 2012), FUD (June 2009), ITD (June 2012, May 2009, and August 2012), EMD (July 2011), and SSD (August and September 2009).

In the field, we measured and weighed each fish, and fixed those in good condition in 10% formalin for laboratory analysis. In the laboratory, we weighed the stomach content of the fixed individuals on a precision scale. We separated and identified all food items from each fish to the lowest taxonomic level possible. We estimated the weight of each food item visually based on its proportion among all items.

We grouped the food items into six food categories (Table 1, Figure 1). The food category 'rare items' included several quite distinctive elements that were consumed in low quantities and frequencies. We excluded from the analyses clearly anthropogenic or non-organic items, such as fishing line, paper, and fragments of substrate. We also excluded the food categories 'unidentified items' (UI) and 'rare items' (RI) because they were not informative regarding the species food preference.

TABLE 1 – Food item components of food categories.

FOOD CATEGORY	FOOD ITEMS
Algae	Algae, filamentous algae, and phytoplankton
Detritus	Detritus
Fish	*Astyanax*, bone, Characidae, Characiformes, Cichlidae, crystalline lens, fish, Pimelodidae, *Pimelodus maculatus*, scale, Siluriformes, and vertebral column
Invertebrates	Annelidae (Oligochaeta and fragments), Arachnida (Acari and fragments), Arthropoda, Crustacea (Cladocera, Copepoda, Decapoda, Isopoda, Ostracoda, and fragments), invertebrates, Mollusca (Bivalvia, Gastropoda, and fragments), Nematoda, parasitic worm, zooplankton and the insects Baetidae, Ceratopogonidae larva, Chironomidae (larva and pupa), Coleoptera (larva and adult), Diptera (larva, pupa, and adult), Ephemeroptera (fragments, larva, and naiad), Formicidae, Hemyptera (larva, young, and adult), Hymenoptera (adult and carapace), Homoptera (adult), Insecta (aquatic, eggs, larva, naiad, parts, pupa, and young), Isoptera (adult), Lepidoptera (larva), Megaloptera (larva), Megaloptera (adult), Muscidae (adult), Neuroptera (adult, larva, and naiad), Orthoptera, Odonata (adult, exuvia, larvae, and naiad), Plecoptera (larva), and Trichoptera (adult, larva, and pupa)
Rare items	Bird feather, bird nest, bone, bovine meat, egg, fat, fungus, fur, insect spawn, Reptilia, and tooth
Vegetae	Bryophyta, bean seed coat, corm, Eudicotyledonea (leaf, stem, and seed), fat vegetal, Gimnospermae leaf, macrophyte (fragments and leaf), Monocotyledonea (seed and leaf), moss, onion, rice, and unidentified plant parts (branch, coat , flour, fruit, inflorescence, leaf, root, seed, seed coat, and twig)

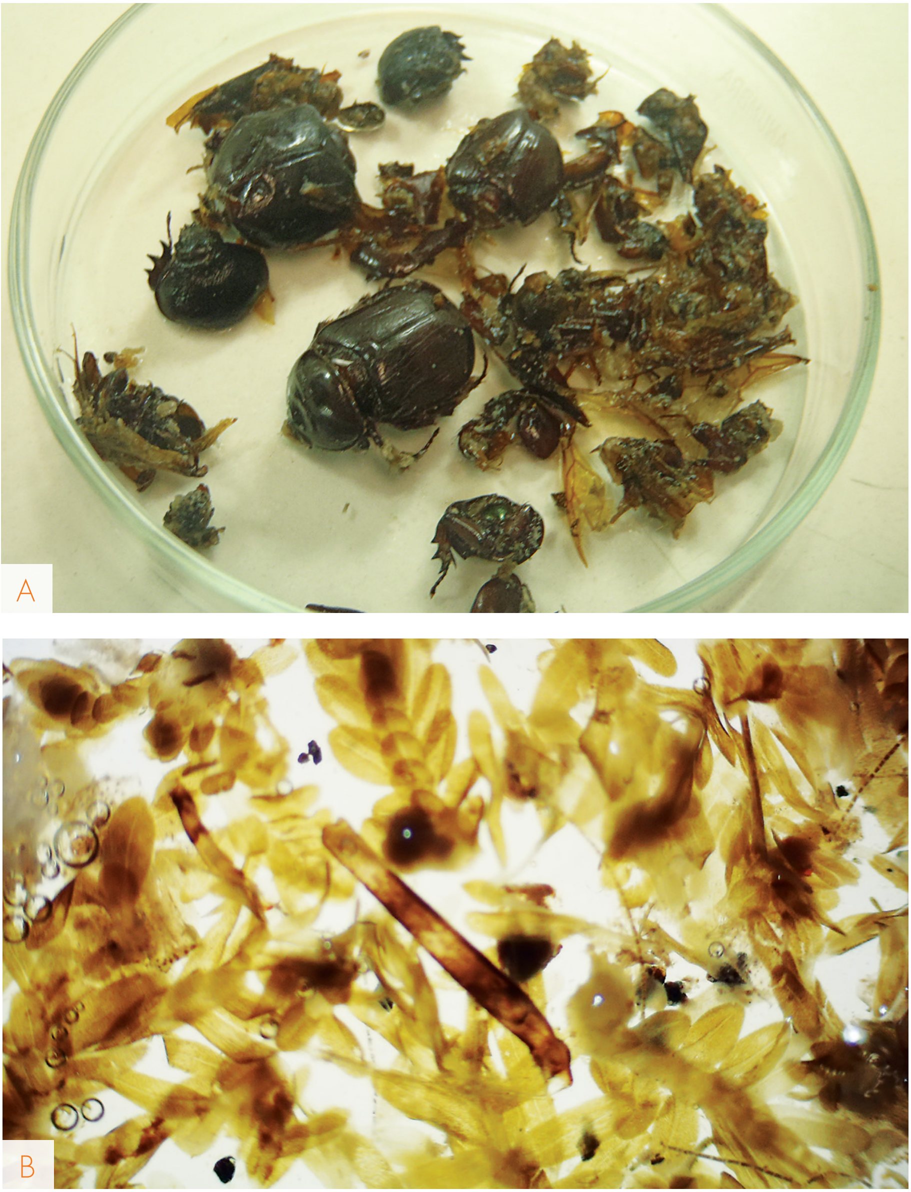

FIGURE 1 – Insect fragments and insects of the order Coleoptera (A), and vegetal fragments (B) found in fish stomachs. Photos: Dayenne Godoy Pellucci Maciel and Luisa Silva Gomes (A), Camila Liberato Ávila and Amanda Del Rio (B).

To evaluate selectivity and relative importance of food items, as well as food overlap, we determined the food index (*FI*) for each species by the mean proportion by weight, according to the equation of Chipps & Garvey (2007):

$$MW_i = \frac{1}{P}\sum_{j=1}^{p}\left(\frac{W_{ij}}{\sum_{i=1}^{Q} W_{ij}}\right) \qquad \text{where,}$$

MW_i = mean proportion by weight of category *i*; *i* = food category; *j* = stomach with the food category *i*; *P* = number of fish with stomach contents; *Q* = number of food categories; and W_i = weight of food category *i* in fish *j*.

We ordered species using non-metric multidimensional scaling (NMDS) after applying the Bray-Curtis similarity index to the matrix of FI by food category and species. This multidimensional scaling is non-parametric because it assigns ranks to the data. Furthermore, NMDS scaling generated with the Bray-Curtis index is generally the most robust for biological data (Melo & Hepp 2008).

We assigned trophic guilds by visual analysis of the groups formed by the NMDS and tested these groups by analysis of similarity (ANOSIM, Bray-Curtis similarity index) at the significance level of 0.05. For this, we used only species that had 10 or more stomachs analyzed with content. We classified the trophic guilds as carnivorous ($FI \geq 0.1$ for invertebrates and/or fish), detritivorous (ingested mostly detritus), herbivorous (species that consumed mainly vegetal and/or algae), or omnivorous ($FI \geq 0.1$ for at least one item of vegetal and one item of animal).

For species with less that 10 stomachs analyzed, we determine their trophic guild based on the scientific literature. In this case, we classified species as carnivorous (feed mostly on invertebrates and fish), detritivorous (consumed principally detritus), herbivorous (ingested mainly vegetal and/or algae), omnivorous (consumed items of vegetal and animal origin), invertivorous (ingested mainly on invertebrates), and piscivorous (feed basically on fish). For species with no information on their trophic guild in the literature, we considered the most cited food items among species of the same genus.

We summed the weights of the food categories independently of species and hydropower plants to show the relative participation of each food category in the diet of the fishes. We developed, for each plant and trophic guild, three matrices of trophic structure: richness, biomass, and abundance (number of individuals). In this step, we used only fish caught with gillnets, since this was the least selective fishing gear used and the only one employed at all hydropower plants. We used percentage in these matrices in order to neutralize the effect of the hydropower plant catchment area because larger catchment areas tend to have higher quantity, biomass, and richness of fish.

We determined if the trophic structure of the fishes captured in gillnets was influenced by the following hydropower plant environmental and operational variables: dam age (*DA*), residence time of the reservoir water (*RT*), length of the downstream lotic stretch (*DL*), area of the first downstream reservoir (*AR*), mean daily variation of outflow discharge (Q_m), and outflow discharge range (Q_r; Table 2). To calculate Q_m and Q_r, we used Q_d, the daily mean outflow discharge (turbine discharge plus spillway discharge) of the plant. Thus, we calculated Q_m by subtracting Q_d from the Q_d of the previous day to get a measure of daily variation in Q_d. We, then, divided the absolute value of this difference by the Q_d of the previous day, which we then multiplied by 100 to transform it into a percentage. To calculate Q_r, we subtracted the lowest Q_d from the highest Q_d and divided the result by the mean Q_d for the study period. So, Q_r reflects the range of the outflow discharge without being influenced by the river discharge. We calculated Q_m and Q_r for the sampling period of each plant.

We performed a principal components analysis (PCA) using a correlation matrix containing the environmental and operational variables. Applying the Bray-Curtis similarity index, we ordered the matrices of trophic structure in richness (NM_R), biomass (NM_B) and abundance (NM_A) with NMDS. Subsequently, we determined the Pearson correlations of axes 1 and 2 of the PCA with the axis 1 of NM_R, NM_B, and NM_A. In these correlations, we considered the score of each plant on the PCA axis a synthesis of its environmental conditions, and the NMDS score a synthesis of the trophic structure of the ichthyofauna. We performed the statistical analyses using the program Past 1 (Hammer *et al.* 2011).

TABLE 2 – Environmental and operational variables for the 12 hydropower plants in the upper Paraná River basin. *DA* = dam age, *RT* = residence time of the reservoir water, *DL* = length of the downstream lotic stretch, *AR* = area of the first downstream reservoir, Q_m = mean daily variation of outflow discharge, and Q_r = outflow discharge range. Plants are ordered from upstream to downstream within river.

River/ hydropower plant	Environmental				Operational	
	DA[1] (years)	*RT* (h)	*DL* (km)	*AR* (km^2)	Q_m (%)	Q_r
ARAGUARI						
Pai Joaquim	70	0.5	0.0	449.2	8.7	6.7
Nova Ponte	17	9,623.3	0.0	51.9	21.3	1.2
Miranda	13	116.0	0.0	18.7	13.9	0.9
Amador Aguiar I	5	10.0	0.0	45.1	15.6	0.9
Amador Aguiar II	5	9.9	30.0	772.0	15.8	1.2
PARANAÍBA						
Emborcação	29	7,420.7	24.0	772.0	28.3	2.5
São Simão	33	640.0	35.0	1,195.0	5.8	1.8
GRANDE						
Itutinga	56	15.2	38.5	33.5	4.9	4.8
Camargos	51	1,412.0	0.0	1.7	5.6	5.1
Funil	10	8.3	54.1	1,440.0	8.5	5.8
Jaguara	40	23.4	0.0	36.5	14.9	2.3
Volta Grande	37	59.4	0.0	143.0	12.7	2.4

1: Time between first year of operation and 2012.

3 – RESULTS AND DISCUSSION

We collected a total of 15,988 fish of 80 species, 21 families, and 4 orders. Of these, 13,886 individuals of 78 species, 21 families, and 4 orders were sampled with gillnets. A fraction of the total (3%) was recovered fish. For the analysis of diet, we used 3,083 fish from 31 speciesz, 13 families, and 3 orders. We identified 137 food items in those fish.

Non-metric multi-dimensional scaling grouped the 31 species into four trophic guilds (Table 3; Figure 2), which were statistically different (ANOSIM: $P < 0{,}01$; Table 4). We classified the remaining 47 species into 6 trophic guilds (Table 5). Gandini *et al.* (2012) found eight trophic guilds downstream of the ITD, differing from the present work in the presence of iliophagous, algivorous, and frugivorous fish and the absence of carnivorous fish. Some of these differences were due to the method of guild assignment, and not to ecological differences. For example, we did not distinguish detritivorous from iliophagous. On the other hand, none of the species we analyzed ingested mainly algae or fruit; a difference that is independent of the methodology used. The trophic plasticity of Neotropical fish species is well known (*e.g.,* Lowe-MacConnell 1999). Thus, it is not uncommon to have herbivorous species eating insects or carnivorous species ingesting vegetal matter (Araujo-Lima *et al.* 1995). Several species classified in this study, or elsewhere, as omnivorous ingested mainly vegetal matter, although they also had ingested a significant proportion of invertebrates or fish. Others consumed mostly invertebrates, but also a representative amount of vegetal matter. Thus, among the omnivorous species, there were some with notable trends toward herbivory or carnivory. Since these species had the ability to consume both plant and animal items, we classified them as omnivorous.

TABLE 3 – Species, code, number of stomachs analyzed (N), food index (*FI*) by food category (Alg = algae, Veg = vegetal, Det = detritus, Inv = invertebrates, Fis = fish), and trophic guild (Car = Carnivorous, Det = Detritivorous, Her = Herbivorous, Omn = Omnivorous).

SPECIES	Code	N	*FI*					Trophic guild
			Alg	Det	Fis	Inv	Veg	
Astyanax altiparanae	AsA	223	0.05	0.04	0.04	0.56	0.32	Omn
Astyanax fasciatus	AsF	155	0.05	0.07	0.13	0.31	0.45	Omn
Cyphocharax gillii	CyG	36	0.08	0.85	0.01	0.03	0.03	Det
Cyphocharax modestus	CyM	38	0.09	0.74	0.03	0.09	0.05	Det
Cyphocharax nagelii	CyN	34	0.04	0.66	0.13	0.08	0.09	Det
Galeocharax knerii	GaK	221	0.04	0.06	0.69	0.14	0.07	Car
Geophagus proximus	GeP	60	0.04	0.34	0.05	0.42	0.14	Omn
Hoplias intermedius	HoI	15	0.10	0.06	0.31	0.31	0.21	Car
Hoplias malabaricus	HoM	18	0.06	0.11	0.51	0.24	0.09	Car
Hypostomus spp.	HSpp	172	0.14	0.51	0.04	0.11	0.20	Det
Iheringichthys labrosus	IhL	124	0.03	0.23	0.03	0.61	0.11	Omn
Leporinus friderici	LeF	210	0.09	0.11	0.26	0.12	0.43	Omn
Leporinus geminis	LeG	40	0.16	0.16	0.07	0.06	0.56	Her
Leporinus obtusidens	LeOb	33	0.06	0.13	0.23	0.21	0.37	Omn
Leporinus octofasciatus	LeOc	35	0.14	0.15	0.16	0.14	0.42	Omn
Megalancistrus parananus	MeP	11	0.14	0.35	0.00	0.29	0.22	Omn
Metynnis maculatus	MtM	17	0.36	0.23	0.00	0.13	0.28	Her
Pimelodella avanhandavae	PaA	20	0.03	0.09	0.28	0.52	0.08	Car
Pimelodus maculatus	PoMa	895	0.04	0.15	0.15	0.49	0.17	Omn
Pimelodus microstoma	PoMi	14	0.02	0.20	0.03	0.52	0.23	Omn
Pinirampus pirinampu	PiP	34	0.15	0.08	0.15	0.44	0.17	Omn
Plagioscion squamosissimus	PlS	221	0.01	0.03	0.52	0.41	0.03	Car
Prochilodus lineatus	PrL	34	0.03	0.75	0.08	0.01	0.14	Det
Rhaphiodon vulpinus	RhV	30	0.00	0.01	0.58	0.32	0.09	Car
Rhinodoras dorbignyi	RhD	16	0.00	0.13	0.00	0.66	0.22	Omn
Satanoperca pappaterra	SaP	12	0.07	0.32	0.08	0.39	0.14	Omn
Schizodon nasutus	ScN	188	0.33	0.21	0.07	0.07	0.32	Her
Serrasalmus maculatus	SeM	11	0.12	0.04	0.39	0.33	0.12	Car
Steindachnerina insculpta	StI	127	0.10	0.73	0.01	0.03	0.14	Det
Trachelyopterus galeatus	TrG	11	0.00	0.00	0.04	0.79	0.18	Omn
Triportheus nematurus	TtN	28	0.04	0.02	0.04	0.63	0.27	Omn

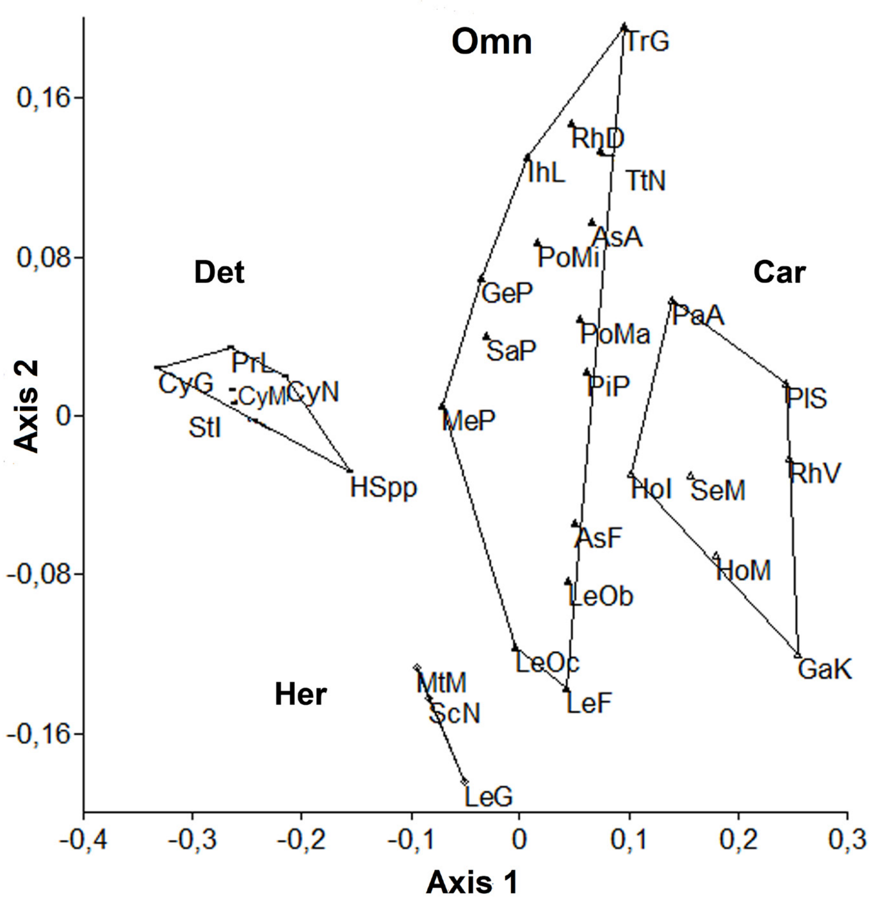

FIGURE 2 – Non-metric multidimensional scaling of the diet of 31 species of fish at 12 hydropower plants of the upper Paraná River basin, Brazil. Species codes according to Table 3. Car = Carnivorous, Det = Detritivorous, Her = Herbivorous, and Omn = Omnivorous.

TABLE 4 – Results of similarity analysis (ANOSIM) for comparison of the trophic guilds formed by species with more than 10 stomachs analyzed. R = test statistic, ranging from -1 to 1; P = probability value.

Comparison of trophic guilds	*R*	*P*
Detritivorous x Carnivorous	1.00	<0.01
Detritivorous x Omnivorous	0.86	<0.01
Herbivorous x Carnivorous	1.00	<0.01
Herbivorous x Detritivorous	0.97	0.01
Herbivorous x Omnivorous	0.58	<0.01
Omnivorous x Carnivorous	0.58	<0.01

TABLE 5 – Trophic guilds attributed to species according to the literature*.

Trophic guild	Species
Carnivorous	*Acestrorhynchus lacustris, Crenicichla jaguarensis, Pimelodus paranaensis, Rhamdia quelen*
Detritivorous	*Apareiodon affinis, A. piracicabae, Hypostomus affinis, H. commersoni, H. margaritifer, Pterygoplichthys anisitsi, Steindachnerina brevipinna*
Invertivorous	*Apteronotus ellisi, Astyanax schubarti, Crenicichla haroldoi, Eigenmannia virescens, Gymnotus sylvius, Leporellus vittatus, Leporinus amblyrhynchus, Moenkhausia intermedia*
Omnivorous	*Brycon orbignyanus, Bryconamericus exodon, Geophagus brasiliensis, Hoplosternum littorale, Leporinus lacustres, L. macrocephalus, L. paranensis, L. piavussu, L. striatus, L. tigrinus, Loricaria lentiginosa, Oreochromis niloticus, Roeboides descalvadensis, Tilapia rendalli*
Piscivorous	*Cichla kelberi, C. piquiti, Hemisorubim platyrhynchos, Megalonema platanum, Oligosarcus paranensis, Pseudopimelodus mangurus, Pseudoplatystoma corruscans, Pygocentrus nattereri, Salminus brasiliensis, S. hilarii, Serrasalmus marginatus*

*: Andrian *et al.* (1994), Yabe & Bennemann (1994), Hahn *et al.* (1998), Cemig & CETEC (2000), Duarte & Araujo (2000), Lobón-Cerviá & Bennemann (2000), Durães *et al.* (2001), Casatti (2002), Giora & Fialho (2003), Balassa *et al.* (2004), Hahn *et al.* (2004), Gomiero & Braga (2004), Andrade & Braga (2005), Dias *et al.* (2005), Luz-Agostinho *et al.* (2006), Behr e Signor (2008), Brasil-Souza *et al.* (2009), Casatti *et al.* (2009), Correa *et al.* (2009), Montana & Winemiller (2009), Salvador-Jr *et al.* (2009), Gomiero *et al.* (2010), Bennemann *et al.* (2011), Rondinelli *et al.* (2011), Abelha *et al.* (2012), Gandini *et al.* (2012), Delariva *et al.* (2013), and Mendonça *et al.* (2014).

Fish was the most consumed item when considering all hydropower plants, while detritus and algae were the least consumed (Figure 3). In fact, agglomerations of fish were observed near or in the tailrace at practically all plants. These agglomerations may attract predatory fishes, as suggested by Godinho *et al.* (2007), or increase fish intake by those already on site since the greater transparency of the hydropower plants outflow discharge (Ward & Stanford 1995) may facilitate capture by visually oriented predators.

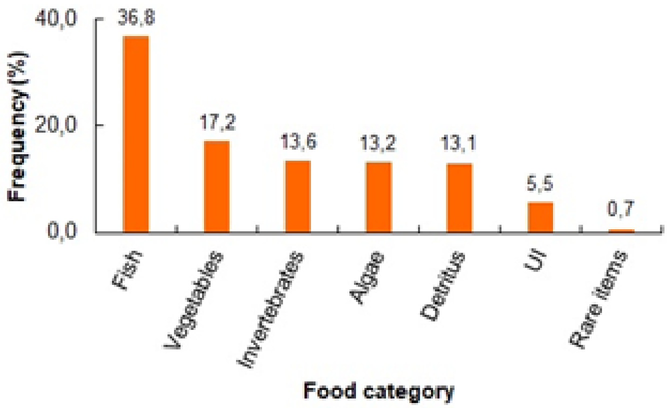

FIGURE 3 – Percentage of weight for the food categories in the stomachs of fishes at 12 hydropower plants of the upper Paraná River basin, Brazil. UI = unidentified items.

Omnivorous was the dominant trophic guild in richness, biomass, and abundance of fishes when all 12 hydropower plants were considered simultaneously (Table 6). It also had the greatest richness for the 12 hydropower plants analyzed separately (Figure 4A). In biomass, omnivorous predominated at four plants (AFD, ASD, EMD, and MRD), detritivorous at three (CMD, ITD, and JGD), herbivorous at two (NPD and VGD), carnivorous at two (PJD and SSD), and piscivorous at one (FUD; Figure 4B). As for abundance, omnivorous dominated at all plants except ITD and VGD, where detritivorous and herbivorous predominated, respectively (Figure 4C).

TABLE 6 – Percentage of richness, biomass, and abundance by trophic guild for the fishes at 12 hydropower plants in the upper Paraná River basin, Brazil.

METRIC	TROPHIC GUILD					
	Carnivorous	Detritivorous	Herbivorous	Invertivorous	Omnivorous	Piscivorous
Richness	14.10	16.67	7.69	10.26	37.18	14.10
Biomass	17.66	16.50	6.77	0.40	57.51	1.16
Abundance	13.70	20.79	7.21	0.61	56.85	0.84

FIGURE 4 – Percentage of richness (A), biomass (B), and abundance (C) by trophic guild of the fishes at 12 hydropower plants of the upper Paraná River basin, Brazil (Car = Carnivorous, Det = Detritivorous, Her = Herbivorous, Inv = Invertivorous, Omn = Omnivorous, Pis = Piscivorous).

According to Gandini *et al.* (2012), the ichthyofauna downstream of ITD is dominated by species that eat a small quantity of a wide variety of foods. In fact, tropical rivers under natural conditions are unstable and seasonal environments, favoring the predominance of species with high trophic plasticity (Araujo-Lima *et al.* 1995, Lowe-McConnel 1999). Bowen (1983) and Bonetto (1986) affirmed that detritivorous predominate in biomass in the Paraná River basin, mainly due to curimba (*P. lineatus*). Thus, we expected to find omnivorous to dominate richness and detritivorous to dominate biomass.

In our study, the dominance of omnivorous in the trophic structure was due in large part to mandi, an omnivorous fish that accounted for 34.5% of the biomass and 28% of the abundance. Mandi is abundant in the tailraces of hydropower plants (*e.g.,* Chapters 2, 4, and 6) and, therefore, was one of the main reasons for the predominance of omnivorous. On the other hand, the biomass of detritivorous was lower than expected. This could be caused by the retention of debris and nutrients in the reservoir cascade (Barbosa *et al.* 1999), which may compromise its availability downstream of the hydropower dams. Another reason may be the effect of flow alteration on other aspects of fish biology (Puckridge *et al.* 1998, Poff & Zimmerman 2010), including reproduction (*e.g.,* Welcomme 1985, 1989), especially because there is synchrony between reproduction and the hydrological cycle for many fishes (Vazzoler 1996). Thus, it can be difficult to determine the effects of the dam on one particular aspect of the biology of any given species. For example, the barrier to migration caused by the dams may contribute significantly to the reduced biomass of detritivorous, especially curimba (Godinho & Kynard 2009), a large detritivorous species with seasonal reproduction and long-distance migrations (Bowen 1983, Bonetto 1986).

The first two axes of the PCA explained 72.5% of the total variance (41.4% by axis 1 and 31.1% by axis 2), which were the only axes retained for interpretation. The highest coefficients of axis 1 were for Q_m and Q_r, while those for axis 2 were for *AR* and *DL* (Table 7). There were no significant correlations between the environmental and operative variables synthesized in axes 1 and 2 of the PCA and trophic structure (Table 8).

TABLE 7 – Coefficients of environmental and operational variables of axes 1 and 2 of the principal components analysis. *DA* = dam age, *RT* = residence time of the reservoir water, *DL* = length of the downstream lotic stretch, *AR* = area of the first downstream reservoir, Q_m= mean daily variation of outflow discharge, and Q_r= outflow discharge range.

VARIABLE	Axis 1	Axis 2
DA	0.59	-0.60
RT	0.66	0.07
DL	0.42	0.83
AR	0.30	0.88
Q_m	0.87	0.14
Q_r	0.81	0.11

TABLE 8 – Pearson correlation (*r*) of axis 1 and 2 of the principal components analysis of the hydropower plants environmental and operational variables with axis 1 of the non-metric multidimensional scaling of richness (NM_R), biomass (NM_B), and abundance (NM_A). *P* = probability value.

METRIC	Axis 1		Axis 2	
	r	*P*	r	*P*
NM_R	-0.01	0.97	0.50	0.09
NM_B	0.41	0.19	-0.38	0.22
NM_A	0.26	0.42	-0.29	0.37

Variation in flow altered the availability of resources to fish, and species of different trophic guilds respond differently to variation in flow due to altered food resources (Luz-Agostinho *et al*. 2009, Gandini *et al*. 2014). Luz-Agostinho *et al*. (2009) reported that piscivorous fishes have better condition in the dry season because their prey have fewer shelters. Abujanra *et al.* (2009), in turn, reported that body condition of invertivorous and insectivorous fishes are negatively affected by the coefficient of variation of flow. Flow variation in un-dammed rivers can be 200 to 300% (Rocha *et al*. 2001, Mortatti *et al*. 2004), leading to the aforementioned effects on the trophic structure of fishes. On the other hand, the variation in flow downstream of the hydropower plants studied here did not exceed 25%, reflecting the flow-control function of the plants in order to reduce the intensity of droughts and floods (Poff *et al.* 1997). This limited flow variation downstream of the studied hydropower plants may explain the lack of a correlation between outflow discharge and the trophic structure of fishes.

Although the hydropower plant environmental and operational variables tested did not have a significant effect on trophic structure, Tundisi & Matsumura-Tundisi (2003) affirmed that the regulation of river discharge by dams is one of the main threats to the conservation of diversity in the upper Paraná River basin. In fact, some studies have shown that changes in the natural hydrological cycle may affect fish of several trophic guilds (*e.g.*, Abujanra *et al.* 2009, Fernandes *et al.* 2009). It is apparent that variables other than those considered in our study need to be evaluated in order to identify those that influence trophic structure of the ichthyofauna. Moreover, the lack of reference environments, with unregulated hydrological cycles, likely contributed to the difficulty in fully understanding the influence of the regulation of river flow on trophic structure.

Stocking native migratory fishes may have had a confounding effect on our analyses. For example, we captured 12 curimbas and 7 piracanjubas (*B. orbignyanus*), all most likely stocked fish, at CMD, which has no lotic stretch downstream. We captured more curimbas and piracanjubas at CMD than at EMD, a plant with 24 km of running water downstream. Stocking may not be sufficient to restore the original trophic structure, but it may increase the abundance of native migratory fishes at hydropower plants with reduced or no lotic stretch downstream, and where their abundance would be expected to be low or null. Thus, stocking may increase the difficulty in identifying the influence of hydropower plant environmental and operational factors on the ichthyofauna.

4 – CONCLUSIONS

Although we used data from hydropower plants with different sampling efforts, grouping fish into comprehensive trophic guilds and using percentages in data analysis aided in neutralizing this bias. Furthermore, since changes caused by damming act in a very similar, or even predictable, way among all large dams (Power *et al.* 1996, Graf 2006), our analyses provided valid information for a better understanding of the trophic ecology of fish at hydropower plants.

We conclude that fish is the food item most consumed by the ichthyofauna just downstream of hydropower plants, and omnivorous species dominate the trophic structure. However, we consider important that future research attempts to determine the hydropower plant environmental and operational factors responsible for the changes we detected in the trophic structure.

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SÉRIE PEIXE VIVO

FISH AND HYDROPOWER PLANTS

CHAPTER 6

BIOLOGY OF MANDI (*Pimelodus maculatus*) IMMEDIATELY DOWNSTREAM OF HYDROPOWER PLANTS OF SOUTHEASTERN BRAZIL

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1 – INTRODUCTION

The Neotropical siluriform fish *Pimelodus maculatus*, commonly known as mandi, mandi-amarelo, mandijuba, and mandi-guaçu, is a native species of the Paraná and São Francisco river basins (Reis *et al.* 2003). It can reach 40 to 50 cm in length and weigh 1.5 to 2.0 kg (Sato *et al.* 1999). A recent description of a new species previously considered to be *P. maculatus* (*e.g.*, Souza-Filho & Shibatta 2007) suggests that *P. maculatus* may not be a homogenous taxonomic unit.

Although common in reservoirs (Dei Tos *et al.* 2002, Santos *et al.* 2010), Santos *et al.* (2013) indicate that mandi are more abundant in the lotic environments downstream of dams. Mandi is also one of the most abundant species in fishways (Bowen *et al.* 2006, Alves 2007, Fernandez *et al.* 2007, Oldani *et al.* 2007, Bizzotto *et al.* 2009, Arcifa & Esguicero 2012), but its migratory status remains controversial (Santos *et al.* 2013), having been considered both a migratory (Zaniboni-Filho & Schulz 2003, Arcifa & Esguicero 2012) and a non-migratory (Oldani *et al.* 2007) fish. Prior to the installation of dams in the middle Grande River, tagged mandi were recaptured at distances greater than 1,000 km from their original point of capture (Godoy 1967). After the construction of the Grande River dams, the largest measured linear home range of mandi was approximately 80 km (Silva, 2012). In the Paraopeba River the furthest recapture was 81.5 km away (Alves 2007).

Mandi occur more frequently in nocturnal samplings (Dei Tos *et al.* 2002, Bowen *et al.* 2006, Bizzotto *et al.* 2009), during the full moon (Bizotto *et al.* 2009), and in months of higher temperature, rainfall, and flow (Loures & Pompeu 2012), and lower water transparency (Dei Tos *et al.* 2002). Although mandi may occupy the entire water column, it is more common in the benthic region (Lobón-Cerviá & Bennemann 2000). Mandi is frequently a target of artisanal and sport fishing (Peixer & Petrere Jr. 2009, Novaes & Carvalho 2011).

The diet of mandi is diverse and includes plants, seeds, fruits, detritus, mollusks, crustaceans, and fish (Lobón-Cerviá & Bennemann 2000), although food of animal origin predominates, with vegetable matter being typically an occasional occurrence (Peretti & Andrian 2004, Maroneze *et al.* 2011). Due to its trophic plasticity, mandi can alter its diet according to the period of the year (Andrade & Braga 2005) and its ontogenetic stage (Lima-Junior & Goiten 2003).

Mandi females are larger than males (Casali *et al.* 2010). The gonadosomatic index correlates positively with precipitation (Basile-Martins *et al.* 1975), reaching 12.9 in mature females (Maia *et al.* 2007). Females perform multiple spawning and possess fecundity in the hundreds of thousands oocytes (Godinho *et al.* 1974, Sato *et al.* 1999, Maia *et al.* 2007). Reported maturation and spawning periods vary among studies (Vono *et al.* 2002, Zaniboni-Filho & Schulz 2003). Mature females occur in reservoirs, but juveniles do not, suggesting that recruitment does not occur in this type of environment (Maia *et al.* 2007). In the Paraná River basin, Baumgartner *et al.* (2008) found mandi larvae in the Itaipu Reservoir and in three tributaries, while Kipper *et al.* (2011) found a greater density of mandi larvae in the fluvial-lacustrine transition zone of the Rosana Reservoir, Paranapanema River, but no larvae in the lacustrine zone.

Mandi is often one of the dominant species in fish communities immediately downstream of hydropower plants (Andrade *et al.* 2012, Chapter 4). It is also among the species most susceptible to death during the operation and maintenance of these plants (Andrade *et al.* 2012, Chapter 3). Therefore, we dedicate this chapter exclusively to investigating the biology and ecology of mandi immediately downstream of 13 hydropower plants of four rivers in southeastern Brazil. This investigation included analyses of factors that influence the capture, reproduction, body condition, diet, and spatiotemporal variation in length of mandi.

2 – METHODS

2.1 Fish sampling

We collected mandi (Figure 1) from February 2009 to December 2013 from the following rivers and hydropower plants: Araguari River - Amador Aguiar I (AFD), Amador Aguiar II (ASD), Miranda (MRD), Nova Ponte (NPD), and Pai Joaquim (PJD) dams; Paranaíba River - Emborcação (EMD) and São Simão

(SSD) dams; Grande River - Camargos (CMD), Funil (FUD), Itutinga (ITD), Jaguara (JGD), and Volta Grande (VGD) dams; and São Francisco River - Três Marias Dam (TMD).

The fishing gear used and the frequency of sampling at each hydropower plant are described in Chapter 2. In addition, we used fish recovered from turbine dewaterings of ASD (March, April, June, August, and December 2009), CMD (October 2010), EMD (July 2011), FUD (June 2009), ITD (May 2009 and August 2010), NPD (June 2009), and SSD (August and September 2009). We excluded certain hydropower plants or sampling periods in some analyses. These exclusions are mentioned where relevant in the topics below.

At all of the hydropower plants studied, except for TMD, we fixed all mandi captured with gillnets in 10% formaldehyde, but only the first 50 that were captured with cast nets and the first 30 captured with hook-and-line. We returned all other individuals to the river. For fixed individuals, we measured standard length (*SL*, mm), body weight (*BW*, g), and gonads weight (GW, g).

We classified the coelomic fat index (*CFI*) as none (0), little (1), moderate (2), and much (3). We classified the stomach repletion index (*SRI*) as empty (0), up to 50% full (1), more than 50% full (2), and completely full (3). For each fish, we macroscopically determined the sex and gonadal maturation stage (*GMS*). We classified the gonads as resting or non-resting, with the stage of resting including young and adult fish with no signs of gametogenesis. The non-resting stage, in turn, included all other stages of gonadal development. We did not determine *CFI*, *SRI*, and *GMS* for TMD mandi.

FIGURE 1 – Mandi, *Pimelodus maculatus*, (185 mm standard length) collected in Araguari River, MG.

2.2 Abiotic data

We measured dissolved oxygen (*DO*), temperature, and transparency of the water during fish sampling using an YSI 550A Oxygen Meter and Secchi disk between 10 and 15 h. We obtained data on precipitation, turbine discharge (Q_t), and outflow discharge ($Q_{o;}$ the sum of the spillway and turbine discharges) from Cemig. We obtained average monthly precipitation for the municipalities where the hydropower plants were located at the website Tempo Agora (Tempo Agora 2014).

2.3 *CPUE* and abiotic variables

For each hydropower plant, we determined the Pearson (normal data) or Spearman (non-normal data) correlation of abiotic variables with catch per unit effort (*CPUE*) of mandi sampled in the tailrace from January 2009 to December 2013. We determined *CPUE* using data from gillnets for ASD, EMD, FUD, and SSD, from hook-and-line for CMD, ITD, and PJD, and from cast nets for TMD. We calculated *CPUE* for each type of fishing gear as described in Chapter 2.

We determined the correlation for the following abiotic variables: *DO*, water temperature (*Temperature*), water transparency (*Transparency*), mean monthly precipitation (*Rainfall*), precipitation on the sampling day (*Rainfall1*), precipitation on the sampling day plus that of the two previous days (*Rainfall3*), precipitation on the sampling day plus that of the six previous days (*Rainfall7*), precipitation on the sampling day plus that of the 14 previous days (*Rainfall15*), turbine discharge on the sampling day (Q_{t1}), turbine discharge on the sampling day plus that of two the previous days (Q_{t3}), turbine discharge on the sampling day plus that of the six previous days (Q_{t7}), turbine discharge on the sampling day plus that of the 14 previous days (Q_{t15}), outflow discharge on the sampling day (Q_{o1}), outflow discharge on the sampling day plus that of the two previous days (Q_{o3}), outflow discharge on the sampling day plus that of the six previous days (Q_{o7}), and outflow discharge on the sampling day plus that of the 14 previous days (Q_{o15}). For these calculations, we used the daily mean for turbine and outflow discharge. For the hydropower plants sampled with gillnets, we used data of the day we set the nets.

2.4 Reproduction

We used the formalin-fixed individuals captured from February 2009 to June 2012, including fish recovered in turbine dewaterings, for analyses of reproduction. We determined the frequency of distribution of GMS per bimester. We calculated the gonadosomatic index (*GSI*) with the equation $GW.BW^{-1}.100$.

2.5 Condition factor

We calculated the Fulton condition factor (K) using the formula $K = BW.SL^{-3}.\ 10^5$ *(Pope & Kruse 2007)* for the fish sampled in the tailrace from June 2010 to June 2012. We evaluated differences in *K* between sexes, *GMS,* rivers, and seasons with factorial ANOVA, associated with Tukey multiple comparison *post hoc* test. We consider the dry season the months of April to September and the rainy season the period from October to March.

2.6 Size

We used factorial ANOVA plus Tukey *post hoc* test to test for differences among the sexes, hydropower plants, and fishing gear in *SL* of mandi from the tailraces of CMD, ITD, FUD, PJD, ASD, EMD, and SSD from June 2010 to June 2012. We also tested differences in frequencies of *SL* between seasons (rainy and dry) separately for each sex with Kolmogorov-Smirnov two-sample test.

2.7 Diet

We study the diet of mandi sampled in the tailraces of the hydropower plants ASD, CMD, EMD, FUD, ITD, MRD, PJD, and SSD between February 2009 and June 2012. We preserved stomachs with contents in 70% ethanol and measured the total wet weight of the stomach contents with two decimal places of precision. We identified food items to the lowest taxonomic level possible under a stereomicroscope and estimated the percentage weight of each item contained in the stomachs. We grouped food items (in parentheses) in the following categories: terrestrial arthropod (adult insects and arachnids), aquatic invertebrate (insects, mollusks, crustaceans, and zooplankton), fish (scales and remains of fish), sediment (silt and sand), and vegetal (phytoplankton, algae, bryophytes, branches, leaves, seeds, flowers, and fruits).

We analyzed the feeding strategy of mandi for each hydropower plant using the Costello (1990) graphic method, as modified by Amundsen *et al.* (1996). This method combines frequency of occurrence (F_i) and specific abundance (P_i) of the food categories to describe the trophic ecology of the population. We correlated the F_i of the food categories of mandi with reservoir area, age, and elevation, and Q_t of the hydropower plant (Table 1).

For the statistical analyses of dietary data and the relationship of *CPUE* with abiotic variables, we used the PAST program (Hammer *et al.* 2011). We performed the analyses of size and reproduction with SAS and those related to the condition factor with Statistica. We used a significance level of 5% for all tests.

TABLE 1 – Characteristics of the hydropower plants of Araguari, Grande, and Paranaíba rivers.

RIVER/ HYDROPOWER PLANT	Reservoir area (km^2)	Age[1] (years)	Elevation (m)	Mean turbine discharge[2] (m^3/s)
ARAGUARI RIVER				
Amador Aguiar II	45.1	6	518	393.8
Miranda	51.9	14	624	367.9
Pai Joaquim	0.5	71	828	24.7
PARANAÍBA RIVER				
Emborcação	480.1	30	521	407.8
São Simão	703.3	34	327	2,061.6
GRANDE RIVER				
Camargos	73.4	52	882	130.7
Funil	36.0	9	770	303.1
Itutinga	1.7	57	857	154.5

1: Time between start of operation and 2012.
2: For the period from August 2009 to June 2012.

3 – RESULTS AND DISCUSSION

3.1 *CPUE* and abiotic variables

Few correlations were significant for ITD and SSD, unlike the other plants. For most other plants, the *CPUE* for mandi was correlated with *Temperature*, *Rainfall,* and *Transparency* (Table 2). The higher the *Temperature* and *Rainfall*, and the lower the *Transparency*, the greater the number of mandi captured. Higher temperatures and precipitation associated with lower water transparency are the typical conditions of the rainy season, which is the mandi spawning season (Basile-Martins *et al.* 1975, Godinho *et al.* 1977, Vazzoler *et al.* 1997, Braga 2001, Dei Tos *et al.* 2002).

The only variable that did not correlate with *CPUE* in any of the hydropower plants analyzed was *DO*, although it is directly related to the maintenance of aquatic life (Esteves 1998, Pinto *et al.* 2010) and is capable of influencing behavior (Ribeiro 2001) and growth (Mallya 2007) of fish. The ability of mandi to withstand extreme levels of oxygen (Felizardo *et al.* 2010) may be the cause for this lack of correlation between *CPUE* and *DO*.

3.2 Reproduction

We determined the *GMS* of 1,239 females and 1,122 males from the Araguari River, 335 females and 264 males from the Grande River, and 847 females and 627 males from the Paranaíba River, for a total of 4,434 fish. We obtained the *GSI* for 99.8% of these fish. Resting females and males predominated, followed by non-resting individuals, except for males of the Paranaíba River (Figure 2). Non-resting fish occurred in almost all bimesters. The highest *GSI* generally occurred in the bimesters at the end and beginning of the year. The majority (95%) of females had *GSI* $\leq$ 1.7, with only six of them (five of the Araguari River and one from the Paranaíba River) reaching *GSI* $\geq$ 8.7; *GSI* $\leq$ 1 occurred in 99.7% of males.

TABLE 2 – Correlation coefficient for capture per unit effort of mandi with abiotic variables immediately downstream of hydropower plants of southeastern Brazil. Significant correlations in bold ($P \leq 0.05$). Acronyms refer to the hydropower plants of Amador Aguiar II (ASD), Camargos (CMD), Emborcação (EMD), Funil (FUD), Itutinga (ITD), Pai Joaquim (PJD), São Simão (SSD), and Três Marias (TMD).

Abiotic variable	Hydropower plant							
	ASD	CMD	EMD	FUD	ITD	PJD	SSD	TMD
DO	-0.36	-0.22	-0.30	-0.26	-0.45	-0.41	-0.22	-0.11
Temperature	**0.74**	**0.66**	**0.69**	0.61	0.14	**0.61**	-0.09	-0.12
Transparency	**-0.47**	**-0.78**	**-0.47**	-0.64	-0.43	**-0.53**	**0.41**	**-0.42**
Rainfall	**0.76**	**0.67**	**0.75**	0.84	**0.31**	**0.64**	0.15	**0.25**
Rainfall1	0.14	0.54	**0.46**	-	0.40	-	-0.001	0.02
Rainfall3	0.31	0.43	**0.59**	-	0.01	-	0.10	0.08
Rainfall7	0.60	**0.36**	0.60	-	-0.13	-	0.25	0.11
Chuva15	0.63	**0.28**	0.56	-	0.07	-	0.24	**0.26**
Qt1	**0.36**	0.37	0.17	0.70	**0.43**	0.57	-0.29	**0.49**
Qt3	**0.35**	0.41	0.27	0.80	**0.41**	0.57	-0.22	**0.49**
Qt7	**0.43**	**0.28**	0.27	**0.79**	**0.45**	0.57	-0.15	**0.50**
Qt15	0.46	**0.24**	0.37	**0.70**	**0.63**	0.51	-0.12	**0.46**
Qd1	0.38	0.63	**0.19**	0.70	**0.35**	0.40	-0.26	**0.36**
Qd3	0.35	0.64	**0.28**	0.80	**0.36**	0.49	-0.22	**0.37**
Qd7	0.43	**0.66**	**0.28**	0.79	**0.44**	0.51	-0.11	**0.36**
Qd15	0.45	**0.73**	**0.46**	**0.70**	**0.63**	**0.52**	-0.09	**0.37**

The almost non-existence of mature females indicates that mandi does not spawn in the tailrace of the sampled hydropower plants. Mature mandi females at the Igarapava Dam, Grande River, had a *GSI* of 12.9 ± 2.1 (Maia *et al.* 2007). Females from our samples with *GSI* ≥ 8.7 could, therefore, be mature, but they were very rare in the places where we sampled. It may be that they had migrated to spawn elsewhere or, if they were residents, had their gonadal development inhibited.

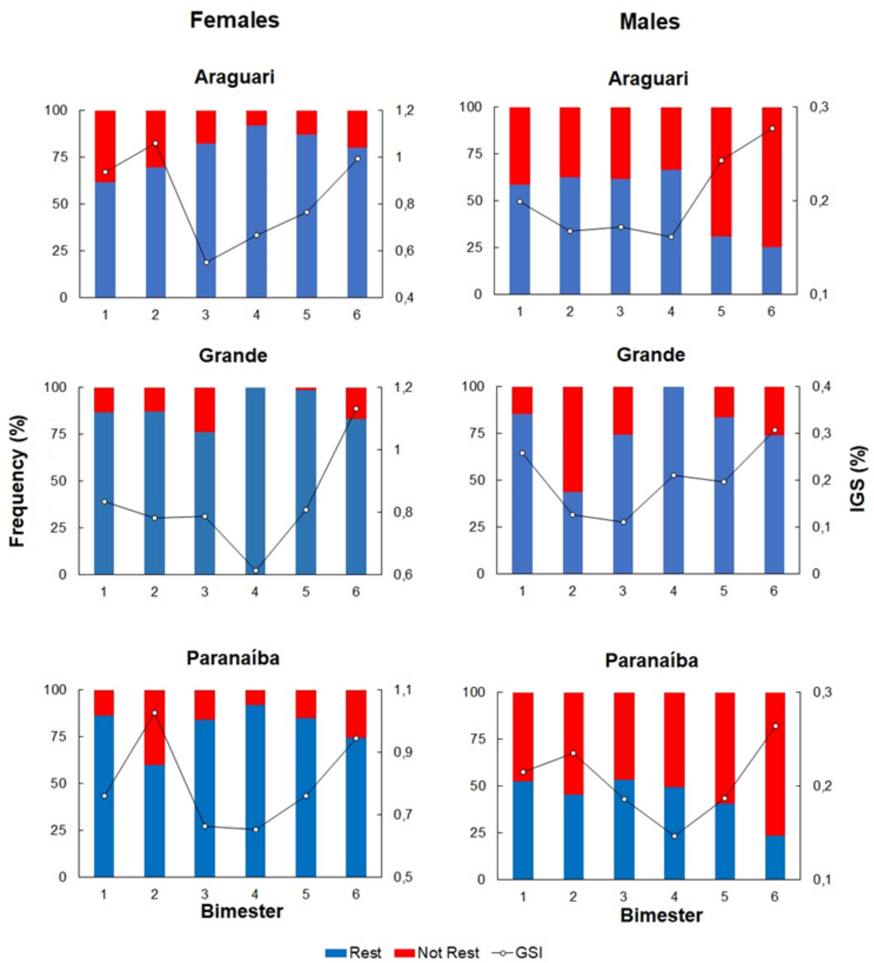

FIGURE 2 – Gonadosomatic index (*GSI*) and frequency of gonadal maturation stages of female and male mandi by bimester in Araguari, Grande, and Paranaíba rivers.

3.3 Condition factor

Factorial ANOVA indicated that all factors except sex significantly influenced *K*. The value of *K* was higher in the Paranaíba River and lower in the Araguari River. The value of *K* was also higher in non-resting fish, during the rainy season, and in the classes 2 and 3 of the *CFI*.

The value of *K* is a measure of the physiological state of fish, and is mainly related to feeding and reproduction (Lima-Junior & Goitein 2006). Sabinson *et al.* (2014) found higher *K* for mandi during gonadal maturation and spawning periods, which occurred in the rainy season. We found the highest values of *K* associated with non-resting fish, in the rainy season, and in fish with more fat.

3.4 Size

Sex, hydropower plant, and fishing gear had a significant influence on *SL* of mandi according to the factorial ANOVA. Females were larger than males, a condition also observed by Casali *et al.* (2010). The mandi of the Grande River hydropower plants (*i.e.*, CMD, ITD, and FUD) were smaller (Figure 3A) than those of the other plants. This difference may be explained by mandi not representing a single taxonomic unit. Although differences occurred in *SL* between the three types of fishing gear, there was great overlap in the size of mandi they captured (Figure 3B).

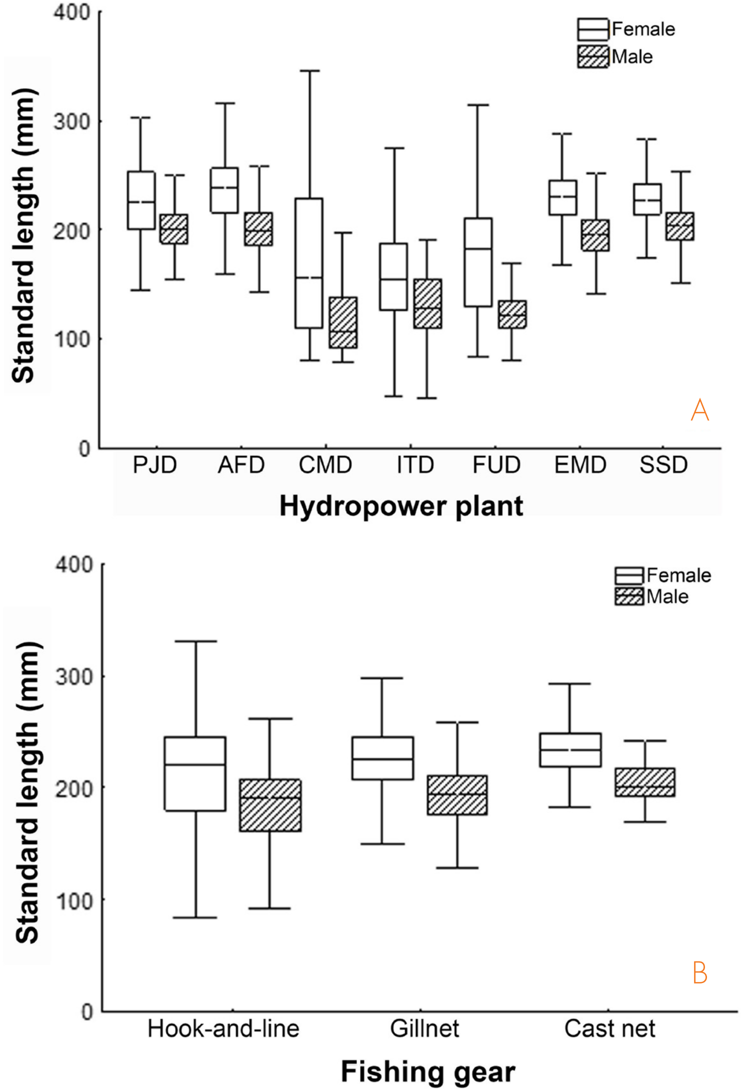

FIGURE 3 – Box-plot (median, interquartile range, and amplitude without data exclusion) of the standard length of female and male mandi by hydropower plant (A) and by fishing gear (B). Acronyms of hydropower plants according to section 2.1

We captured more mandi in the rainy (F = 978; M = 723) than in the dry season (F = 192; M = 200). Females exhibited significant differences in *SL* distribution between rainy and dry seasons (Kolmogorov-Smirnov two sample test, $P < 0.0001$), but males did not ($P = 0.06$). Smaller females were more frequent in the rainy season (Figure 4), a condition that can be generated if adult females of the tailrace migrate to spawn elsewhere.

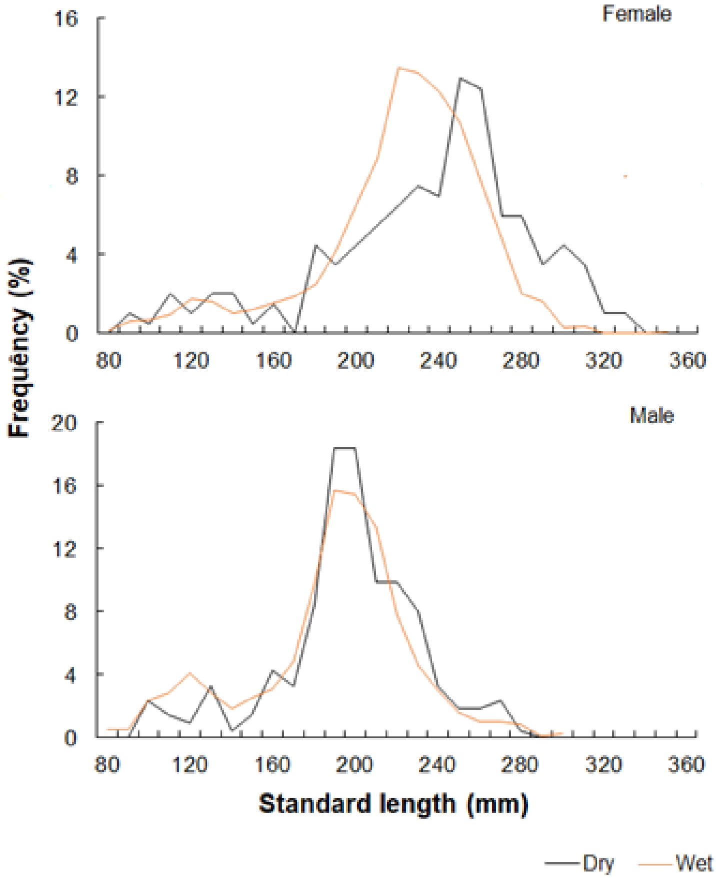

FIGURE 4 – Percentage of mandi by standard length class of females and males in the dry and rainy seasons.

3.5 Diet

At the Grande River hydropower plants (*i.e.*, CMD, FUD, and ITD), mandi specializes on consuming fish, with frequency of occurrence (F_i) and specific abundance (P_i) above 36% and 89%, respectively (Figure 4). At CMD, food categories other than fish were occasional, while at ITD the piscivorous diet was supplemented with terrestrial arthropods, aquatic invertebrates, sediment, or vegetal matter. At FUD, mandi were also specialists on sediment ingestion.

Mandi exhibited a mixed feeding strategy at ASD, EMD, MRD, and SSD (Figure 5). At MRD, fish or vegetal consumption was supplemented by sediment, aquatic invertebrates, and arthropods. Vegetal matter was the category with highest *Fi* and *Pi*. At ASD, mandi ingested sediment, vegetal matter, and fish, supplemented with aquatic invertebrates and terrestrial arthropods. Sediment and fish were the categories with the highest *Fi* and *Pi*, respectively. At EMD, mandi fed on vegetal matter, fish, and sediment, supplemented with terrestrial arthropods and, mainly, aquatic invertebrates. Vegetal matter exhibited the highest F_i and P_i. At SSD, mandi ate mainly aquatic invertebrates, fish, and terrestrial arthropods, with sediment and vegetal matter supplementing the diet. Vegetable matter was the category with the highest F_i, while terrestrial arthropods had the highest P_i. Mandi exhibited a generalist feeding strategy at PJD; terrestrial arthropods had the highest F_i, while fish had the highest P_i.

Mandi adapts its feeding strategy to its environmental conditions. Our analysis of mandi diet at hydropower plants of the upper Paraná River basin showed that mandi exploits its omnivorous capability to survive the most diverse environmental conditions, as has been observed in other types of environments (Ramos *et al.* 2011). Silva *et al.* (2007) suggest that the diet of mandi reflects the food availability due to its opportunistic feeding habits.

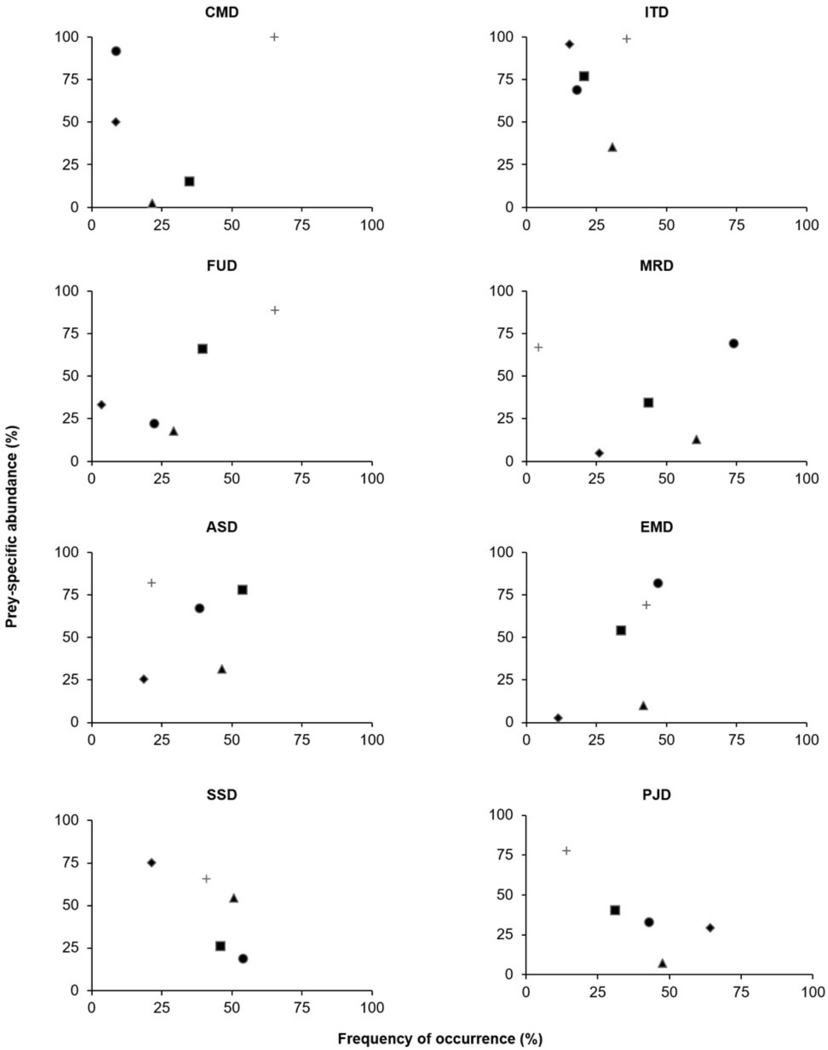

FIGURE 5 – Specific abundance and frequency of occurrence of food categories in the diet of mandi at hydropower plants in southeastern Brazil. Hydropower plants are grouped by specialist (CMD, FUD, and ITD), mixed (ASD, EMD, MRD, and SSD), and generalist (PJD) diets. Acronyms of hydropower plants according to section 2.1. Food categories: ■ = sediment; ▲ = aquatic invertebrate; ● = vegetal; ◆ = terrestrial arthropod; + = fish.

There was a negative correlation between F_i of sediment and hydropower plant age (r = -0.76; P = 0.03; Figure 6). Thus, populations of mandi at the youngest hydropower plants exhibited a higher frequency of sediment in their diet, while sediment was less frequent in mandi at older plants. Other correlations with independent variables were not observed.

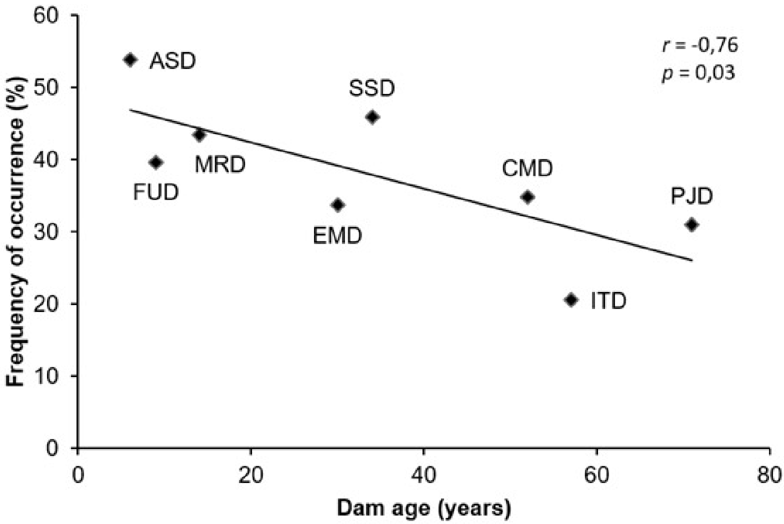

FIGURE 6 – Correlation between the frequency of occurrence of sediment in mandi diet and hydropower plant age. Acronyms of hydropower plants according to section 2.1.

The negative correlation between the frequency of occurrence of sediment in mandi diet and hydropower plant age was likely due to changes in sedimentary dynamics caused by the plants. Dams alter the discharge regime of the downstream river. Consequently, the deposits of fine sediment accumulated in the riverbank and bed undergo an intense erosive process (Ward & Stanford 1983), and the older the plant, the longer the river stretch and the greater the number of sediment deposits eroded (Collier *et al.* 1996).

Erosion of fine sediment downstream of older hydropower plants alters the diet of mandi and may adversely affect young fish. In this life stage, mandi ingests large amounts of organic matter from the substrate (Lima-Júnior & Goitein

2003). In newer plants, with greater availability of fine sediment deposits, the diet of mandi was composed of plants and benthic invertebrates, which are found in these types of deposits. On the other hand, at older plants, with fewer fine sediment deposits, the diet of mandi was based on fish.

Despite the dietary plasticity of mandi, we do not know how its abundance will be affected by habitat changes that modify the availability of food items for its diet. Fish, benthic insects from sedimentary deposits, and vegetal matter, largely from riparian vegetation, were important items of the mandi diet in our study, but the future availability of these items for mandi that live immediately downstream of hydropower dams is not guaranteed. Thus, only continued study of mandi diet can determine whether their diet will change over time and how this will eventually affect their abundance.

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SÉRIE PEIXE VIVO

FISH AND HYDROPOWER PLANTS

CHAPTER 7

FISH CARCASSES ADRIFT IN THE PARANAÍBA RIVER DOWNSTREAM OF THE SÃO SIMÃO DAM, BRAZIL

ALEJANDRO GIRALDO, ÁTILA RODRIGUES DE ARAÚJO, MATEUS MOREIRA DE CARVALHO, RAONI ROSA RODRIGUES & ALEXANDRE LIMA GODINHO

Giraldo A., Araujo A.R., Carvalho M.M., Rodrigues R.R. & Godinho A.L. (2017) Fish carcasses adrift in the Paranaíba River downstream of the São Simão Dam, Brazil. In: R.C. Loures & A.L. Godinho (eds.) *Risk assessment of fish death at hydropower plants in southeastern Brazil.* Belo Horizonte: Companhia Energética de Minas Gerais, pp. 179-198 (Série Peixe Vivo, 6).

1 – INTRODUCTION

Fish deaths are recurrent events at Brazilian dams (Agostinho *et al.* 2007), and are mainly due to the passage of upstream fish through the spillway and/or turbine, or by downstream fish entering the draft tube (Andrade *et al.* 2012). The São Simão Dam (SSD) is no exception to this phenomenon. Since it was built, the SSD has had fish death occurrences of varying magnitudes, mainly during the rainy season. As a result, fish carcasses can be seen drifting at the surface of the Paranaíba River downstream from the dam. Protocols to protect fish have been established by Cemig, the dam's concessionaire, but fish death at SSD remains chronic.

Massive die-offs of fish from of the operation of dams and/or other environmental accidents (*e.g.*, Hackett 2005) are addressed in a predominantly diagnostic manner. In Brazil, the approach has been mainly to estimate the number and/or biomass of dead or near dead fish, without any systematic investigation into the cause.

The quantity of dead fish resulting from the operation of a dam varies from a few individuals of a few kilograms of weight, to several tons. This amplitude is a result of the variety of operational procedures that dams perform, their civil and hydraulic structure, and the peculiarities of each river and fish fauna, which makes it difficult to obtain general standards on mortality (Agostinho *et al.* 2007).

The secrecy with which information about fish kills at dams is treated is one of the factors that make it difficult to study the phenomenon. Negative impacts seen in the media, and large fines eventually applied by environmental agencies, hinder open discussion and the exchange of information among concessionaires and with research institutions (Agostinho *et al*. 2007).

Variation in the magnitude and temporality of fish deaths are aspects to be considered in the analysis of this phenomenon. Fish deaths may be acute (*i.e.*, fish kill), involving large numbers of fish, sometimes tens of tons, over a short period of time, or, as with SSD, chronic, with the death of a relatively small but constant amount of fish over time.

Studies that quantify floating carcasses as a method of evaluating fish death due to the operation of dams seem absent in the specialized literature worldwide. Quantifying these carcasses can help to estimate fish death generated by the operation of dams, and to better understand the phenomenon in order to propose alternatives. Thus, our objective with this study was to determine the dynamics of floating fish carcasses adrift in the Paranaíba River downstream from SSD in order to establish: (i) their temporal and spatial variation; (ii) the influence of turbine startups on quantity; and (iii) the percentage of drifting carcasses collected.

2 – METHODS

2.1 Study site

The SSD is located on the lower Paranaíba River (50° 29' 58" W 19° 01' 06" S), in the municipalities of São Simão and Santa Vitória, in the states of Goiás and Minas Gerais. It is the most downstream dam of the Paranaíba River prior to its confluence with the Grande River to form the Paraná River. Inaugurated in 1978, the SSD is a storage hydropower plant. Its dam is 127 m high and 3,440 m wide, while the reservoir covers approximately 703 km^2 (Cachapuz 2006). It has an installed capacity of 1,710 MW, with six Francis turbines, each having a maximum generation capacity of 285 MW and maximum intake of 425 m^3/s.

2.2 Spatiotemporal occurrence of carcasses

We sampled fish carcasses (defined here as the body of a dead or dying fish, at any stage of decomposition) floating on the water surface in the first 10 km of the Paranaíba River downstream of SSD from 2010 to 2013 (Figure 1).

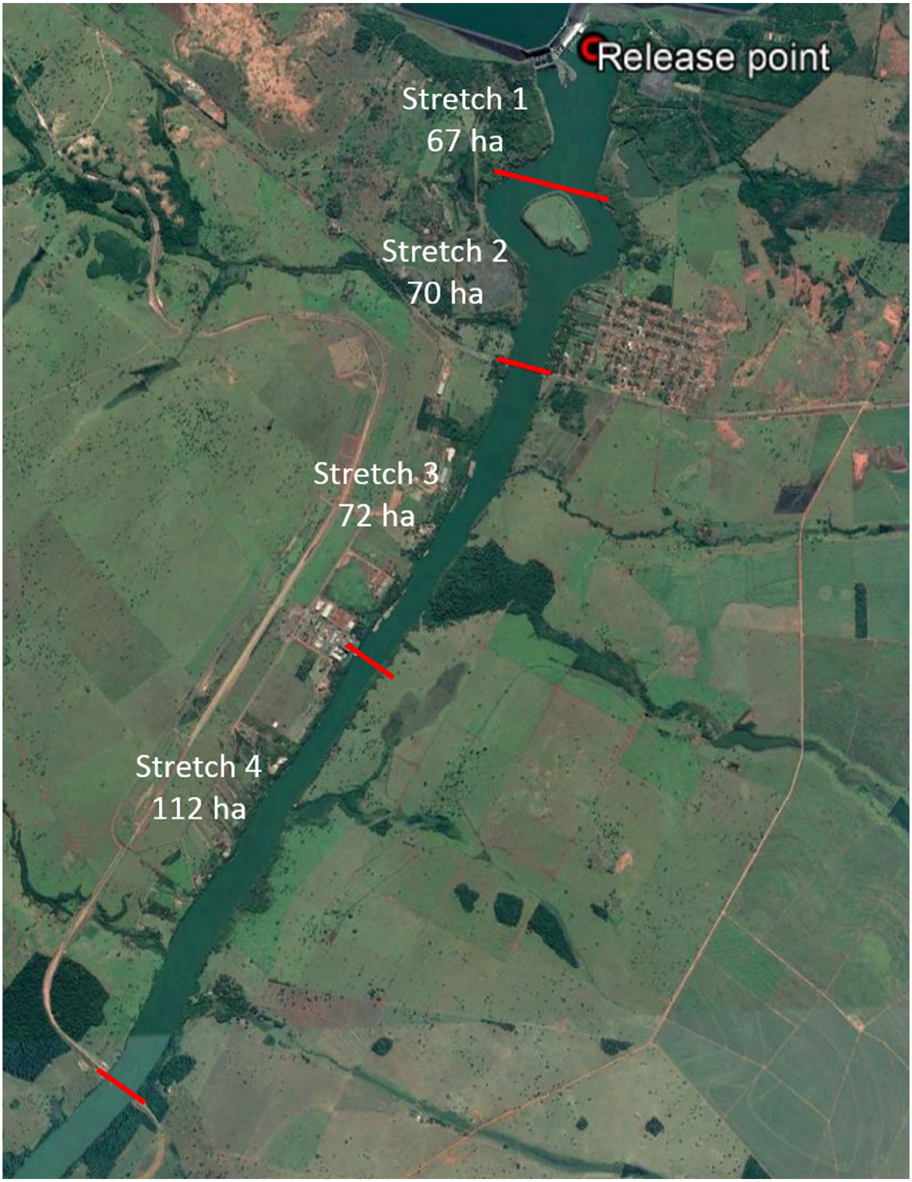

FIGURE 1 – Sampling area for carcasses downstream of the São Simão Dam. Image: Google Earth.

For sampling, we divided the area into four stretches: Stretch 1 (1.5 km long with an area of 67 ha), Stretch 2 (1.8 km, 70 ha), Stretch 3 (2.8 km, 72 ha), and Stretch 4 (4.2 km, 112 ha). Sampling took place from January to March 2010 (Season 1, 47 days of sampling), October 2010 to April 2011 (Season 2, 82 days), November 2011 to April 2012 (Season 3, 130 days), and November 2012 to May 2013 (Season 4, 155 days), for a total 414 days. Sampling of the carcasses was done daily (except Sundays and holidays) by a team of two people who surveyed the entire sampling area by boat at 8–10 km/h. Surveys were performed in the morning, starting at 7:00 a.m., and in the afternoon, beginning at 2:00 p.m. Surveys took place along the left margin in the downstream direction and along the opposite margin in the upstream direction. All carcasses seen on the water surface were collected during surveys. The following were determined for each carcass: species, standard length (*SL*), body weight (*BW*), stretch where collected (from January 2011), stage of decomposition (initial, intermediate, or advanced), macroscopic signs associated with barotrauma (exophthalmia and stomach eversion), and/or mechanical shock (fractures, abrasions, and mutilations). We excluded individuals of the genus *Hypostomus* from the analysis because it was not possible to identify them to species.

2.3 Mark-recapture of mandi carcasses

We performed a mark-recapture experiment with mandi carcasses including two treatments (bottom and surface) and three replicates (January 2012, March 2012, and February 2013) to determine the recapture percentage of carcasses in the sampled area (Table 1).

TABLE 1 – Information from the mark-recapture experiment with mandi carcasses. B = bottom, S = surface, SL = Standard Length, BW = Body Weight.

REPLICATE	**Number of marked carcasses per treatment**		***Standard length (mean ± SD)***	***Body weight (mean ± SD)***	**Maximum cooling time (h)**
	B	S			
1	50	50	25,6 ± 2.1	319.6 ± 86.7	48
2	49	51	23.7 ± 2.2	206.5 ± 53.5	24
3	50	50	23.4 ± 2.3	224.4 ± 70.1	48

We collected mandi for marking by hook-and-line from the tailrace of SSD and Amador Aguiar II Dam on the Araguari River, a tributary of the Paranaíba River. We euthanized fish immediately after their capture and kept them cool for 24–48 h until the time of marking and release. We marked each specimen in the mouth with a colored plastic clamp (one color for each treatment) and measured *SL* and *BW*.

We released the marked carcasses on the surface and bottom of the center of the tailrace of SSD about 100 m downstream from the powerhouse. To release the fish at the bottom of the tailrace, we used a bucket with a hole in the bottom through which we passed a rope attached to a weight, which remained inside the bucket. We put the fish in the bucket and closed it with a plastic bag. The weight of the fish, the weight, and the water in the free spaces of the bucket allowed it to sink to the bottom of the tailrace. Upon reaching the bottom, we pulled the rope to dispense the fish. We used 49–51 individuals per treatment for each replicate. The recapture of the marked carcasses occurred during the surveys described above. From each recaptured carcass we obtained date, time, and stretch of recapture, as well the color of the plastic clamp.

2.4 Data analysis

We calculated catch per unit effort by number ($CPUE_n$) and biomass ($CPUE_b$) as, respectively, the number and biomass of the carcasses collected per sampling day. We determined the density in number and biomass of carcasses for each stretch for the entire sampling period (total density) and for each day (daily density). For calculation of the *CPUE*s and densities, we only used the morning survey data. For all other analyses, we used data from both the morning and afternoon surveys.

We used effect size, calculated by the generalized eta squared for repeated measures (Chapter 10), to determine the influence of the number of turbine startups per season on $CPUE_n$ and $CPUE_b$. We used the same effect size to determine the influence of stretch on density. Cemig provided the number of turbine startups per day.

We also used regression to determine the influence of the number of turbine startups on the monthly mean $CPUE_n$. We excluded the number of turbine startups that occurred on days without surveys. We used the χ^2 test to assess differences in the number of carcasses sampled between the morning and afternoon surveys.

3 – RESULTS AND DISCUSSION

3.1 Spatiotemporal occurrence of carcasses

We found carcasses on 97.3% of the days sampled. Excluding three individuals of *Hypostomus*, we sampled 5,750 carcasses of 32 species of fish weighing a total of 4,066.5 kg. The carcasses belonged to species of the orders Characiformes (17 species), Siluriformes (9), and Perciformes (6). The majority of the carcasses were of Siluriformes (69.0% of the number and 70.6% of the biomass), followed by Perciformes (20.7% and 14.8%), and Characiformes (10.3% and 14.5%).

The species with the greatest number and biomass of carcasses sampled were mandi (*Pimelodus maculatus*), corvina (*Plagioscion squamosissimus*), cachorro-facão (*Rhaphiodon vulpinus*), barbado (*Pinirampus pirinampu*), pintado (*Pseudoplatystoma corruscans*), and jaú (*Zungaro jahu*; Figure 2). Together these species accounted for 92.3% of the number and 87.8% of the biomass of sampled carcasses. Barbado, pintado, and jaú are species important to professional fishing in the study area, as well as caranha (*Piaractus mesopotamicus*), whose carcasses accounted for 0.4% of the number and 2.8% of the biomass sampled.

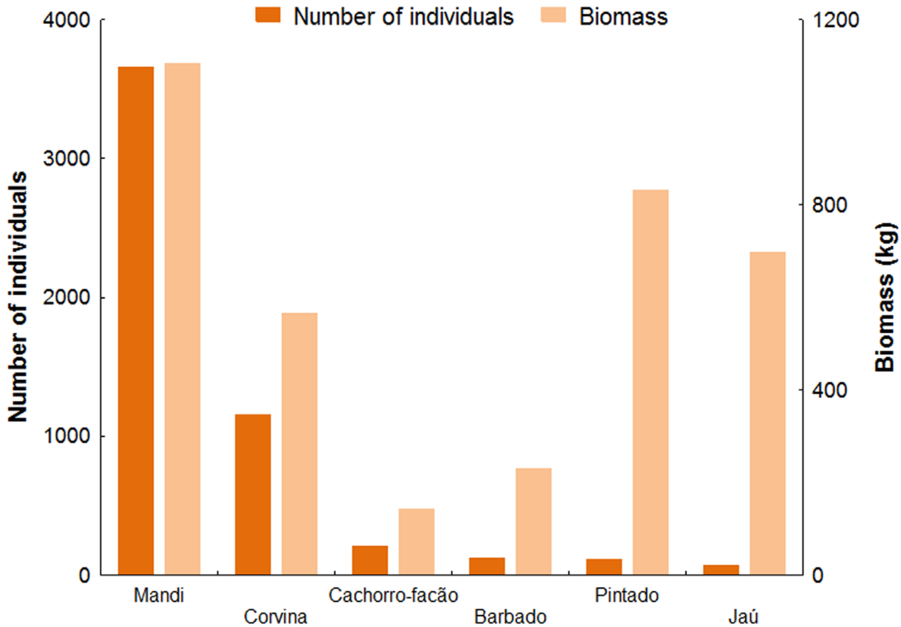

FIGURE 2 – Number of individuals and biomass of the six dominant species among the carcasses downstream of the São Simão Dam.

The *CPUE*s exhibited significant daily variation and the lowest values occurred in Season 3 (Figure 3). The monthly mean $CPUE_n$ for the six dominant species also exhibited marked fluctuations (Figure 4). Mandi was dominant in all seasons, both in $CPUE_n$ and in $CPUE_b$, except in Season 2, when the $CPUE_b$ for jaú and pintado surpassed that of mandi. No carcasses of jaú were sampled in Season 3.

Mandi is an abundant species in reservoirs and rivers, and can be remarkably dominant immediately downstream of hydropower plants and in fishways (*e.g.*, Vono 2003a, b). It is the species most affected by the operation of the Três Marias Dam (Andrade *et al.* 2012), as well as several other dams in southeastern Brazil (Chapter 3).

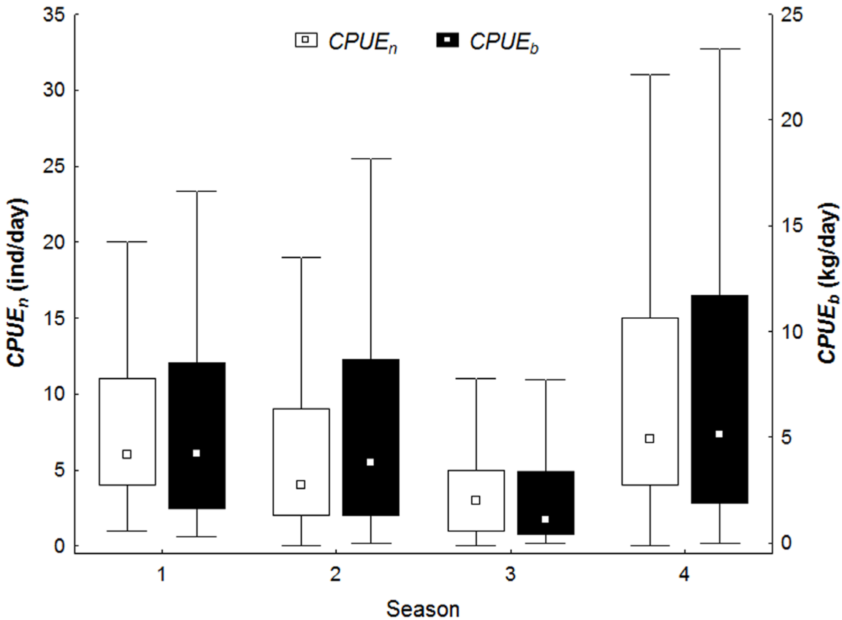

FIGURE 3 – *CPUE$_n$* and *CPUE$_b$* of carcasses downstream of the São Simão Dam. Square = median, vertical bar = interquartile range, vertical line = amplitude. Outliers and extremes as defined by Statistica 7 are not shown.

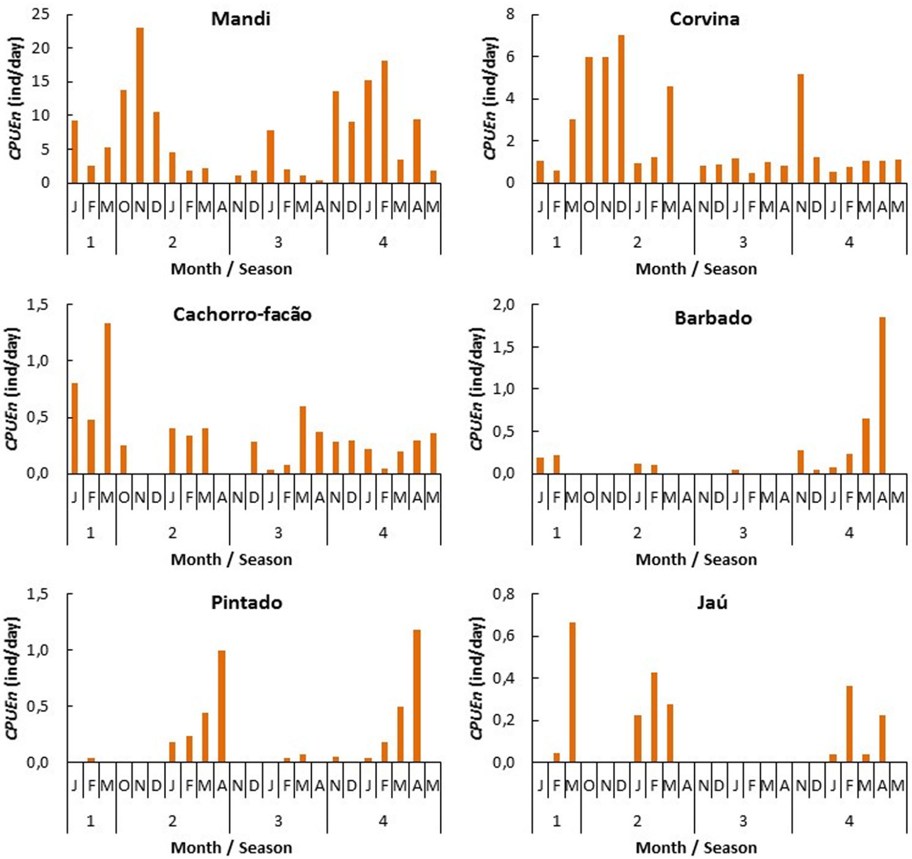

FIGURE 4 – Monthly mean $CPUE_n$ of the six dominant species among the carcasses downstream of the São Simão Dam. Scale of $CPUE_n$ adjusted by species.

Mandi was the species with the greatest density in all stretches, except for biomass density in Stretch 1, where it was surpassed by pintado (Figure 5). For the six dominant species, the effect size of stretch on daily density in number and biomass was null, probably due to the large daily variation in these densities (Figure 6). Despite this, densities over 0.47 ind/ha occurred only in Stretch 1 (Figure 5).

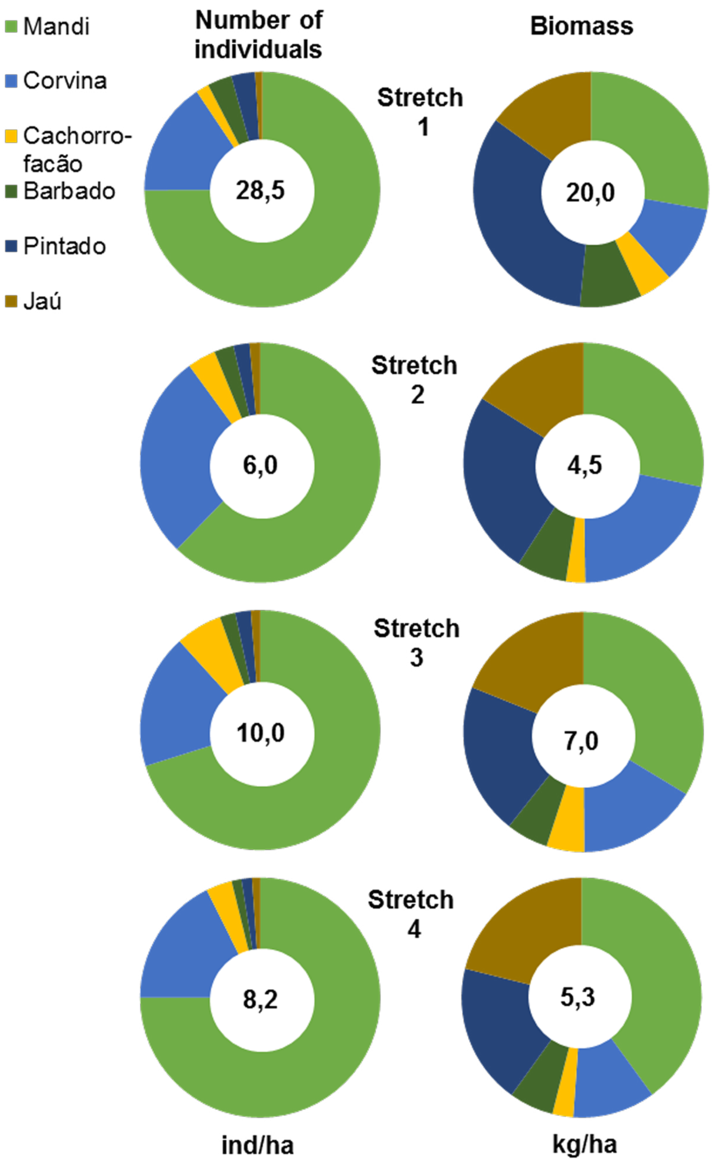

FIGURE 5 – Total density of carcasses in number (ind/ha) and biomass (kg/ha) of the six dominant species in stretches downstream of the São Simão Dam. Total density of the six species combined for each stretch is in the center of each panel.

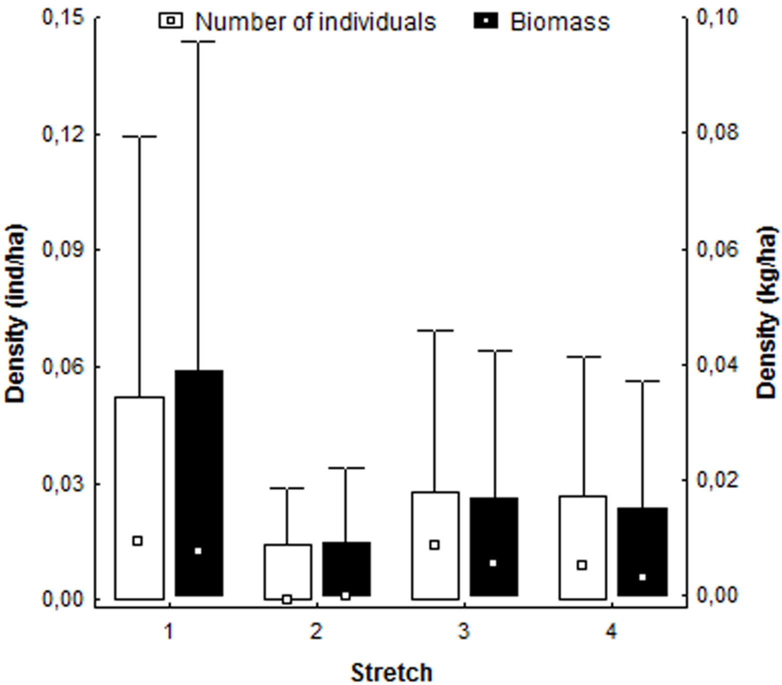

FIGURE 6 – Daily density of carcasses in number of individuals and biomass per stretch downstream of the São Simão Dam. Square = median, vertical bar = interquartile range, vertical line = amplitude. Outliers and extremes excluded according to Statistica 7.

With the exception of jaú, significantly more carcasses were sampled in the morning surveys (χ^2 test, $P \leq 0.01$ for all five species). For jaú, there was no significant difference in the number of carcasses collected between the two periods (χ^2 test, $P = 0.41$). We suspect that more carcasses occurred in the morning due to increased turbine discharge and the longer interval between surveys. The increase in turbine discharge is due to greater energy demand in the early hours of the morning. We are not sure how the higher turbine discharge increases the number of carcasses, but perhaps it suspends more carcasses deposited at the bottom of the river. On the other hand, more carcasses may have been collected in the morning because the longer time (14 h) between the afternoon and morning surveys allows the accumulation of more carcasses in the sampled area. Experiments *in loco*, involving carcasses at different stages of decomposition, may help to elucidate these questions.

3.2 Stage of decomposition and signs of trauma

The initial stage of decomposition prevailed among the carcasses of mandi and corvina (Figure 7). Among these carcasses, there were signs of barotrauma (exophthalmia and stomach eversion) and mechanical shock (fractures, abrasions, and mutilations), but those associated with barotrauma were slightly more frequent in mandi and even more frequent in corvina (Figure 8). The predominance of signs of barotrauma can be indicative of decompression during turbine startup (Andrade *et al.* 2012) or when the fish passes through the turbine from the reservoir (Agostinho *et al.* 2007). Studies, then, need to be conducted to characterize the signs of injury to fish from turbine passage (*e.g.*, Brown *et al.* 2012, Colotelo *et al.* 2012) and from turbine startup to assist in determining the origin of the carcasses.

In other species, carcasses in intermediate (cachorro-facão, barbado and pintado) or advanced (jaú) stages of decomposition prevailed (Figure 7). The small number of fresh carcasses of these species prevented the cause of the trauma from being determined. In the few fresh carcasses found, however, there were signs of mechanical shock indicative of trauma generated by contact with the blades of the turbine and/or the walls of the draft tube of SSD.

Fresh carcasses were predominantly of smaller-sized fish (mandi and corvina), whereas carcasses in later stages of decomposition predominated among fish of the larger species, such as jaú, pintado, and barbado. Most mandi and corvina carcasses exhibited signs of barotrauma. These carcasses, although fresh, may still float due to decompression. On the other hand, fish with only lesions from mechanical shock floated only in advanced stages of decomposition, likely because of the need to accumulate enough gas. This seems to be the reason why so few fresh carcasses of large fish were collected.

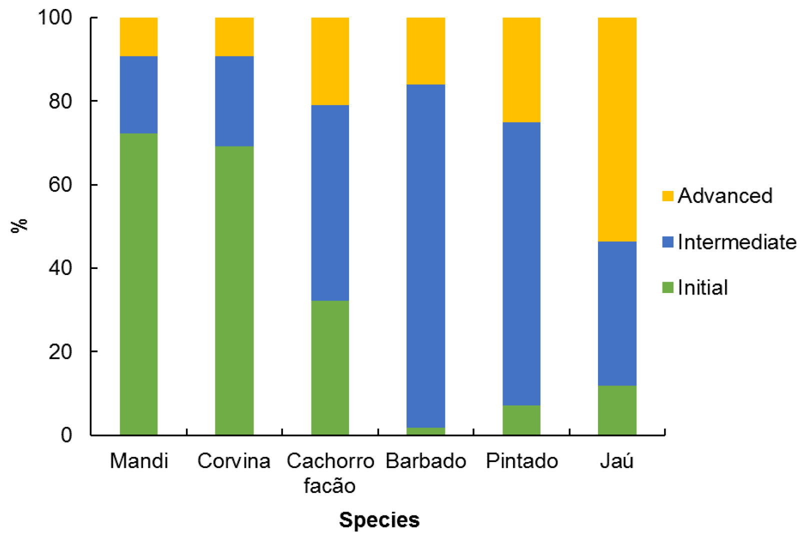

FIGURE 7 – Percentage of occurrence of stages of decomposition among carcasses of the six dominant species downstream of the São Simão Dam.

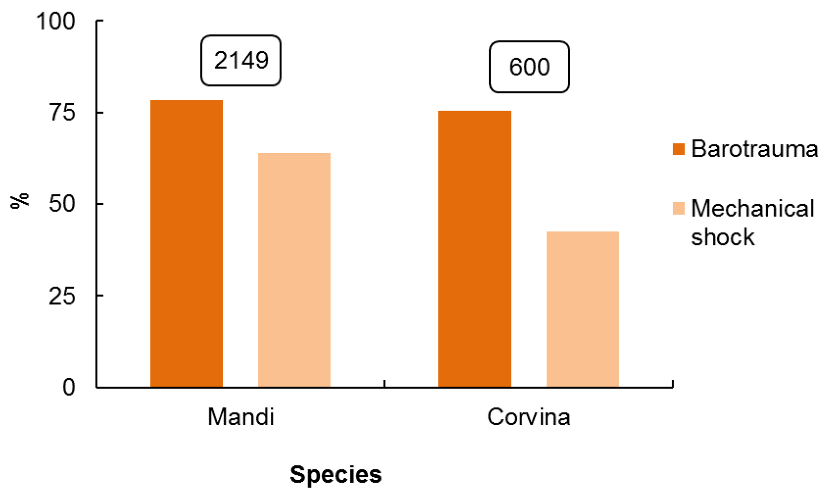

FIGURE 8 – Percentage of causes (barotrauma and mechanical shock) of signs of trauma on fresh carcasses of mandi and corvina downstream of the São Simão Dam. Numbers of carcasses with at least one of the evaluated signs are above the bars.

3.3 Turbine startups and their influence on $CPUE_n$

A total of 110 turbine startups occurred during all sampling days. The monthly number of turbine startups ranged from 0 to 14, with the least in Season 1 (7.3% of the total) and the most in Season 2 (41.8%). Monthly variation in mean $CPUE_n$ of fresh carcasses of mandi tended to follow the monthly variation in number of turbine startups in Seasons 3 and 4, but not in Seasons 1 and 2 (Figure 9). The linear regression of the logarithms of monthly means of $CPUE_n$ for mandi by number of turbine startups in the month for the entire study period was not significant (P = 0.18), but it was significant ($P < 0.001$) when done only with the data from Seasons 3 and 4. In the latter case, the logarithm of the number of turbine startups in the month explained 68% of the variation of the logarithm of the monthly average of $CPUE_n$. Thus, the quantity of drifting carcasses was directly influenced by the number of turbine startups.

The monthly mean $CPUE_n$ did not follow the variation in the number of turbine startups in Season 2. We suspect that the higher $CPUE_n$ in November associated with only one turbine startup may have been caused by mandi from the reservoir that passed through the turbines or yet from mandi of the tailrace that died in the turbines during low turbine discharge. These causes may explain the occurrence of fresh mandi carcasses on days without turbine startup. On the other hand, we still do not have a hypothesis to explain the cases of low $CPUE_n$ in months with a greater number of turbine startups, such as during January to March of Season 2.

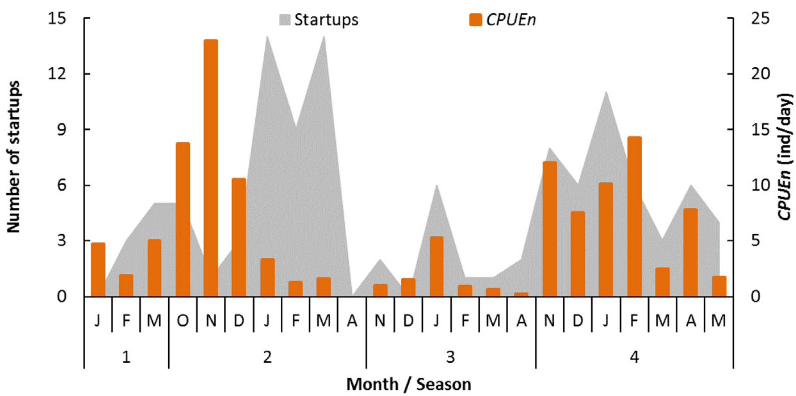

FIGURE 9 – Number of turbine startups per month and monthly mean $CPUE_n$ of fresh carcasses of mandi downstream of the São Simão Dam.

3.4 Mark-recapture of mandi carcasses

We recaptured five marked carcasses, all in the morning, 24 to 96 h after release. The carcasses were in intermediate and advanced stages of decomposition and some of them had exophthalmia, caused by decomposition, and abrasions. The carcasses were in Stretches 2, 3, and 4. Their drift velocity ranged 3–10 km/day. The mean percentage of recaptured carcasses was 1.7%.

The mandi carcasses collected in the Paranaíba River during this study represent only a small fraction of the dead mandi. The low percentage of recovered marked carcasses suggests that most of the carcasses adrift in the Paranaíba River were not collected during the surveys. It was not possible to accurately estimate the number of dead mandi with the data of the recovered marked carcasses because, unlike most of the carcasses collected of mandi, they did not suffer barotrauma. Lesions caused by barotrauma increase the buoyancy of carcasses and, consequently, the likelihood of them being collected during surveys. Although the mark-recapture experiment was performed only with carcasses of mandi, we suspect that most of the carcasses of other species were also not collected.

Several methodological issues may have influenced the underestimation of mortality in our study. One of the most important is late mortality (Čada 2001; Ferguson *et al.* 2006), by which individuals are subjected to sublethal impacts, and thus are made more susceptible to predation or pathogens (Agostinho *et al.* 2007). By not dying immediately, these individuals would not be available among the carcass during surveys. Late mortality was associated with changes in turbine discharge rates in the Northern Hemisphere, particularly for dams of the Columbia River (Ferguson *et al.* 2006), but it has not yet been studied in Brazil, and was not evaluated in our study.

4 – FINAL CONSIDERATIONS

The number and biomass of the carcasses collected are only a sample of the number of fish killed by SSD and, therefore, cannot be used as an estimate of the total amount of dead fish. The low number of recovered carcasses in the mark-recapture experiment indicates that many carcasses, perhaps the vast majority, were not collected during surveys. Mandi carcasses alternate periods of positive and negative buoyancy (Giraldo 2014) and certainly drift 24 h a day, but the surveys were restricted to 4–6 h of the day. Thus, most carcasses were likely not collected because their surface drift occurred outside the survey schedules or they crossed the entire sampling area without reaching the surface. All of this indicates that an unknown fraction of carcasses must have passed through the entire sample area without being sighted. Another unknown fraction, composed of carcasses and fish with late mortality, may have been removed from the system by birds or scavenger and piscivorous fishes.

In the analysis, we assumed that the proportion of carcasses sampled in the surveys and the carcasses drifting was constant in time and space. Collecting carcasses while they float seems to be one of the simplest ways to sample them, but for this methodology to be accurate the premise of constant proportion between floating and drifting carcasses must be verified. Including non-floating carcass sampling is critical for verifying this premise.

Further studies are needed to better understand fish death associated with the operation of SSD. Flotation experiments and night surveys may help improve the procedures currently used to determine fish death downstream of SSD. *In situ* documentation of the process of decomposition of various species will support establishing time of death and its relation to dam operation. Necropsies of carcasses are crucial for determining the occurrence of internal lesions, such as hemorrhage and distension or rupture of the swim bladder.

5 – ACKNOWLEGMENTS

We thank the SSD operation team for their help during the *in situ* experiments; Aloísio de Carvalho and Miriam de Castro (Cemig) for gathering SSD operational data; the Amador Aguiar II Dam of Consórcio Capim Branco Energia for allowing the collection of fish in the area of the hydropower plant; and the professional fisher Genilson Medeiros for assistance in the field. Hugo Godinho, Lisiane Hahn, Luiz Gustavo da Silva, and Domingos Garrone commented a previous version of this chapter.

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CHAPTER 8

DOES SPILLWAY DISCHARGE REDUCE THE AMOUNT OF FISH TRAPPED IN THE TURBINE OF THE AMADOR AGUIAR II DAM DURING DEWATERING?

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Rêgo A.C.L., Silva T.T. & Godinho A.L. (2017) Does spillway discharge reduce the amount of fish trapped in the turbine of the Amador Aguiar II Dam during dewatering? In: R.C. Loures & A.L. Godinho (eds.) *Risk assessment of fish death at hydropower plants in southeastern Brazil.* Belo Horizonte: Companhia Energética de Minas Gerais, pp. 199-208 (Série Peixe Vivo, 6).

1 – INTRODUCTION

Tons of fish may get trapped and die in Brazilian hydropower turbines during dewatering (Andrade *et al.* 2012; Chapters 1 and 3). A specific set of procedures, called the divert fish operation, have been used to reduce the amount of fish trapped in the turbines, thus lowering the risk of fish death. This operation consists of opening the spillway gates and/or stopping the turbine(s) adjacent to the one undergoing maintenance. Increasing turbine discharge or speed no load may also be used in this operation. Anecdotal evidence suggests that spillway discharge will attract fish from the tailrace to the spillway region. Stopping the adjacent turbine(s) is to divert fish away from the turbine to be drained. Furthermore, increasing turbine discharge, as well as the speed no load, serve to expel fish from the turbine that will be dewatered. The divert fish operation may be classified, according to its purpose, as an attract fish operation when using spillway discharge and/or adjacent turbine(s) stop, and a deflect fish operation when using increased turbine discharge or speed no load.

The divert fish operation is often employed by plants of the Cemig Group. In 78 turbine dewaterings that occurred between 2009 and 2012, the divert fish operation was performed in 64.1%. Among dewaterings with the divert fish operation, 50% opened the spillway and performed adjacent turbine(s) stops, 30% only performed adjacent turbine(s) stops, and 2% only opened the spillway. Speed no load or increased turbine discharge was used in 18% of the dewaterings. Although frequent, few studies have been conducted to test the efficiency of the divert fish operation, with those at Três Marias Dam being, apparently, the only ones (Andrade *et al.* 2012).

At the Amador Aguiar II Dam (ASD), located on the Araguari River in the municipalities of Uberlândia and Araguari (Minas Gerais State), the attract fish operation usually involves opening of the spillway and stopping of the adjacent turbine(s). In turbine dewaterings at ASD, mandi (*Pimelodus maculatus*) represented 90% or more of the number of fish recovered.

In this study, we performed two experiments at ASD. In the first, we compared mandi catches in the areas of the tailrace and spillway plunge pool prior to and after spillway discharge to test whether the abundance of mandi reduces in the tailrace and increases in the spillway plunge pool with spillway discharge. In the second experiment, we evaluated whether spillway discharge reduces the amount of mandi trapped in turbine dewaterings by comparing the number of mandi trapped in dewaterings with and without spillway discharge.

2 – METHODS

2.1 Study area

The ASD is the most downstream plant of the reservoir cascade of the Araguari River. It has an installed capacity of 210 MW, maximum penstock discharge of 510 m^3/s, and maximum spillway discharge of 8,990 m^3/s (Cachapuz 2006). Its tailrace is separated from the spillway by a rocky septum (Figure 1), with a distance between them of about 220 m by river.

Downstream of the plant is a river remnant whose extent varies according to the water level of the Itumbiara reservoir on the Paranaíba River. The remnant is about 5–7 km at the highest operational level, while it is about 26 km at the lowest operational level. The mouth of the Uberabinha River, the most important tributary of the remnant, is 16 km from ASD.

2.2 Experimental design

For the first experiment, we performed fish sampling campaigns in the months of June 2011, and April, October, November, and December 2012. Using gillnets, we sampled the area adjacent to the tailrace (22K 0770350 7934770) and the spillway plunge pool area (22K 0770265 7935086; Figure 1). We designated these areas as the tailrace and spillway, respectively. We set the nets in the tailrace and spillway before and after spillway discharge. In each sampling phase (before and after spillway discharge) and at each sampling point (tailrace and spillway), we used a battery of gillnets with stretched mesh of 3, 4, 6, 7, and 8 cm, and of about 1.7 m in height and 10 m (mesh size of 3 and 4 cm) or 20 m (others) in length.

We set the nets late in the afternoon of one day and removed them the following morning.

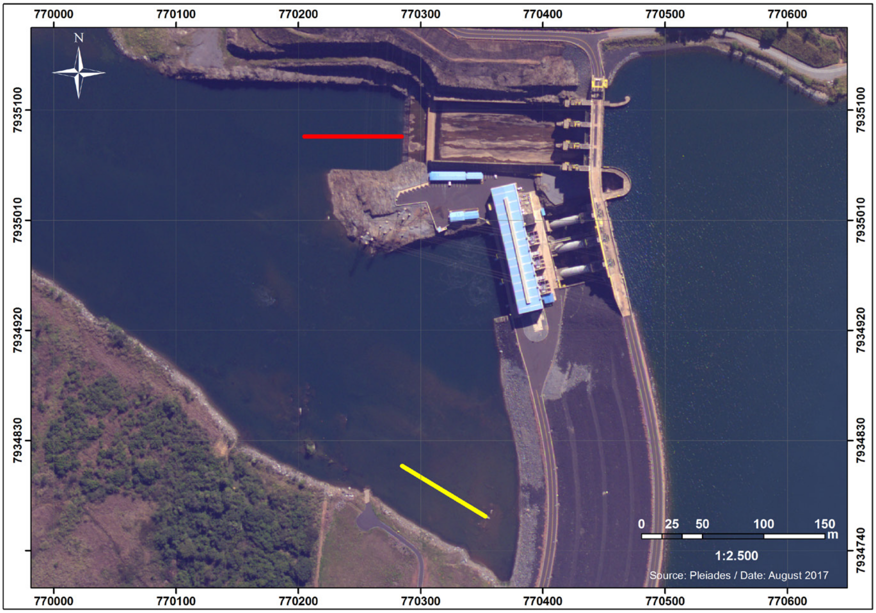

FIGURE 1 – Araguari River in the area of Amador Aguiar II Dam showing the position of gillnets in the area adjacent to the tailrace (in yellow) and in the spillway plunge pool area (in red).

On the first day of each sampling campaign, prior to the spillway discharge, we set the nets in the tailrace and spillway. The spillway was opened on the second day at 3:30 p.m. and remained open for 24 h with a spillway discharge of 100 m^3/s, which is the standard discharge for the attract fish operation at ASD. This discharge represents 28.6% of the mean long-term discharge of this plant (Cachapuz 2006). On the third day, after the end of the spillway discharge, we set the nets in the tailrace and spillway again. We identified, counted, and weighed all fish caught. We used the *t*-test for paired samples to determine differences in the number of mandi collected in the tailrace and spillway before and after spillway discharge.

In the second experiment, we determined the number of mandi trapped in the draft tube during two dewaterings (April and May 2011) using the attract fish operation with adjacent turbine stop, but without spillway discharge. During dewatering, we collected the mandi trapped in the draft tube with dip and seine nets, and put them in buckets. We counted the number of mandi in one of every three buckets of fish collected from the draft tube. To ensure the randomness of samples, we previously drew a number from 1 to 3 to determine which buckets would be counted. For example, if the number 2 was drawn, buckets of numbers 2, 5, 8, 11, 14, and so on, had individuals counted.

We compared the number of mandi collected in the draft tube with the number of trapped mandi predicted by the equation $\ln Y = 5.692 + 0.552\ln(X + 1)$ ($r^2 = 0.60$), where Y is the number of mandi trapped in the draft tube and X is the catch per unit effort (*CPUE*) of mandi in the tailrace on the eve of the turbine dewatering, as described in Chapter 3. This equation comes from dewatering with the use of the attract fish operation with spillway discharge and adjacent turbine stop.

3 – RESULTS AND DISCUSSION

With gillnets, we trapped 1,816 fish belonging to 30 species. Mandi was the most common species and accounted for 63.1% of the number and 67.7% of the biomass captured. This species is commonly recognized as one of the dominant fish affected by turbine operations at various dams in Brazil (Andrade *et al.* 2012), which may be related to its wide distribution, high abundance, and migrations.

The mean number of mandi captured in the tailrace per phase ranged from 45.6 to 54.4 (Figure 2); there was no significant difference in this number before and after the spillway discharge ($t = 0.78$; $P = 0.48$; Power = 0.15). Although the mean number of mandi caught in the spillway before discharge was half of that obtained afterwards, we did not find significant differences in the mean number of mandi caught in the spillway before and after spillway discharge ($t = -2.41$; $P = 0.07$; Power = 0.64; Figure 3).

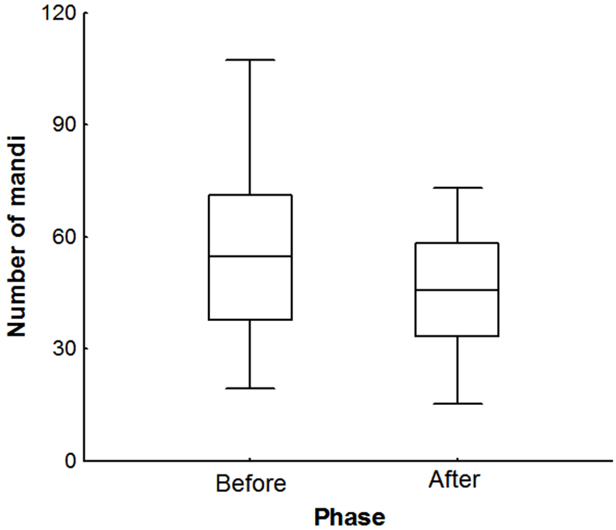

FIGURE 2 – Boxplot (mean, standard error, and amplitude) of the number of mandi (*P. maculatus*) captured in the area adjacent to the tailrace of Amador Aguiar II Dam before and after spillway discharge.

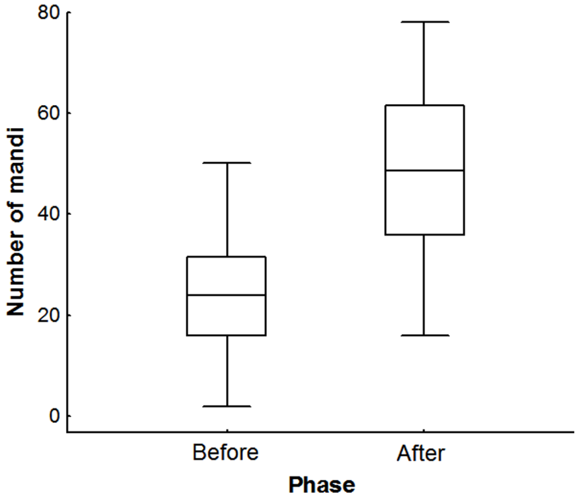

FIGURE 3 – Boxplot (mean, standard error, and amplitude) of the number of mandi (*P. maculatus*) captured in the spillway plunge pool area of Amador Aguiar II Dam before and after spillway discharge.

The estimated number of mandi recovered in the two turbine dewaterings with the attract fish operation without spillway discharge were 13,352 and 6,294. The *CPUE* of mandi in the tailrace on the eve of dewatering was 19.7 and 13.0 individuals/100m^2 of net, respectively. These *CPUEs*, applied to the prediction equation, generated a predicted number of trapped mandi of 1,578 and 1,272. Thus, the number of mandi actually trapped was, respectively, 8.5 and 4.9 times greater than the number of mandi predicted by the equation and above the upper limit of the 95% confidence interval of the regression.

The gillnet samples suggested that the spillway discharge did not significantly alter the abundance of mandi in the tailrace and spillway. In the attract fish operation, the supposed role of the spillway discharge is to attract fish from the tailrace to the region of the spillway. Thus, we expected that the number of mandi collected in the tailrace would decrease, and in the spillway increase, with spillway discharge. This prediction was not verified in our experiment suggesting the spillway discharge may not attract fish from the tailrace to the spillway region. At Três Marias Dam, spillway discharge also seemed not to attract fish from the tailrace (Andrade *et al.* 2012).

The absence of a significant difference in the number of mandi caught before and after spillway discharge may have been a consequence of the sampled site and the number of replicates. Due to the influence of the turbine discharge on gillnet efficiency, sampling could not be done in the tailrace, and the nets had to be set in a backwater adjacent to it. We did not use a cast net and/or hook-and-line because previous sampling indicated that these methods were inefficient at capturing mandi. The reduced number of replicates, in turn, may have contributed to an experiment with low power.

On the other hand, spillway discharge may reduce the number of mandi trapped in the turbine during dewatering. This number was lower for the attract fish operation with spillway discharge than for the attract fish operation without. Thus, fewer mandi entered in the draft tube during dewatering with spillway discharge than without. Although spillway discharge does not seem to alter the abundance of mandi in the tailrace, it may be able to reduce the number of fish trapped in the turbine.

In addition to spillway discharge, we suspect that adjacent turbine stop also acts to reduce the amount of fish trapped in the turbine during dewatering. Large numbers of fish were recorded in the draft tube of stopped turbines at the São Simão Dam and ASD with Didson (Giraldo, pers. com.). Thus, adjacent turbine(s) stop would allow some of the fish to enter these turbine(s) rather than the one being dewatered, thereby reducing the amount of fish that will be trapped.

In the first experiment, we used Didson to observe fish in the tailrace of ASD. We mounted the Didson on a rail attached to the powerhouse between two draft tube exits. Unlike gillnets, the Didson images were of fish in the tailrace, not in the adjacent area. Therefore, Didson should provide more precise data than gillnets, and the role of spillway discharge in attracting fish from the tailrace needs to be reevaluated based on Didson data.

Our study was not entirely conclusive as to the supposed benefit of the attract fish operation. It suggests that spillway discharge may not attract mandi from the tailrace to the region of the spillway, but may reduce the number of mandi trapped in the turbine. More sampling and the use of other methodologies, such as Didson and biotelemetry, are necessary to reduce or eliminate the uncertainties generated by a small number of replicates and limitations of the sampling method used by us.

4 – ACKNOWLEDGMENTS

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Didson. Finally, we thank the environmental analyst Ricardo José da Silva and the Superintendence of Planning and Operation of Generation and Transmission of Cemig for aid in programming and release of the tests performed.

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SÉRIE
PEIXE VIVO

FISH AND
HYDROPOWER PLANTS

CHAPTER 9

FISHES OF SÃO SIMÃO DAM TAILRACE, PARANAÍBA RIVER, BRAZIL

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Carvalho M.M., Araújo A.R. & Godinho A.L. (2017) Fishes of the São Simão Dam tailrace, Paranaíba River, Brazil. In: R.C. Loures & A.L. Godinho (eds.) *Risk assessment of fish death at hydropower plants in southeastern Brazil.* Belo Horizonte: Companhia Energética de Minas Gerais, pp. 209–230 (Série Peixe Vivo, 6).

1 – INTRODUCTION

With the growing demand for electricity in Brazil there is increased need and pressure for new hydropower plants, a sector responsible for 66% of national energy production (ANEEL 2015). Agostinho *et al.* (2007a) affirm that dam construction and reservoir formation directly affect the downstream aquatic biota due to changes in water flow and flood control, as well as blocking migratory fish routes causing the accumulation of migrating adults and dispersing young.

Operation and maintenance of hydropower plants are also likely to impact fishes present just downstream of plants. These fishes, for example, can enter the draft tube during turbine stop (Andrade *et al*. 2012). Therefore, depending on the procedures adopted by a plant, there is risk of environmental accidents of the most varied magnitude during turbine stop and startup. The results of such accidents can range from marring the reputation of the plant and the concessionaire in the eyes of the general public to the assessment of fines by public inspection agencies.

The implementation of operational procedures for fish protection at hydropower plants depends on understanding how fish distribution and abundance are affected by abiotic factors just downstream the dam. There have been only a handful of studies on this subject (*e.g.* Andrade *et al.* 2012, Loures & Pompeu 2012, 2015), which were carried out at Três Marias Dam, on São Francisco River. They recommend that operational procedures with high risk of fish death (*e.g.* turbine dewatering and startup) be performed at times when fish abundance in the tailrace is minimal, which corresponds with the dry season. This recommendation is currently followed by a larger number of Companhia Energética de Minas Gerais (Cemig, the power company of the state of Minas Gerais) plants (Chapter 2).

In this work, we sampled fishes for two consecutive years in the Paranaíba River at the São Simão Dam (SSD) to determine: (i) constancy of occurrence, richness, and dominance; (ii) temporal and spatial variation in abundance; and (iii) influence of abiotic factors on abundance. The results obtained will be helpful in the development of protective measures for fishes in SSD operation and maintenance.

Located on the lower Paranaíba River, in the municipalities of São Simão (GO) and Santa Vitória (MG), SSD (UTM 22K 0552855 7896875) was inaugurated in 1978. It is Cemig's largest hydropower plant with 1,710 MW installed capacity. Its dam holds a storage reservoir of approximately 703 km² (Cachapuz 2006).

2 – METHODS

2.1 Study area

The source of the Paranaíba River is in the state of Minas Gerais, from which it travels 1,008 km to join the Grande River, where the Paraná River is formed. With a drainage area of 222,711 km², it is the second largest watershed of the Paraná River basin, occupying 25.4% of its area. Positioned in the central region of Brazil, it occupies about 2.6% of national territory (CBH Paranaíba 2015). Currently, there are four hydropower plants on the Paranaíba River: the most upstream is Emborcação Dam, followed by Itumbiara Dam, Cachoeira Dourada Dam and, lastly, São Simão Dam. About 220 km downstream from SSD is Ilha Solteira Dam, already on the Paraná River. Among the tributaries in this stretch, we highlight Claro and Verdinho rivers, 23 and 37 km from SSD, respectively. Both of these rivers were dammed in 2009, less than 8 km from their mouths. None of the dams mentioned above has fishways (ANA 2013).

2.2 Fish sampling

We carried out 24 monthly sampling campaigns from October 2010 to September 2012 to collect fish at SSD. In each campaign, we sampled fish with a cast net for 2 to 4 days at five sampling points (P1 to P5) of about 20–30 m² each, located in the tailrace and in its vicinity (Figure 1). The sampling points were 80–380 m from the powerhouse.

We selected the location of the sampling points because the turbulent flow of the tailrace prevented random sampling points from being used. Points P2 and P3, adjacent to the flow of the turbine discharge and with higher flow velocity, were as close to the draft tube exit as possible while still being able to be sampled.

Points P1 and P4 were next to P2 and P3, respectively, but without evident flow. Point P5, in turn, was the furthest from the tailrace in a location also without apparent flow.

Fish were captured during the day by a professional fisher using a cast net, which was 2.7 m high, 17.0 m in circumference and with 5.5 cm stretched mesh. On each sampling day, we sampled all sampling points in sequence, twice in the morning and twice in the afternoon. We recorded the start time of each sampling sequence, which lasted less than 1 h. The fisher threw the cast net three consecutive times at each point for a total of 60 casts per sampling day. We identified all fish caught and released them back into the water. To estimate fish abundance, we used catch per unit effort (*CPUE)*.

FIGURE 1 – Locations of the sampling points at São Simão Dam (Photo: Cemig).

2.3 Abiotic factors

On all sampling days, we measured water transparency with a Secchi disk and water temperature and dissolved oxygen concentration (*DO*) with an YSI 550A digital oximeter. For the same days, we obtained from Cemig data on daily rainfall and on the following operational factors of SSD: incoming discharge (Q_i), turbine discharge (Q_t), spillway discharge (Q_s), and tailrace water level (WL_t). In the analyses, we used rainfall per campaign calculated by the sum of daily rainfall. For all other factors, we used the mean per campaign.

We used monthly rainfall data from 1993 to 2012, recorded at the meteorological station of the Instituto Nacional de Meteorologia (INMET, National Meteorology Institute) (INMET 2015) closest to the study area, which was located in Itumbiara (GO), to determine the rainy season (October to March, with 93% of the annual rainfall) and dry season (April to September).

2.4 Occurrence, richness and dominance

For each sampled species, we determined its constancy of occurrence (*K*) by the equation $K = n.t^{-1}.100$, where n = number of campaigns with the occurrence of the species and t = total number of campaigns (Dajoz 1983). We classified the species as occasional if $K < 25\%$, accessory $K \geq 25\%$ and $K \leq 50\%$, or constant $K > 50\%$.

We classified species as migratory or non-migratory according to Agostinho *et al.* (2003). We determined the percentage of individuals of migratory and non-migratory species per sampling point. We determined spatial variation (per sampling point) of richness (*S*) and the dominance (*D*). We calculated *D* using the equation of Kwak & Peterson (2007).

2.5 Temporal and spatial variation of *CPUE*

We calculated $CPUE_m$ for each month as the number of fish caught divided by the number of cast of the cast net. We evaluated temporal (month), spatial (sampling point), seasonal (season), and diel (period of the day) variation in $CPUE_m$.

2.6 Influence of abiotic factors on $CPUE_m$

2.6.1 Monthly scale

We determined the Spearman correlation coefficient (r_s) between $CPUE_m$ and abiotc factors, except Q_s, and tested their significance. We used r_s because of the non-normal character of the frequency distribution of most of the abiotic factors. For Q_s, we tested differences in $CPUE_m$ between campaigns with and without spillway discharge using Kruskal-Wallis test. We used a significance level of 5% for all statistical tests.

2.6.2 Hourly scale

We evaluated possible differences in the operational factors of SSD between sampling sequences with and without fish. For this, we used operational factor data per hour and paired it with the start time of each sequence. We excluded the campaigns from May to December from this analysis because the majority of sequences in those months did not capture any fish.

3 – RESULTS AND DISCUSSION

3.1 Occurrence, richness and abundance

We captured 845 individuals of 24 species, 9 families, and 3 orders. We classified 14 species as occasional, 9 as accessory, and 1 as constant (Table 1). In addition, dourado (*Salminus brasiliensis*), jaú (*Zungaro jahu*), and barbado (*Pinirampus pirinampu*) also occurred in the tailrace of SSD, but were not captured. The first two are rare, but the latter is common and is often caught by professional fishers in the region.

The most captured species were *Metynnis maculatus* and *Rhaphiodon vulpinus*, which together accounted for just under half of all fish collected. *Metynnis maculatus* is an introduced species, originating from the Paraguay River basin. It became common in reservoirs in the upper Paraná River basin after the formation of the Itaipu Reservoir, which flooded Sete Quedas Falls, a barrier that separated the upper Paraná River from the rest of the watershed (Langeani *et al.* 2005). *Rhaphiodon vulpinus* is autochthonous, carnivorous, and migratory, reaching a maximum length of 72 cm (Agostinho *et al.* 2003, Chapter 5).

The percentage of individuals of migratory and non-migratory fishes varied among the sampling points (Figure 2). The migrators were most common at P1 and P2, while scarce at the other points (< 10%). *Rhapiodon vulpinus* was the most common migratory species, accounting for 81% of all sampled migrants.

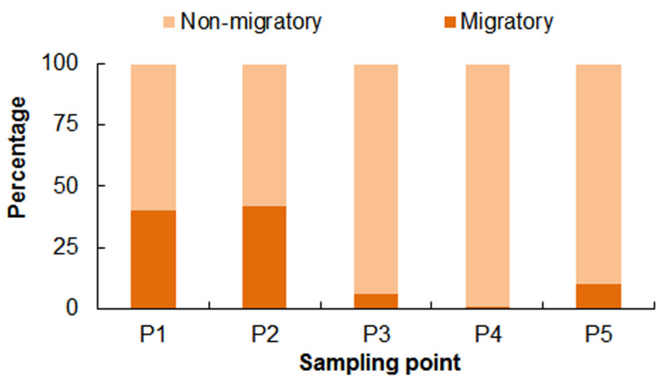

FIGURE 2 – Percentage of migratory and non-migratory fish captured per sampling point at São Simão Dam, Paranaíba River.

Richness and dominance varied among sampling points (Table 2). More fish were caught at the points closest to the turbine discharge (P2 and P3), while an intermediate quantity was captured at the points adjacent to these (P1 and P4); P5, the point furthest from SSD, had the least amount captured. Richness was higher at P1, P2, and P3 and lower at P4 and P5. These latter two points had greater dominance, with *T. nematurus* and *M. maculatus* being the most dominant species, respectively. The preference of *Rhaphiodon vulpinus* for P1 and P2, particularly the first, may be related to the availability of fish prey, one of the main items of their diet (Chapter 5). *Metynnis maculatus*, which was one of the three dominant species at all collection points, seems to be less demanding than *R. vulpinus*.

TABLE 1 – Absolute (*N*) and relative (%) abundance of individuals sampled and constancy of occurrence (*K*) by fish species at São Simão Dam, Paranaíba River. Order of taxa is according to Reis *et al.* (2003). Migratory classification of fishes is according to Agostinho *et al.* (2003) and introduced status according to Langeani *et al.* (2007). (C = constant, A= accessory, O = occasional, m = migratory, i = introduced).

TAXON	*N*	%	*K*
CHARACIFORMES			
PROCHILODONTIDAE			
Prochilodus lineatus[m]	6	0.7	O
ANOSTOMIDAE			
Leporinus amblyrhynchus	3	0.4	O
Leporinus friderici	88	10.4	C
Leporinus macrocephalus[i]	1	0.1	O
Leporinus obtusidens[m]	2	0.2	O
Leporinus piavussu[m]	7	0.8	O
Leporinus tigrinus	8	0.9	O
Schizodon intermedius	37	4.4	O
Schizodon nasutus	11	1.3	O
CHARACIDAE			
Metynnis maculatus[i]	234	27.7	A
Piaractus mesopotamicus[m]	1	0.1	O
Serrasalmus maculatus	14	1.7	A
Serrasalmus marginatus	56	6.6	A
Triportheus nematurus[i]	75	8.9	O
CYNODONTIDAE			
Rhaphiodon vulpinus[m]	158	18.8	A
ERYTHRYNIDAE			
Hoplias malabaricus	2	0.2	O
SILURIFORMES			
LORICARIIDAE			
Hypostomus sp.	1	0.1	O
Pterygoplichthys anisitsi	41	4.9	A
PIMELODIDAE			
Pimelodus maculatus[m]	27	3.2	A
Pseudoplatystoma corruscans[m]	1	0.1	O
PERCIFORMES			
SCIANIDAE			
Plagioscion squamosissimus[i]	22	2.6	A
CICHLIDAE			
Cichla piquiti[i]	27	3.2	A
Geophagus proximus[i]	22	2.6	A
Oreochromis niloticus[i]	1	0.1	O

TABLE 2 – Number of individuals sampled (*N*), richness (*S*), dominance (*D*) and dominant species by sampling point at São Simão Dam, Paranaíba River.

Point	*N*	*S*	*D*	Dominant species (percentage of *N*)
P1	102	20	0.17	*Rhaphiodon vulpinus* (30%), *Pterygoplichthys anisitsi* (24%), *Metynnis maculatus* (7%)
P2	321	15	0.20	*Rhaphiodon vulpinus* (35%), *Metynnis maculatus* (22%), *Schizodon intermedius* (9%)
P3	290	17	0.23	*Metynnis maculatus* (41%), *Leporinus friderici* (21%), *Serrasalmus marginatus* (12%)
P4	93	6	0.45	*Triportheus nematurus* (63%), *Metynnis maculatus* (20%), *Leporinus friderici* (8%)
P5	39	8	0.29	*Metynnis maculatus* (46%), *Leporinus friderici* (20%), *Geophagus proximus* (18%)

3.2 Temporal and spatial variation of *CPUE*

$CPUE_m$ exhibited distinct seasonal variation, with higher values in the months of January to April/May (the second half of the rainy season and the beginning of the dry season) and the lowest during the rest of the year (Figure 3). There was no clearly apparent explanation for the low $CPUE_m$ of February 2011.

The period of increased $CPUE_m$ was due mainly to increased catches of *R. vulpinus* (migratory) and *M. maculatus* (non-migratory). These two species represented 57% of the fish collected in 2010-2011 and 22% in 2011-2012 rainy seasons. The reproductive period of *R. vulpinus* comprises October to December (Graça *et al.*, 2007), but other studies extend this to January (Agostinho *et al.* 2003) or even April (Neuberger *et al.* 2007). It is possible that the reproductive period of *R. vulpinus* at SSD extends until March. Half of the males we sampled during March still released semen with pressure to the coelomatic cavity, while the following month no males released semen. *Metynnis maculatus* is a non-migratory species with a long reproductive period with a peak in the rainy season (Gomes *et al.* 2012).

The increased abundance of *R. vulpinus* in the rainy season can be associated with its reproductive migrations, which occur during this period. On the other hand, the increase in abundance of *M. maculatus* suggests factor(s) other than migration influenced the increase of $CPUE_m$.

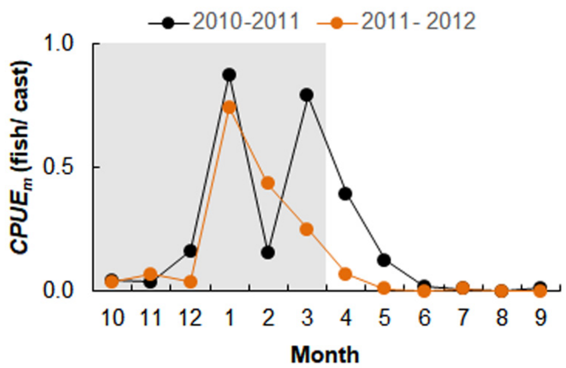

FIGURE 3 – Temporal variation in $CPUE_m$ in the Paranaíba River at the São Simão Dam. Shaded area corresponds to the rainy season.

$CPUE_m$ was higher for the sampling points adjacent to the turbine discharge and with greater flow velocity (P2 and P3) and lower in those with imperceptible flow (P1 and P4) and further from the tailrace (P5), in both the rainy and dry seasons (Figure 4). When approaching the tailrace, fish move upstream as far as velocity or turbulence allow (Larinier 2002). When they tire, they clump together in places close to slower flow to rest, which would explain the higher $CPUE_m$ of P2 and P3.

There was a minimal difference in the number of fish collected between the morning (423) and the afternoon (418) periods. Consequently, there was also a large overlap of $CPUE_m$ between these periods (Figure 5).

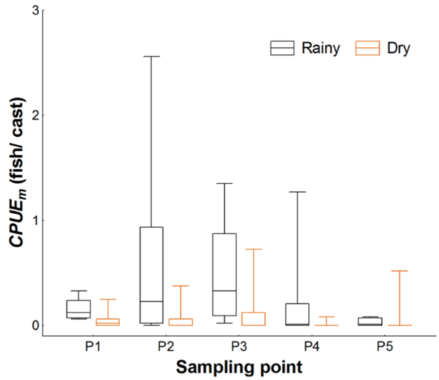

FIGURE 4 – Median, interquartile interval, and amplitude without data exclusion of $CPUE_m$ by sampling point at the São Simão Dam, Paranaíba River, in rainy and dry seasons.

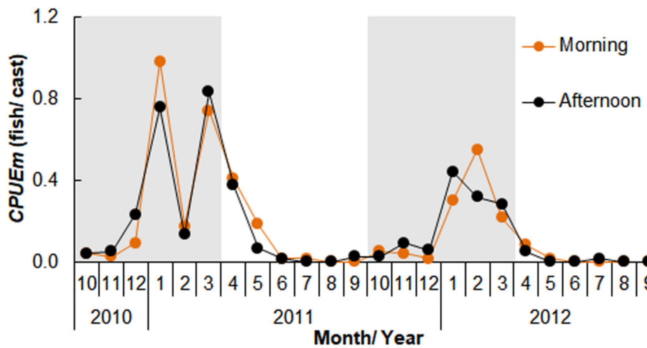

FIGURE 5 – Temporal variation in $CPUE_m$ in the morning and afternoon at São Simão Dam, Paranaíba River. Shaded area corresponds to the rainy season.

3.3 Influence of abiotic factors on *CPUE*

3.3.1 Monthly scale

There was significant correlation between $CPUE_m$ and water transparency, water temperature, *DO*, rainfall, and Q_i, but not with Q_t and WL_t (Table 3). Kruskal-Wallis test indicated that there was no significant difference ($P = 0.06$) in $CPUE_m$ among the campaigns with (N = 5) and without (N = 19) spillway discharge.

Most studies on the influence of abiotic factors on the biology of Brazilian fishes have associated them with reproductive activity, such as Basile-Martins *et al.* (1975), Barbieri *et al.* (2000), Andrade & Braga (2005), and Godinho *et al.* (2007). It has long been known that outflow discharge attracts fish to the proximity of hydropower plants (Clay 1995) and that hydrodynamic, chemical, and environmental factors can influence population dynamics (Marchetti & Moyle 2001) and, consequently, community structure (Kauffman & Pinheiro 2009). Buisson *et al.* (2007) found that water temperature is one of the determining factors in the distribution of fish species. Dei Tos *et al.* (2002) found correlation between increased water temperature and the capture of *Pimelodus maculatus.* In their research on the São Francisco River, Loures & Pompeu (2012) found that outflow discharge and precipitation explained 73% of the observed variance in the number of individuals captured at Três Marias Dam.

TABLE 3 – Spearman correlation (r_s) of $CPUE_m$ with abiotic factors. In bold, r_s with $P \leq 0.05$. N = 24 for all of the correlations.

ABIOTIC FACTOR	r_s
Water transparency	**-0.82**
Water temperature	**0.81**
Dissolved oxygen (*DO*)	**-0.68**
Rainfall	**0.48**
Incoming discharge (Q_i)	**0.63**
Turbine discharge (Q_t)	0.12
Tailrace water level (WL_t)	0.36

Water transparency and temperature were the factors with the highest r_s values (Table 3). Water transparency at SSD varied from 78 to 566 cm, with the highest values (> 300 cm) in the beginning/first half of the dry season until the middle of the next rainy season (Figure 6A). This was also the period of the lowest $CPUE_m$ (Figure 3). Two possible mechanisms can explain this influence of transparency on $CPUE_m$. First, in more transparent waters, fish may be in sheltered locations, out of reach of the cast net. Visually oriented piscivorous fish predominate in more transparent waters (Petry 2013), where they can detect prey at greater distances, which are forced to seek shelter (Gregory & Levings 1998). Second, in more transparent water there is a greater chance the cast net will be seen by fish, increasing their likelihood of escape. Determining the contribution of each of these two mechanisms in determining $CPUE_m$ is important for understanding the limitations of the cast net as a sampling technique.

The increase in $CPUE_m$ at SSD with the elevation of water temperature must be related to the increase in fish activity. The highest $CPUE_m$ values, which occurred from January to April/May, occurred in the months of the highest water temperature (Figure 6B). The increase in water temperature increases fish metabolism (Garcia *et al.* 2008) and, consequently, their activity.

The distinct ways in which water temperature and transparency influences $CPUE_m$ need to be considered when sampling fish for risk assessment of fish death. The abundance of fish at SSD is likely determined by water temperature, but the amount of fish collected in the cast net seems to be influenced by water transparency. Thus, if two samplings were made at different times, but with the same abundance of fish, the one made in less transparent water will result in higher *CPUE*. Indeed, this may have happened on two occasions (December 2011 and March 2012) when the water temperature was higher, but $CPUE_m$ was lower, presumably due to the high water transparency at these times. Consequently, risk assessment of fish death made with data generated with only the cast net may not be adequate, given the transparency-dependent nature of the catchability of the fish.

Dissolved oxygen concentration was negatively correlated with $CPUE_m$, indicating that more fish are caught when *DO* levels are lower. This contradicts the work of Kramer (1987), who described the trend of horizontal and vertical shifts of fish in search of areas with higher *DO*. The correlation between *DO* and

$CPUE_m$ at SSD may not represent a cause and effect relationship because the negative value of r_s was caused mainly by the many zero or near zero values for *$CPUE_m$* in the dry season, the period of the hydrological year when *DO* is the highest (Figure 6C).

Rainfall exhibited evident seasonality during the fish sampling campaigns (Figure 6D) and correlated with *$CPUE_m$*. Rainfall is an important abiotic factor in the regulation of the biological cycle of fishes. Several studies have reported the importance of rainfall to the reproduction of fishes in Brazil (*e.g.* Braga 1990, Lowe-McConnell 1999, Andrade 2005, Agostinho *et al.* 2007a,b, Godinho *et al.* 2010) and other tropical regions (Baran 2006). However, the correlation between *$CPUE_m$* and rainfall may have been caused by the influence of the rainy season on water transparency.

The significant correlation of *$CPUE_m$* with Q_i may also have been a consequence of the change Q_i causes to water transparency. Higher Q_i, which occurs at the end of the rainy season (Figure 6E), decreased water transparency in the tailrace due to the transport of sediment to the São Simão Reservoir. Despite most suspended material being retained in the reservoirs (Petry 2013), some is still carried downstream.

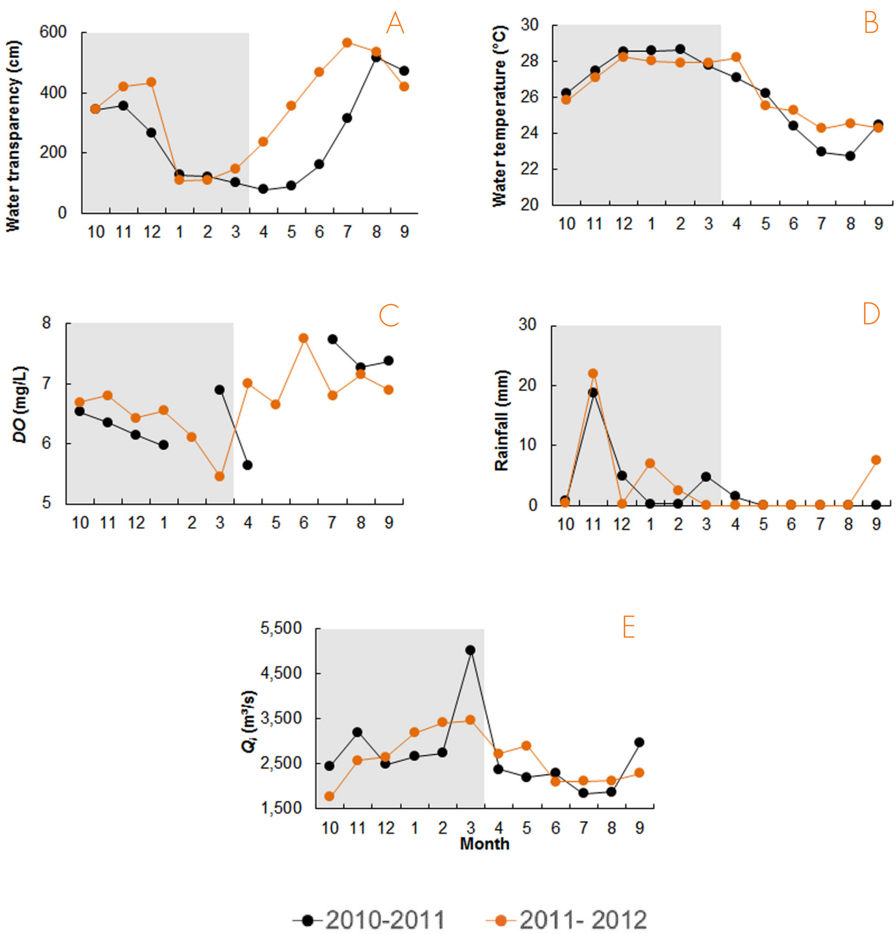

FIGURE 6 – Temporal variation in (A) water transparency, (B) water temperature, (C) dissolved oxygen (*DO*), (D) rainfall, (E) incoming discharge (Q_i), and (F) spillway discharge (Q_s) during sampling campaigns at São Simão Dam, Paranaíba River. Shaded area corresponds to the rainy season.

3.3.2 Hourly scale

Marked differences in operational factors did not occur between sampling sequences with and without fish, except for Q_s (Figure 7). Higher values of Q_s were more frequent for sampling sequences with fish.

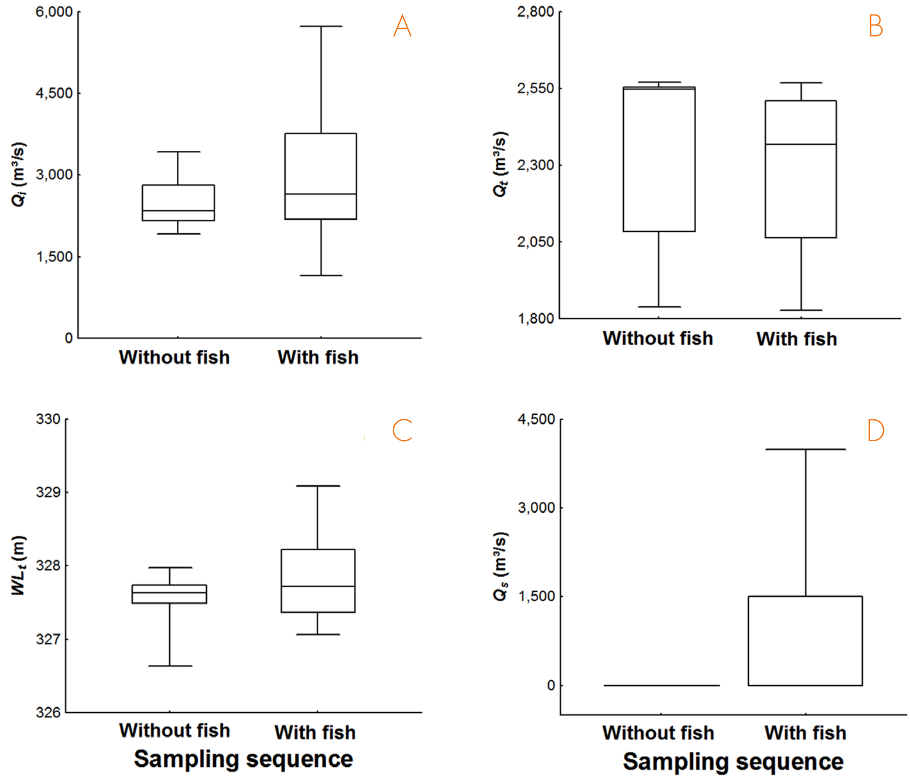

FIGURE 7 – Median, interquartile interval, and amplitude without data exclusion of (A) incoming discharge (Q_i), (B) turbine discharge (Q_t), (C) tailrace water level ($WL_{t)}$, and (D) spillway discharge (Q_s) in the samplings sequences with and without fish at São Simão Dam, Paranaíba River.

4 – FINAL CONSIDERATIONS

The highest $CPUE_m$ at SSD on the Paranaíba River occurs in the second half of the rainy season and early in the dry season. Fish abundance is highest at the sampling points closer to the flow of turbine discharge. Water temperature and transparency are the abiotic factors that most influence $CPUE_m$. However, in months of high water temperature, such as in December, the $CPUE_m$ is only higher when the water transparency is lower, presumably due to the greater efficiency of the cast net in water of lower transparency.

A good understanding of the spatial distribution and habitat use of fishes can be obtained with the use of active catching methods (Hayes *et al.* 2013), such as the cast net. Its efficacy, however, is heavily dependent on the fisher's skill, sampling site depth, flow velocity, and, as shown in this work, by water transparency. The depth and velocity of the turbine discharge at SSD, particularly in the tailrace, limits the locations where the cast net can be properly thrown. These conditions, coupled with the high water transparency over an extended period of the year, indicate that the cast net has limited use in sampling at SSD. These restrictions notwithstanding, sampling with a cast net for determining $CPUE_m$ can be done in a single period of the day (morning or afternoon) and at one or more fish sampling points with highest $CPUE_m$ (*i.e.*, P1, P2, and P3).

The divert fish operation, which involves opening the spillway prior to turbine dewatering in order to attract the fish out of the tailrace (Chapter 8), may not have the desired effect at SSD. The data presented here suggest that samples with fish are more common when there is spillway discharge, but this discharge may not influence the abundance of fish in the tailrace. Studies specifically designed to evaluate the efficacy of the divert fish operation need to be developed at SSD.

5 – ACKNOWLEDGMENTS

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SÉRIE PEIXE VIVO

FISH AND HYDROPOWER PLANTS

CHAPTER 10

INFLUENCE OF ABIOTIC FACTORS ON THE CAPTURE AND CONDITION OF FISH IMMEDIATELY DOWNSTREAM OF THE TRÊS MARIAS DAM, SÃO FRANCISCO RIVER, BRAZIL

IVO GAVIÃO PRADO, FRANCISCO DE ANDRADE, ÂNGELO BARBOSA MONTEIRO, RAFAEL COUTO ROSA SOUZA & ALEXANDRE LIMA GODINHO

Prado I.G., Andrade F., Monteiro A.B., Souza R.C.R. & Godinho A.L. (2017) Influence of abiotic factors on the capture and condition of fish immediately downstream of the Três Marias Dam, São Francisco River, Brazil. In: R.C. Loures & A.L. Godinho (eds.) *Risk assessment of fish death at hydropower plants in southeastern Brazil.* Belo Horizonte: Companhia Energética de Minas Gerais, pp. 231-246 (Série Peixe Vivo, 6).

1 – INTRODUCTION

The growing demand for electricity has increased the need and pressure for new hydropower plants in Brazil since most (74%) of the country's energy is hydropower and only about 30% of the Brazilian hydropower potential is being used (ANEEL 2008). Construction of dams and the formation of reservoirs directly affect the entire aquatic biota. The main impact upstream from dams is the transformation of a lotic environment into a lentic one, which triggers a series of physical, chemical, and ecological changes in the region. Downstream of dams, changes occur in the river discharge due to the control of the flood regime and the blockage of migratory fish routes (Agostinho *et al.* 2007). Moreover, the operation and maintenance of hydropower plants pose major risks to the fish immediately downstream of dams (Andrade *et al.* 2012).

The physical barrier created by dams hampers or impedes the free transit of fish, which can result in the accumulation of significant quantities of fish immediately downstream (Agostinho *et al.* 2007) in the spawning season and during the dispersion of juveniles (Chapter 12). Fish in the first kilometer downstream of the Três Marias Dam (TMD) tend to be resident or in the process of dispersion, since most riverine migratory species do not spawn near the dam (Sato *et al.* 2005, Godinho & Kynard 2006, Godinho *et al.* 2007, Nunes *et al.* 2015). The accumulation of large amounts of fish downstream of dams represents a huge risk for their operation, since more fish may enter the draft tube during operations involving turbine stop than during periods when the fish are not accumulated (Andrade *et al.* 2012).

Hydrological conditions of rivers downstream of dams can act as a source of attraction for fish (Agostinho *et al.* 2007). Hydrodynamic, chemical and environmental factors may influence community structure, species diversity, and the dynamics of aquatic populations (Marchetti & Moyle 2001, Kaufman & Pinheiro 2009). Temperature seems to be one of the abiotic factors that determine fish distribution (Buisson *et al.* 2007). Dei Tos *et al.* (2002) found a correlation between increased water temperature and the capture of mandi (*Pimelodus maculatus*).

Knowing the abiotic factors that influence the abundance of fish immediately downstream of dams is crucial for proposing and implementing measures to reduce fish kills during the operation and maintenance of hydropower plants. Therefore, in this chapter, we present the main results of an investigation into the influence of limnology, precipitation, and the operation of TMD on the abundance of fish immediately downstream. We attempted to define time periods of lower fish abundance and, consequently, lower risk of fish kills with data obtained from samples from 2007 to 2012. In addition, we evaluated the influence of season on the condition factor of the fish downstream of the dam.

2 – METHODS

2.1 Fish sampling

We sampled fish from the tailrace (TR) and spillway plunge pool area (SW) of TMD from November 2007 to September 2012. We sampled fish for 1 to 13 days per month (median = 3) in all months of the sampling period. The fish were collected with cast nets of 5.5 cm (stretched mesh) mesh by professional fishers who made 30 to 50 casts per day at each sampling site. We identified and measured body weight (B*W*, g) and standard length (*SL*, mm) of all the fish captured in each cast of the net before returning them alive to the river.

We determined catch per unit effort (*CPUE*) as the number of fish caught divided by the number of casts per sampled day. We calculated the *CPUE* by site (TR and SW), independently of species. We also calculated the *CPUE* for mandi (*Pimelodus maculatus*), curimba (*Prochilodus argenteus*), pioa (*Prochilodus costatus*) and dourado (*Salminus franciscanus*), independently of sampling site. Mandi is the dominant species in environmental occurrences at TMD (Andrade *et al.* 2012), while the other species are important to commercial, sport, and subsistence fishing downstream of TMD (Godinho & Godinho 2003).

2.2 Collection of abiotic factors data

During each fish sampling, we measured dissolved oxygen concentration

(DO) with an oxygen meter, temperature with a digital thermometer and water transparency with a Secchi disk. We obtained daily data on rainfall, turbine discharge, and spillway discharge from Cemig, the TMD concessionaire. We calculated the rainfall accumulated since the 2nd, 3rd and, 5th day before the fish sampling. We obtained limnological data from 2009 and the other data for the entire study period.

2.3 Influence of abiotic factors on *CPUE*

We divided the year into dry (April to September) and rainy (October to March) seasons. We used quartiles and median to classify values of DO, water temperature, water transparency, and turbine discharge as Class 1 (< 1st quartile), Class 2 (≥ 1st quartile and < median), Class 3 (≥ median and < 3rd quartile) or Class 4 (≥ 3rd quartile). We classified precipitation (including accumulated) and spillway discharge into two classes (present and absent) because the medians of these variables were zero.

We determined the influence of all abiotic factors on *CPUE* of TR, SW, mandi, curimba, pioa and dourado using effect size (ES) for repeated measures. We calculated ES by the generalized eta squared (Olejnik & Algina 2003; Bakeman 2005), because successive samples at one location, as was the case in our study, are correlated and if treated as replicates would lead to pseudoreplicaiton (Hurlbert 1984) and greater chances of committing a Type I error (*i.e.*, finding differences when they do not exist). The use of generalized eta squared neutralizes the correlation between samples (Olejnik & Algina 2003), nullifying the increased chances of such an error. For the abiotic factors with the largest ES, we made Boxplot graphs with the exclusion of outliers and extremes as defined by Statistica 7. For the statistical analyses we used Statistica 7 and SAS.

2.4 Condition factor

For mandi, curimba, pioa and dourado, we calculated the Fulton condition factor (K) by the formula $K = BW.SL^{-3}.10^5$. We used Kruskal-Wallis to test for differences in K between the dry and rainy seasons.

3 – RESULTS AND DISCUSSION

In the 198 days of sampling, we captured 21,248 fish from 3 orders, 10 families and, at least, 39 species. Mandi was the species most captured (35.4%, mean *CPUE* = 0.93 fish/cast), followed by dourado (20.1%, 0.55 fish/cast), pioa (16.5%, 0.40 fish/cast) and curimba (15.3%, 0.55 fish/cast; Figure 1). The highest *CPUEs* were 32.3 fish/cast in TR and 21.3 fish/cast in SW. Among the species, the highest *CPUEs* were for dourado (9.96 fish/cast) and mandi (9.13 fish/cast). The lowest *CPUEs* were always equal to zero. Water temperature ranged from 20.1 to 31.4 °C, *DO* from 1.6 to 9.1 mg/L, and water transparency 0.2 to 4.5 m. The lowest turbine and spillway discharges were 266 and 0 m^3/s, while the greatest were 1,081 and 2,604 m^3/s, respectively. Rainfall ranged from 0 to 75 mm.

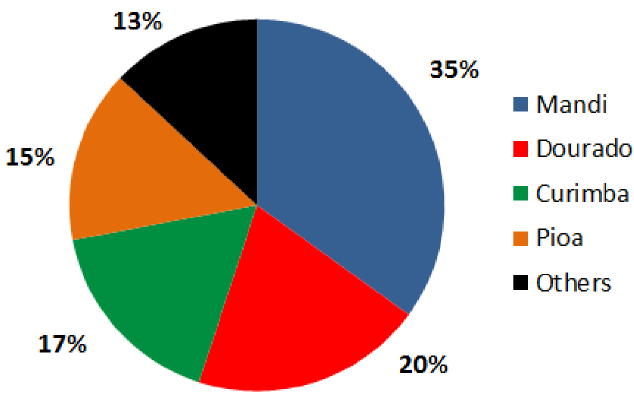

FIGURE 1 – Percentage of the number of individuals captured per species in the São Francisco River immediately downstream of the Três Marias Dam from 2007 to 2012.

3.1 Influence of abiotic factors on *CPUE*

All ESs were less than 0.10 (Table 1). Since ES determined by the generalized eta squared ranges from 0 to 1 (Olejnik & Algina 2003, Bakeman 2005), the ESs obtained in the present study were low. Thus, abiotic factors had little influence on *CPUE*. The highest ES (= 0.09) in the *CPUE* of mandi was for seasons of the year. Water transparency and *DO* were the abiotic factors with the highest ESs (≥ 0.05) for the largest number of response variables. Season of the year, *OD*, and water transparency had the highest ESs because higher values of *CPUE* occurred in certain classes of the abiotic factors. Thus, higher *CPUE*s for mandi happened in the rainy season (Figure 2), higher *CPUE*s for TR, SW, curimba, and pioa appeared in the lower *DO* classes (Figure 3), and the higher *CPUE*s of TR, pioa, and dourado occurred in the classes of lower water transparency (Figure 4). Rainfall on the day of sampling, accumulated rainfall, and turbine and spillage discharges influenced *CPUE*s even less (ES ≤ 0.04).

TABLE 1 – Size effect of abiotic factors on *CPUE* in the tailrace (TR), spillway (SW), for mandi, curimba, pioa, and dourado. Size effect ≥ 0.05 is in highlighted. Rainfall (at the fish sampling day), Rainfall 2 (accumulated since the 2nd day before the fish sampling), Rainfall 3 (accumulated since the 3rd day before the fish sampling) e Rainfall 5 (accumulated since the 5th day before the fish sampling).

Abiotic factors	TR	SW	Mandi	Curimba	Pioa	Dourado
Season	0.01	0.02	0.09	0.00	0.00	0.03
Rainfall	0.02	0.02	0.01	0.01	0.02	0.03
Rainfall 2	0.02	0.02	0.01	0.00	0.01	0.04
Rainfall 3	0.02	0.01	0.03	0.00	0.01	0.03
Rainfall 5	0.02	0.02	0.02	0.00	0.01	0.03
Dissolved oxygen	0.06	0.06	0.01	0.06	0.07	0.04
Temperature	0.04	0.04	0.03	0.02	0.02	0.06
Transparency	0.07	0.04	0.02	0.03	0.05	0.05
Turbine discharge	0.00	0.01	0.02	0.00	0.00	0.01
Spillway discharge	0.01	0.01	0.02	0.00	0.01	0.04

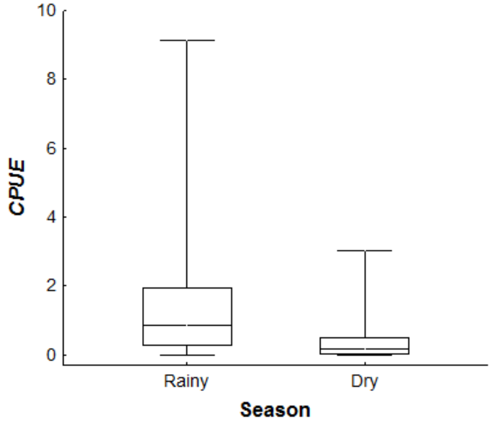

FIGURE 2 – Boxplot of *CPUE* of mandi in the rainy and dry seasons immediately downstream of the Três Marias Dam.

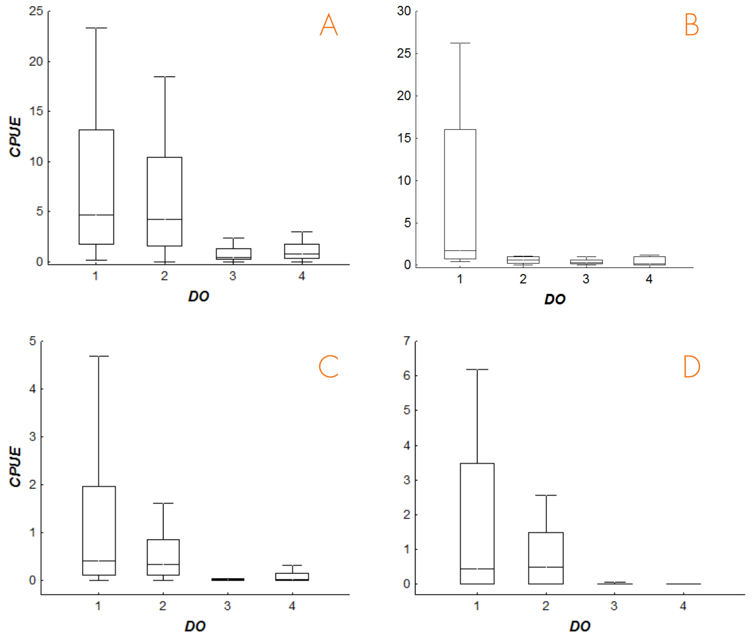

FIGURE 3 – Boxplot of *CPUE* in the tailrace (A), in the spillway (B), for curimba (C), and pioa (D) by class of dissolve oxygen (*DO*) immediately downstream of the Três Marias Dam.

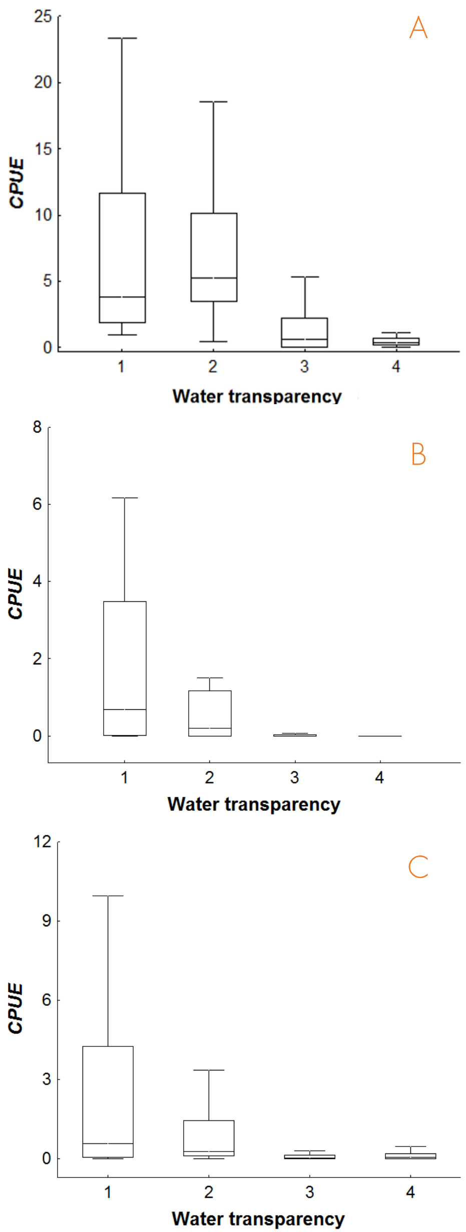

FIGURE 4 – Boxplot of *CPUE* in the tailrace (A), for pioa (B), and dourado (C) by class of water transparency immediately downstream of the Três Marias Dam.

The occurrence of higher *CPUE*s for TR, SW, curimba, and pioa associated with lower *DO* is not related to TMD tailrace limnology, but with the *arribação*, the dispersion migration of juvenile migratory fish of the São Francisco River (Chapter 12). The reservoir of TMD is thermally stratified during most of the year with low *DO* values in the hypolimnion (Esteves *et al.* 1985), where turbine water intakes are located. Thermal destratification occurs only in the winter. Consequently, much lower *DO* values in the TMD tailrace occur in the first half of the year, prior to reservoir destratification, and the highest values in the second half of the year following destratification (Figure 5). Peak in abundance of curimba and pioa at TMD occurred in the first half of 2012, during *arribação* (Chapter 12), when the *DO* in the TR was low.

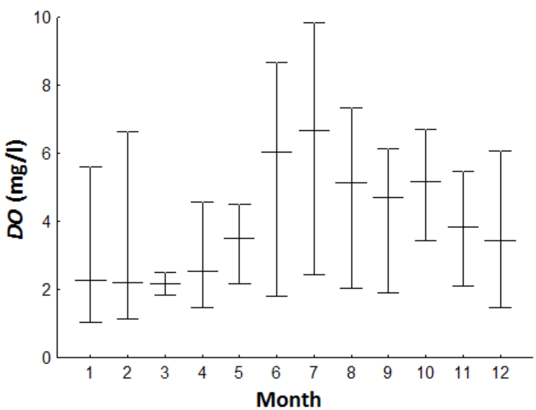

FIGURE 5 – Monthly mean and amplitude of dissolved oxygen (*DO*) concentration in the tailrace of the Três Marias Dam between 2009 and 2012.

Higher *CPUE*s of TR for pioa and dourado occurred in periods of lower water transparency. The water transparency of the TMD tailrace decreased beginning in November, with the onset of the rainy season, and the lowest values occurred in the first five months of the year (Figure 6). As with *DO*, the relationship of *CPUE* with water transparency is explained by the agglomeration of pioa and dourado from the *arribação* at the TMD tailrace in the first semester of 2012, when water transparency was lower.

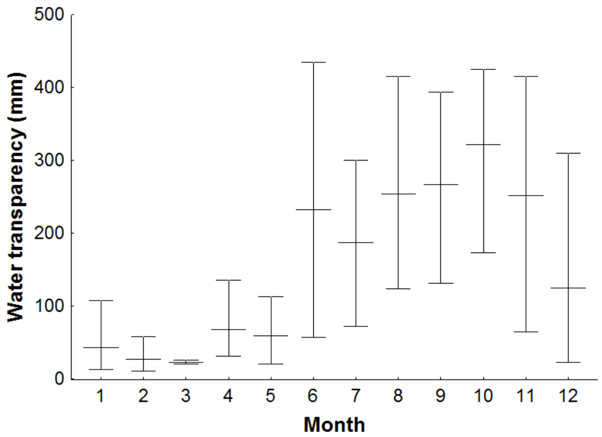

FIGURE 6 – Monthly mean and amplitude of water transparency in the tailrace of the Três Marias Dam between 2009 and 2012.

The highest *CPUEs* for mandi occurred in the rainy season (Figure 2). Peaks in mandi capture occurred predominantly in the rainy season (Chapter 12). We recommend, therefore, that operations that may kill fish (*e.g.*, turbine dewatering) should be performed in the dry season, when mandi, the fish most affected by these operations (Chapter 3), is less abundant at the TR. From 2007 to 2012, we sampled about 80 operations at TMD with high risk of fish kill, most (65%) of which occurred in the rainy season.

Continued sampling of *CPUE* and abiotic factors immediately downstream of TMD is critical for monitoring and evaluation of long term, cyclical, and occasional phenomena. The knowledge generated will provide safety and reliability to the operation and maintenance of TMD, including compliance with the term of conduct adjustment of the Public Prosecution Service of the State of Minas Gerais regarding fish kill risk at TMD.

3.2 Condition factor

The *K* of pioa, dourado, and mandi, but not curimba, were significantly different between the seasons of the year (Figure 7), with them being slightly lower in the rainy season than in the dry season. For individuals of the same size, those with greater weight will have a larger *K*. The value of *K* may reflect nutritional status, amount of fat or gonadal maturation (Lima-Junior & Goitein 2006). Temporal variation in *K* may be related to feeding and reproduction (Lima-Junior *et al.* 2002). Long migrations can reduce the energy reserves of fish (Lucas & Baras 2001) and, consequently, reduce *K*. Seasonal differences in *K* for pioa and dourado from immediately downstream of TMD may be related to migration and feeding. The higher values of *K* in the dry season suggests recovery of condition by feeding.

The higher value of *K* for mandi in the dry season may reflect the accumulation of energy to be used in the rainy season. Most mandi close to TMD are adult (Chapter 12). Their spawning, which happens in the rainy season, may occur some tens of kilometers downstream from TMD where the São Francisco River has suitable conditions for mandi spawning (Oliveira Junior 2002). Mandi likely accumulate energy in the dry season to spend on displacement and spawning.

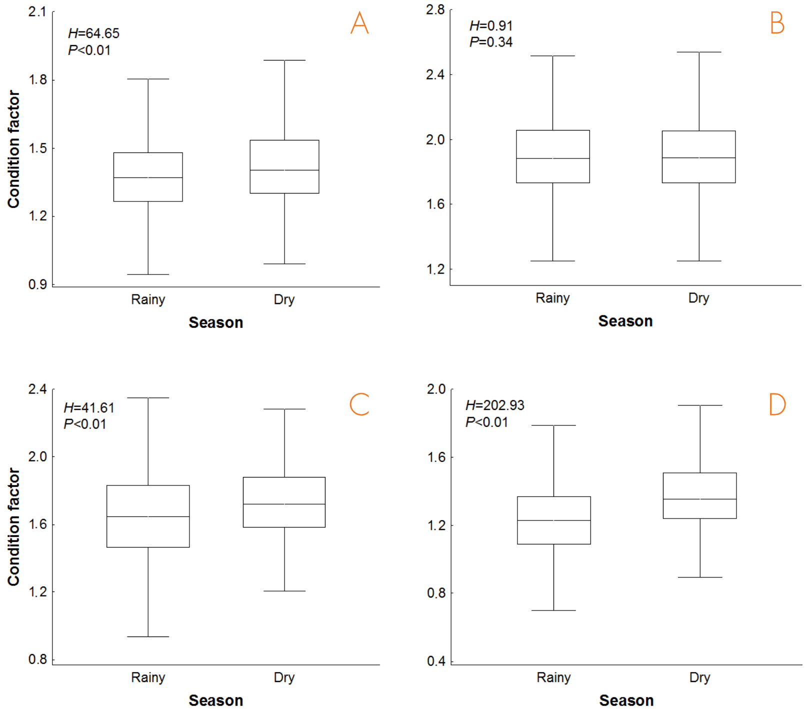

FIGURE 7 – Boxplot of the Fulton condition factor (*K*) for mandi (A), curimba (B), pioa (C), and dourado (D) in the rainy and dry seasons. (*H* = Kruskal-Wallis statistic; *P* = P-value))

4 – CONCLUSIONS

Different species of fish respond to abiotic stimuli in diverse ways. Temperature, *DO*, and water transparency can act individually or together on fish to influence their migration and even their interaction with the environment. In environments that are directly influenced by hydropower plants, such as the one studied by us, knowing how fish interact with local conditions is the first step towards enabling actions and operational procedures for the operation and maintenance of hydropower plants that have the least impact on fish. Reducing the risk for fish death downstream from hydropower plants is a challenge for all energy companies. Data, such as those presented in this work, usually give more direct answers and are better interpreted within the context of hydropower plants.

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SÉRIE
PEIXE VIVO

FISH AND
HYDROPOWER PLANTS

CHAPTER 11

INFLUENCE OF DISCHARGE OF TRÊS MARIAS DAM OVER DIFFERENT TEMPORAL SCALES ON THE CAPTURE OF MANDI IN THE TAILRACE

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Andrade F., Prado I.G., Rodrigues R.R., Godinho A.L. (2017). Influence of discharge of Três Marias Dam over different temporal scales on the capture of mandi in the tailrace. In: R.C. Loures & A.L. Godinho (eds.) *Risk assessment of fish death at hydropower plants in southeastern Brazil.* Belo Horizonte: Companhia Energética de Minas Gerais, pp. 247–258 (Série Peixe Vivo, 6).

1 – INTRODUCTION

Fish deaths caused by the operation and maintenance of hydropower plants have been occurring in Brazil for decades, but only recently have the processes involved in these deaths been studied with the aim of avoiding them. Studies for environmental licensing of small hydropower plants in Minas Gerais report the occurrence of fish deaths in turbines, but mitigation measures for this type of impact have never been proposed (Silve & Pompeu 2008).

Less than a decade ago, knowledge related to fish deaths at Brazilian hydroelectric plants was incipient (Agostinho *et al.* 2007). One of the first studies was published a few years later. It related the biomass of recovered fish at turbine dewatering with the capture of fish in the tailrace and the turbine discharge prior to dewatering (Andrade *et al.* 2012). This same study also evaluated some measures used by hydropower plants for protecting fish before turbine stop, startup, or dewatering.

In studies of this nature, catch per unit effort (*CPUE*) of fish in the tailrace of hydropower plants has been used and interpreted in the context of the accomplishment of the operational procedure. By using *CPUE*, it is possible to evaluate if fish abundance is high at the moment of an operational procedure and, consequently, estimate the fish death risk. Time series of *CPUE* allows the evaluation of how abundance varies among different environmental and operative conditions in order to search for patterns that indicate when there will be greater or lesser fish present.

In this study, we identified the relationships between *CPUE* of mandi (*Pimelodus maculatus*) in the tailrace of Três Marias Dam (TMD) and turbine, spillway, and outflow discharges over three temporal scales (daily, monthly, and semiannually). We chose to study discharge because it plays an important role in fish orientation and migration (Northcote 1984), is easily obtained, and to some extent can be controlled by the hydropower plant. We studied mandi because it is an abundant species downstream of hydropower plants and so is commonly involved in cases of fish death related to the operation and maintenance of hydropower plants (Andrade *et al.* 2012).

2 – METHODS

2.1 Study area

The TMD is located on the upper São Francisco River in the municipality of Três Marias, Minas Gerais (S18°12'47.67" and W45°15'44.94"). It was constructed from 1957 to 1960 and began operation in 1962, with the objectives of regulating river flow for navigation, flood control, irrigation, and hydropower generation. The dam is 2.7 km long and has a maximum height of 75 m. At its maximum level, the reservoir floods an area of 1,050 km^2 and has a volume of 21 x 10^9 m^3 (Sampaio & López 2003). The reservoir is classified as warm monomictic (Esteves *et al.* 1985). The installed capacity is 396 MW, with six Kaplan turbines with maximum turbine discharge of 900 m^3/s and maximum spillway discharge of 8,700 m^3/s (Capachuz 2006). From 2005 to 2014, the months of highest average spillway discharge were December, January, and February, with values between 179 and 527 m^3/s.

There are two well-defined seasons in the region of TMD (Sampaio & López 2003): rainy (October to March) and dry (April to September). The mean annual rainfall is from 1,200 to 1,300 mm and the mean annual temperature is 21.9 °C (Esteves *et al.* 1985). The rainiest quarter (November, December, and January) contributes 55 to 60% of the total annual rainfall, while the driest quarter (June, July, and August) contributes less than 5% (ANA 2009).

2.2 Obtaining and analyzing data

Our sampling followed the methodology of Andrade *et al.* (2012). Thus, we collected mandi from the TMD tailrace with cast nets between May 2007 and September 2014, except for October 2007. We calculated catch per unit effort per day of sampling ($CPUE_d$). We then determined the monthly ($CPUE_m$) and semiannual ($CPUE_s$) medians of $CPUE_d$. We considered the semiannual periods to be from October to March and from April to September of each hydrological year.

Cemig provided us with data on the daily average of turbine discharge (Q_t), spillway discharge (Q_s), and outflow discharge (Q_o), from which we also obtained the monthly and semiannual medians. We used medians as measures of central tendency of these variables because they do not have normal distributions.

The universe of analyzed discharges encompassed the 2,923 days from 1 October 2006 to 30 September 2014 (Figure 1). During this period, there were 285 sampling days in 88 months and 15 semiannual periods. The number of sampling days per month ranged from 1 to 13 (mean = 3.3).

To determine if the discharges of the sampled days compose a representative sample of the discharges of the entire period, we tested the distribution of discharge of the sample with the sample universe by the Kolmogorov-Smirnov test for goodness of fit.

We used Spearman's correlation coefficient (r_s) to test, at the 5% level, for correlations among Q_t, Q_s, and Q_o for each time scale (*i.e.*, day, month, and semester). We also tested the significance of r_s of $CPUE_d$, $CPUE_m$, and $CPUE_s$ with each of the discharges for the three time scales. We performed this test in prior time (cross-correlation with delay of one unit of time) and in present time (without delay). We used cross-correlation because changes in the composition of fish assemblages resulting from variation in discharge may occur later (Lamouroux *et al.* 2006). The analyses were performed using the programs Statistica 7.0 and Past 3.0.

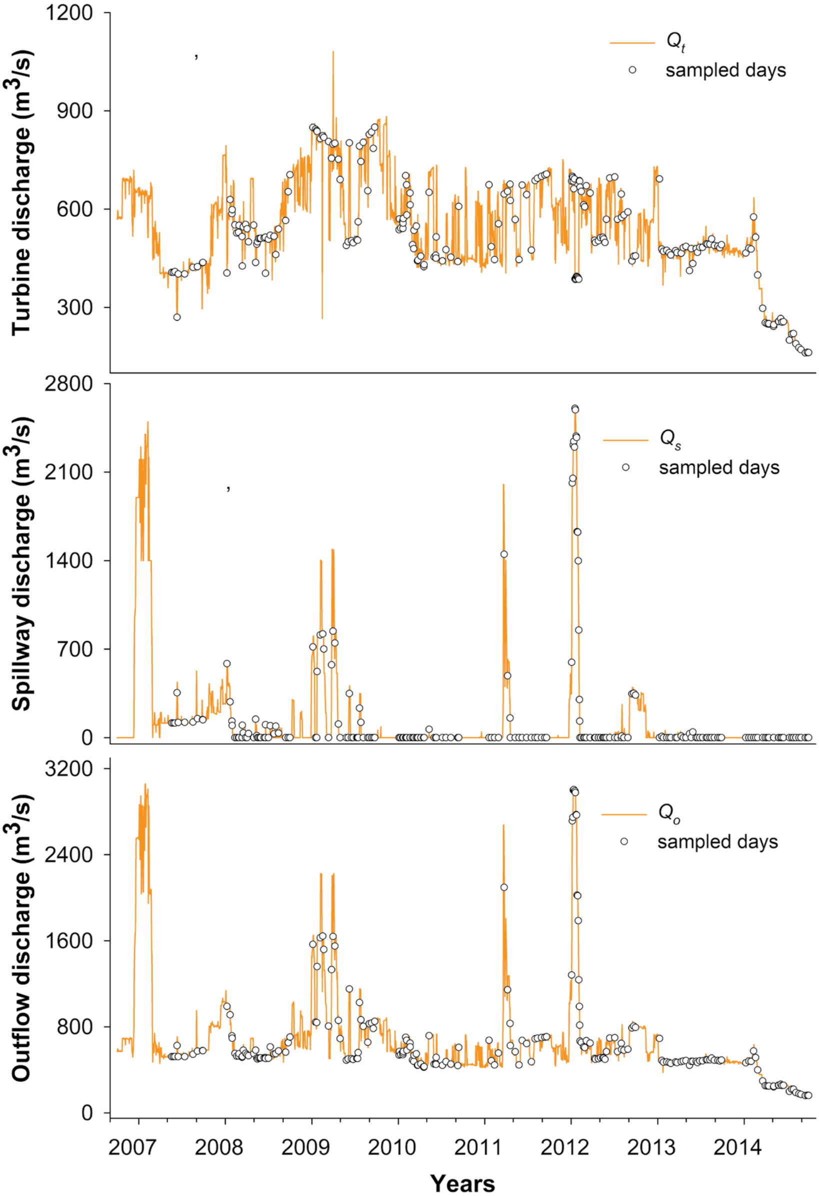

FIGURE 1 – Turbine (Q_t), spillway (Q_s) and outflow (Q_o) discharges during the study period. Sampling days are indicated by ○.

3 – RESULTS AND DISCUSSION

During the entire analyzed period, Q_t varied from 152 to 1,081 m^3/s (median = 512.5 m^3/s), while Q_o varied from 152 to 3,058 m^3/s (median = 550.0 m^3/s). On 26.9% of the days, there was spillway discharge and Q_s ranged from 0 to 2,604 m^3/s (median = 0.0 m^3/s). On the sampled days, Q_t ranged from 161 to 882 m^3/s (median = 514.0 m^3/s) and Q_o ranged from 161 to 3,005 m^3/s (median = 564.0 m^3/s). There was spillway discharge on 25.3% of the sampling days and Q_s varied from 0 to 2,604 m^3/s (median = 0.0 m^3/s). The $CPUE_d$ varied from 0.0 to 9.1 fish/cast (median = 0.17 fish/cast).

Discharges on the sampling days comprised a representative sample of discharges for the entire analyzed period. The frequency distributions of the sample discharges were similar to those of the sample universe (Figure 2) and, therefore, there was no significant difference between them (Kolmogorov-Smirnov test; $P > 0.09$ for the three discharges). It was important that there were no differences between the representative sample and the sample universe so that *CPUE* samples were not biased in relation to the discharges.

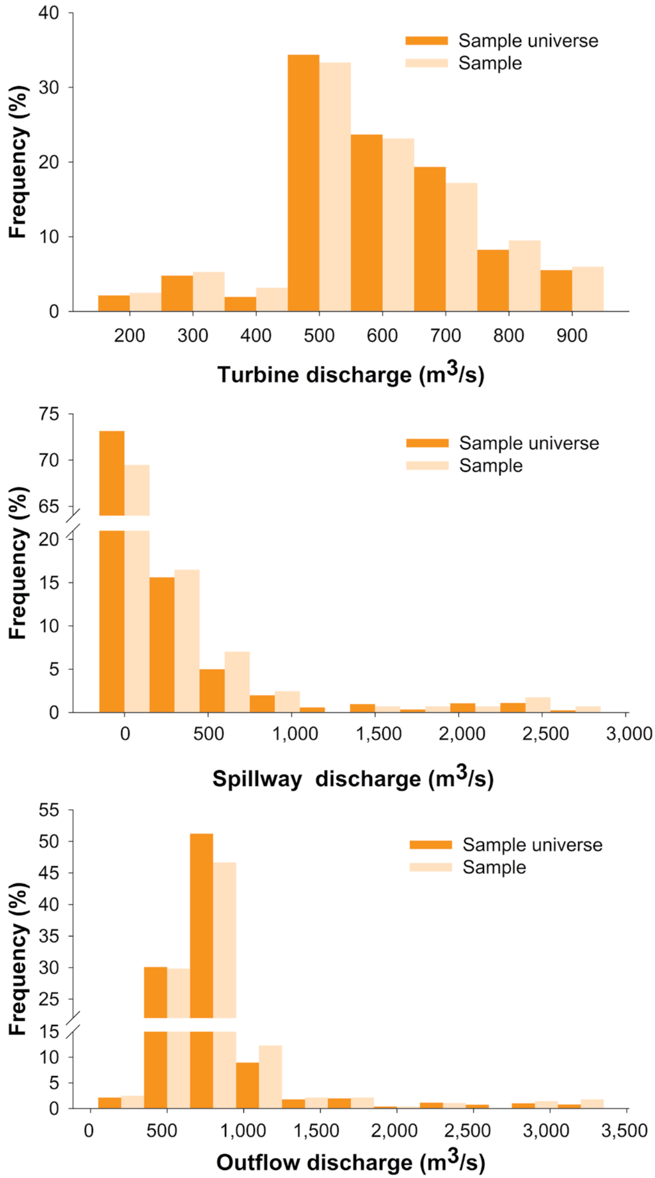

FIGURE 2 – Relative frequency distributions for the discharges of the sample universe and sample.

There were no significant correlations between Q_t and Q_s for any of the temporal scales, while Q_t and Q_o were significantly correlated for all of the temporal scales (Table 1). Between Q_s and Q_o, there was significant correlation for the daily and monthly scales. Q_o was correlated with Q_t and Q_s because $Q_o = Q_t + Q_s$. Even so, the strongest Q_o correlations were with Q_t because Q_o and Q_t were equal on 73.1% of the days. On the semiannual scale, the values of Q_o were even closer to those of Q_t and, therefore, had the highest correlation. The correlations of Q_s and Q_o were lower than those of Q_t and Q_s for all of the temporal scales (Table 1), and reduced from the daily scale to the semiannual scale because many medians of Q_s were zero.

TABLE 1 – Correlations between discharges over each temporal scale. Significant correlations ($P \leq 0.05$) in bold.

TEMPORAL SCALE	Q_t x Q_s	Q_t x Q_o	Q_s x Q_o
Daily	0.02	**0.81**	**0.50**
Monthly	0.04	**0.84**	**0.48**
Semiannually	-0.21	**0.91**	0.20

At the daily scale, $CPUE_d$ was positively correlated with all discharges in both prior and present time (Figure 3). The lowest values were with Q_s and the highest with Q_t. At the monthly scale, there was no significant correlation between $CPUE_m$ and Q_s, either in the prior or present time. The highest correlations were with Q_o, but these were just slightly higher than those with Q_t. At the semiannual scale, there was also no significant correlation between $CPUE_s$ and Q_s, nor was there a correlation with any discharge in prior time. The highest correlations were between Q_t and Q_o.

All discharges had some positive relationships with *CPUE*, whether in the prior or present time. Thus, the higher the discharge, the higher was the *CPUE*. Discharge determines the physical habitat, mainly depth and velocity (Bunn & Arthington 2002), and higher discharge makes habitats more complex, favoring an increase in abundance (Bunn & Arthington 2002).

Correlations differed among discharge and temporal scales; that is, the importance of each discharge decreased or increased depending on the temporal scale (Figure 3). This reinforces the importance of analyzing *CPUE* at different temporal scales. Only time series data can provide this type of analysis. In this work, we used data from a period of seven years, in which almost 10% of the days were sampled. Such a sampling effort has never been used in studies of fish death in Brazil and is compatible with long-term studies conducted by the Brazilian Long-Term Ecological Research Program (Seeliger 2002).

Correlations between *CPUE* and discharge in prior time only occurred for the daily and monthly scales, and these cases always had values close to those of present time. These results are important for reducing the risk of fish death during the operational procedure at TMD because they provide a certain level of predictability of mandi abundance in the tailrace from the discharge of the previous day or month. Unfortunately, the highest correlations with *CPUE* occurred on the semiannual temporal scale, but at the present time, which reduces predictive possibility.

The semiannual Q_o median is supposed to be determined from the 180 consecutive days that make up each semester. However, if it is determined sometime before the end of the semester, its value tends to differ from the median determined with data for the whole semester. In other words, the fewer days that have passed in the semester, the higher will be the difference between the two medians. Thus, if the median is determined after 30 or 150 days of the begging of the semester, we expect the value at 150 days to be closer to the median determined with data for the whole semester. In the three semesters with the highest Q_o median (those for which the prediction would be most needed), at least 50 days had passed until the median approached the median observed at the end of the semester. Due to this limitation, we do not recommend the use of the semiannual Q_o median for correlation with *CPUE* to predict mandi abundance.

Our results suggest that when performing an operational procedure with risk of fish death (*e.g.*, dewatering), a reduction of Q_t on the day previous to the operational procedure will reduce fish abundance in the tailrace on the day the operational procedure is performed. The effectiveness of this type of operation is not known. Thus, studies are needed to verify their possible benefits. In commissioning, when turbine stop, startup, and even dewatering are done frequently, one can consider reducing Q_o in the prior month, and monitor *CPUE* of the tailrace to determine if it is also reduced in the month of the commissioning.

Of the three discharges, Q_s is the least useful for programming of operational procedures with fish death risk due to its lower correlations with *CPUE*, particularly for monthly and semiannual temporal scales, whose excesses of zeros by the use of medians generated non-significant correlations. This does not necessarily mean that Q_s does not influence the abundance of fish in the tailrace. Andrade *et al.* (2012), for example, observed an increase of fish in the tailrace due to spillway discharge and does not recommend it to be performed on days of risky operations.

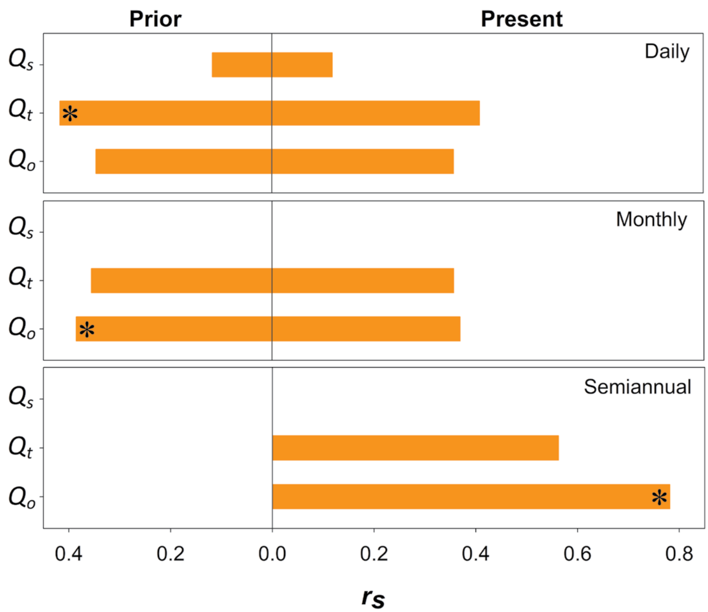

FIGURE 3 – Spearman's correlation coefficient (r_s) of *CPUE* with spillway (Q_s), turbine (Q_t), and outflow (Q_o) discharges for the daily, monthly, and semiannually temporal scales in prior and present time periods. Only significant r_s are presented. * indicates the discharge with the highest r_s for each temporal scale and which is to be considered in the programming of operational procedures with fish death risk.

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SÉRIE
PEIXE VIVO

FISH AND
HYDROPOWER PLANTS

CHAPTER 12

THE *ARRIBAÇÃO* IN THE UPPER-MIDDLE SÃO FRANCISCO RIVER, BRAZIL

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Prado, I.G.; Andrade, F.; Souza, R.C.R; Rodrigues, R.R.; Monteiro, A.B; Godinho, A.L. (2017) The *arribação* in the upper-middle São Francisco River, Brazil. In: R.C. Loures & A.L. Godinho (eds.) *Risk assessment of fish death at hydropower plants in southeastern Brazil*. Belo Horizonte: Companhia Energética de Minas Gerais, pp. 259-272 (Série Peixe Vivo, 6).

1 – INTRODUCTION

After initial development in floodplains, juveniles of migratory fish disperse throughout the rivers (Lucas & Barras 2001) in search of habitats to finish their development and find food and protection from predators (Pompeu & Godinho 2003). In the São Francisco River, this migration is known as "*arribação*" (Godinho & Kynard 2006, Loures & Pompeu 2012). In the upper reaches of the São Francisco River, the *arribação* tends to happen every year (Godinho & Kynard 2006). The *arribação* fish agglomerate just downstream of Três Marias Dam (TMD). Few studies have dealt specifically with these agglomerations in order to identify the patterns and processes involved.

The agglomeration of fish during an *arribação* at TMD can vary in intensity (Rodrigues 2009), and can be classified as of lower (ALI) or greater (AGI) intensity. The AGI occurs sporadically, and since the mid-2000s have occurred in the hydrological years of 2006/2007 (Rodrigues 2009) and 2011/2012 (pers. obs.).

In hydrological years of AGI, compared to years of ALI, the risk of fish death during operation and maintenance of TMD is increased significantly. Preparation and caution in the operational procedures that represent risk to fish are necessary to avoid mortality. Consequently, the evaluation of the factors related to the intensity of fish agglomerations, and the possibility of predicting them, are important for reducing the risk of fish death. Preventive measures, such as reprogramming plant activities and increased caution during operational procedures, will have greater success if performed well in advance.

In this study, we sampled fish agglomerations immediately downstream of the TMD over five hydrological years to: (i) determine the occurrence of juveniles of the dominant species; (ii) determine the time of occurrence of AGI; (iii) compare the dominance of the most common species among hydrological years; (vi) compare the condition factor of the dominant species between periods of ALI and AGI; and (v) evaluate the characteristics of floods and their relationship to AGI.

Downstream of TMD, the São Francisco River has a 1,090 km free-flow stretch where its main tributaries drain. Floodplains with abundant lakes occur downstream of the mouth of Paracatu River, 243 km downstream of TMD (Godinho *et al.* 2007).

2 – METHODS

2.1 Fish sampling

We captured fish just downstream of TMD at the tailrace and the spillway plunge pool area and its surroundings, up to about 500 m downstream from the dam. We performed 3 to 13 days of sampling per month from November 2007 to September 2012. We captured fish using a cast net with a stretched mesh of 5.5 cm, 0.50 mm wire, and 8 kg of lead. An on-board fisher threw the cast net 60 to 100 times per day of sampling. We identified the captured individuals according to Britski *et al.* (1988), measured their standard length (*SL*) and body weight (*W*), and released them at the sampling site.

2.2 Abiotic factors data collection

On sampling days, we determined water transparency using a Secchi disc and measured dissolved oxygen (*DO*) and water temperature with a multiprobe. Cemig provided rainfall data for the sampling days as well as the 2005 to 2012 daily average turbine discharge (Q_t), spillway discharge (Q_s) and outflow discharge (Q_o) for TMD, and the discharge of the São Francisco River in the municipality of Januária, 575 km downstream of TMD.

2.3 Data analysis

For each sampling day, we calculated catch per unit effort (*CPUE*) with the formula $CPUE = P.T^{-1}$, where P = number of fish captured and T = number of cast. We calculated *CPUE* independent of species ($CPUE_t$) and separately for each of the four dominant species in the samples ($CPUE_e$). For these same species, we calculated the Fulton condition factor (*K*) with the formula $K = W.SL^{-3}.10^5$. The dominant species were mandi (*Pimelodus maculatus*), curimba (*Prochilodus* *argenteus*), pioa (*Prochilodus costatus*), and dourado (*Salminus franciscanus*).

We defined AGI as the months with greatest quantity of juvenile fish of at least one of the dominant species in the agglomeration in the sample stretch just downstream of TMD. Thus, AGI occurred when $CPUE_e$ for these species was ≥ 3 fish/cast and juveniles represented 70% or more of the number of individuals caught. We defined agglomerations of lower intensity (ALI) as the period with increased density of juvenile fish just downstream of the TMD, but with $CPUE_e$ < 3 fish/cast. We considered juvenile mandi to be those smaller than 160 mm SL, curimba smaller than 250 mm SL, pioa smaller than 240 mm SL, and dourado smaller than 360 mm SL. We considered size at maturity to be that defined for mandi by Dei Tos (2002) and for the other species by Bazzoli (2003).

We tested for differences in K between the AGI and ALI with Wilcoxon test due to the non-normal distribution of this variable. We used Statistica 7.0 (StatSoft, 2009) for the statistical analyses and adopted a 0.05 level of significance (α).

3 – RESULTS AND DISCUSSION

3.1 Occurrence of juvenile fish

Among all the fish sampled, 75.6% of the mandi were larger than the size at first maturation, while most curimba (68.1%), pioa (89.2%), and dourado (99.3%) were smaller than this size (Figure 1).

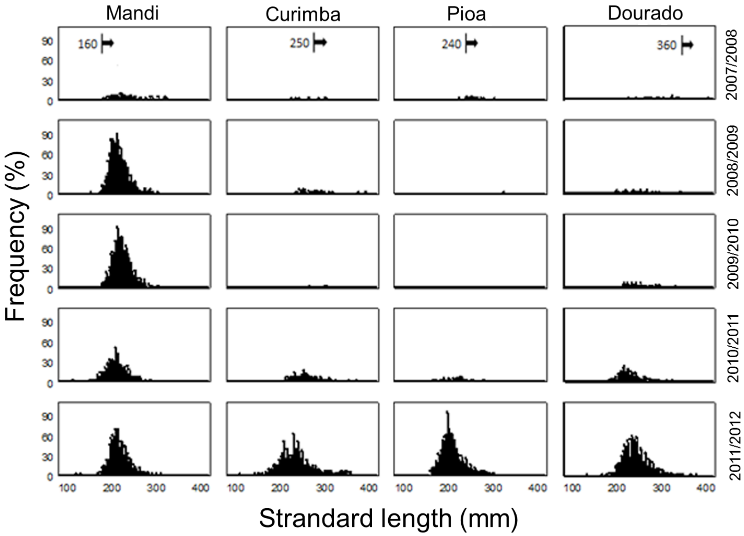

FIGURE 1 – Relative frequency distribution of standard length of the dominant species in the agglomerations of fish immediately downstream of the Três Marias Dam. Arrows and values in the panels of 2007/2008 indicate size at maturity (in mm).

3.2 Period of AGI occurrence

Throughout the entire study period, the lowest $CPUE_e$ values of the four dominant species were zero. The highest $CPUE_e$ values were 9.1 for mandi, 14.4 for curimba, 11.0 for pioa, and 10.0 for dourado. The $CPUE_e$ for mandi was, in the majority of samples, greater than zero. Peaks of monthly mean $CPUE_e$, some greater than 3 fish/cast, occurred in all hydrological years sampled (Figure 2). Most of these peaks were of mandi, but adult mandi represented more than 96% of all mandi sampled. Unlike mandi, the $CPUE_e$ for the other three species was frequently zero or close to zero, and with few peaks. The highest peaks of monthly mean $CPUE_e$ of these three species occurred in the first half of 2012. In these peaks, the monthly mean $CPUE_e$ was ≥ 3 fish/cast and juvenile fish represented over 86% of the sampled fish. We classified these peaks as AGI. The AGI were comprised of one, two, or three species. Thus, the AGI of January 2012 had only dourado, while the AGIs of March and April of 2012 had curimba and pioa. These three species were in the AGIs of April and July of 2007 (Rodrigues 2009).

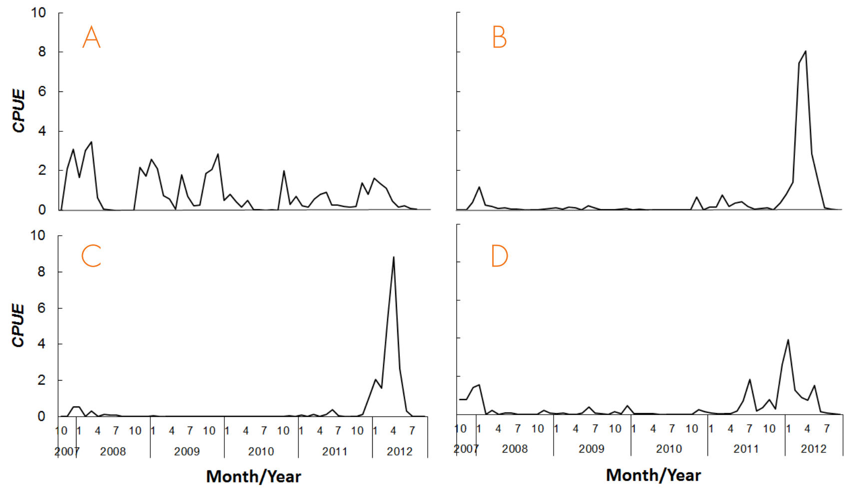

FIGURE 2 – Monthly mean of catch per unit effort ($CPUE_e$) of mandi (A), curimba (B), pioa (C), and dourado (D) immediately downstream of the Três Marias Dam for October 2007 to September 2012.

3.3 Dominance

Mandi was the dominant species sampled in all hydrological years except 2011/2012, when the AGI of the three other species occurred (Figure 3). In this hydrological year, pioa was the most captured species, followed by dourado, curimba, and mandi. Species dominance was lower in this hydrological year of AGI compared to other hydrological years. Godinho & Kynard (2009) suggested that agglomerations of young curimba from the *arribação* occurred every year just downstream of TMD. Our data confirmed the annual occurrence of these agglomerations and also showed that their intensity can vary significantly from year to year.

Although it was the most common species in samples just downstream of TMD in almost all of the hydrological years, the agglomerations of mandi did not seem to be a consequence of an *arribação* because the majority of the individuals collected were larger than the size at maturity (Figure 1). Mandi is known to be abundant near hydropower plants and is commonly involved in fish entrapments and/or recovery from turbines (Andrade *et al.* 2012). The migratory/non-migratory behavior of mandi is not well understood, but it is considered a short-distance migratory species (less than 100 km), despite its capacity to migrate up to 1,000 km (Agostinho *et al.* 2003, Sato & Godinho 2003, Zaniboni Filho, Shulz 2003). Individuals of this species need smaller lotic stretches to carry out their life cycle (Maia *et al.* 2007).

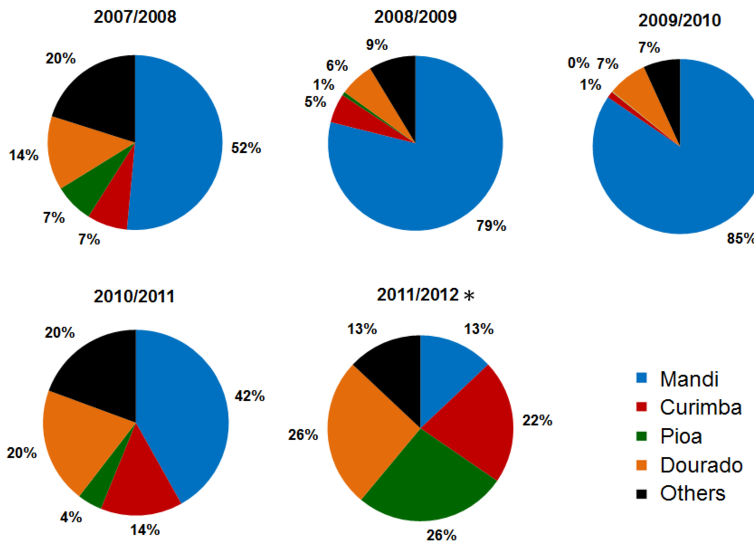

FIGURE 3 – Percentage of the most caught species in the agglomerations of fish immediately downstream of the Três Marias Dam by hydrological year. * indicates the hydrological year with agglomeration of greater intensity.

The use of a cast net to collect fish makes it possible to perform disperse, agile sampling with immediate results, in addition to allowing the release of captured individuals in excellent physical condition. However, the method is selective. During AGI, the capture of high quantities of fish in a single cast makes it difficult, or at least impedes, the net from reaching the bottom. In this situation, the species that swim closer to the surface of the water column, such as curimba, pioa, and dourado, are more likely to be captured than those that are closer to the bottom, such as mandi (Rodrigues 2009). Thus, curimba, pioa, and dourado were probably sampled more adequately during AGIs, while mandi may have been sub-sampled.

3.4 Condition factor

Significant differences in *K* between the months of ALI and AGI occurred only for pioa, despite the large overlap in their values (Figure 4). Thus, the higher fish density during AGI does not appear to significantly affect fish condition.

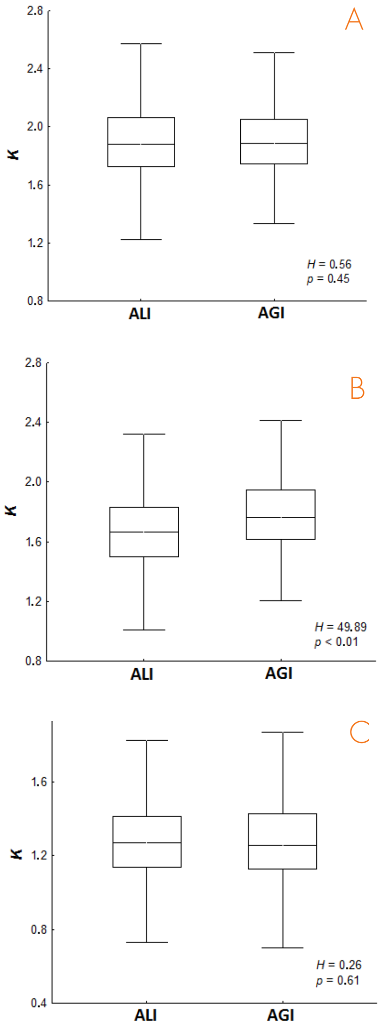

FIGURE 4 – Boxplot of Fulton condition factor (*K*) for curimba (A), pioa (B), and dourado (C) immediately downstream of the Três Marias Dam in months with agglomerations of lower (ALI) and greater (AGI) intensity (*H*: Kruskal-Wallis statistic).

3.5 Floods and AGI

Two consecutive hydrological years of high intensity flooding are required for the occurrence of an AGI. Meanwhile, ALI appears to be the more frequent condition just downstream of TMD, but it is replaced by an AGI when two hydrological years with more intense floods occur consecutively. Thus, preceding the three-species AGI of 2006/2007, Q_o reached 1,722 m^3/s in 2005/2006 and 3,050 m^3/s in 2006/2007. For the one-species and two-species AGIs of 2011/2012, the Q_o reached 2,674 m^3/s in 2010/2011 and 3,000 m^3/s in 2011/2012 (Figure 5). The first flood allows fish in the early stages of life to reach their nurseries in the floodplains. The second flood, in the next hydrological year, allows them to leave the nurseries and return to the main river. Godinho *et al.* (2007) suggested that two consecutive floods might be necessary to restore fish to the São Francisco River via artificial floods, but data are still needed to determine when the second flood should occur. Our study showed that these second floods really are necessary and that they must occur in two consecutive hydrological years.

Curimba and pioa of AGI were larger than the young of the year of hatchery fish (CODEVASF 2005, 2006, 2007). In addition, the curimba of AGI were also larger than less than one-year old conspecifics in the floodplain lakes of Velhas River, a São Francisco River tributary (Alves & Pompeu 2007). This suggests that curimba and pioa of AGI must have been born in the previous hydrological year, corroborating the hypothesis of the dependence on floods in two consecutive hydrological years for the occurrence of AGI with these species.

The Q_o of TMD seems to have been decisive for the occurrence and intensity of the three-species AGI in the hydrological year of 2006/2007. The connection of the floodplain lakes with the São Francisco River demands high discharge rates at TMD, particularly spillway discharge, which can, and should, be utilized for this purpose. Pompeu and Godinho (2006) suggested that the discharge of the São Francisco River in the municipality of Manga must reach 5,000 m^3/s (flood discharge) so that the floodplain lakes of the region can receive water. In the municipality of Januária, separated from Manga by 100 km of river with only small tributaries, flows above flood discharge occurred on 29 days of the hydrological year prior to the three-species AGI. For all of these days, except for one, flood discharge would not be reached without the contribution of Q_o. In the hydrological year of the three-species AGI, the flows in Januária were greater than the flood discharge during 80 consecutive days. Without the Q_o of TMD, flood discharge would not have been reached in 46 of those days. In addition to increasing the duration of the flood, Q_o increased its intensity. In the Paraná River, the magnitude of recruitment seemed to be directly related to the duration and intensity of floods (Agostinho *et al.* 2004).

The Q_o of TMD also seems to have been decisive for the occurrence of the one-species and two-species AGIs of the hydrological year 2011/2012. In this year, flows in Januária were above flood discharge on 40 days, 39 of which were consecutive. During this period, the Q_o of TMD reached 3,000 m^3/s, 87% of which was due to spillway discharge. Without this contribution, the São Francisco River at Januária would have reached flood discharge on only 6 days (Figure 6).

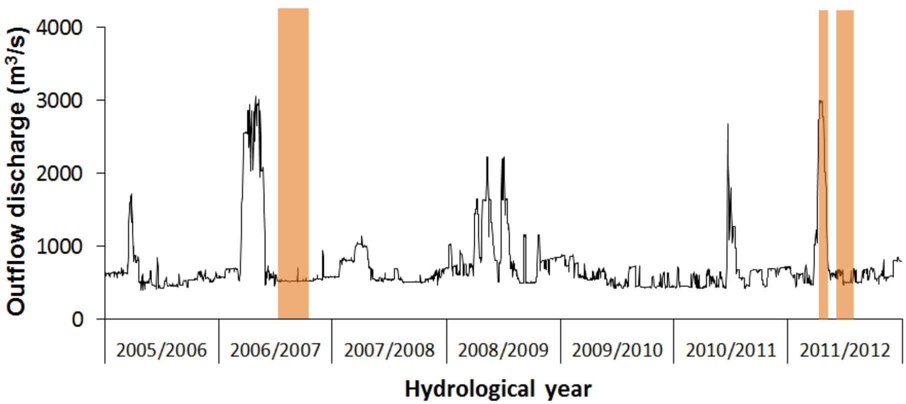

FIGURE 5 – Daily outflow discharge of the Três Marias Dam per hydrological year. The areas highlighted in orange represent the periods of occurrence of agglomeration of greater intensity.

To increase the chances that eggs and larvae of fish reach their nurseries in the floodplain, Godinho *et al.* (2007) suggested that the spillway discharge of TMD should be synchronized with the floods of the main downstream tributaries of the São Francisco River. Although spillway discharge has not been used for this purpose, this synchronicity occurred in the 2011/2012 hydrological year when peak Q_o occurred six days before the peak flow in Januária, such that the flood wave arrived in Januária when flows were the highest. In other years, however, Q_o occurred after the peak flow in Januária or even after the end of the spawning period, conditions that do not favor recruitment and, consequently, the formation of an AGI.

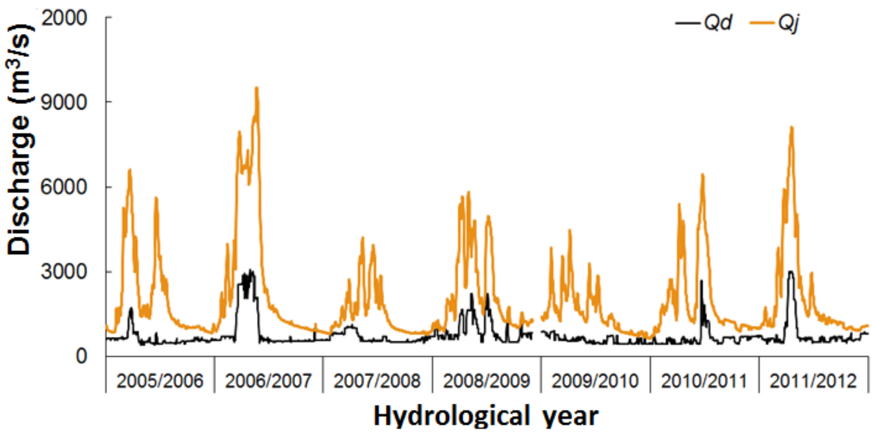

FIGURE 6 – Daily mean of outflow discharge (Q_o) of the Três Marias Dam and the discharge of the São Francisco River in Januária (Q_j) between 2005 and 2012.

Previous knowledge of the conditions that increase the risk of fish death is an important tool for programming activities at TMD such that mortality is minimized. The present study indicated the conditions that create AGI, a situation in which potentially more fish can die if protective measures are not taken in the operation and maintenance of TMD. Due to the importance of AGI, more information about it needs to be obtained so that it is better understood and improved predictive models developed. Moreover, the necessity of two consecutive hydrological years with floods of greater intensity for the occurrence of an AGI is a determining factor that should be considered in the implementation of artificial floods for the restoration and maintenance of the abundance of the migratory fishes of the São Francisco River.

4 – ACKNOWLEDGMENTS

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CHAPTER 13

RECOMMENDATIONS FOR FISH PROTECTION AT NEW HYDROPOWER PLANT PROJECTS

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Loures R.C., Prado N.J.S., Silva R.J., Joncew I., Dias J.S & Pontelo E.G.G. (2017) Recommendations for fish protection at new hydropower plant projects. In: R.C. Loures & A.L. Godinho (eds.) *Risk assessment of fish death at hydropower plants in southeastern Brazil.* Belo Horizonte: Companhia Energética de Minas Gerais, pp. 273–294 (Série Peixe Vivo, 6).

1 – INTRODUCTION

The Brazilian Electricity Sector is increasingly concerned about mitigating impacts from hydropower generation. Despite the increased diversification of the Brazilian energy matrix, the *Plano Decenal de Energia 2030* (Ten-Year Energy Plan 2030) foresees an increase in the consumption of electrical energy, which could reach between 950 and 1,250 TWh/year by 2030. This increase in demand will require the installation of significant additional hydropower sources (EPE 2007). Therefore, regarding impacts on fishes, we believe that not only should there be more studies evaluating the need for changes to operational procedures of existing hydropower plants, but also that new ventures should consider structural improvements to reduce impacts on fish.

This chapter presents recommendations and suggestions to be considered in the design of new hydropower plant projects, aiming the protection of the local fish fauna in its interaction with the plant. Several of these recommendations and suggestions come from practices adopted by the Cemig Group based on the results obtained from studies in partnerships with universities, environmental organizations, consultants, engineers, and biologists, among others.

2 – BEHAVIORAL *VERSUS* PHYSICAL BARRIERS

2.1 Behavioral barriers

Behavioral barriers are designed to influence fish behavior by attracting them to areas of lower risk or repelling them from areas of higher risk (Noatch & Suski 2012). Among repulsion systems, the use of stroboscopic light, bubbles, sound, and electric fields stand out. The effectiveness of behavioral barriers varies according to fish species and size, as well as site and environmental conditions, including water turbidity and flow (Popper & Carlson 1998). The development and improvement of fish repulsion systems have been of particular interest to the electricity sector, due to the opportunity to reduce the risks involved in operation and maintenance of its hydropower plants.

Several species of fish have well-developed visual systems, and for them light is an important stimulus. Stroboscopic light is generated by devices capable of emitting short-duration bright flashes of light at an extremely rapid rate (Ploskey & Johnson 2001). Studies in temperate regions have demonstrated the effectiveness of this technique for the repulsion of various fish species when using light emission at 300 flashes/min (Patrick *et al.* 1985, Sager & Hocutt 1987, Sager *et al.* 2000, Ploskey & Johnson 2001). The results obtained by studies in Brazil have been promising (Silva & Martinez 2010). However, studies have shown that some species tend to become accustomed to stroboscopic light with time, neutralizing its repulsive effect (Silva & Martinez 2010). Water velocity is another factor important to the effectiveness of stroboscopic light repulsion.

The bubble-curtain system consists of generating bubbles at the risk area to create a barrier that prevents fish from seeing through it (Noatch & Suski 2012). The efficiency of this system is variable and depends mainly on the environmental conditions of the region (Silva 2010a). However, the technique is inexpensive compared to others, and should be studied with other behavioral repulsion techniques (Taft 2000).

Unlike light, sound propagates very well in water, and fish can perceive it through the lateral line system. Like stroboscopic light and bubbles, results of sound repulsion of fish have been variable. Some studies have shown efficiency, while others have not (Feist & Anderson 1991, Ploskey *et al.* 1995, Dunning *et al.* 1992). In addition, the type of sound emitted produces different results. Until recently, studies of fish hearing have reported that the audible bandwidth of less-sensitive fish generally ranges from below 100 Hz to around 1,000 Hz, while in more specialized species sound detection may range 5,000–7,000 Hz (Mann *et al.* 2001). Sound barriers have been studied since the 1980s using three categories of sound waves: infrasound (<20 Hz), audible sound (20–20,000 Hz) and ultrasound (>20,000 Hz). Tests performed with audible frequencies showed very inconsistent results, often with low efficiency. In addition, sound stimulus seems to be species-specific, which usually hinders its usefulness (Taft 2000).

Fish are sensitive to electric fields and can be guided or repelled by their use. Electric barriers use an electric field to drive or guide fish to specific areas (Hocutt 1980). The waveform, frequency, and intensity of the electric current directly affect the sensitivity of fish. In addition, limnological factors and fish size also influence the efficiency of this technique (Pugh *et al.* 1970). These systems can repel fish by the nuisance caused by the electric field or by electronarcosis, and show greater efficiency when repulsing fish in upward movement. When fish approach an electrical barrier sufficiently enough to be paralyzed, water flow carries them away from the risk area (Silva 2010b). Despite its efficiency, the range of an electric field is generally small, installation and maintenance are difficult, and there are safety concerns with its use, especially in rivers and regions with fishers. Therefore, specific studies are needed to improve these barriers for effective use in protection of fish fauna at hydroelectric plants. Among behavioral barriers, electrical barriers may be the most promising, in the mid-term, for installation in the draft tube of hydropower plants to prevent fish from entering.

2.2 Physical barriers in the draft tube

Fish frequently concentrate in the tailrace of hydropower plants, and thus are subject to changes in water flow, gas supersaturation, increased levels of predation, and flood control regime (Baxter 1977, Chapter 2). Fish in this area can access structures that present potential risk of injury and death, like the turbine draft tube and the spillway. Flow strength and velocity in these places can be obstacles for the installation of fish screens. Fish entering the draft tube during turbine stop is the most critical situation given the magnitude of fish death occurrences in these structures. To reduce this impact, fish screen systems have begun to be used to prevent such entry.

Fish screens are placed on the stop log slots of the draft tube during turbine stop, preventing fish from entering. It is possible that some fish, specifically those already near the draft tube, are able to enter the structure just after the turbine has stop and during the fish screen descent, thus becoming trapped. Therefore, to prevent large quantities of fish from entering, the screens should be deployed as fast as possible, immediately after the turbine stops. The screens allow water renewal, keeping any trapped fish alive. Despite this water renewal, it is important to establish a maximum time that a turbine can remain stopped with a fish screen in place, since confinement can increase stress, leaving fish more susceptible to injury and death (Portz *et al.* 2006). Fish screens must be removed just prior to the turbine startup in order to minimize the time that other fish in the tailrace could enter the draft tube. The Retiro Baixo (Paraopeba River), Funil (Grande River), and Três Marias (São Francisco River) dams already have fish screen systems in place (Figure 1).

Tests performed at Três Marias and Funil dams indicate that the screen mesh should be on the order of 1.0 cm^2 to prevent fish entrance, and that the time of screen descent should be, at most, one minute after the application of the turbine brakes. Fish must be provided with hatches to permit access by divers and/or robots (remotely operated vehicle – ROV) for subaquatic inspection.

In the general design of new hydropower plant, it is important to consider including specific slots for fish screens in the concrete structure, independent from the stop log slots. If included before the procurement of a new project, the financial impact of installing the slots would be minimized. The independence of fish screens and stop logs enables the turbine stop with water renewal in the draft tube and, if turbine dewatering is needed, the stop log can be lowered to seal the draft tube, which would already be free of trapped fish.

FIGURE 1 – Fish screen system at hydropower plants of Cemig Group.

Results from the installation of fish screens at Três Marias Dam

Since July 2007, fish screens have been used during the scheduled turbine stops at Três Marias Dam. Since their implementation, there have been no events of fish death greater than 10 kg during turbine startup (Andrade *et al.* 2012). The screens at this hydropower plant can be lowered after satisfying the preconditions of complete closure of the wicket gates and application of the turbine brakes, which occurs with about 30% of nominal rotation.

We emphasize the importance of periodic inspections of fish screens to prevent fish from entering the draft tube in the case mesh integrity is compromised. In addition, we do not recommend the use of fish screens for long periods of time because this would increase the risk of death for fish that happen to be trapped, due to starvation, physical injury when in high concentrations, and stress. In the case of prolonged turbine stop, the screens should be removed periodically to allow fish to exit the draft tube. Although this operational procedure may result in the entry of new individuals, it must be performed to allow trapped fish to leave. Studies are needed to determine the maximum time that screens can be used since there are not enough records to determine this yet.

3 – SPILLWAY DISSIPATION BASINS, TAILRACES, AND DOWNSTREAM SECTIONS

Frequently, there are spots where fish can get entrapped in the spillway dissipation channel, tailrace, and irregular areas downstream from the dam. These spots should be assessed and actions taken to eliminate entrapment. As an example of a modification to civil structure, we highlight regular excavation or filling of entrapment spots, thus avoiding the formation of pools due to changes in discharge flow during the operation of the hydropower plant (Figure 2).

FIGURE 2 – The spillway dissipation basins of Jaguara (A) and Itutinga (B) dams, with people catching fish after spillway closure. Spillway dissipation basin after work to remove fish entrapment spots at Jaguara (C) and Itutinga (D) dams.

For those hydropower plant projects that require a reduced outflow stretch (ROS), the necessity and technical and economic feasibility of regularizing the stretch should be studied (Figure 3). Such practice would prevent the formation of pools and enable the establishment of a water column through the construction of dikes and channels, which can reduce fish entrapment. The establishment of an operational rule for ROS, or another solution that takes into consideration the physico-chemical characteristics of the water that may limit its quality in the section, can also help to reduce the impact on fish.

FIGURE 3 – The reduced outflow stretch of the Amador Aguiar I Dam before (A) and after (B) the regularization to eliminate the various fish entrapment spots. Photos: Lazaro Carlos de Freitas.

Water from the power generation units cooling system and the powerhouse drainage system released into the tailrace can be attractive to fish in the area. Fish can jump and suffer injuries when colliding with the powerhouse walls. Therefore, whenever possible, the release of this water should be relocated to places farther away from physical structure, or at least should not have a cascade effect, to eliminate this impact (Figure 4).

FIGURE 4 – Cooling water pipe of the Três Marias Dam power generation units (A). Elongation of the cooling water outlets away from the powerhouse walls of Funil Dam (B).

4 – RESOURCES FOR MONITORING AND HANDLING FISH IN THE DRAFT TUBE, DEWATER SUMP, AND TAILRACE

4.1 Oximeter

A fast reduction in dissolved oxygen in the draft tube water during turbine dewatering can be indicative of a large number of entrapped fish (see Chapter 3 for a description of operational procedures risky to fish). The design of new hydropower plants should include facilities for direct monitoring of dissolved oxygen levels (Figure 5; see Chapter 2 for "Monitoring protocol for turbine dewatering with fish rescue"). In the future, the possibility and relevance of monitoring ammonia concentration should be investigated in order to evaluate the stress level of the fish (Portz *et al.* 2006).

FIGURE 5 – Installation of stations for monitoring dissolved oxygen in the hatch of the draft tube at Funil Dam (A) and Rosal Dam (B).

4.2 Air and water injection

The use of fish screen for fish retention allows the water and oxygen to be renewed in the draft tube during turbine stop, but when dewatering is necessary (for turbine maintenance or inspection), the stoplog is deployed and there is no more water renewal from downstream. New hydropower plant projects should plan for the possibility of installing a system for the injection of compressed air and good quality water into the draft tube and dewater sump, to allow fish to survive until they can return to the river channel (Figure 6).

FIGURE 6 – Water (green pipe) and compressed air (blue pipe) injection pipes of Emborcação Dam (A) and an aeration system (white pipe) on the stoplog panel of Funil Dam (B).

4.3 Platforms and boxes for fish recovered from the draft tube and dewater sump

The rapid recovery of fish entrapped in the draft tube and dewater sump is critical to ensure that fish are removed still alive. In order to do this, platforms and hatches of adequate size are necessary for fast and safe handling of the materials used during recovery (Figure 7A to C).

The boxes for transport of recovered fish should be designed to optimize transportation to the release area, taking the largest quantity of fish and water as possible, at the same time avoiding overcrowding and stress. They should be fitted with a protective cover or net to prevent fish from jumping out of the box during transport. The boxes must have oxygen or compressed air injection and allow fish to be moved from "water to water", avoiding the formation of a "fish waterfall", which can increase stress. Hydropower plant block outs should allow the safe and quick lifting of the boxes to the maneuvering platform where they will be placed on a vehicle that will take the fish to the release area (Figure 7D to F). It is desirable to provide tanks for acclimatization of fish prior to release. These tanks should be slightly inclined and receive running water.

The release point for recovered fish should be determined by technical and biological criteria, taking into account the knowledge of the local fish fauna. For example, aspects of genetics should be taken into consideration because of possible natural barriers, which no longer allow a downstream/upstream connection, as well as the presence of exotic species of fish or other organisms such as the golden mussel.

FIGURE 7 – Platform mounted inside the draft tube of São Simão Dam (A). Fish transport box positioned at the exit of the draft tube hatch (B). Ramp set at the opening of the transport box for transferring fish recovered from the draft tube (C). Transport box being hoisted through the block outs of the plant (D and E). Transport box being loaded on a truck that will take the recovered fish to the release area (F). Photos: Átila Rodrigues (A) and Alexandre Peressin (B to F).

4.4 Echo sounding (sonar)

High-resolution sonar can be used to monitor fish in the tailrace (Figure 8) (Crossman *et al.* 2011, Grote *et al.* 2014, Loures & Pompeu 2015). Echo sounding has been increasingly used in aquatic systems for acquiring information, from bathymetry and substrate classification to determining the abundance and distribution of biota, including macrophytes, zooplankton and particularly fish (Brandt 1996, Simmonds & MacLennan 2005). The technique has the advantage of not being intrusive, that is, it allows visualization and counting of organisms that are under the surface of the water without disturbances in the environment. It also allows nearly the entire water column to be sampled quickly (Brandt 1996, Parker-Stetter *et al.* 2009). However, its limitations may restrict its use in tailrace, because environments with noises and disturbances, such as turbulence and bubbles in the water can impair a clear signal analysis (Lucas & Baras 2000). Other limitations are that fish cannot be directly identified and sampling is impaired in shallow environments (less than 2 m). Furthermore, it is necessary to have personnel trained to operate the acoustic equipment and interpret data obtained. Unfortunately, such training and experience is rarely available in the market (Unger & Brandt 1989, Brandt 1996).

Thus, this technique still needs further studies and adaptations of the equipment to the unstable and turbulent environment of the tailrace, both for mobile and fixed-point use. The possibility of installing sonar and/or cameras and/or industrial endoscopy in the draft tube (or in the hatch) should be evaluated as an alternative for monitoring the presence of fish in the draft tube. We emphasize, however, that the use of cameras is not always possible due to water turbidity.

FIGURE 8 – Digital scientific echosounder (Biosonics Inc.) used to evaluate the distribution of fish in the tailrace of Três Marias Dam (A). On the left, surface unit connected to a computer; on the right, transducer attached to the side of the vessel, 50 cm above water surface, and connected to the surface unit. Dual-frequency IDentification SONar (DIDSON; Sound Metrics) used to evaluate fish density in São Simão and Amador Aguiar II dams (B). Photo B: Alejandro Giraldo

4.5 Robotic underwater inspection

The maturity of robotic technology, reductions in cost of underwater instrumentation, and new developments in underwater image processing have opened doors for the use of ROV in new scientific, industrial, and safety applications (Ridao *et al.* 2010, Neto *et al.* 2014). In addition to industrial use, underwater vehicles have been increasingly used for studies of fish abundance and distribution due to the possibility of visually counting individuals (Stoner *et al.* 2008). Its use in hydropower plants, however, requires careful assessments to combine safety and efficiency so that it can be used for inspections and monitoring of both civil structures and environmental.

A ROV can be equipped with autopilot (GPS), sonar, camera, multi-parameter probes, and arms. Such a vehicle can be used for inspection of the turbine rotor, draft tube, and submerged civil structures downstream and upstream of hydropower plants. Endowed with sonar and cameras, it can also be used for estimating abundance and distribution of fish within the hydropower plant structure itself and during prior assessments for operational procedures that present risk to fish. Thus, in the development of new hydropower plants projects it may be interesting to analyze the cost-benefit of using ROV for underwater inspections and monitoring. The legal requirement of NORMAN 15-DPC/1st Revision, which concerns professional dives for inspections and underwater work in Brazil, should be considered as well. An important factor for success is the selection of equipment resistant to depth and which size and power allows stability against the flow of possible leakage of the wicket gates.

5 – FINAL CONSIDERATIONS

The adoption of the criteria and precautions listed here during the design phase of new hydropower power plants allows the structures to be at least compatible with the future installation of technical resources. Such potential installations will provide alternative responses for making operational procedures safer to fish. Furthermore, because they are included in the construction phase, they are comparatively simpler and less expensive than future corrective actions.

Impacts to fish are inherent to the hydropower generation process, from construction to operation and maintenance. Knowing the fish fauna downstream of hydropower plants is extremely important for making decisions related to the actions to be implemented for their protection. Therefore, investing in research is crucial. The reduction of these impacts not only benefits the environment, but also contribute to the sustentability and image of companies and ensures the best interaction with related parties, reducing the risk of conflicts.

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SÉRIE PEIXE VIVO

FISH AND
HYDROPOWER PLANTS

APPENDIX A

LIST OF FISH SPECIES SAMPLED IN THE RISK ASSESSMENT OF FISH DEATH AT HYDROPOWER PLANTS PROJECT

RAFAEL COUTO ROSA SOUZA,
ANA CAROLINA LACERDA RÊGO &
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Souza R.C.R., Rêgo A.C.L. & Godinho A.L. (2017) List of fish species sampled in the Risk Assessment of Fish Death at Hydropower Plants project. In: Loures R.C. & Godinho A.L (ed.) *Risk assessment of fish death at hydropower plants in southeastern Brazil.* Belo Horizonte: Companhia Energética de Minas Gerais, pp. 295 - 306 (Série Peixe Vivo, 6).

1 – SPECIES LIST

The 136 fish taxa sampled at the 19 hydropower plants of the Cemig Group studied in the project Risk Assessment of Fish Death in Hydropower Plants are listed below. Scientific names and authorship according to the Catalog of Fishes Online Database (accessed 25/06/2015).

ORDER/FAMILY/SPECIES	AUTHORSHIP	COMMON NAME	DAM WHERE IT WAS SAMPLED*
CHARACIFORMES			
PARODONTIDAE			
Apareiodon affinis	(Steindachner 1879)	Canivete	FU
Apareiodon piracicabae	(Eigenmann 1907)	Canivete	EM/FU/IT/PJ/SS
CURIMATIDAE			
Curimatella lepidura	(Eigenmann & Eigenmann 1889)	Sardinha	TM
Cyphocharax gillii	(Eigenmann & Kennedy 1903)	Saguiru	EM/FU/MR/NP
Cyphocharax modestus	(Fernández-Yépez 1948)	Saguiru	AF/FU/IT
Cyphocharax nagelii	(Steindachner 1881)	Sardinha / Saguiru	AS/EM/SS
Steindachnerina brevipinna[E]	(Eigenmann & Eigenmann 1889)	Saguiru	EM
Steindachnerina insculpta	(Fernández-Yépez 1948)	Sardinha / Saguiru	AF/AS/EM/FU/ JG/MR/NP/SS

Continued

ORDER/FAMILY/SPECIES	AUTHORSHIP	COMMON NAME	DAM WHERE IT WAS SAMPLED*
PROCHILODONTIDAE			
Prochilodus argenteus[M]	Agassiz 1829	Curimba	TM
Prochilodus costatus[M]	Valenciennes 1850	Pioa	TM
Prochilodus hartii	Steindachner 1875	Curimatã	IR
Prochilodus lineatus[M]	(Valenciennes 1837)	Curimba	All but AF/AS/ BG/IR/PJ/RO/ TM/VG
ANOSTOMIDAE			
Hypomasticus garmani	(Borodin 1829)	Timboré	IR
Leporellus vittatus	(Valenciennes 1850)	Piau-rola / Solteira	AS/EM/FU/ IT/ MR/SS/TM
Leporinus amblyrhynchus	Garavello & Britski 1987	Timboré / Piau	AF/MR/NP
Leporinus elongatus[M]	Valenciennes 1850	Piapara	IR
Leporinus friderici[M]	(Bloch 1794)	Piau-três-pintas	All but BG/IR/ NP/RO/TM/ VG
Leporinus piavussu[M]	Britski, Birindelli & Garavello 2012	Piapara	EM/PJ/SS
Leporinus geminis[E]	Garavello & Santos, 2009	Piau	AS/EM/SS
Leporinus lacustris	Campos 1945	Piau	SS
Leporinus macrocephalus[E,M]	Garavello & Britski 1988	Piaussu	AS/EM/FU
Leporinus obtusidens[M]	(Valenciennes 1837)	Piapara / Piau-verdadeiro	AS/CM/EM/ FU/ IT/PJ/SS/ TM
Leporinus octofasciatus	Steindachner 1915	Ferreirinha / Flamenguinho	All but BG/IR/ RO/TM

Continued

ORDER/FAMILY/SPECIES	AUTHORSHIP	COMMON NAME	DAM WHERE IT WAS SAMPLED*
Leporinus paranensis	Garavello & Britski 1987	Piau	SS
Leporinus piau	Fowler 1941	Piau-gordura	TM
Leporinus reinhardti	Lütken 1875	Piau-três-pintas	TM
Leporinus striatus	Kner 1858	Piau-listrado	AS/FU/IT/SS
Leporinus steindachneri	Eigenmann 1907	Piau	IR
Leporinus taeniatus	Lütken 1875	Piau-jeju	TM
Leporinus tigrinus[E]	Borodin 1929	Piau	EM/SS
Schizodon intermedius	Garavello & Britski 1990	Piau-bosteiro	SS
Schizodon knerii	(Steindachner 1875)	Piau-capim / Piau-branco	TM
Schizodon nasutus[M]	Kner 1858	Taguara	All but BG/IR/RO/TM
CRENUCHIDAE			
Characidium sp.	-	Mocinha / Canivete	QM
CHARACIDAE			
Astyanax altiparanae	Garutti & Britski 2000	Lambari-do-rabo- amarelo	All but BG/IR/RO/TM
Astyanax bimaculatus	(Linnaeus 1758)	Lambari-do-rabo- amarelo	TM
Astyanax fasciatus	(Cuvier 1819)	Lambari-do-rabo-vermelho	All but BG/MR/RO/SS
Astyanax schubarti	Britski 1964	Lambari	FU
Brycon sp.	-	Piabanha	IR

Continued

ORDER/FAMILY/SPECIES	AUTHORSHIP	COMMON NAME	DAM WHERE IT WAS SAMPLED*
Brycon cephalus[E,M]	(Günther 1869)	Matrinchã	VG
Brycon orbignyanus[M]	(Valenciennes 1850)	Piracanjuba	CM/IT/NP/SS
Brycon orthotaenia[M]	Günther 1864	Matrinchã	TM
Bryconamericus exodon[E]	Eigenmann 1907	Piaba	CM/EM
Bryconamericus stramineus	Eigenmann 1908	Piaba	FU/IT
Galeocharax knerii	(Steindachner 1879)	Peixe-cachorro / Cadela	All but AS/BG/ CM/ IR/RO/ TM/VG
Hasemania sp.	-	Lambari	QM
Hyphessobrycon sp.	-	Lambarizinho	QM
Metynnis lippincottianus[E]	(Cope 1870)	Pacu-cd	MR/SS
Metynnis maculatus[E]	(Kner 1858)	Pacu-cd	EM/MR/NP/ PJ/SS/TM
Moenkhausia intermedia	Eigenmann 1908	Piaba / Maco-nheirinho	EM
Moenkhausia intermedia	Eigenmann 1908	Piaba / Maco-nheirinho	EM
Myleus micans	(Lütken 1875)	Pacu	TM
Myloplus tiete	(Eigenmann & Norris 1900)	Pacu-prata	AF
Oligosarcus argenteus	Günther 1864	Peixe-cachorro	PE
Oligosarcus paranensis	Menezes & Géry 1983	Saicanga	CM/FU/IT
Oligosarcus pintoi	Campos 1945	Lambari	FU
Piaractus mesopotamicus[M]	(Holmberg 1887)	Pacu-caranha	SS
Colossoma macropomum[E,M]	(Cuvier 1816)	Tambaqui	SS

Continued

ORDER/FAMILY/SPECIES	AUTHORSHIP	COMMON NAME	DAM WHERE IT WAS SAMPLED*
Pygocentrus nattereri	Kner 1858	Piranha-vermelha	PJ
Pygocentrus piraya	(Cuvier 1819)	Piranha-amarela	TM
Roeboides descalvadensis[E]	Fowler 1932	Saicanga	SS
Salminus brasiliensis[M]	(Cuvier 1816)	Dourado	FU/IT
Salminus hilarii[M]	Valenciennes 1850	Tabarana	IT/PJ/TM
Salminus franciscanus[M]	Lima & Britski, 2007	Dourado	TM
Serrasalmus brandtii	Lütken 1875	Pirambeba	TM
Serrasalmus maculatus	Kner 1858	Pirambeba	AS/AF/EM/PJ/SS/VG
Serrasalmus marginatus	Valenciennes 1837	Pirambeba	AS/EM/SS
Tetragonopterus chalceus	Spix & Agassiz 1829	Piaba-rapadura	TM
Triportheus guentheri	(Garman 1890)	Piaba-facão	TM
ACESTRORHYCHIDAE			
Acestrorhynchus lacustris	(Lütken 1875)	Peixe-cachorro	AF/MR/NP/TM
CYNODONTIDAE			
Rhaphiodon vulpinus[M]	Spix & Agassiz 1829	Cachorro-facão	SS
ERYTHRINIDAE			
Hoplias intermedius	(Günther 1864)	Traírão	All but AF/BG/IR/RO
Hoplias malabaricus	(Bloch 1794)	Traíra	All but BG/FU/JG/TM/VG/RO

Continued

ORDER/FAMILY/SPECIES	AUTHORSHIP	COMMON NAME	DAM WHERE IT WAS SAMPLED*
SILURIFORMES			
CALLICHTHYIDAE			
Hoplosternum littorale	(Hancock 1828)	Tamboatá	AS/EM
LORICARIIDAE			
Delturus carinotus	(La Monte 1933)	Cascudo	PE
Hypostomus spp.	-	Cascudo	All but BG/RO
Hypostomus affinis	(Steindachner 1877)	Cascudo	SS
Hypostomus commersoni	Valenciennes 1836	Cascudo-avião	SS
Hypostomus francisci	(Lütken 1874)	Cascudo	TM
Hypostomus cf. margaritifer	(Regan 1908)	Cascudo	CM/FU/TM
Loricaria lentiginosa	Isbrücker 1979	Cascudo-chinelo	JG/VG
Loricaria sp.	-	Cascudo-chinelo	SS
Megalancistrus parananus	(Peters 1881)	Cascudo-abacaxi	AS/MR/SS/VG
Pterygophlichthys anisitsi	Eigenmann & Kennedy 1903	Cascudo	SS
Rineloricaria sp.	-	Cascudo-chinelo	AF
Rhinelepis aspera[M]	Spix & Agassiz 1829	Cascudo-preto	TM
PSEUDOPIMELODIDAE			
Cephalosilurus fowleri	Haseman 1911	Pacamã / Lobó	TM
Lophiosilurus alexandri	Steindachner 1876	Pacamã	TM

Continued

ORDER/FAMILY/SPECIES	AUTHORSHIP	COMMON NAME	DAM WHERE IT WAS SAMPLED*
Pseudopimelodus charus	(Valenciennes 1840)	Peixe-sapo	TM
Pseudopimelodus mangurus	(Valenciennes 1835)	Bagre-sapo	AS/AF/EM/MR/SS/PJ
Zungaro jahu^{M}	(Ihering 1898)	Jaú	SS
HEPTAPTERIDAE			
Pimelodella avanhandavae	Eigenmann 1917	Mandi-chorão	AS/CM/EM/FU/PJ/SS
Pimelodella sp.		-	Mandi-chorão
Rhamdia quelen^{M}	(Quoy & Gaimard 1824)	Bagre	AS/EM/PJ/SS
PIMELODIDAE			
Bergiaria westermanni	(Lütken 1874)	Mandi-beiçudo	TM
Conorhynchos conirostris^{M}	(Valenciennes 1840)	Pirá	TM
Duopalatinus emarginatus	(Valenciennes 1840)	Mandi-açu	TM
Hemisorubim platyrhynchos	(Valenciennes 1840)	Jurupoca	SS
Iheringichthys labrosus	(Lütken 1874)	Mandi-beiçudo	All but BG/IR/RO/TM/VG
Megalonema platanum^{E,M}	(Günther 1880)	Bagre	AS
Pimelodus argenteus	Perugia 1891	Mandi	PJ
Pimelodus fur	(Lütken 1874)	Mandi-prata	TM
Pimelodus maculatus^{M}	Lacepède, 1803	Mandi / Mandi-amarelo	All but RO
Pimelodus microstoma	Steindachner 1877	Mandi	All but BG/FU/JG/IR/NP/RO/ TM/VG

Continued

ORDER/FAMILY/SPECIES	AUTHORSHIP	COMMON NAME	DAM WHERE IT WAS SAMPLED*
Pimelodus paranaensis	Britski & Langeani 1988	Mandi	AS/EM/PJ
Pimelodus pohli	Ribeiro & Lucena 2006	Mandizinho	TM
Pinirampus pirinampu[M]	(Spix & Agassiz 1829)	Barbado	AS/AF/EM/MR/PJ/SS
Pseudoplatystoma corruscans[M]	(Spix & Agassiz 1829)	Surubim / Pintado	AS/EM/SS/TM
Pseudoplatystoma fasciatum[E,M]	(Linnaeus 1766)	Pintado	SS
TRICHOMYCTERIDAE			
Trichomycterus sp.	-	Candiru/ Cambeva	SC
DORADIDAE			
Rhinodoras dorbignyi	(Kner 1855)	Abotoado	AS/AF/EM/SS
Franciscodoras marmoratus	(Reinhardt 1874)	Serrudo	TM
Wertheimeria maculata	Steindachner 1877	Roncador	IR
AUCHENIPTERIDAE			
Pseudoauchenipterus sp.	-	Judeu	IR
Trachelyopterus galeatus	(Linnaeus 1766)	Babão / Cangati	AS/AF/NP/PJ
Trachelyopterus striatulus	(Steindachner 1877)	Jauzinho	IR
GYMNOTIFORMES			
GYMNOTIDAE			
Gymnotus aff. carapo	Linnaeus 1758	Sarapó	PE/QM/SC
Gymnotus sylvius	Albert & Fernandes-Matioli 1999	Sarapó	AS/PJ

Continued

ORDER/FAMILY/SPECIES	AUTHORSHIP	COMMON NAME	DAM WHERE IT WAS SAMPLED*
STERNOPYGIDAE			
Eigenmannia virescens	(Valenciennes 1842)	Tuvira	AS/CM/EM/ IT/ JG/MR/SS
APTERONOTIDAE			
Apteronotus ellisi	(Alonso de Arámburu 1957)	Ituí	AS/SS
SYNBRANCHIFORMES			
SYNBRANCHIDAE			
Synbranchus marmoratus	Bloch 1795	Mussum	SC
PERCIFORMES			
SCIAENIDAE			
Pachyurus squamipennis	Agassiz 1831	Corvina	TM
Pachyurus francisci	(Cuvier 1830)	Corvina	TM
Plagioscion squamosissimus[E]	(Heckel 1840)	Corvina	JG/SS/VG
CICHLIDAE			
Cichla kelberi[E]	Kullander & Ferreira 2006	Tucunaré-amarelo	AD/AU/EM/ MR/NP/SS/ TM
Cichla piquiti[E]	Kullander & Ferreira 2006	AS/AF/EM/ MR/NP/ SS/ TM	AD/AU/EM/ JG/PJ/ SS/TM
Cichlasoma paranaense	Kullander 1983	Cará	AS/VG
Crenicichla haroldoi	Luengo & Britski 1974	Joaninha / João-bobo	EM/SS
Crenicichla jaguarensis	Haseman 1911	Joaninha / João-bobo	AS/EM/JG/SS/ VG

Continued

ORDER/FAMILY/SPECIES	AUTHORSHIP	COMMON NAME	DAM WHERE IT WAS SAMPLED*
Geophagus brasiliensis	(Quoy & Gaimard 1824)	Cará	AS/AF/CM/SS/SC
Geophagus proximus[E]	(Castelnau 1855)	Cará	SS
Oreochromis niloticus[E]	(Linnaeus 1758)	Tilápia-do-Nilo	AS/AF/NP/SS
Satanoperca pappaterra[E]	(Heckel 1840)	Cará / Papaterra	AS/AF/EM/SS
Tilapia rendalli[E]	(Boulenger 1897)	Tilápia	AF/VG
CYPRINODONTIFORMES			
POECILIIDAE			
Poecilia vivipara[E]	Bloch & Schneider 1801	Barrigudinho	SC
CYPRINIFORMES			
CYPRINIDAE			
Cyprinus carpio[E]	Linnaeus 1758	Carpa	SC

E: non-native fish on the São Francisco River or upper Paraná River basins according to Reis et al. (2003) and Langeani et al. (2007).
M: long-distance migratory fish according to Carolsfeld et al. (2003), Agostinho et al. (2007), and Graça & Pavanelli (2007).
*: AF = Amador Aguiar I Dam, AS = Amador Aguiar II Dam, BG = Baguari Dam, CM = Camargos Dam, EM = Emborcação Dam, FU = Funil Dam, IR = Irapé Dam, IT = Itutinga Dam, JG = Jaguara Dam, MR = Miranda Dam, NP = Nova Ponte Dam, PJ = PCH Pai Joaquim Dam, PE = Porto Estrela Dam, QM = Queimado Dam, SC = Sá Carvalho Dam, SS = São Simão Dam, RO = Rosal Dam, TM = Três Marias Dam, and VG = Volta Grande Dam.

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SÉRIE
PEIXE VIVO

FISH AND
HYDROPOWER PLANTS

APPENDIX B

HYDROPOWER PLANTS
SPECIFICATIONS

Loures R.C. & Godinho A.L (ed.) *Risk assessment of fish death at hydropower plants in southeastern Brazil.* Belo Horizonte: Companhia Energética de Minas Gerais , pp. 307 - 327 (Série Peixe Vivo, 6).

Specifications of the hydropower plants studied in the project Risk Assessment of Fish Death at Hydropower Plants.

AMADOR AGUIAR I (formerly Capim Branco I)

Municipalities: *Araguari and Uberlândia*
State: *Minas Gerais*
Start of operation: *2006*
River basin: *Paranaíba*
River: *Araguari*
Dam (m): *660 length and 55 height*
Reservoir area (km^2): *18.66*
Installed capacity (MW): *240*
Number of turbines: *3*
Turbine power (MW): *80*
Turbine type: *Francis*
Rated head (m): *54.1*
Maximum turbine discharge (m^3/s): *169.5*
Spillway type: *Gated overflow*
Number of spillway gates: *3 (tainter gate)*
Maximum spillway discharge (m^3/s): *9,354*
Coordinates (decimal degree): *lat -18.7890916770 and long -48.1485464689*

AMADOR AGUIAR II (formerly Capim Branco II)

Municipalities: *Araguari and Uberlândia*
State*: Minas Gerais*
Start of operation: *2006*
River basin: *Paranaíba*
River: *Araguari*
Dam (m): *980 length and 57 height*
Reservoir area (km^2): *45.11*
Installed capacity (MW): *210*
Number of turbines: *3*
Turbine power (MW): *70*
Turbine type: *Kaplan*
Rated head (m): *43.4*
Maximum turbine discharge (m^3/s): *170*
Spillway type: *Gated overflow*
Number of spillway gates: *3 (tainter gate)*
Maximum spillway discharge (m^3/s): *8,990*
Coordinates (decimal degree): *lat -18.6592101649 and long -48.4374511997*

BAGUARI

Municipality: *Governador Valadares*
State: *Minas Gerais*
Start of operation: *2010*
River basin: *Doce*
River: *Doce*
Dam (m): *478 length and 25 height*
Reservoir area (km²): *16.06*
Installed capacity (MW): *140*
Number of turbines: *4*
Turbine power (MW): *35*
Turbine type: *Bulb*
Rated head (m): *17.3*
Maximum turbine discharge (m³/s): *224.4*
Spillway type: *Gated overflow*
Number of spillway gates: *6 (tainter gate)*
Maximum spillway discharge (m³/s): *12,800*
Coordinates (decimal degree): *lat -19.0209278367 and long -42.1249188320*

CAMARGOS

Municipality: *Itutinga*
State: *Minas Gerais*
Start of operation: *1960*
River basin: *Grande*
River: *Grande*
Dam (m): *608 length and 36 height*
Reservoir area (km^2): *73.35*
Installed capacity (MW): *45*
Number of turbines: *2*
Turbine power (MW): *22.5*
Turbine type: *Kaplan*
Rated head (m): *25*
Maximum turbine discharge (m^3/s): *118*
Spillway type: *Gated overflow*
Number of spillway gates: *2 (bottom valve) and 6 (bottom gate)*
Maximum spillway discharge (m^3/s): *2,224*
Coordinates (decimal degree): *lat -21.3250290791 and long -44.6161147522*

EMBORCAÇÃO

Municipality: *Araguari*
State: *Minas Gerais*
Start of operation: *1982*
River basin: *Paranaíba*
River: *Paranaíba*
Dam (m): *1,507 length and 158 height*
Reservoir area (km^2): *408.08*
Installed capacity (MW): *1,192*
Number of turbines: *4*
Turbine power (MW): *298*
Turbine type: *Francis*
Rated head (m): *128.5*
Maximum turbine discharge (m^3/s): *239.5*
Spillway type: *Gated overflow*
Number of spillway gates: *4 (tainter gate)*
Maximum spillway discharge (m^3/s): *8,200*
Coordinates (decimal degree): *lat -18.4515579784 and long -47.9871301044*

FUNIL

Municipalities: *Lavras and Perdões*
State: *Minas Gerais*
Start of operation: *2003*
River basin: *Grande*
River: *Grande*
Dam (m): *420 length and 50 height*
Reservoir area (km^2): *42.65*
Installed capacity (MW): *180*
Number of turbines: *3*
Turbine power (MW)*: 60*
Turbine type: *Kaplan*
Rated head (m): *40*
Maximum turbine discharge (m^3/s): *194*
Spillway type: *Gated overflow*
Number of spillway gates: *4 (tainter gate)*
Maximum spillway discharge (m^3/s): *8,348*
Coordinates (decimal degree): *lat -21.1436437383 and long -45.0366623360*

IRAPÉ

Municipalities: *Berilo and Grão-Mogol*
State: *Minas Gerais*
Start of operation: *2006*
River basin: *Jequitinhonha*
River: *Jequitinhonha*
Dam (m): *540 length and 205 height*
Reservoir area (km^2): *142.95*
Installed capacity (MW): *360*
Number of turbines: *3*
Turbine power (MW): *120*
Turbine type: *Francis*
Rated head (m): *158.5*
Maximum turbine discharge (m^3/s): *260*
Spillway type: *Gated ogee crest*
Number of spillway gates: *4 (tainter gate)*
Maximum spillway discharge (m^3/s): *7,503*
Coordinates (decimal degree): *lat -16.7398962206 and long -42.5723005205*

ITUTINGA

Municipality: *Itutinga*
State: *Minas Gerais*
Start of operation: *1955*
River basin: *Grande*
River: *Grande*
Dam (m): *550 length and 23 height*
Reservoir area (km²): *1.72*
Installed capacity (MW): *52*
Number of turbines: *4*
Turbine power (MW): *2(12.5); 2(13.5)*
Turbine type: *Kaplan (3); Hélice (1)*
Rated head (m): *25*
Maximum turbine discharge (m³/s): *2 (58); 2(63)*
Spillway type: *Free overflow and gated overflow*
Number of spillway gates: *5 (tainter gate)*
Maximum spillway discharge (m³/s): *1,554*
Coordinates (decimal degree): *lat -21.2917247842 and long -44.6252790628*

JAGUARA

Municipality: *Sacramento and Rifaina*
States: *Minas Gerais and São Paulo*
Start of operation: *1971*
River basin: *Grande*
River: *Grande*
Dam (m): *325 length and 40 height*
Reservoir area (km^2): *34.6*
Installed capacity (MW): *424*
Number of turbines: *4*
Turbine power (MW): *108*
Turbine type: *Francis*
Rated head (m): *45*
Maximum turbine discharge (m^3/s): *265.5*
Spillway type: *Gated overflow*
Number of spillway gates: *6 (tainter gate)*
Maximum spillway discharge (m^3/s): *14,100*
Coordinates (decimal degree): *lat -20.0235636944 and long -47.4339493889*

MIRANDA

Municipality: *Indianápolis*
State: *Minas Gerais*
Start of operation: *1998*
River basin: *Paranaíba*
River: *Araguari*
Dam (m): *1,050 length and 79 height*
Reservoir area (km²): *51.86*
Installed capacity (MW): *408*
Number of turbines: *3*
Turbine power (MW): *136*
Turbine type: *Francis*
Rated head (m): *67.4*
Maximum turbine discharge (m³/s): *216.5*
Spillway type: *Gated overflow*
Number of spillway gates: *4 (tainter gate)*
Maximum spillway discharge (m³/s): *9,000*
Coordinates (decimal degree): *lat -18.9097995895 and long -48.0409225668*

NOVA PONTE

Municipality: *Nova Ponte*
State: *Minas Gerais*
Start of operation: *1994*
River basin: *Paranaíba*
River: *Araguari*
Dam (m): *1,620 length and 142 height*
Reservoir area (km^2): *449.24*
Installed capacity (MW): *510*
Number of turbines: *3*
Turbine power (MW): *170*
Turbine type: *Francis*
Rated head (m): *96*
Maximum turbine discharge (m^3/s): *190*
Spillway type: *Gated overflow*
Number of spillway gates: *4 (tainter gate)*
Maximum spillway discharge (m^3/s): *5,800*
Coordinates (decimal degree): *lat -19.1330341149 and long -47.6977681528*

PAI JOAQUIM

Municipalities: *Sacramento and Santa Juliana*
State: *Minas Gerais*
Start of operation: *2004*
River basin: *Paranaíba*
River: *Araguari*
Dam (m): *212 length and 10 height*
Reservoir area (km^2): *0.5*
Installed capacity (MW): *23*
Number of turbines: *1*
Turbine power (MW): *23*
Turbine type: *Kaplan*
Rated head (m): *26.5*
Maximum turbine discharge (m^3/s): *87.5*
Spillway type: *(ungated) ogee crest spillway*
Number of spillway gates: *2 (bottom gate)*
Maximum spillway discharge (m^3/s): *2,230*
Coordinates (decimal degree): *lat -19.4858810135 and long -47.5419020359*

PORTO ESTRELA

Municipalities: *Joanésia and Açucena*
State: *Minas Gerais*
Start of operation: *2001*
River basin: *Doce*
River: *Santo Antônio*
Dam (m): *420 length and 61 height*
Reservoir area (km^2): *0.17*
Installed capacity (MW): *112*
Number of turbines: *2*
Turbine power (MW): *66*
Turbine type: *Kaplan*
Rated head (m): *49.3*
Maximum turbine discharge (m^3/s): *125.92*
Spillway type: *Gated overflow*
Number of spillway gates: *3 (tainter gate)*
Maximum spillway discharge (m^3/s): *6,157*
Coordinates (decimal degree): *lat -19.1168052683 and long -42.6628655952*

QUEIMADO

Municipalities: *Unaí and Cristalina*
States: *Minas Gerais and Góias*
Start of operation: *2004*
River basin: *São Francisco*
River: *Preto*
Dam (m): *1,060 length and 70 height*
Reservoir area (km^2): *39.43*
Installed capacity (MW): *105*
Number of turbines: *3*
Turbine power (MW): *35*
Turbine type: *Francis*
Rated head (m): *168*
Maximum turbine discharge (m^3/s): *21.5*
Spillway type: *Gated overflow*
Number of spillway gates: *3 (tainter gate)*
Maximum spillway discharge (m^3/s): *1,959*
Coordinates (decimal degree): *lat -16.2092371832 and long -47.3104184477*

ROSAL

Municipalities: *Bom Jesus do Itabapoana, Guaçuí, and São José do Calçado*
States: *Rio de Janeiro and Espírito Santo*
Start of operation: *1999*
River basin: *Itabapoana*
River: *Itabapoana*
Dam (m): *159.5 length and 36.0 height*
Reservoir area (km^2): *1.91*
Installed capacity (MW): *55*
Number of turbines: *2*
Turbine power (MW): *27.5*
Turbine type: *Francis*
Rated head (m): *170*
Maximum turbine discharge (m^3/s): *16.3*
Spillway type: *free overflow*
Number of spillway gates: *0*
Maximum spillway discharge (m^3/s): *717*
Coordinates (decimal degree): *lat -20.9538364223 and long -41.7167084540*

SÁ CARVALHO

Municipality: *Antônio Dias*
State: *Minas Gerais*
Start of operation: *1951*
River basin: *Doce*
River: *Piracicaba*
Dam Antônio Dias(m): *112 length and 15 height*
Reservoir area (km^2): *1.5*
Installed capacity (MW): *78*
Number of turbines: *4*
Turbine power (MW): *14.7(2), 16.9(1), and 31.5(1)*
Turbine type: *Francis*
Rated head (m): *110*
Maximum turbine discharge (m^3/s): *83.76*
Spillway type Antônio Dias: *Gated overflow*
Number of spillway gates: *2 (bottom gate) and 5 (tainter gate)*
Maximum spillway discharge (m^3/s): *1,138*
Coordinates (decimal degree): *lat -19.6355751652 and long -42.8061830804*

SÃO SIMÃO

Municipalities: *Santa Vitória and São Simão*
States: *Minas Gerais and Góais*
Start of operation: *1978*
River basin: *Paranaíba*
River: *Paranaíba*
Dam (m): *3,440 length and 127 height*
Reservoir area (km^2): *703.29*
Installed capacity (MW): *1,710*
Number of turbines: *6*
Turbine power (MW): *285*
Turbine type: *Francis*
Rated head (m): *72*
Maximum turbine discharge (m^3/s): *425*
Spillway type: *Gated overflow*
Number of spillway gates: *9 (tainter gate)*
Maximum spillway discharge (m^3/s): *24,100*
Coordinates (decimal degree): *lat -19.0191994986 and long -50.4993287460*

TRÊS MARIAS

Municipalities: *Três Marias*
State: *Minas Gerais*
Start of operation: *1962*
River basin: *São Francisco*
River: *São Francisco*
Dam (m): *2,700 length and 75 height*
Reservoir area (km^2): *1,090*
Installed capacity (MW): *396*
Number of turbines: *6*
Turbine power (MW): *66*
Turbine type: *Kaplan*
Rated head (m): *46.1*
Maximum turbine discharge (m^3/s): *150*
Spillway type: *Gated overflow*
Number of spillway gates: *7 (tainter gate)*
Maximum spillway discharge (m^3/s): *8,700*
Coordinates (decimal degree): *lat -18.2131859540 and long -45.2616676323*

VOLTA GRANDE

Municipalities: *Conceição das Alagoas and Miguelópolis*
States: *Minas Gerais and São Paulo*
Start of operation: *1974*
River basin: *Grande*
River: *Grande*
Dam (m): *2,329 length and 56 height*
Reservoir area (km^2): *205*
Installed capacity (MW): *380*
Number of turbines: *4*
Turbine power (MW): *95*
Turbine type: *Kaplan*
Rated head (m): 26.2
Maximum turbine discharge (m^3/s): *450*
Spillway type: *Gated overflow*
Number of spillway gates: *10 (tainter gate)*
Maximum spillway discharge (m^3/s): *12,700*
Coordinates (decimal degree): *lat -20.0333955960 and long -48.2224522408*

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VI

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