

Article

Total Dissolved Gas Supersaturation as a System-Level Constraint on Flexible Hydropower Dispatch: An Engineering Assessment Within the Water–Energy–Environment Nexus

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Abstract

The increasing contribution of non-dispatchable renewable energy sources has changed the operating patterns of hydropower plants, especially in run-of-river schemes with limited storage capacity. Under intermittent dispatch, turbine shutdowns may occur while environmental-flow requirements must still be maintained. In these situations, spillway releases become more frequent, creating hydraulic conditions that can lead to total dissolved gas (TDG) supersaturation downstream. This study evaluates TDG supersaturation as an operational constraint in an Amazonian run-of-river hydropower plant. This assessment combines field measurements with controlled laboratory exposure tests using representative native fish species. Total gas pressure (TGP) was measured in both field and laboratory settings and converted into TDG saturation percentages. A laboratory-scale TDG generation system was developed to reproduce supersaturation conditions associated with spillway operation. Field measurements recorded TDG levels above 130% during spillway-activation events associated with dispatch decisions. In the laboratory, exposure tests showed rapid loss of viability in native Amazonian fish at TDG levels of 115% and above. These results indicate operational warning ranges for sustained spillway use. The findings suggest that TDG supersaturation should not be treated solely as an environmental issue. Rather, it represents a technical constraint on hydropower dispatch in systems with increasing renewable penetration. Incorporating TDG-related limits into operational planning and spillway management may help preserve hydropower flexibility while supporting environmental compliance.



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1. Introduction

Brazil's electricity matrix is predominantly renewable, and hydropower accounts for more than 60% of national generation [1]. In recent years, the rapid expansion of non-dispatchable renewable sources, mainly wind and solar, has changed the operating dynamics of the National Interconnected System (SIN). Under the dispatch rules adopted by the National System Operator (ONS), these sources are prioritized because of their near-zero marginal cost. As a result, flexible and dispatchable resources, including hydropower plants (HPPs), have been increasingly exposed to curtailment. Such curtailment may result from energy surplus, transmission constraints, or power-flow limitations required to maintain system reliability [2]. In practice, many HPPs now operate under more intermittent regimes, with frequent turbine shutdowns and rapid generation changes in response to real-time grid-balancing requirements.

These effects are especially relevant for run-of-river hydropower plants, which are common in recent Amazonian developments. Unlike storage reservoirs, these plants have limited capacity to buffer inflow variations and are therefore highly sensitive to dispatch instructions. When turbines are shut down, regulated downstream environmental flows must still be maintained. Spillway releases may then become the main mechanism for sustaining minimum flows. This transfers part of the operational variability from the generating units to the hydraulic structures. Consequently, spillway operation may shift from an occasional safety-related function to a recurrent component of daily plant operation. From an energy-system perspective, this creates an additional constraint on hydropower flexibility, because spillway use under intermittent dispatch can impose environmental and hydraulic limits that affect plant dispatchability.

In this operational sequence, curtailment or dispatch reduction typically reduces turbine discharge. Because downstream environmental-flow requirements must still be met, part of the flow may need to be redirected through the spillway. Depending on spillway geometry, gate operation, tailwater conditions, and discharge magnitude, the spillway release can intensify air entrainment and gas dissolution, increasing downstream TDG levels. If elevated TDG persists for sufficiently long exposure durations, biological responses may occur in fish downstream, ranging from sublethal stress to mortality. Therefore, the link between flexible hydropower dispatch and fish responses is not direct, but mediated by spillway operation and the hydraulically driven generation of TDG supersaturation.

Most run-of-river HPPs in the Amazon basin use submerged-crest spillways followed by stilling basins with hydraulic jumps. This configuration helps reduce construction costs, limit flooded areas, and mitigate downstream erosion. However, during spill events, such arrangements can generate intense turbulence and substantial air entrainment. These processes become more pronounced when rapid load reductions require sudden gate openings.

Under these hydraulic conditions, atmospheric gases, mainly nitrogen and oxygen, may be entrained and dissolved into the water column. This process can generate total dissolved gas (TDG) supersaturation downstream, with gas levels exceeding natural equilibrium conditions [3,4]. Elevated TDG concentrations are widely recognized as a cause of gas bubble disease (GBD) in fish, affecting physiological functions such as respiration, buoyancy control, and neurological stability [1,2,5].

TDG supersaturation has usually been treated as an environmental and ecological issue. However, its increasing occurrence during intermittent hydropower operation also makes it a technical and operational constraint for hydropower plants in systems with a growing share of non-dispatchable renewables. The problem involves water management, energy dispatch, and environmental compliance, and therefore fits within the water–energy–environment nexus [6]. In the Amazon basin, this interaction is particularly relevant because high biodiversity, strong hydrological variability, and cascades of run-of-river HPPs occur in the same river systems. In this context, spillway-induced TDG supersaturation represents an important link between power-system operation and environmental risk.

Previous studies, particularly in North America and China, have advanced the understanding of TDG generation, transport, mitigation, and biological effects on fish. Even so, the direct relationship between spillway operation associated with curtailment, field-measured TDG supersaturation, and mortality responses of native Neotropical species remains poorly documented, especially in Brazilian Amazonian run-of-river hydropower systems. Politano et al. [7], for example, investigated TDG modelling for the optimal operation of multireservoir systems using computational fluid dynamics, with emphasis on hydraulic processes and operational optimization. The present study differs from that approach by combining field monitoring at a Brazilian Amazonian run-of-river hydropower plant with controlled laboratory exposure tests using native fish species. This design allows spillway-induced TDG levels to be related to biological responses, including mortality as a function of TDG saturation level and exposure time.

To the authors' knowledge, this study provides one of the first integrated field and laboratory assessments of TDG supersaturation in Brazilian Amazonian run-of-river hydropower systems. Its novelty lies in connecting three elements that are often treated separately in the literature: curtailment-related spillway operation, field-measured TDG supersaturation, and laboratory-observed mortality responses of native Neotropical fish species. Previous studies have advanced the understanding of TDG generation, hydraulic modelling, mitigation alternatives, and biological effects, especially in North America and China. However, few studies have directly linked dispatch-driven spillway operation to measured TDG levels and controlled exposure responses in native tropical fish species. This integrated approach is particularly relevant because field evidence of TDG supersaturation in Amazonian run-of-river systems remains limited, and the sensitivity of Neotropical fish species to TDG exposure is still less documented than that of temperate species commonly considered in international guidelines.

The present study addresses this gap through an engineering and operational assessment of TDG supersaturation during intermittent hydropower operation. Field measurements downstream of an Amazonian run-of-river plant are combined with controlled laboratory exposure tests. This approach makes it possible to characterize TDG levels associated with spillway operation and to identify indicative exposure ranges of operational concern. The analysis does not focus on detailed biological response mechanisms. Instead, it examines how dispatch decisions, spillway operation, and TDG formation interact, treating gas supersaturation as an operational constraint that should be considered in hydropower planning and operation under increasing renewable penetration.

The remainder of the paper is organized as follows. Section 2 reviews TDG supersaturation and its biological and operational implications. Section 3 presents the study area and the operational context of the selected HPPs. Section 4 describes the materials and methods, including the laboratory-scale TDG generation system. Section 5 presents the field and laboratory results and discusses their operational meaning. Section 6 outlines mitigation strategies, and Section 7 summarizes the main conclusions.

2. Background and Related Work

Hydropower plants can generate gas supersaturation downstream during spillway operation. This occurs when intense turbulence entrains air and promotes the dissolution of atmospheric gases, especially nitrogen, into the water column. Elevated total dissolved gas (TDG) levels are closely associated with gas bubble disease (GBD) in fish. This condition involves the formation of gas bubbles in tissues and the circulatory system and may lead to physiological stress, lesions, impaired swimming, and death [1,2]. The severity of GBD depends on the degree of supersaturation, exposure duration, and species-specific tolerance [3]. Studies from the Northern Hemisphere, particularly in the United States, indicate that TDG levels above 110% may pose risks to aquatic life, supporting the need for monitoring and mitigation during spill events [4].

Zhang et al. [5] note that TDG supersaturation is a recurrent concern in hydropower systems because water-conveyance structures can intensify air entrainment and gas dissolution. Experimental and field studies have reported acute mortality in several fish species at TDG saturation levels above 125% [8–10]. In contrast, levels around 120% are often reported as non-lethal during short-term exposure, although responses vary among species, life stages, and exposure conditions [11,12]. Wang et al. [10] observed that chronic exposure to 115% TDG did not cause immediate mortality, but produced mild symptoms of GBD and reduced tolerance to later exposure at higher supersaturation levels. These findings indicate that moderate TDG supersaturation may have cumulative physiological effects, even when acute mortality is not observed.

To protect aquatic life, the United States Environmental Protection Agency (EPA) recommends a TDG limit of 110%, which is commonly used as a protective benchmark [13]. Although this value may be considered conservative in some operational contexts, it provides a useful reference for assessing potential risks to aquatic organisms. In general, acute lethality increases with higher TDG saturation and longer exposure duration. LT_{50} studies indicate that 100% mortality may occur within hours at TDG levels between 135% and 145%. At lower but still elevated TDG levels, such as 125–130%, symptoms and mortality may occur later, often after several hours, depending on species, body size, and exposure conditions [8,12,14].

Common responses observed under high TDG exposure include erratic swimming, loss of equilibrium, exophthalmia, and hemorrhaging. These symptoms are frequently used as physiological indicators when evaluating threshold ranges for fish protection. The literature often identifies TDG levels near or above 125% as a critical range for acute effects, while chronic exposure to moderate supersaturation, especially between 115% and 120%, has been associated with sublethal stress and increased physiological vulnerability [9,10,12,15].

From an energy-systems perspective, recent studies have begun to discuss hydropower flexibility within the water–energy–environment nexus, including environmental constraints in operational models [6,16]. However, the specific link between curtailment-related dispatch, spillway operation, and TDG formation remains insufficiently explored, particularly in tropical run-of-river systems. The present study contributes to this discussion by measuring TDG levels under real operating conditions and relating them to species-specific responses observed in controlled laboratory tests.

3. Study Area and Operational Context

The study initially considered four major HPPs in the Brazilian Amazon: Sinop, Teles Pires, São Manoel, and Colíder. These plants operate as run-of-river schemes with limited storage capacity and use submerged-crest spillways followed by stilling basins with hydraulic jumps. This configuration makes them particularly sensitive to dispatch instructions from the ONS. Operational data from the ONS [17] were used to examine the

frequency, duration, and magnitude of intermittent generation events, especially when dispatchable hydropower generation was reduced in favor of non-dispatchable renewable sources. Particular attention was given to spillway-activation events, because such events can produce rapid changes in downstream flow.

During these events, TDG levels were measured downstream of the spillways to relate plant operation to gas-supersaturation conditions. Weekly operational data from one HPP on the Teles Pires River showed that daily variations in dispatched energy, associated with transmission constraints and machine-commissioning tests, triggered the need for spillway releases, as shown in Figure 1.

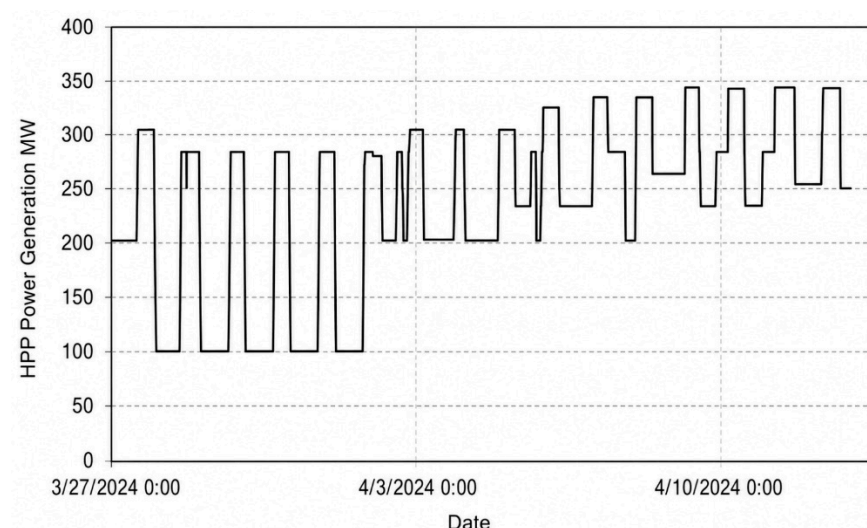


Figure 1. Dispatched generation from the plant over two weeks showing abrupt variation; SINOP HPP data adapted from the ONS operational database [17].

The sequence of spillway openings coincided with episodes of elevated fish mortality downstream. Figure 2 shows the downstream monitoring record at the SINOP HPP during a spillway discharge event. TDG levels increased progressively during spillway operation and decreased after the plant returned to generation with the spillways closed.

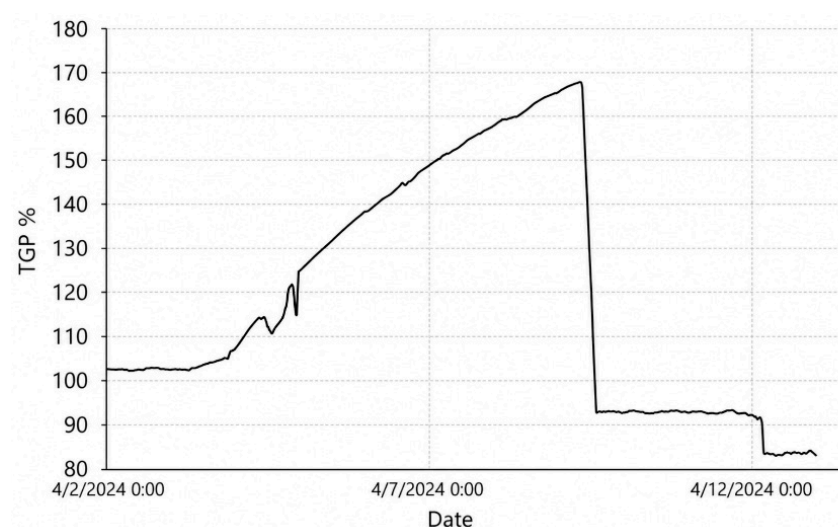


Figure 2. TDG concentration measured over a two-week period downstream of the spillway at a depth of 2 m, after a moving-median filter. Data obtained with an InWater Technologies Stationary TGP Probe [18]; SINOP HPP dataset [19].

This temporal association does not, by itself, demonstrate direct causality. Nevertheless, the observed pattern is consistent with TDG supersaturation as a plausible contributing factor to the fish-kill event. Other potential stressors, such as abrupt temperature changes or mechanical shear stress, were also considered. Abrupt temperature variations are not typically expected in this Amazonian river reach over the short time scale of the observed event. In addition, the available field observations did not indicate visible signs commonly associated with mechanical shear injury.

Even so, alternative contributing factors cannot be completely ruled out. The post-mortem examination was inconclusive, and dissolved-gas bubbles may dissipate rapidly after death, making diagnosis difficult when collection occurs several hours later. For this reason, the field data are interpreted as circumstantial operational evidence, supported by the controlled laboratory exposure tests, rather than as definitive proof of a single causal mechanism.

4. Materials and Methods

A laboratory-scale TDG generation system was developed at the Federal University of Itajubá (UNIFEI), Brazil, to reproduce supersaturation conditions observed downstream of spillways. The system was designed to control gas saturation levels in water and to support exposure tests with fish species native to Amazonian rivers. These tests provide experimental evidence on how selected species respond to TDG variations associated with spillway-discharge conditions.

Although the apparatus can support longer exposure periods, from several days to several weeks, the experiments reported here focused on acute responses to TDG levels considered relevant to hydropower operation. The system is automated and operated through a centralized electrical panel connected to a supervisory control and data acquisition (SCADA) platform. It can also be operated manually through local controls, allowing adjustments during testing. This flexibility was important because the equipment was developed for experiments with fish and other aquatic organisms and may require reconfiguration as operational experience is gained.

The TDG generation system, shown in Figure 3, consists of an open hydraulic circuit with pressurized-air injection. Water is drawn from a 500 L storage reservoir by a centrifugal pump with a rated power of 5 kW and an efficiency of 84.7%. Flow regulation is performed using variable-frequency drives (VFDs) and solenoid valves. Air is injected into a vertical saturation column, where fine bubbles are produced under controlled pressure. This arrangement reproduces, at laboratory scale, the main aeration and gas-dissolution processes associated with spillway discharge.

In the experimental configuration used in this study, the total water flow supplied to the system ranged from 0.32 to 1.6 L s⁻¹ and was distributed to four experimental tanks operated in parallel. The pressure in the saturation column was maintained between 1 and 5 bar, according to the target TDG saturation level. During system operation, stabilization, and exposure testing, TDG levels between 100% and 135% were investigated. The final configuration of the apparatus could generate adjustable TDG saturation levels from 100% to 140%, covering the range commonly associated with spillway-induced supersaturation.

Total gas pressure (TGP) was measured during both field campaigns and laboratory exposure tests and was converted into TDG saturation percentages using local atmospheric pressure. TDG levels were monitored using Handy Polaris TGP probes (OxyGuard International A/S, Farum, Denmark) and an InWater Technologies® Total Gas Pressure sensor with an RIU3 display (InWater Technologies Inc., Logan, UT, USA). Temperature, water level, flow rate, and pressure were monitored using a Pt100 temperature sensor, a Keyence FR-S01 level sensor (KEYENCE Corporation, Osaka, Japan), a Keyence FD-Q32C flow

meter (KEYENCE Corporation, Osaka, Japan), and a Festo SPTW pressure sensor (Festo SE & Co. KG, Esslingen am Neckar, Germany), respectively.

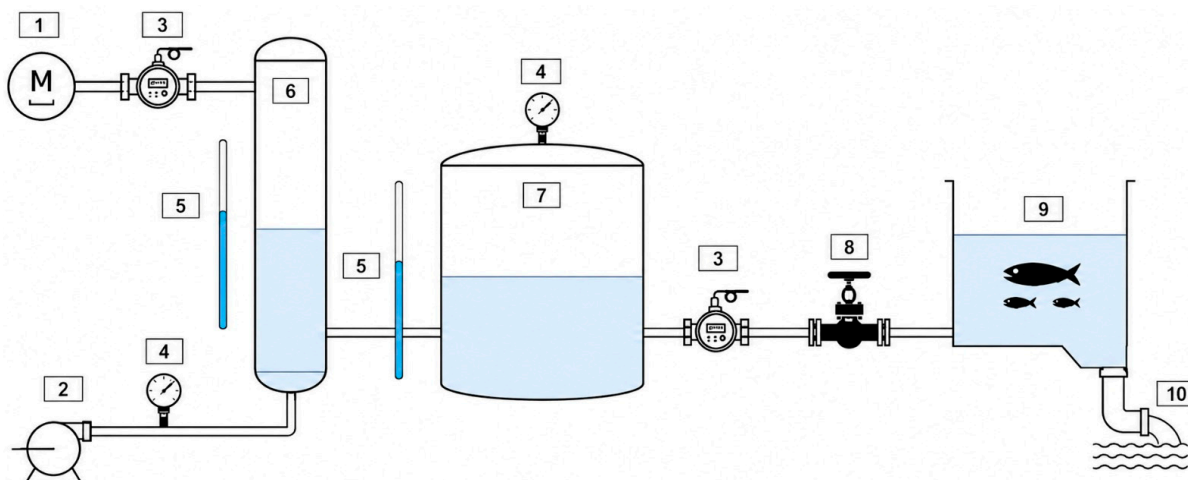


Figure 3. Flowchart of the laboratory-scale TDG generation system: (1) motor pump, (2) compressors, (3) flow meter, (4) proportional pressure valve, (5) level meter, (6) saturator tank, (7) stabilization tank, (8) tank-selection solenoid valve, and (9) test aquariums, (10) test-tank water discharge system.

The SCADA system allowed real-time control of flow rate, pressure, and the active distribution channels. The control program was implemented on an Altus NX controller (Altus Sistemas de Automação S.A., São Leopoldo, RS, Brazil). During the development phase, the apparatus was adjusted in successive steps to improve operation, safety, and thermal stability. Post-exposure assessments were carried out in a dedicated analysis room adjacent to the aquarium system, allowing visual examination and documentation of sublethal and lethal effects in the tested organisms.

The testing protocol followed procedures recommended in previous international studies on TDG exposure [3,8–12]. The laboratory tests were approved by the Animal Use Ethics Committee of the Federal University of São João del-Rei (CEUA/UFSJ), under CEUA No. 3265040425, on 5 September 2025. Each test followed the same sequence. First, the hydraulic circuit was stabilized until the target TDG level reached stable conditions, and the fish were acclimated for 2 h before exposure. The TDG stabilization behavior during this stage is shown in Figure 4. The saturator was then adjusted to the target TDG level. Six individuals were placed in the test tank for each condition and monitored every 15 min. Individuals that died during the test were removed, examined immediately, and documented through visual observation using magnifying lenses and photographic records of symptoms. After examination, the specimens were disposed of according to the approved protocol.

A sample size of six individuals per condition was adopted as an exploratory screening design. This choice balanced the need to identify TDG exposure ranges relevant to hydropower operation with the ethical requirement to reduce the number of organisms used in lethal tests. The experiments were therefore not designed as a full ecotoxicological dose–response assay, nor as a definitive determination of species-specific biological thresholds. Instead, they were intended to identify acute mortality responses under TDG levels representative of spillway-induced supersaturation. Because of the limited number of individuals per condition and the absence of replicated tanks for each TDG level, formal survival modelling and hypothesis testing were not performed. The results are presented as descriptive evidence, based on observed time to mortality and on the consistency of responses among the tested species. Individual time-to-death records, when available, were used to support this interpretation. Accordingly, the observed TDG lev-

els should be interpreted as indicative operational warning ranges rather than universal biological thresholds.

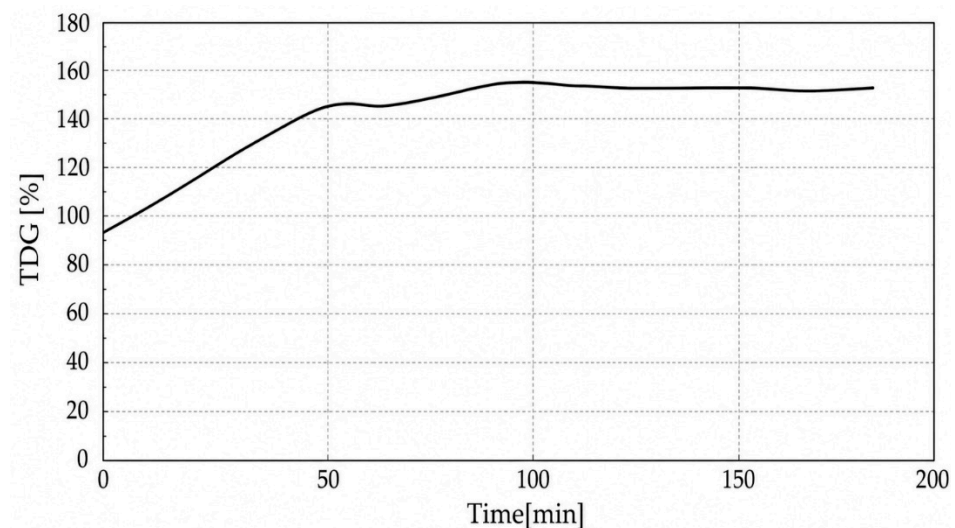


Figure 4. TDG stabilization after approximately 100 min during system commissioning tests; dashed lines denote the desired lower and upper limits.

These records were obtained from the doctoral thesis of Ribeiro [20], which reports controlled laboratory exposures of fish species to different TDG supersaturation levels. They were reorganized in Supplementary Table S1 to show individual mortality times for each species and exposure level. The table also includes descriptive statistics, such as mean, median, minimum and maximum values, standard deviation, and interquartile range.

5. Results and Discussion

This section brings together the field observations and the laboratory results. Section 5.1 presents the TDG levels recorded at the SINOP HPP during intermittent operation involving spillway releases. Section 5.2 then examines the responses of representative Amazonian native fish species exposed to comparable TDG ranges under controlled laboratory conditions. Together, these findings support the interpretation of spillway-induced TDG supersaturation as a potential operational constraint on hydropower flexibility.

5.1. Field Observations at the SINOP HPP

Field TDG measurements at the SINOP HPP recorded levels above 130% during spill events with discharge rates greater than $250 \text{ m}^3 \text{ s}^{-1}$. These events occurred during periods of spillway operation and coincided with downstream fish mortality observations, as shown in Figures 1 and 2. This temporal association suggests that intermittent operation involving spillway releases can produce TDG conditions outside the range generally considered protective of aquatic life. At the SINOP site, the observed increase in TDG was closely linked to spillway activation associated with power-system operation.

The field observations should be interpreted as operational evidence of TDG supersaturation during spillway operation, rather than as a quantitative ecological impact assessment. Species composition, total mortality counts, mortality rates, spatial distribution of affected individuals, and baseline population data were not available for the event. Therefore, the field data do not allow the estimation of population-level impacts or the direct quantification of ecological damage. Instead, they provide the operational context indicating that spillway activation under intermittent dispatch can generate TDG levels above 130%. The laboratory tests complement this evidence by providing controlled screening results on species-specific vulnerability under comparable supersaturation ranges.

5.2. Laboratory Exposure Tests with Representative Neotropical Fish Species

Representative native fish species from Amazonian and Neotropical freshwater assemblages were selected for the laboratory exposure tests: *Rhamdia quelen* (Jundiá), *Leporinus friderici* (Piau-Três-Pintas), *Pseudoplatystoma corruscans* (Pintado), *Colossoma macropomum* (Tambaqui), and *Astyanax lacustris* (Lambari-rabo-amarelo). These species were chosen to provide a practical screening set covering different body sizes, habitat uses, and functional groups. The set includes a small-bodied characiform, *Astyanax lacustris*; a medium-sized omnivorous or detritivorous species, *Leporinus friderici*; benthic or benthic-associated catfish, *Rhamdia quelen* and *Pseudoplatystoma corruscans*; and a large-bodied characiform of ecological and fishery relevance, *Colossoma macropomum*. This selection allows the results to be interpreted as indicative responses across different groups of tropical freshwater fish, rather than as the response of a single model organism.

All specimens underwent a two-week acclimation period under controlled environmental conditions. No mortality or abnormal behavior was observed during this period. The test specimens were obtained from local aquaculture farms, with documented purchases. After acclimation, the fish were exposed to TDG saturation levels ranging from 110% to 135%, representing conditions that may occur downstream of hydroelectric spillways. Behavioral responses, visible stress indicators, and mortality were recorded throughout the exposure period.

The number of individuals per condition was limited to six. This sample size was adopted as an exploratory screening approach, balancing the need to identify operationally relevant TDG exposure ranges with the ethical objective of reducing the number of organisms used in lethal tests. Water temperature varied from approximately 15.7 °C to 24.2 °C across the tests. This variation is reported to make the experimental limitations clear and to allow the results to be interpreted cautiously in the context of the combined TDG and temperature conditions of each exposure.

The results presented in Table 1 show that, at TDG saturation levels of 115% or greater, all tested species exhibited acute sensitivity. The mean time to death ranged from approximately 0:50 to 4:00 h. These values indicate exposure ranges of operational concern, rather than definitive biological thresholds. Although the results should not be treated as universal limits, the observation of complete mortality at 115% TDG provides an indicative warning of the potential vulnerability of Neotropical fish to gas supersaturation under spillway-related operating conditions. The differences observed among species may suggest species-dependent tolerance, but this interpretation should be treated with caution. Because temperature was not controlled as an independent experimental factor and each condition included only six individuals, the observed differences cannot be attributed exclusively to species-specific sensitivity. Instead, they should be interpreted as indicative patterns obtained under the combined TDG and temperature conditions of each exposure test.

Individual time-to-death records were also used to calculate descriptive statistics for each species and TDG exposure level, including mean, median, minimum and maximum values, standard deviation, and interquartile range, as presented in Supplementary Table S1. These statistics help document the consistency of the observed acute mortality responses, especially at TDG levels of 115% or higher. However, because each condition included only six individuals and no replicated tanks were available for each TDG level, these values should be interpreted as descriptive support, not as formal statistical inference.

Table 1. Mortality response (computed mean individual time to death, $n = 6$ per condition) of representative Amazonian native fish species exposed to TDG saturation levels of 115%, 125%, and 135% under laboratory-controlled conditions.

Species	TDG (%)	Computed Mean Individual Time to Death (h:min)	Weight (g)	Temperature (°C)
<i>Rhamdia quelen</i> (Jundiá)	115	4:00	12.2	17.7
	125	2:52	13.0	23.0
	135	2:20	13.0	23.4
<i>Leporinus friderici</i> (Piau-Três-Pintas)	115	2:40	19.5	16.1
	125	2:12	22.2	19.1
	135	1:48	25.0	20.1
<i>Pseudoplatystoma</i> <i>corruscans</i> (Pintado)	115	3:38	24.3	18.1
	125	2:42	13.3	15.9
	135	0:50	11.7	15.7
<i>Colossoma</i> <i>macropomum</i> (Tambaqui)	115	3:10	2.8	17.1
	125	2:40	3.8	16.3
	135	1:35	4.5	17.5
<i>Astyanax lacustris</i> (Lambari-rabo-amarelo)	115	3:22	2.8	15.6
	125	2:20	3.0	22.3
	135	1:20	2.5	24.2

Notes: Values correspond to computed mean individual time to death calculated from the individual records presented in Supplementary Table S1, with $n = 6$ individuals per condition. Mean values were rounded to the nearest minute. Temperature refers to the water temperature recorded during each exposure test. Acclimation took place over two weeks prior to exposure; no mortality or abnormal behavior was observed during acclimation. These values are intended as descriptive support and should not be interpreted as formal survival modelling or as universal biological thresholds.

To support the interpretation of the laboratory results, Figure 5 summarizes the mean time to death of the tested species as a function of TDG saturation level. The figure highlights the consistent reduction in survival time as TDG increased from 115% to 135%, while preserving the descriptive and exploratory nature of the dataset.

Temperature was recorded in each exposure test and is reported in Table 1. However, it was not controlled as an independent experimental factor and was not included as a covariate in a statistical model. This is an important limitation, because water temperature affects gas solubility, fish metabolism, and physiological stress responses. Therefore, the mortality responses reported here should be interpreted as exploratory evidence obtained under the combined TDG and temperature conditions of each test, rather than as the isolated effect of TDG alone.

Even with this limitation, rapid mortality was consistently observed under supersaturated TDG conditions, supporting the interpretation of TDG as a relevant operational stressor. Future experiments with replicated tanks and controlled temperature treatments are needed to separate the independent and interactive effects of TDG and temperature on species-specific tolerance.

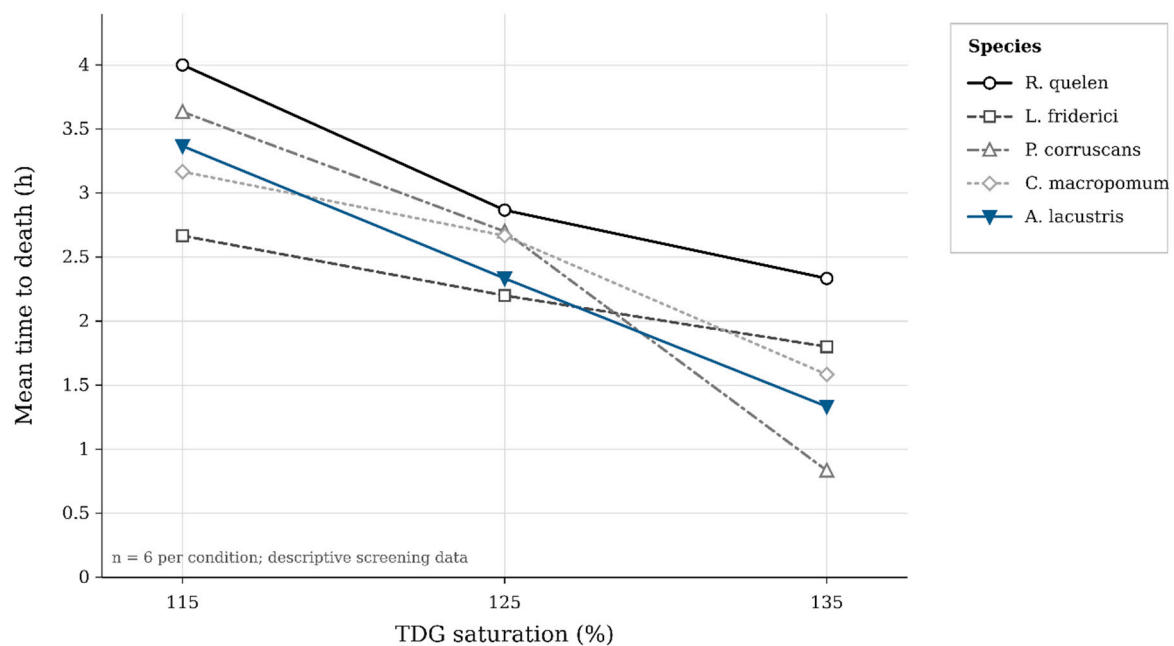


Figure 5. Mean time to death of representative Neotropical fish species exposed to TDG saturation levels of 115%, 125%, and 135%. Values are based on the descriptive records presented in Tables 1 and S1 and should be interpreted as indicative operational warning ranges rather than universal biological thresholds.

The laboratory findings are consistent with the field data obtained at the SINOP HPP, discussed in Section 5.1. During spill events, the TDG levels recorded in the field exceeded the range in which all tested species lost viability within a few hours in the laboratory. Taken together, these results support the use of practical operational warning ranges for spillway operation under intermittent dispatch.

In addition to acute mortality at higher TDG levels, chronic or repeated exposure to moderate supersaturation should also be considered. This is especially relevant in the range of 110% to 115%. Previous studies have shown that TDG levels near 115% may not cause immediate mortality during short-term exposure, but can induce sublethal responses. These responses include physiological stress, mild symptoms of gas bubble disease, reduced swimming performance, and lower tolerance to later exposure at higher TDG levels [9,10,12,15].

Therefore, even when moderate TDG supersaturation does not lead to rapid fish mortality, it may reduce individual fitness and increase vulnerability to other stressors. Over time, repeated exposure may also affect population resilience. This concern is particularly important in run-of-river cascades subject to recurrent spillway operation, where fish may experience repeated or prolonged episodes of moderate TDG supersaturation.

These findings also highlight the environmental risks associated with submerged-crest spillways and hydraulic-jump stilling basins, especially under intermittent flow regimes. In these configurations, the absence of bottom-discharge structures may reduce operational flexibility and limit flow control during high-flow periods. This can increase the potential for TDG supersaturation and downstream ecological effects. Within the water–energy–environment nexus, the effective flexibility of these plants is therefore not determined only by turbine ramping capability. It is also constrained by the TDG levels that spillway operation must respect.

6. Mitigation Strategies

Mitigating TDG supersaturation downstream of hydropower facilities requires a combination of operational, monitoring, and structural measures. From an operational perspective, coordination among cascaded HPPs is important to avoid overlapping spill events and the cumulative increase in gas saturation downstream. Gradual and coordinated spillway-gate openings can also help reduce sudden air entrainment and rapid TDG increases. During high-flow periods, synchronized operation among plants becomes particularly relevant for keeping TDG levels within ecologically safer ranges. Table 2 summarizes the main mitigation options discussed in this section. The table compares operational, monitoring/modelling, and structural strategies according to their expected effects on TDG, implementation complexity, and main limitations.

Table 2. Visual mapping of TDG mitigation strategies according to implementation level, expected effects, complexity, and applicability in Amazonian run-of-river hydropower cascades.

Mitigation Level	Strategy	Expected TDG Effect	Implementation Complexity	Main Limitation
Operational	Avoid abrupt spillway-gate openings	Reduces sudden air entrainment and rapid TDG increase	Low	Depends on dispatch flexibility and environmental-flow obligations
Operational	Improve cascade coordination	Reduces overlapping spill events and cumulative downstream exposure	Low to medium	Requires coordination among plants and system operators
Operational	Schedule spill releases to reduce exposure duration	Limits repeated or prolonged exposure of downstream biota	Low to medium	May involve opportunity costs or modified dispatch instructions
Monitoring/modelling	Continuous TDG monitoring	Provides real-time warning of TDG exceedances	Medium	Requires sensors, maintenance, calibration, and data integration
Monitoring/modelling	Hydraulic or CFD modelling of spillway scenarios	Anticipates TDG formation under different gate configurations and discharges	Medium to high	Requires site-specific calibration and technical expertise
Structural	Spillway deflectors	Reduces deep air entrainment and promotes surface gas release	High	Site-specific design; requires hydraulic validation and construction planning
Structural	Stilling-basin modifications	Improves bubble separation and downstream degasification	High	Capital-intensive and may require outages or dam-safety review
Structural	Dedicated degasification structures	Promotes gas release before downstream transport	High	High implementation cost and feasibility depends on site constraints

Hydrodynamic conditions during spill events play an important role in TDG formation. High turbulence, especially in plunging-jet regimes, promotes deeper air entrainment and increases gas dissolution. It also reduces the opportunity for gas release near the water surface. In submerged-crest spillways followed by stilling basins, the discharge is often spread over large areas, which may favor higher TDG levels. Modelling studies indicate that more concentrated spill releases tend to form coherent surface jets and may

be associated with lower TDG levels. In contrast, distributed spill discharges increase the air–water interfacial area and may reduce degasification efficiency, leading to higher TDG levels downstream [7].

Structural measures can also be used to manage TDG supersaturation. These include controlled aeration and degasification systems, which are intended to promote gas release before downstream transport. Modifications to energy dissipators, including changes in basin geometry and flow conditions, may improve bubble separation and degasification. Spillway deflectors are another alternative, as they can redirect the flow, reduce deep air entrainment, and favor gas release near the surface [7].

The mitigation measures discussed above differ in cost, complexity, and time required for implementation. Operational measures, such as gradual spillway-gate openings, improved cascade coordination, and scheduling of spill events, are usually the most immediately applicable options. They require limited structural intervention and can be incorporated into dispatch and real-time operation procedures. However, their effectiveness depends on hydrological conditions, dispatch requirements, environmental-flow obligations, transmission constraints, and coordination among plants in the same river cascade. In some cases, these measures may also involve opportunity costs, especially when generation flexibility must be reduced or dispatch instructions need to be modified.

Monitoring and modelling strategies represent an intermediate level of implementation. Continuous TDG monitoring, combined with hydraulic or computational models, can support operational decisions by anticipating the effects of different spillway configurations. These approaches require investment in sensors, data acquisition, model calibration, and technical expertise. Even so, they are generally less invasive than structural retrofits and can provide the basis for defining site-specific TDG operating limits.

Structural measures, such as spillway deflectors, stilling-basin modifications, and dedicated degasification structures, may provide more permanent reductions in TDG generation. However, they are also more site-specific and capital-intensive. Their feasibility depends on spillway geometry, hydraulic head, discharge range, foundation conditions, construction constraints, environmental licensing, dam-safety requirements, and the possibility of carrying out works without compromising plant availability. In Amazonian run-of-river cascades, these constraints are especially relevant because large discharges, high biodiversity, limited storage capacity, and environmental-flow requirements can reduce operational flexibility. For this reason, structural interventions should be preceded by physical or numerical modelling, pilot assessment, and cost–benefit analysis, considering ecological benefits, operational gains, implementation costs, and outage risks.

The Brazilian experience with TDG mitigation at the Colider HPP illustrates the value of this staged approach. In that case, the ANEEL R&D project “Methodology for Computational Modelling of TDG in Water in Spillway Effluent Flows” developed modelling tools to simulate air-bubble transport, gas dissolution, and TDG formation to support the evaluation and design of spillway deflectors [21]. The publicly available description of the project indicates that diagnosis, modelling, technical development, and validation were needed before structural implementation [21]. This example shows that TDG mitigation in large hydropower plants may require considerable technical and financial effort even before construction costs are considered. For Amazonian run-of-river cascades, a realistic mitigation pathway is therefore likely to combine low-intervention operational measures in the short term, continuous TDG monitoring and modelling in the medium term, and structural retrofits only where recurrent TDG exceedances justify the higher implementation cost and operational risk.

The present study does not propose a complete dispatch-optimization algorithm, nor does it aim to replace existing national power-system operation models. Its purpose is

more specific: to identify TDG supersaturation as an environmental constraint that should be considered in future operational and decision-support frameworks.

In practical terms, this constraint could be represented at the site scale. Predicted downstream TDG levels, estimated from spillway discharge, gate configuration, tailwater conditions, temperature, and hydraulic-structure characteristics, should remain below a site-specific allowable exposure range. This range would need to be defined using monitoring data, ecological criteria, and species-specific tolerance information. Under this approach, hydropower dispatch would not depend only on energy demand, hydraulic availability, and transmission constraints. It would also account for the environmental consequences of spillway releases.

Developing and validating optimization formulations for integration into national dispatch models is outside the scope of this study. This remains an important direction for future research. From a water–energy–environment nexus perspective, mitigation measures should therefore be assessed together with dispatch constraints, because the magnitude and timing of spill releases are ultimately influenced by power-system decisions.

7. Conclusions

Intermittent operation of Amazonian hydropower plants equipped with submerged-crest spillways and hydraulic-jump stilling basins can increase the risk of TDG supersaturation downstream. The controlled laboratory experiments indicated acute responses at TDG saturation levels of 115% and above. Under these conditions, tested native fish species showed rapid mortality and signs of stress. Although these results should not be interpreted as universal biological thresholds, they provide operationally relevant evidence of exposure ranges that should be avoided during sustained spillway operation.

The Amazonian context reinforces the importance of these findings. The Teles Pires River alone hosts up to 342 fish species, distributed among 191 genera, 42 families, and 11 taxonomic orders. This diversity highlights the ecological sensitivity of river systems affected by large-scale hydropower development. In this context, the responses observed in representative native species provide an indicative warning of the potential vulnerability of Neotropical ichthyofauna to TDG supersaturation under intermittent operating regimes. Additional field studies covering a broader range of species, life stages, and hydrological conditions are therefore needed to improve the understanding of TDG effects in tropical river systems.

Field TDG measurements downstream of the SINOP HPP showed values above environmentally protective ranges during spillway operation and coincided with fish-kill observations. These field data are consistent with the laboratory results and support the interpretation that spillway operation under intermittent dispatch can generate TDG levels of operational and ecological concern. Taken together, the results reinforce the need to treat TDG supersaturation not only as an environmental issue, but also as a technical and operational constraint on hydropower flexibility under increasing renewable penetration.

To the authors' knowledge, this study is among the first integrated field and laboratory assessments from Brazilian Amazonian run-of-river hydropower systems to indicate that spillway operation associated with intermittent dispatch can generate TDG supersaturation levels of operational and ecological concern. Its main novelty lies in combining field-measured TDG levels during spillway operation with controlled laboratory exposure tests involving representative native Neotropical fish species. By relating operational spillway events to observed mortality responses as a function of TDG saturation level and exposure time, the study provides field and laboratory evidence that remains limited for tropical run-of-river hydropower systems.

The results also complement existing international guidelines, which are largely based on evidence from temperate regions and on a limited set of model or commercially relevant species. The acute responses observed in the tested Neotropical species suggest that tropical fish may be highly sensitive to TDG supersaturation under certain hydraulic and operational conditions. Therefore, existing TDG guidelines should be applied to Amazonian hydropower systems with caution. Site-specific monitoring, species-specific experimental support, and attention to repeated or prolonged exposure events are needed.

To mitigate these risks while preserving system dispatch capability, operational adjustments should be combined with monitoring and, where justified, structural measures. Recommended actions include avoiding abrupt spillway-gate openings, distributing spill discharges where hydraulically appropriate, and improving coordination among spill events, particularly in cascade systems. Given the strategic role of Amazonian hydropower plants in balancing the Brazilian electricity grid, TDG-related limits should be considered in dispatch planning and real-time operation as environmental constraints within water–energy–environment nexus models.

Finally, the operational warning ranges discussed in this study are broadly consistent with international references, including the U.S. EPA guideline of 110% TDG saturation ($\Delta P = 76$ mmHg at sea level) and literature associating TDG levels above 125% with acute mortality [13]. In this context, the present results indicate that, under certain hydraulic and operational conditions, TDG-related constraints may become particularly relevant in tropical systems. This reinforces the need for site-specific monitoring and operational criteria tailored to Neotropical environments.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18131633/s1>, Figure S1, gas saturator system used in the laboratory-scale TDG generation apparatus; Figure S2, test tanks used in the laboratory exposure experiments; Figure S3, control panel of the experimental test system and an Excel file containing; Table S1, individual time-to-death records; Table S2, descriptive statistics for each species and TDG exposure level; and Table S3, notes for use in the manuscript.

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Data Availability Statement: The results and processed data supporting the findings of this study are included in the article and in the Supplementary Material. The raw operational and TDG monitoring datasets from the SINOP Hydroelectric Plant were obtained from SINOP Energia S.A. and are subject to availability restrictions. These raw datasets may be made available by the corresponding author upon reasonable request and with permission from SINOP Energia S.A.

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Abbreviations

The following abbreviations are used in this manuscript:

ANEEL	Brazilian Electricity Regulatory Agency (Agência Nacional de Energia Elétrica)
CEUA	Animal Use Ethics Committee (Comitê de Ética no Uso de Animais)
CFD	Computational Fluid Dynamics
COPEL	Paraná Energy Company (Companhia Paranaense de Energia)
EPA	United States Environmental Protection Agency
GBD	Gas Bubble Disease
HPP	Hydropower Plant
LT ₅₀	Lethal Time for 50% Mortality
ONS	National System Operator (Operador Nacional do Sistema Elétrico)
PDI	Research, Development and Innovation (Pesquisa, Desenvolvimento e Inovação)
SCADA	Supervisory Control and Data Acquisition
R&D	Research and Development
SIN	National Interconnected System (Sistema Interligado Nacional)
TDG	Total Dissolved Gas
TGP	Total Gas Pressure
UFMG	Federal University of Minas Gerais
UFSJ	Federal University of São João del-Rei
UNIFEI	Federal University of Itajubá
VFD	Variable-Frequency Drive

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