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Hydraulic flow rate increase maneuver for ichthyofauna repulsion in bulb-type generating units – Jirau Hydroelectric Power Plant

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SUMMARY

Several repulsion systems have been developed to minimize the confinement of ichthyofauna in draft tubes. In this perspective, this study intends to analyze the efficiency of the hydraulic flow rate increase maneuver, using a hydroacoustic system for real-time monitoring of the movement of the ichthyofauna confined within the draft tube of the generating units of Jirau Hydroelectric Power Plant. It is located on the Madeira River, in Rondônia, Brazil. We analyzed footage of 105 machine shutdowns taken between 2019 and 2020 at Jirau Hydroelectric Power Plant that used the hydraulic flow rate increase maneuver as a strategy to repulse ichthyofauna. Also, the footage of 7 two-stage shutdowns in the year 2020 was analyzed, the first stage without the maneuver and the second with the maneuver. The follow-up of 105 shutdowns demonstrate that approximately 85% of the footage showed little or no movement of ichthyofauna in the draft tube, with images of movements showing patterns characteristic of small fish (~97%). Furthermore, the quantitative evaluation of the two-stage maneuver indicated a reduction of approximately 91% in the movement of ichthyofauna after the hydraulic flow rate increase maneuver. Thus, the increase in the rate of the hydraulic flow procedure, developed by Jirau Energia, proved to be an innovative and efficient strategy in reducing extensive social and environmental impacts and in favoring positive economic impacts.

KEYWORDS: Ichthyofauna confinement. Risk. Impact reduction.

1 INTRODUCTION

Brazil holds about 12% of the total volume of fresh water available in the world. Part of this water availability is stored in man-made reservoirs, with a large portion of these reservoirs destined for the production of electricity (BARBOSA et al., 2019). Due to this great volume and public policies aimed at the development of some strategic axes, the Brazilian hydroelectric sector has grown exponentially. According to the National Electric System Operator (ONS) (2019), in 2018, the installed power in Brazil was at 161.53 GW, of which 67.6% corresponded to hydropower.

Among the possible impacts arising from the implementation of hydroelectric projects, there is interference in the distribution and migration of aquatic communities, in addition to the possibility of damage to the ichthyofauna. During scheduled and/or untimely shutdowns of generating units (UG), the low operating flow leads to the accumulation of ichthyofauna inside the draft tube (TB), especially rivers with large amounts of fish, which may therefore impact the aquatic community (SCHILT, 2007). After closure of the TB, the survival of the confined ichthyofauna basically depends on the quality of the water, especially on the dissolved oxygen and ammonia concentrations. Thus, the reality experienced today is that, during the shutdown of a turbine, little is known, beforehand, about the real needs and urgency of activating the team responsible for rescuing the imprisoned ichthyofauna. From the perspective of sustainability, which has characterized and guided the hydroelectric sector in relation to other forms of power generation, the environmental issue is of great importance, as it is one of the pillars of the sustainability principle.

Currently, there is little knowledge about methodologies that enable the repulsion of ichthyofauna confined in draft tubes of generating units in hydroelectric projects in the Amazon region. From this perspective, several repulsion strategies or barriers have been developed in order to minimize the impacts on the ichthyofauna as well as their confinement in draft tubes. Physical or mechanical barriers such as screens, gratings and traps are widely used. However, they require a lot of maintenance and can be relatively costly. Another form of barrier is the behavioral one, which uses stimuli such as light and sound to reach fish sensory systems

(ZIELINSKI et al., 2014). Physical barriers are proven to be efficient, being indicated for a wide range of species (ANDRADE et al., 2012). In contrast, behavioral barriers, such as sound, strobe lights, electrical currents, and bubble curtains, depend on the response of each species to certain sensory stimuli, in addition to being influenced by environmental conditions, such as water flow and turbidity (PERRY et al., 2014).

The increase in the hydraulic flow rate is a fish repulsion method developed by Jirau Energia, which consists of the gradual reduction of the UG load until the complete descent of the fixed wheel roller gate, and this increase is due to the reduction of the discharge area of the draft tube during the descent of the gate.

This study is part of a research and development project (R&D - 06631-0009/2019), which aims to develop and validate technological strategies integrating physical and chemical systems for the repulsion of ichthyofauna from the draft tube during shutdowns of generating units. This study also aims to analyze the efficiency of the hydraulic flow rate increase maneuver, using a hydroacoustic system for real-time monitoring of the movement of ichthyofauna confined within the draft tube of the generating units of the Jirau Hydroelectric Power Plant (UHE – HPP), located on the Madeira River, in Rondônia, Brazil.

1.1 Real-time Hydroacoustic Monitoring System

Electromagnetic waves, an association between electrical charges and a magnetic field, are characterized by a wide frequency range – such as light, radio waves, X-rays, microwaves – that occupy a long range of the spectrum and can be transmitted through various media, including through vacuum. Electromagnetic waves travel at a speed close to 300,000 km/s through vacuum, whereas in other media, such as air and water, their speed is slightly slower. In turn, mechanical waves propagate only through material media, and not in vacuum, as is the case with sound waves that interact through the phenomenon of oscillation and disturbance with the medium through which they are propagating. The speed of a sound wave in air is 343 m/s at 20°C. In water , it increases to 1,450 m/s.

The application of sound waves for the investigation of aquatic environments (hydroacoustics) has been explored since the beginning of the last century, and the first patent is dated 1913. The term SONAR (Sound Navigation and Ranging) was coined in 1942. The principle of the technique is the interpretation of the reflection of waves (echo) of different frequencies, and the speed of sound, which depends on the temperature and on the type of fluid used, is given by:

$$C = (K/\rho)1/2$$

where: K = fluid compressibility; ρ = density of the fluid at a given temperature.

In the last twenty years, there has been a notable development in the instrumentation of hydroacoustic systems, either because of the miniaturization and robustness of frequency transducers, or because of the combination of different frequencies in the same instrument. Thus, the technique came to be used in the most diverse situations where image resolution, speed and safety are required. The use of multifrequency instruments allows you to enlarge or reduce the sound scanning area (cone or fan-shaped), changing the resolution of the image obtained not only due to the improvements that have been introduced in the generator of these waves, but also in the software that work in filtering and improving of the received echoes.

2 METHODOLOGY

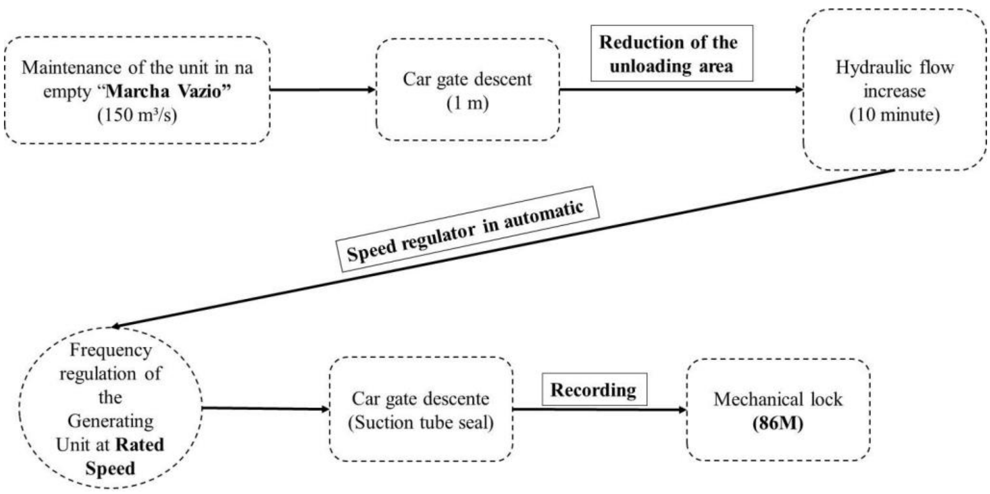
2.1 Study Area

The Madeira River hydrographic basin comprises an area of approximately 1,420,000 km^2, which represents 23% of the Amazon Basin. It also corresponds to 18% of rainfall in the Amazon region and 15% of the total volume of water in the Amazon River (BACELLAR & ROCHA, 2010). The Jirau HPP has been operating on the Madeira River since September 2013. The plant is located 136 km from Porto Velho, in Rondônia. Its total installed capacity is 3,750 MW, distributed over 50 Bulb-type generating units, which gives it a reduced reservoir area and, consequently, a lower degree of environmental impact (ESBR, 2009).

2.2 Hydraulic flow rate increase maneuver

In the procedure developed by Jirau Energia, there is an increase in the hydraulic flow by maintaining the unit in idle running state (marcha a vazio), maintaining the nominal discharge of 150 $m^3.s^{-1}$ for this state. Then, downstream of the UG, the fixed wheel roller gate is lowered until it is 1 m from the sill. With the reduction of the TB discharge area, the hydraulic flow speed increases. This flow is maintained for about 10 min. During this procedure, the speed regulator is kept in automatic, regulating the frequency of the generating unit at nominal speed, while the gate reaches the sill, causing the complete sealing of the draft tube. Immediately after confirming the closing of the generating unit, the mechanical block (86M) of the generating unit is manually activated and the unit shutdown procedure is consolidated (Figure 1).

Figure 1 – Flowchart of the steps of the hydraulic flow increase procedure



Source: Author, 2021.

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2.3 Confined Ichthyofauna Monitoring

The monitoring of confined biomass in the draft tube is done through hydroacoustics, that is, the propagation of an electromechanical wave through the liquid medium, with the echoes being analyzed with the aid of a sonar. For this purpose, 2 multi-frequency image transducers were fixed on the external face of the front panel of the downstream gates of Jirau HPP, exactly 14 m above the bottom of the gate, so that the transducer was in the center of the draft tube after sealing (Figure 2).

Figure 2 – Hydroacoustic system fixed to the gate at Jirau HPP (Patent no. BR 102015000457-5 A2 / www.venturoconsultoria.com.br).

Source: Venturo Consultoria Ambiental Archive, 2020.

2.3.1 Categorical assessment of confined ichthyofauna movement in the draft tube (TB)

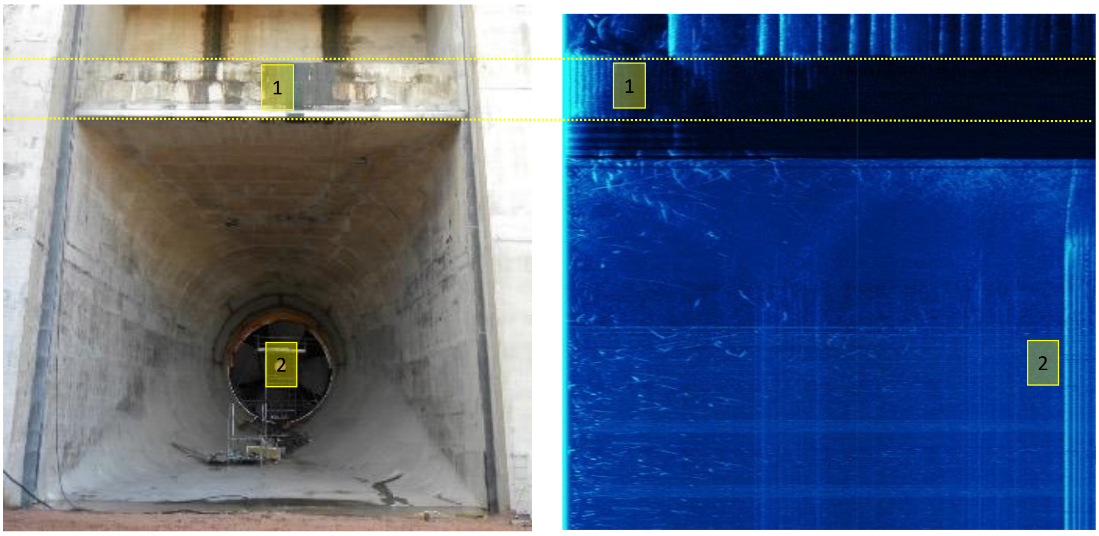
In order to analyze the history of confined ichthyofauna movement after the hydraulic flow rate increase maneuver, 105 machine shutdowns that occurred between 2019 and 2020 were considered.

After the hydraulic flow rate increase maneuver, monitoring using the hydroacoustic system was carried out for approximately 40 minutes inside the TB (Figure 3). The footage was analyzed using a false color composition "Blue – Turquoise" with a pixel value of 0.000361 m², and classified into 4 categories (Figure 4), according to the movements of confined ichthyofauna, as follows:

- Incipient: corresponds to footage with no movement;
- Detectable: movement pattern allows counting, however, it accounts to less than 5 movements min^{-1};

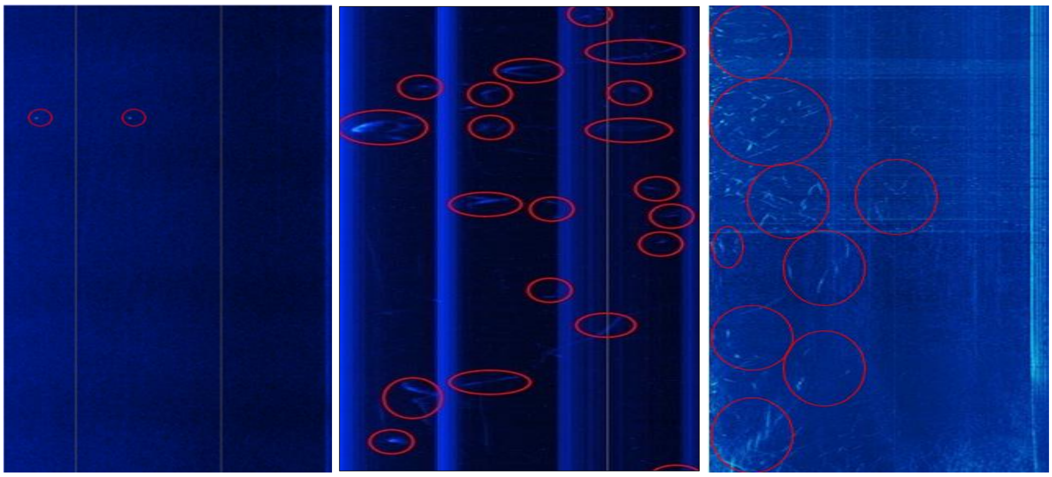
- Measurable: movement pattern allows counting, however, it accounts to more than 5 movements min^{-1};
- Elevated: movement pattern does not allow counting due to overlapping movements.

Figure 3 – Jirau HPP draft tube (left). Image capture of the confined ichthyofauna movement in the draft tube after applying the hydraulic flow rate increase maneuver (right).



Source: Venturo Consultoria Ambiental Archive, 2020.

Figure 4 – Examples of underwater images and categorical classifications of the confined ichthyofauna movement in the draft tube: left – detectable; center – measurable and right – elevated.



Source: Venturo Consultoria Ambiental Archive, 2020.

2.3.2 Categorical assessment of the size of the ichthyofauna confined in the draft tube (TB)

To assess the relative size of the confined ichthyofauna, the footage was analyzed using a false color composition "Blue - Turquoise" with a pixel value of 0.000361 m², and according to the size of the movement observed in the footage, a reference parameter was established. The relative size of the ichthyofauna present in the draft tube was divided into 3 indices, namely:

- Index 1 – when the target corresponds to ≤ 1 cm on the screen;
- Index 2 - when the target corresponds to > 1 cm and ≤ 2 cm on the screen;
- Index 3 - when the target corresponds to > 2cm on the screen.

2.3.3 Quantitative evaluation of two-stage hydraulic flow rate increase maneuver

From October to December 2020, the shutdown procedure of seven UG of the Jirau Hydroelectric Power Plant (UG02, UG07, UG15, UG12, UG30, UG18 and UG28) was carried out in two stages. In the first, the UG stopped without the hydraulic flow rate increase maneuver. Subsequently, the fixed wheel roller gate was removed, the UG was activated again, and the stoppage occurred with the hydraulic flow rate increase maneuver.

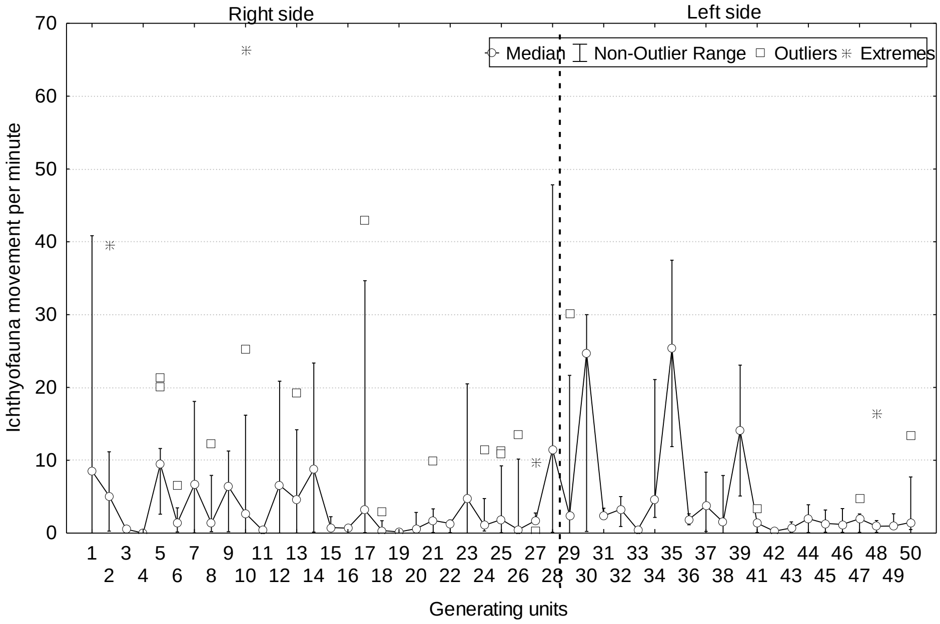
In both stages, after complete sealing of the TB, the monitoring of the confined ichthyofauna movement was carried out for about 20 minutes. Subsequently, the images obtained were evaluated, the movements counted manually, and the results compared to determine the efficiency of the hydraulic flow rate increase method.

3 RESULTS E DISCUSSION

From 2019 to 2020, 105 machine shutdowns were monitored using the hydraulic flow rate increase maneuver, totaling 423 footage (282 hours of observation). The movement recorded presented an average of 6 $\pm$ 9 movements min^{-1}, with a median of 2 movements.min^{-1}, ranging between 0 and 66 movements.min^{-1}. The integrated analysis of the multifrequency images of the internal region of the TB after the hydraulic flow rate increase maneuver shows that 85% do not present any or present less than 4 movements, being classified as incipient or detectable. Only about 15% of the footage showed a measurable classification pattern, with no footage with elevated movement being observed.

Figure 5 shows the rate of movement of the total ichthyofauna per minute after the execution of the hydraulic flow rate increase maneuver, considering all the generating units of Jirau Hydroelectric Power Plant in the years 2019 and 2020.

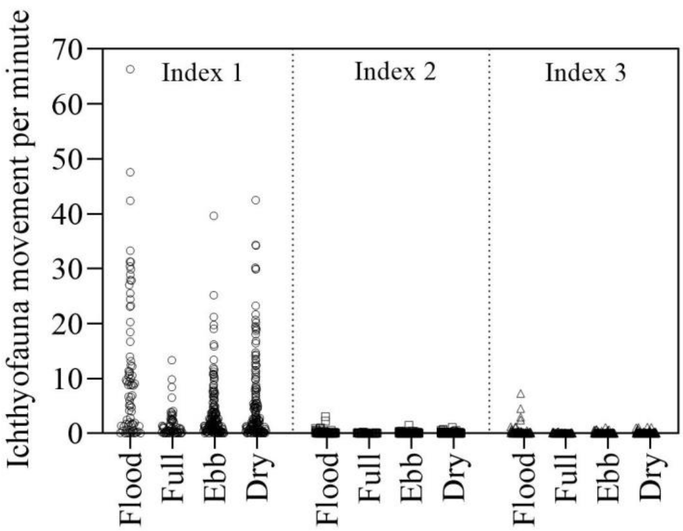
Figure 5 – Confined ichthyofauna movements per minute of filming in the draft tube of the generating units at Jirau HPP. The dashed line indicates the separation between the right margin (UG 01 to 28) and the left margin (UG 29 to 50).



Source: Author, 2021.

With regard to the categorical assessment of the ichthyofauna size confined in the TB, comparing the different hydrological periods (flood, full, ebb and drought) in relation to indices 1, 2 and 3, a significant difference was observed between the periods (Kruskal Test Wallis; < 0.05) with decreased movement of the ichthyofauna confined to the tube in the sequence: Flood > Full > Ebb > Drought. However, species classified as index 1 (≤ 1 cm;) were more recurrent, regardless of the hydrological period analyzed, with 94.3 to 96.1% of movements classified as index 1; 2.0 to 2.6% as index 2; and 1.6 to 3.1% as index 3.

Figure 6 – Categorical assessment of the relative size of the ichthyofauna confined in TB in the different hydrological periods of the Madeira River, during the years 2019 and 2020.



Source: Author, 2021

The average annual precipitation in the Madeira River basin ranges from 1,900 to 2,200 mm, however, about 75% of the volume of the Madeira River is determined by the climate of the Andean region of eastern Bolivia, only 25% comes from small rivers downstream of the city of Porto Velho. The flow varies between 30,000 and 35,000 $m^3 s^{-1}$ during the flood period and between 5,000 and 10,000 $m^3 s^{-1}$ during the dry season. The greater flow of water in the rainy season justifies the greater movement close to the downstream face of hydroelectric projects powerhouses during the flood period (BACELLAR & ROCHA, 2010). The greater attraction of small fish to the draft tubes is associated with the fact that their lower body mass decreases the resistance to water speed. However, the low movement of the ichthyofauna (15%) and the predominance of small fish (95%) in the draft tubes after the interruption of the operation of the generating units at Jirau HPP indicate that the increase in hydraulic flow is efficient in minimizing the confinement of ichthyofauna.

In the quantitative evaluation of the two-stage hydraulic flow rate increase maneuver, 14 footages were analyzed. The data obtained from the shutdowns without the hydraulic flow rate increase maneuver indicated a median of 323 and an average of 488 ± 395 movements per hour in the TB of the evaluated UG. In the second stage, with the increase of the hydraulic flow, the median was 3 and an average of 20 ± 34 movements per hour in the TB of the evaluated UG.

Integrated analysis of the data obtained from the two experimental groups together shows significant differences in the number of movements of the ichthyofauna in the draft tube (Wilcoxon test, $p < 0.05$), and the comparison between the two stages of the experiment demonstrates a reduction, on average, of 91% in the movement of the ichthyofauna in the TB after the hydraulic flow rate increase procedure (Table 1).

Table 1 – Quantitative assessment of the movement of the ichthyofauna confined in the draft tube after the machine stopped without the hydraulic flow rate increase maneuver (1st stage) and with hydraulic flow rate increase maneuver (2nd stage).

UG	Movement/hour		Reduction percentage
	Stage 1	Stage 2	
UG02	617	0	100%
UG07	128	0	100%
UG15	160	90	47%
UG12	293	3	99%
UG30	635	41	94%
UG18	323	3	99%
UG28	1261	3	100%

Source: Author, 2021.

Adopting monitoring and repulsion systems are greatly important in order to minimize possible impacts on the ichthyofauna and, at the same time, allow the operation of generating units (ANDRADE & ARAUJO, 2011). Along these lines, several repulsion strategies or barriers have been developed to minimize impacts on the ichthyofauna as well as their confinement in draft tubes. Physical or mechanical barriers, such as screens, gratings, and traps, are widely used (ANDRADE et al., 2012). However, these require a lot of maintenance and can be relatively costly (ZIELINSKI et al., 2014).

The results of the monitoring history (2019 and 2020) indicated low movement of ichthyofauna inside the draft tube after the execution of the maneuver. In addition, it is important to verify what the movement of ichthyofauna would be like if this resource were not available and, thus, create a comparative panorama between the two scenarios. From this perspective, the quantitative assessment of the hydraulic flow rate increase maneuver in two stages indicated a reduction of about 91% of movement after the maneuver.

4 CONCLUSION

The procedure of increasing the rate of the hydraulic flow in a bulb turbine (2.5 to 40.5 $m.s^{-1}$) showed high efficiency in minimizing the confinement of ichthyofauna in the draft tubes. This maintenance procedure positively impacts the conservation of ichthyofauna, and the economic costs involved in shutting down the unit, minimizing the work of the teams responsible for rescuing ichthyofauna in confined spaces.

5 ACKNOWLEDGEMENTS

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