Reaction of ichthyofauna in the amazon region to different sound impulses

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ABSTRACT
This work is part of a research and development project (R&D - 06631-0009/2019), which aims to develop and validate technological strategies integrating physicochemical systems for the repulsion of the ichthyofauna from the suction pipe during the shutdown of the generating units of the Jirau Hydroelectric Power Plant, located on the Madeira River, state of Rondônia, Brazil. One of the strategies is the acoustic barrier, which is being developed to meet the particularities of the Amazonian fish species in the study area. The barrier will prevent and/or minimize fish entering the suction pipes during turbine stops and restarts. In the first stage, acoustic parameters were identified: auditory threshold and hearing frequency range of the most common fish caught at the plant. In the second stage, computer simulations were carried out that defined the configuration and power of the sound source required for the barrier. In the third stage, the characterization of aerial and underwater sounds in the vicinity of the plant was carried out. In this stage, in situ tests were carried out using the simulated arrangement with the sound source of the Lubell LL916 and the C75 hydrophone of Cetacean Research, testing the efficiency of 4 different noise configurations: pink, thunder, shooting and with well-defined tonal components. The tests were carried out at the spillway of the Jirau Hydroelectric Power Plant, where the movement of fish was monitored before and during the activation of the sound source. The results indicated that all the different types of sounds have the potential to increase the movement of the fish, but with different performances. Sound generated with tonal components increased movement by 57 percent, thunder noise by 43 percent, gunshot noise by 37 percent, and pink noise by 29 percent. These results are promising and will be applied in tests on suction tubes in the next stage of the study.

Keywords: Sound barrier, Amazonian fish, Turbines, Hydroelectric, Underwater noise.

1 INTRODUCTION

In recent years, Brazil has shown significant advances in the production of wind and solar energy. Despite this, hydraulic energy from hydroelectric plants still represents a relevant portion of the Brazilian electricity matrix, corresponding to about 65% (ANEEL, 2020). Although it is considered a clean and renewable energy source (BONDARIK, 2018), the operation of these projects can generate significant environmental impacts, such as changes in waterways and local aquatic fauna (CEMIG, 2015; ALBIERI & ARAÚJO, 2021).

Adverse impacts on fish populations such as changes in spatial distribution and behavior, stress, temporary hearing loss, and other damage to the auditory system resulting from the operation and maintenance of hydroelectric power plants are reported in the literature (REIS *et al*., 2016; EEA, 2020). In the case of these projects, a major environmental challenge is to maintain the functionality of the river continuum, allowing the transit of fish between the areas altered by the dam in the river (DE QUEIROZ *et al*., 2013; SANTOS *et al.*, 2020).

To preserve migratory fish routes and minimize possible impacts, hydroelectric power plants have adopted fish transposition systems and studied repulsion alternatives to avoid the accumulation of specimens at the foot of dams, which can result in deaths in turbines and spillways, especially during scheduled or untimely maintenance (CEMIG, 2015).

Several strategies have been developed with the aim of repelling fish, and recent studies have shown that the use of acoustic barriers can be a highly effective technique in the hydroelectric sector. Acoustic barriers have been applied to prevent fish from entering suction pipes of hydroelectric plants and factories, in addition to guiding them to safe routes, minimizing potential damage to the ichthyofauna (JESUS et al., 2019).

This work is part of a research and development project (R&D ANEEL-06631-0009/2019) whose objective is to create and validate technological strategies that integrate physicochemical systems to repel the ichthyofauna of the suction pipe during the shutdown of generating units in hydroelectric plants. One of these strategies is the acoustic barrier, which is being developed to meet the particularities of the Amazonian fish species present in the study area.

From this perspective, this work presents the results of the fourth stage of the development of the acoustic barrier. In situ tests were carried out with an underwater acoustic source and a hydrophone to verify the efficiency of four different noise settings. The results presented are preliminary, but provide a satisfactory initial assessment of the effectiveness of each type of noise used.

The selection and development of the noises used in this study were based on the results obtained in the previous stages of the development of the acoustic barrier. In the first stage, a survey was made of the species detected in the suction pipes of the Jirau Hydroelectric Power Plant (HPP) in recent years and compared with data from studies in other countries, considering the order/family of equivalent fish, since specific data for Amazonian fish are not available. The results indicate that the sound source for the production of the acoustic barrier suitable for the ichthyofauna of the Madeira River must have an intensity of at least 161 dB (re 1μPa) and be able to reproduce both low and medium frequencies, in the range of 100 to 5000 Hz, the audible range of the species detected in the plant (DIAS et al., 2020).

In the second stage of the project, computer simulations were carried out to define the configuration and power of the sound source necessary for the construction of the acoustic barrier. As a result, it was verified that, in principle, a single high-power underwater sound source (180 dB re 1μPa) would be sufficient to produce the acoustic barrier.

In the third stage, the characterization of aerial and underwater sounds in the vicinity of the Jirau HPP was carried out. The results indicate that the airborne environmental noise (SPL) in the external area of the plant and in the surrounding forest area are within the values established by the current standards. The sound spectrum does not present tonal sounds, even in measurements made at points close to the generating units. Sound levels range from 65 dB in the vicinity of the power house, where there is a flow of vehicles, to values close to 40 dB in the forest area surrounding the plant. Additionally, it was found that the underwater noise generated by the hydroelectric power plant's generating units has a limited impact on its immediate area of influence, with the underwater soundscape returning to its basal level about 5 km away from the emitting source.

2 METHODOLOGY

2.1 AREA OF STUDY

The study area comprises the Jirau HPP, the fourth largest hydroelectric plant in terms of installed power generation in Brazil, with 50 bulb-type generating units (UG), resulting in an installed capacity of 3,750 MW. The plant was implemented in 2010 on the Madeira River, 120 km from Porto Velho, in the state of Rondônia, and has been in operation since October 2013. The flooded area varies throughout the year (21.0 km2 to 207.7 km2), depending on the hydrological cycles of the region, however the reservoir area is 361.6 km2 (DIAS *et al*., 2020).

The Jirau Hydroelectric Power Plant consists of 50 generating units, which are distributed in two power houses: one located on the right bank, comprising the generating units from UG01 to UG28, and another located on the left bank, comprising the generating units from UG29 to UG50. Between the two power houses, there is the spillway, which consists of 18 spans (ESBR, 2021). **Figure 1** illustrates the power house on the right bank as well as the spillway.

Figure 1 – Structure of the study areas of the Jirau HPP (Source: Google Earth) with emphasis on (a) View span 18 of the spillway, with a closed gate upstream, preventing the flow of water through the downstream opening (Source: Authors), and (b) Front view of the suction pipes.

(Source: ESBR, 2021).

In the process of selecting the site for the pilot test, safety criteria, similarity with the suction pipes of the generating units in relation to dimensions, and the presence of fish were used. Thus, the chosen location was span 18 of the plant's spillway. The measurements were carried out during the hydrological dry season, when the spillway remains closed upstream most of the time. The spillway openings of the Jirau HPP have dimensions similar to those of the suction pipe. The front opening downstream of span 18 is 12 meters wide, 14 meters long, and 18 meters deep (**Figure 2**).

Figure 2 – Dimensions of span 18 of the Jirau HPP spillway.

Source: Authors.

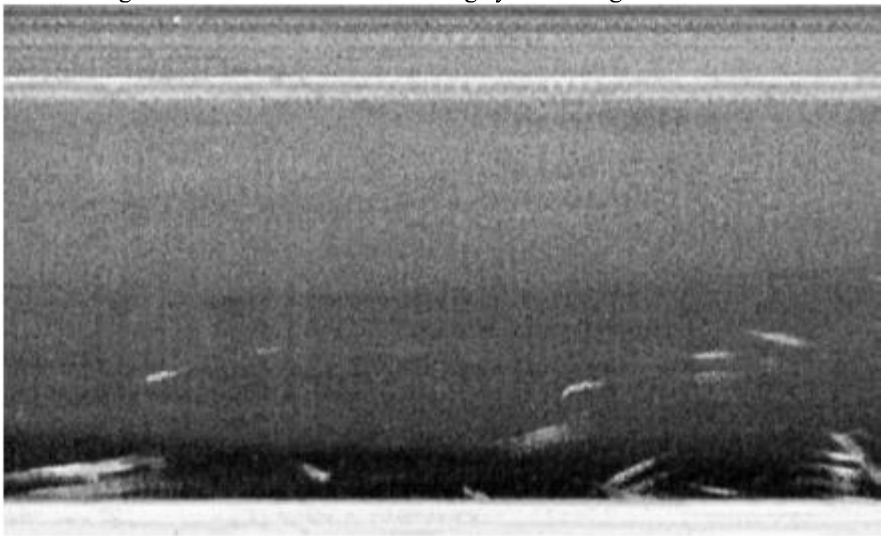
2.2 MONITORING OF THE ICHTHYOFAUNA

To evaluate in real time the movement of the ichthyofauna present in the inner part of span 18 of the spillway of the Jirau Hydroelectric Power Plant, the low and high frequency sweeping hydroacoustic system developed by Venturo Environmental Consulting and adapted to the conditions of the spillway span was used. For this, a transducer was positioned close to the waterline in the region downstream of the spillway, which was connected by a specific cable resistant to the hydroacoustic equipment (DA SILVA et al., 2022).

The imaging system used different frequencies, allowing the demarcation of specific coverage areas for the movement of the ichthyofauna in the inner part of the span. The hydroacoustic system was adjusted for frequencies from 455 to 880 kHz, with a horizontal beamwidth of 0.9 degrees, a vertical beamwidth of 39 degrees, and a vertical tilt angle of 26 degrees (DA SILVA et al., 2022).

The images obtained were analyzed, and the number of movements per minute was counted for each measurement. **Figure 3** shows the white lines superimposed on the background, which represent the movement of the ichthyofauna recorded by the sonar.

Figure 3 – Screen image of the fish movement counting system using sonar on the inside of the spillway.



Source: Authors.

2.3 NOISE PRODUCED FOR SOUND BARRIER TESTING

Based on the results obtained in the first and third stages of the project, four types of noise were produced for the sound barrier test: Pink Noise (Standard), Ramp Noise (500 to 4000Hz), Thunder (low and medium frequencies) and Shooting (low and medium frequencies - Pulse). To this end, the noises were produced using the FL Studio and Audacity audio editors. Sounds generated in the editors and sounds available in the BBC *Sound Effects repository* were used (BBC, 2022).

To emit noise during the test, an acoustic source composed of a Lubell LL916 underwater speaker (with a maximum output level of 180 dB/µPa/m @ 1kHz and frequency response of 200Hz-23kHz), an AC1400 amplifier and accessories was used. The loudspeaker was centrally positioned at the entrance to the spillway, downstream, at a depth of 9 meters. Next to the loudspeaker, the hydrophone was positioned, at a depth of 9 meters and 1 meter to the right of the source. Cetacean Research Technology's C75 hydrophone assembly was connected to the calibrated SpectraDAQ-200 USB interface. The interface collected the measurement data using the Spectra Plus-SC software. Both the source and the hydrophone were controlled by a computer at the top of the spillway (**Figure 4**).

Figure 4 – Acoustic and ichthyofauna monitoring system implemented in the spillway of the Jirau HPP.

(Source: Authors).

2.4 PILOT TEST OF THE ACOUSTIC BARRIER AT THE SPILLWAY

The tests were carried out between November 4 and 12, 2021, the hydrological period of drought of the Madeira River. In order to verify the existence of sonar influence on underwater residual noise, on the first day of the experiment, initial measurements were made in the frequency ranges from 10Hz to 20kHz. To this end, residual noise was measured with sonar on and off for later comparison.

For the acoustic barrier test, the noises were divided into two groups: GROUP 1: (i) Pink and (ii) Ramp; and GROUP2: (iii) Thunder and (iv) Shooting. The groups were tested on alternate days, with four measurements of the same group of noises on each day: two in the morning and two in the afternoon. A total of six measurements were obtained for each type of noise, totaling 24 measurements.

The experimental procedure for the measurements followed the following protocol: Initially, the underwater residual noise was measured for three minutes with the hydrophone to evaluate the variation in the intensity of the residual noise over time. Then, the monitoring of the movement of the fish in the inner part of the span began. After 15 minutes of monitoring, the first sound began to be emitted, which continued for 15 minutes. At the end of this period, the sound was turned off and the monitoring of the fish was maintained for another 30 minutes. The same procedure was then repeated for the second sound of the morning. In the afternoon, the measurements taken in the morning were repeated.

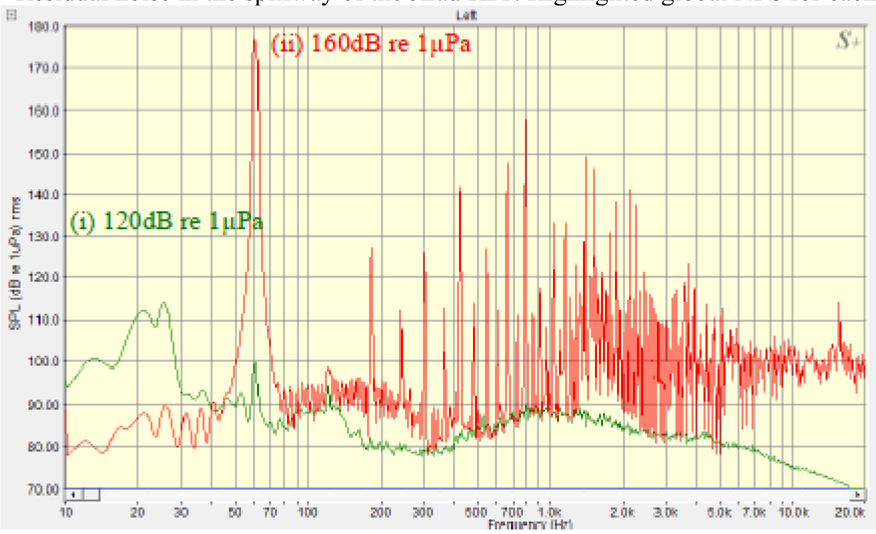
3 RESULTS AND DISCUSSIONS

During the spillway test to assess the influence of sonar on underwater environmental noise measurements, no change in the intensity and spectrum of residual noise was observed when the sonar was operating, in the range of 10Hz to 40kHz.

However, during the first day of the experiment, values higher than those of the initial measurements carried out near the dam were observed, with a strong harmonic tone at 60Hz. This tone appears suddenly, causing the increase in the overall NPS of the measurement of levels around 120dB re 1µPa (measured (i)) to 160dB re 1µPa (measured (ii)) (**Figure 5**), and the discrete peak at 60Hz is replaced by a strong resonant tone at 60Hz.

The sound reproduced is clear and similar to that of a running engine. However, no external noise source was observed in the vicinity of the monitored area during the experiments. Thus, it is possible that this noise originates from the machinery of the spillway gates, given that the sound frequency of 60Hz and the sudden increase in intensity suggest this possibility. It is important to highlight that no peak at 60Hz was observed in the underwater environmental noise measurements carried out in the vicinity of the dam, which may indicate that the noise from the floodgates did not propagate there, or that other factors influenced its detection.

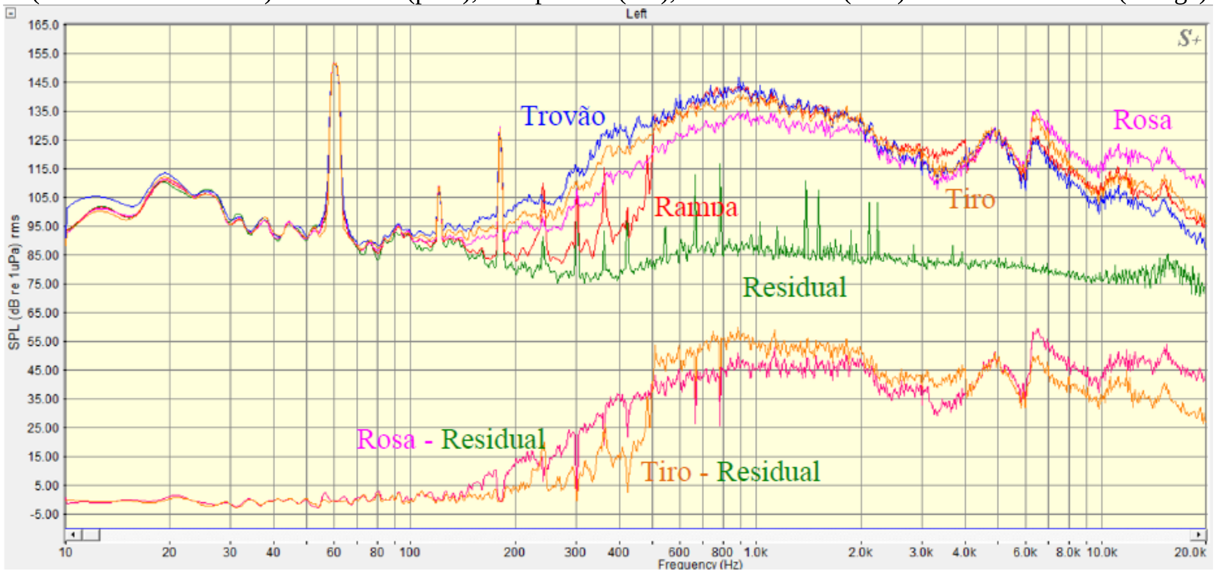
Figure 5 – Residual noise in the spillway of the Jirau HPP. Highlighted global NPS for each measure.



Source: Authors.

In **Figure 6,** the top shows the spectrum of environmental noise in the spillway when the acoustic source plays each of the pre-set noises (with the sonar turned off): Pink noise (pink), Ramp noise (red), Thunder noise (blue), and gunshot noise (orange). Residual noise is displayed in green, when no sound is reproduced by the source. The two curves at the bottom of the figure present the spectra only for the pink noise and the shot noise. Strong resonance of the various types of noise in the suction tube for high frequencies is clearly observed, even for Ramp noise (500Hz-4000Hz). In the lower curves, the absence of sounds below 200Hz is due to the lower frequency response threshold of the underwater speaker being 200Hz (LUBELL, 2022).

Figure 6 – Spectrum of environmental noise in the spillway when the acoustic source reproduces each of the pre-defined noises (with sonar turned off): Pink noise (pink), Ramp noise (red), Thunder noise (blue) and Gunshot noise (orange).



Regarding the movement of fish during the emission of noises, the sound generated with tonal components increased the movement of fish by 57%; thunder noise increased by 43%; gunshot noise increased by 37%; and pink noise increased by 29%. The numbers represent the average variation in fish movement monitored in the 5 minutes before the sound source was turned on, compared to the peak of movements during the 15 minutes that the acoustic source remained running.

The preliminary results presented above indicate that the noises produced by the acoustic source have the potential to generate behavioral responses of the fish present in the spillway. This result is supported by other studies that show the incidence and increase of behavioral responses in fish as a result of the increase in specific sounds (HAWKINS et al., 2014; DELEAU *et al.*, 2019).

It is important to note that sonar is a motion detection system, which uses transducers to send and receive sound waves. This means that the same fish can be detected multiple times by the transducer. Thus, in an open environment, it is not possible to accurately quantify the number of fish during noise barrier tests.

4 CONCLUSIONS

Considering the results presented, it can be inferred that the acoustic barrier is efficient in generating behavioral responses in fish in the underwater environment. The experiments carried out demonstrated that the different types of noise produced by the acoustic source were able to increase the movement of the fish in the spillway. These results are relevant for the hydroelectric sector, since the movement of fish can be directed to safe places and away from risk areas, minimizing the possible environmental impacts of electricity generation. In addition, the use of acoustic barriers can contribute to the development of more efficient strategies for monitoring and conservation of aquatic species, becoming an important tool for water resources management.

However, it is important to emphasize that the research has some limitations that should be considered in future studies. One of the limitations is the impossibility of accurately quantifying the number of fish in the underwater environment, which can affect the analysis of the data and the interpretation of the results. Thus, further studies are needed to evaluate the effectiveness of the acoustic barrier in natural environments and in different environmental conditions, considering different fish species and relevant environmental variables.

Overall, the results of this research have important implications for the hydropower sector and academia. The use of acoustic barriers can contribute to minimize the environmental impacts of electricity generation, preserving aquatic fauna and water resources. In addition, the results obtained can support the development of new technologies and strategies for water resources management, as well as contribute to the advancement of scientific knowledge around acoustic ecology and animal behavior.

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