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Science, Policy and Management for Sustainable Use

ORIGINAL ARTICLE OPEN ACCESS

GIS-Based Aquaculture Spatial Suitability in Western Amazonian Hydroelectric Reservoirs

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Received: 2 January 2025 | **Revised:** 8 June 2025 | **Accepted:** 16 June 2025

Funding: This work was supported by the Foundation for the Support and Development of Scientific Actions and Research of Rondônia State (FAPERO) for financial support and the provision of scholarships.

Keywords: aquaculture site selection | GIS | hydroelectric reservoirs | net-cage farming | water quality | Western Amazon

ABSTRACT

This study applies a GIS-based approach to evaluate the spatial suitability of net-cage aquaculture and analyse key water quality parameters in four hydroelectric reservoirs located in the Jamari River basin, Western Brazilian Amazon. The assessment includes one large hydropower reservoir (HPP Samuel) and three small hydropower reservoirs (SHDs): SC Monte Negro, Jamari and Canaã. The methodology followed five stages: (1) temporal analysis of Total Water Surface Area (TWSA); (2) identification of vegetation-free areas; (3) evaluation of depth suitability; (4) compilation of historical water level data and limnological parameters (chlorophyll-*a*, BOD, total phosphorus, dissolved oxygen); and (5) mapping and estimation of Potential Aquaculture Sites (PAS). Due to excessive seasonal variation (> 70% fluctuation in TWSA), the Samuel HPP reservoir was excluded from the final suitability mapping. In contrast, the SHD reservoirs exhibited environmental stability and fulfilled legal requirements for net-cage installation. Together, they offer an estimated production potential of up to 466 t per year using native species such as *Colossoma macropomum*. Most water quality parameters complied with Brazilian environmental standards (CONAMA Resolution no. 357/2005). This spatial and limnological assessment provides a technical foundation for implementing sustainable aquaculture systems in Amazonian hydroelectric reservoirs. Further studies should incorporate ecological carrying capacity modelling and environmental impact projections to support long-term sustainable aquaculture practices in these freshwater ecosystems.

1 | Introduction

Extensive livestock farming has proven to be an unsustainable activity in the Brazilian Amazon, significantly contributing to deforestation and exacerbating biodiversity loss (Vale et al. 2019). In response to these challenges, aquaculture emerges as a viable alternative, offering higher economic returns per unit area (improved productivity) and presenting significant potential for the sustainable production of high-value animal protein in the region (Sachs 1985; Hilsdorf et al. 2021; Pacheco et al. 2025).

The conservation of the Amazon Rainforest must remain a central focus of public policy across Amazonian countries, underpinning strategies for animal food production management (Soares-Filho et al. 2006). While aquaculture productivity rates far exceed those of extensive livestock farming—the predominant source of animal protein in the Brazilian Amazon (IBGE 2024)—aquaculture policies must also emphasise anti-deforestation practices (Pacheco et al. 2025). In this regard, net-cage aquaculture in natural and artificial water bodies offers a sustainable approach to fish production, making use of non-forested areas such as lakes, rivers and hydroelectric reservoirs (Costa-Pierce 2002).

Brazil's vast inland water resources, including rivers, reservoirs and lakes within the Amazon basin, hold considerable potential for aquaculture. However, scientific studies are essential to conduct socio-environmental assessments before these water bodies are utilised for fish production (Valenti et al. 2021; Henry-Silva et al. 2022). Feasibility studies are particularly required to evaluate net-cage aquaculture in Amazonian water bodies and assess its potential impacts on aquatic ecosystems, especially those with limited dispersal capacity, like hydroelectric reservoirs (Zaniboni-Filho et al. 2018; Garno et al. 2024). Despite this potential, there is a lack of spatially explicit studies that combine Geographic Information Systems (GIS) with environmental and legal criteria to define suitable areas for aquaculture in hydroelectric reservoirs of the Amazon.

Legally, Presidential Decree no. 10,576/2020 regulates the use of Brazilian public inland and coastal waters for aquaculture. This decree is complemented by Ordinance no. 412/2021 from the Ministry of Agriculture, Livestock and Supply (MPA) and the Aquaculture and Fisheries Secretariat, which standardise the procedures for legalising aquaculture ventures in public waters within Brazil. These regulations mandate specific studies to identify aquaculture zones, aiming to minimise environmental impacts on natural and artificial aquatic ecosystems. Despite Brazil's extensive water resources and the advantages of net-cage fish farming, environmental sustainability must remain a priority due to potential ecological risks for both producers and aquatic ecosystems (Fialho et al. 2021).

Net-cage fish farming has already demonstrated its potential in the Brazilian Amazon, with successful examples such as the Tucuruí hydroelectric power plant reservoir in Pará state (Brabo et al. 2013). Furthermore, open-water fish farming projects promote equitable access to aquaculture, as production infrastructure is situated in public water bodies under state management (Gomes et al. 2006; Costa-Pierce 2024). This aquaculture system aligns with bioeconomic principles, particularly those that empower traditional communities, including riverside residents and fishers. Compared to systems reliant on private land ownership, net-cage aquaculture may offer greater socioeconomic benefits to Amazonianrural communities (Henry-Silva et al. 2022).

Over the past five years (2019–2024), the Brazilian state of Rondônia, situated in the western Brazilian Amazon, has led national deforestation rankings, with approximately 580,000 ha of rainforest cleared (MapBiomas 2024). This deforested area represents nearly 25% of Rondônia's total territory. Nevertheless, Rondônia has also distinguished itself as Brazil's leading producer of farmed native Amazonian fish. In 2023, the state's total fish production reached 56,700 t, placing it fourth nationally, behind Paraná (206,000 t), São Paulo (75,700 t) and Minas Gerais (58,200 t) (IBGE 2024). However, in terms of native fish production alone, Rondônia ranks first, with 100% of its aquaculture output consisting of Amazonian fish farmed in inland ponds (IBGE 2024). Rondônia's native fish production in 2023 was nearly 30% higher than that of Mato Grosso, the second-largest producer (40,500 t). This positions Rondônia as a key player in native fish production both regionally and globally—particularly in the farming of tambaqui (*Colossoma macropomum* Cuvier), an iconic fish species of the Amazon basin (Hilsdorf et al. 2021; Val and de Oliveira 2021).

Given Rondônia's predominantly agricultural economy and its location within the Amazon basin, reconciling agricultural development with rainforest conservation is essential. In this context, identifying potential aquaculture sites in Amazonian hydroelectric reservoirs offers a strategic pathway to sustainable aquaculture expansion (Beveridge 2004), while simultaneously enhancing the region's bioeconomy (Garrett et al. 2020; Pacheco et al. 2025).

Therefore, this study addresses the following research question: which areas in the hydroelectric reservoirs of the Jamari River basin are environmentally suitable for net-cage aquaculture, considering spatial attributes and water quality standards required by Brazilian legislation?

The research methodology was divided into five key steps: (1) analysing the temporal variation of the Total Water Surface Area (TWSA) of these reservoirs using Geographic Information Systems (GIS); (2) identifying and estimating Water Surface Areas (WSAs) free from remaining vegetation and with appropriate depths in compliance with Brazilian legislation; (3) collecting and analysing historical water level and water quality data of these reservoirs; (4) GIS mapping to visually identify potential aquaculture sites (PAS); and (5) calculating the potential fish production for net-cage aquaculture in the PAS of these reservoirs.

2 | Material and Methods

2.1 | Study Area

The Jamari River, classified as a third-order river (Strahler 1957), spans approximately 550 km (IBGE 2021), originating at an elevation of about 500 m and flowing to its confluence with the Madeira River (Figure 1). Covering an area of roughly 29,000 km^2 (IBGE 2021), the Jamari River basin includes several significant tributaries, such as the Canaã River. The river's headwaters are located within the Pacaás Novos National Park, a protected area that significantly overlaps with the Uru-Eu-Wau-Wau Indigenous Land (FUNAI 2024). According to Sioli's (1984) classification of Amazonian river waters, the Jamari's waters are categorised as clear to acidic (black) (Venticinque et al. 2016).

The Jamari River is one of the primary tributaries of the Madeira River, playing a critical role in the water supply and hydrographic network of the state of Rondônia (RO). The river lends its name to the Vale do Jamari region, which is centred around the municipality of Ariquemes (approximately 100,000 inhabitants), the principal urban hub in the area. This region has experienced accelerated demographic growth since the 1980s, driven by agricultural expansion and rural migration. Its economy is based

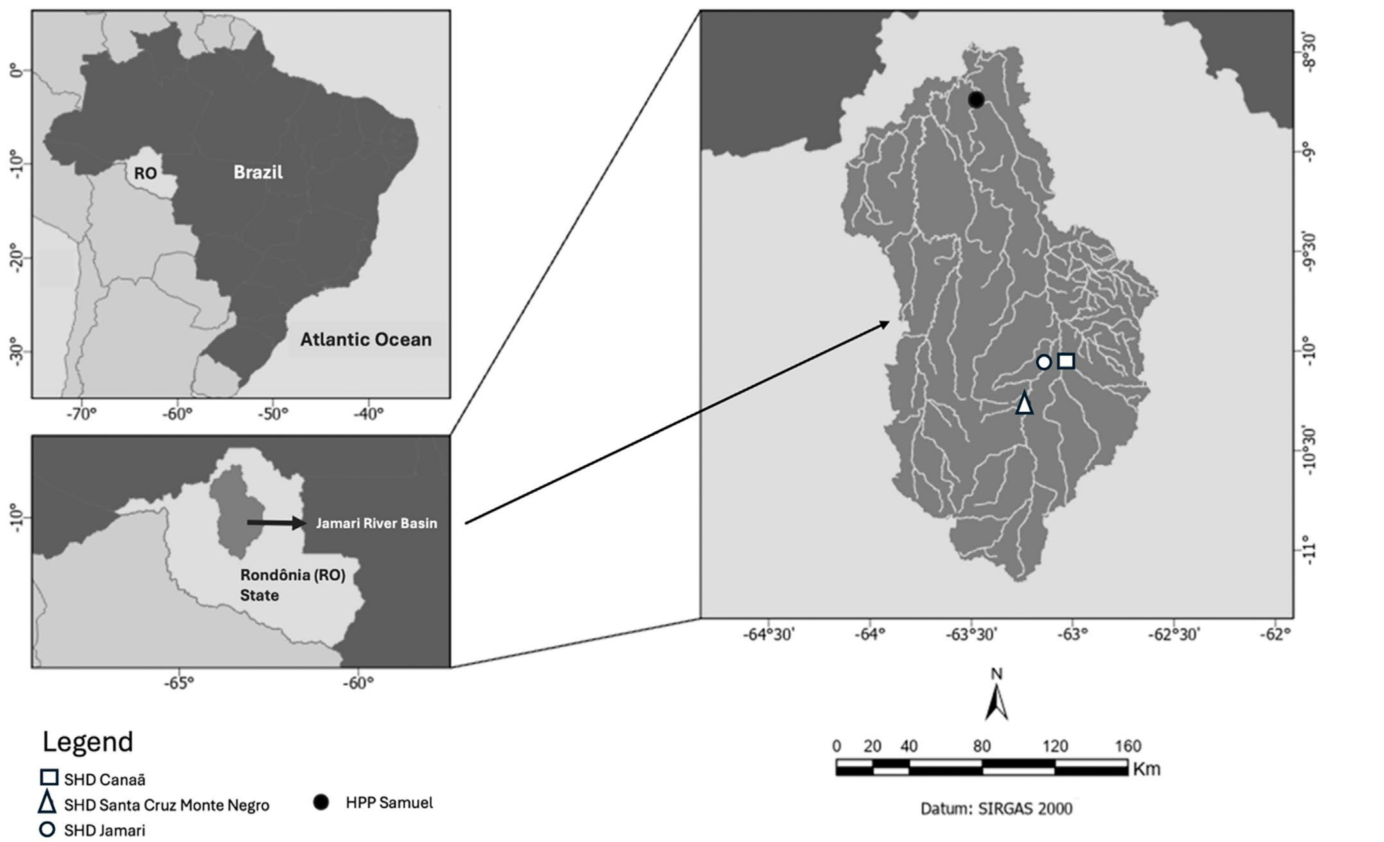

FIGURE 1 | Location of the Jamari River basin, Rondônia State (Western Brazilian Amazon), showing the positions of the small hydroelectric dams (SHDs) Canaã, Santa Cruz (SC) Monte Negro, Jamari, and the Samuel Hydroelectric Power Plant (HPP).

primarily on livestock farming, grain production, timber extraction, and more recently, aquaculture activities (IBGE 2024).

According to the Köppen–Geiger climate classification, the Jamari basin falls under the 'Am' climate category, indicative of a tropical rainforest climate. This climate is characterised by consistently high temperatures and substantial annual precipitation, with a distinct dry season (de Lima et al. 2023). Rainfall averages between 2200 and 2800 mm per year, concentrated between November and April, while the dry season extends from June to September, with monthly rainfall often falling below 50 mm (IBGE 2024). These seasonal dynamics directly influence river discharge and reservoir levels, which are key variables in aquaculture planning.

Vegetation in the Jamari basin is predominantly composed of ombrophilous open rainforest, with scattered seasonal forest patches in transitional zones (Perigolo et al. 2017). Despite significant deforestation since the 1980s, particularly for pasture and agriculture, remnants of native forest remain in protected areas and along riparian corridors. Palustrine zones, flooded igapó forests and areas with aquatic macrophytes are also found along reservoir margins and lowland tributaries. These ecological features are important when assessing aquaculture viability, as they influence water quality and site accessibility.

Currently, four hydroelectric projects are operational within the Jamari River basin, with their reservoirs forming the focus of the spatial aquaculture suitability assessments in this study (Figure 1). The oldest is the Samuel Hydroelectric Power Plant (HPP), established in the 1980s. The other three reservoirs, located approximately 150 km upstream near Ariquemes, consist of the Santa Cruz (SC) de Monte Negro, Jamari and Canaã small hydroelectric dams (SHDs), implemented in the mid-2010s. The SC Monte Negro and Jamari SHDs are situated along the main course of the Jamari River, while the Canaã SHD was constructed on the Canaã River. The SC Monte Negro SHD is the highest of the three dams. Approximately 35 km downstream is the Jamari SHD, which lies about 15 km perpendicular to the Canaã SHD.

2.2 | Total Water Surface Area (TWSA) of the Reservoirs

Geospatial layers (shapefiles) were sourced from official repositories, including the websites of Brazilian government agencies: IBGE (Brazilian Institute of Geography and Statistics), INPE (National Institute for Space Research), EMBRAPA (Brazilian Agricultural Research Corporation), FUNAI (National Indian Foundation) and SEDAM/RO (State Secretariat for Environmental Development of Rondônia), as well as satellite imagery from Sentinel. Satellite imagery from these agencies also included data from the CBERS-4A and LANDSAT-8 satellites (Valadão et al. 2023).

CBERS-4A images were utilised to define the TWSA of the four reservoirs studied through manual vectorisation. Prior to this step, image bands were merged to produce a true-colour RGB (Red-Green-Blue) composite (Valadão et al. 2023). SRTM (Shuttle Radar Topography Mission) images, accessed via EMBRAPA, provided the Digital Elevation Model (DEM), which was used to delineate the Jamari River basin. This DEM was subsequently used to crop other images and generate study maps. A DEM mosaic was created, and the Hydrology tool in ArcGIS was applied to map the TWSA of the reservoirs.

To assess variation in TWSA between flood and dry periods, Sentinel-2 satellite images with a spatial resolution of 10 m were employed. Reservoirs were classified using the Iso Cluster Unsupervised Classification tool for flood and drought periods on the Jamari River during 2022 and 2023. Optimal class differentiation for TWSA definition was achieved using the infrared (IR) spectrum, specifically band 8 for Sentinel-2. After classification, only reservoir features were retained, and all other polygons were excluded.

2.3 | Water Surface Areas (WSAs) Free of Remaining Vegetation in the Reservoirs

Remaining vegetation refers to remnants of forest cover that were not removed during the construction, installation, and filling of the dams and reservoirs (Ploskey 1985). For net-cage aquaculture in hydroelectric reservoirs, such remaining vegetation is considered undesirable (Bueno et al. 2015). Therefore, Potential Aquaculture Sites (PAS) in this study were required to be located away from areas containing remaining vegetation.

The identification of remaining vegetation areas was conducted in two stages: (1) geographic coordinates were recorded using a Garmin GPS to mark points of high- and medium-density vegetation during a pronounced dry season in November 2022; and (2) these geographic coordinates were analysed in geoprocessed imagery using ArcGIS, followed by classification according to the methodology proposed by Bueno et al. (2015).

During fieldwork, the WSAs free of remaining vegetation were classified into: (1) areas with low density of remaining vegetation; (2) areas with medium density; and (3) areas with high density. This classification was supported by the validation of in situ data during the field campaign in November 2022, a month marked by extremely dry hydrological conditions in the Jamari River basin and much of the Amazon Basin (ANA 2024).

2.4 | Water Surface Areas (WSAs) With Adequate Depth in the Reservoirs

The depth of the reservoirs was determined using a Garmin Striker 5 CV Vivid sonar, equipped with a GT20 transducer, which collected data from bank to bank along the reservoirs. In the field, depth measurements were taken in areas predetermined by the studies on WSAs free of remaining vegetation. With the aid of geoprocessing, the points were interpolated to create a continuous surface identifying WSAs with adequate depth in the reservoirs.

Depth sampling followed linear transects perpendicular to the longitudinal axis of the reservoirs, focusing on areas without the presence of remaining vegetation—that is, areas with aquaculture potential. At least four perpendicular transects were conducted in each WSA free of remaining vegetation for the analysed reservoirs. Along the transects, depth measurements were taken every 10 s, with the vessel travelling at 10 km/h, covering the entire width of the reservoirs from bank to bank.

For depth analysis, GPS data from the Garmin Striker 5 CV sonar were digitised. As this device is not specifically designed for depth mapping and lacks a direct computer interface, data were manually entered into a spreadsheet using Microsoft Excel, including depth values and corresponding geodetic coordinates. These data were subsequently imported into ArcGIS for interpolation and reservoir bottom analysis using geoprocessing tools.

According to Ordinance no. 412/2021 of the Ministry of Agriculture, Livestock and Supply (MAPA) and the Aquaculture and Fisheries Secretariat (SAP), in conjunction with Normative Instruction (NI) no. 07/2005 of the Ministry of Environment (MMA) and the Special Secretariat of Aquaculture and Fisheries (SEAP), depth must be considered when selecting areas for net-cage aquaculture systems. These regulations stipulate that the appropriate depth for aquaculture parks and areas can be calculated by multiplying the net-cage height by a factor of 1.75. In this study, we adopted net-cage heights of 2.0 and 1.5 m (Bueno et al. 2015); therefore, the minimum required depths were 3.50 and 2.62 m, respectively, as prescribed by the Ordinance and NI.

2.5 | Water Level Time Series of the Reservoirs

The ANA (National Water Agency of the Brazilian Government) HIDROWEB system is an online platform for hydrological, climatic and limnological data that covers a large proportion of Brazil's water bodies (rivers, lakes and reservoirs) (SNIRH 2024). This system provides access to historical time series, enabling analyses from various perspectives depending on the objectives of each study.

For the present study, the HIDROWEB system provided water level time series for the three small hydroelectric dam (SHD) reservoirs on the Jamari River (Monte Negro, Jamari and Canaã), from their installation to the present. The time series spanned from 1 January 2016 to 31 March 2024, with daily resolution. All water level records were taken at 00:00 h each day.

2.6 | Water Quality Time Series of the Reservoirs

Time-series information on water quality is essential for defining aquaculture areas in hydroelectric reservoirs (Kaggwa et al. 2011; Canzi et al. 2017). However, the logistical, material and personnel demands for collecting water quality data at consistent temporal frequencies over long periods are extremely high. In this context, the water quality data for this study were obtained from SEDAM/RO (State Secretariat for Environmental Development of Rondônia) through the environmental licensing procedures for the three hydroelectric facilities in the Jamari River Basin.

Each of the three reservoirs had time-series data for the following water quality parameters: chlorophyll-*a* (Chl-*a*, $\mu g\,L^{-1}$), biochemical oxygen demand (BOD, $mg\,L^{-1}$), total phosphorus (P, $mg\,L^{-1}$), and dissolved oxygen (DO, $mg\,L^{-1}$). These parameters were selected based on the criteria of CONAMA Resolution no. 357/2005, which regulates the use of water bodies for aquaculture purposes in Brazil.

All sampling points reported in SEDAM/RO technical documents were mapped using GIS, and data for each parameter were averaged across three surface-level sampling stations within each reservoir. The water quality time-series data cover distinct periods for each of the three SHD reservoirs. For the SC Monte Negro SHD, the data spanned from April 2015 to February 2017, with monthly records throughout this period. For the Jamari SHD, the time series ranged from February 2018 to April 2019, also with monthly data. Finally, for the Canaã SHD, the data extended from February 2017 to May 2018, again recorded monthly. No water quality data were available or analysed for the Samuel HPP reservoir.

2.7 | Map Formulation

All geographic data management was conducted within a GIS environment, and the field-collected data were processed to be compatible with ArcGIS software (Longley et al. 2015). Depth and vegetation data collected during field campaigns were pre-processed and georeferenced prior to integration into the spatial database. Once imported into ArcGIS, data interpolation was applied to produce a comprehensive overview of the spatial distribution of the sample data across the entire study area.

For interpolation, a linear approach using the Natural Neighbour method was applied to both depth and remaining vegetation data within ArcGIS. This method calculates estimated values where direct measurements are absent, which is particularly effective in areas of high point density. The technique also incorporates Delaunay triangulation to compute weights based on neighbouring points. In this manner, the Natural Neighbour method preserved the integrity of the original sample data, especially in densely surveyed areas (Liu et al. 2019).

Remote sensing analysis included Sentinel-2 satellite imagery processed within ArcGIS, using tools such as Image Analysis and Raster Calculator. The Modified Normalised Difference Water Index (MNDWI) was employed to delineate water bodies. Additional raster processing, interpolation, and spatial overlay procedures were performed using the Spatial Analyst and Geostatistical Analyst extensions.

2.8 | Fish Production Estimate for Net-Cage in the Potential Aquaculture Sites (PAS) of the Jamari River Hydroelectric Reservoirs

The fish production estimate for the predefined areas suitable for cage aquaculture in the hydroelectric reservoirs of the Jamari River was based on Ordinance no. 412/2021 of the Ministry of Agriculture, Livestock and Supply (MPA) and the Aquaculture and Fisheries Secretariat (SAP), which establishes a minimum area ratio of 1:10. This means that for every 1 m^2 of effective fish production area, an additional 10 m^2 must be allocated for the dilution of the organic load generated, primarily due to the accumulation of phosphorus- and nitrogen-rich substances that may lead to eutrophication in aquatic environments (Beveridge 2004). The ordinance also specifies a maximum area ratio of 1:20. Accordingly, two production estimates were calculated: one using the minimum production/dilution ratio of 1:10 and another using the maximum ratio of 1:20. In both cases, spacing between cages was accounted for, deducted at a rate of 10% of the effective production area.

Another technical element incorporated into the calculations was the size of the cages. The dimensions of the cages are generally determined by local water current dynamics and the operational scale of aquaculture systems authorised in public waters under Brazilian jurisdiction. Based on the models proposed by Ono and Kubitza (2003), two cage types were considered: (1) large-volume, low-density cages (LVLD) with a total volume of 18 m^3, corresponding to a height of 2 m and an area of 9 m^2; and (2) small-volume, high-density cages (SVHD) with a volume of 6 m^3, corresponding to a height of 1.5 m and an area of 4 m^2. For LVLD cages, a stocking density of 40.0 kg/m^3 was applied, while for SVHD cages, the density was set at 80.0 kg/m^3 (Merola and de Souza 1988; Gomes et al. 2006; Frisso et al. 2020).

3 | Results

3.1 | Variation of the Total Water Surface Areas (TWSA): Exclusion of the HPP Samuel Reservoir

The prominent droughts affecting the region in 2022 and 2023 were among the environmental factors that underscored the limited suitability of the HPP Samuel reservoir for aquaculture purposes. Among the reservoirs studied, the Samuel reservoir exhibited significant and pronounced fluctuations in the surface area of its usable water, unlike the three small hydroelectric dam (SHD) reservoirs. Spatial variability during the dry season was recorded in situ, and geospatial analyses revealed a stark contrast between the seasonal surface area variation of the HPP Samuel and that of the other SHDs.

Table 1 presents the numerical values, calculated within a GIS environment (ArcGIS), illustrating the variation in TWSA across all hydroelectric reservoirs, including HPP Samuel. These data confirm the relative stability of the SHD reservoirs on the Jamari River in terms of water level, as opposed to the significant fluctuations observed in the Samuel reservoir. In both 2022 and 2023, the TWSA of the HPP Samuel reservoir varied by more than 70% between flood and dry seasons, whereas the variation in the SHD reservoirs remained below 5%.

Figure 2 displays a series of images from the MSI Sentinel-2 satellite, taken at three points in time (May, August and November 2022), which visually demonstrate the changes in water surface area and spatial extent observed in the reservoirs during the monitored period. The extent of variation in the HPP Samuel reservoir is clearly distinguishable when compared to the other three reservoirs on the same observation dates. This figure

TABLE 1 | Numerical values of the Total Water Surface Areas (TWSA) (in km^2) of the reservoirs located in the Jamari River Basin (Western Brazilian Amazon) and percentage variation (%) between flood and dry seasons for two hydrological cycles. Dates for the TWSA calculations: Flood/2022 = 25/05; Dry/2022 = 06/11; Flood/2023 = 30/04 and Dry/2023 = 06/11.

	2022		2023	
Reservoirs	**Flood**	**Dry**	**Flood**	**Dry**
HPP Samuel	341.66	99.75	349.78	104.72
Variation (%)	70.8		70.1	
SHD Jamari	15.00	14.79	16.19	16.27
Variation (%)	1.4		−0.5	
SHD Canaã	13.47	12.77	13.64	13.13
Variation (%)	5.2		3.7	
SHD SC Monte Negro	4.05	4.00	4.10	4.06
Variation (%)	1.2		1.0	

visually illustrates the seasonal dynamics of the reservoirs and complements the numerical data presented in Table 1.

3.2 | WSA Free of Remaining Vegetation in the SHD Reservoirs

In the three SHD reservoirs of the Jamari River basin, WSAs free of remaining vegetation were identified, and Figure 3 presents the corresponding maps. The classification of vegetation remnants was based on field geolocation points collected during the dry season, integrated with satellite imagery and processed using geospatial tools within a GIS environment.

Table 2 presents the numerical values of remaining vegetation areas identified across the three SHD reservoirs. In percentage terms, the SC Monte Negro SHD reservoir had the largest proportion of potential area without remaining vegetation. However, in absolute terms, the Jamari SHD reservoir presented the largest WSA free of vegetation, totalling 325.0 ha (3.25 km^2). These results are spatially illustrated in Figure 3, which enables a visual comparison between the reservoirs and highlights the distribution patterns of submerged vegetation across the study area. This analytical step was essential for excluding areas unsuitable for net-cage aquaculture due to potential physical interference from submerged trees.

3.3 | WSA With Appropriate Depth of the SHD Reservoirs by Brazilian Legislation

The WSAs with suitable depths for aquaculture were estimated based on two net-cage height categories commonly used in Brazilian aquaculture systems: (1) cages with a height of 2.0 m and (2) cages with a height of 1.5 m. Table 3 provides the numerical values of TWSA and the corresponding WSAs that meet the required depths for net-cage aquaculture across the three SHD reservoirs of the Jamari River.

According to Table 3, for net-cages with 2.0 m height, WSAs with adequate depth represented 0.88% of the total TWSA in SC Monte Negro, 39.80% in Jamari, and 15.61% in Canaã. For cages with 1.5 m height, the percentages increased to 6.71% in SC Monte Negro, 49.75% in Jamari, and 16.01% in Canaã.

These data indicate notable differences in the depth profiles among the reservoirs. Such differences influence the proportion of WSA that meets the legal requirements for net-cage installation, depending on the selected cage height.

3.4 | SHD Reservoir Water Levels—Historical Data Series From ANA/Brazil

The historical series of water level variations in the three SHD reservoirs—SC Monte Negro, Jamari and Canaã—from their initial operation to the present was obtained from gauge records at each dam and is shown in Figure 4. The figure depicts the full range of recorded reservoir level fluctuations from the ANA system, allowing a comparative visual assessment across the SHDs.

The low seasonal variations in WSAs observed during 2022 and 2023 can be attributed to the modest fluctuations in water levels throughout the historical period. Among the three, the SC Monte Negro SHD reservoir—located furthest upstream—showed the largest amplitude over the approximately 7-year time series, with water levels ranging from a peak of 13.2 m (recorded between December 2022 and February 2023) to a minimum of 11.6 m on 25 July 2022, totalling a variation of 2.0 m.

In the Jamari SHD reservoir, level variation was comparatively smaller, with a maximum difference of approximately 0.70 m. The highest level was 11.2 m in March 2018, and the lowest was 10.5 m, recorded on 21 November 2016.

The Canaã SHD reservoir exhibited a variation pattern similar to that of Jamari SHD reservoir. The minimum water level recorded was 10.7 m on 23 December 2019, and the maximum was approximately 12.1 m in February 2023, representing a variation of around 1.4 m.

The data series further demonstrate that intra-annual variations—that is, within individual hydrological years—were smaller than the total variations observed over the entire period. It is also noteworthy that the highest and lowest values for each reservoir occurred in different years, which is visually represented in Figure 4.

3.5 | Water Quality Time Series of the SHD Reservoirs

Table 4 provides a summary of the variation in water quality parameters for the three SHD reservoirs located along the Jamari River, alongside the reference values established by CONAMA Resolution no. 357/2005. The analysed parameters include Chl-*a*, BOD, P and DO, all expressed in $mg\,L^{-1}$. Sampling periods were: April 2015 to January 2017 for the SC Monte Negro SHD; February 2018 to April 2019 for the Jamari SHD; and February 2017 to March 2018 for the Canaã SHD.

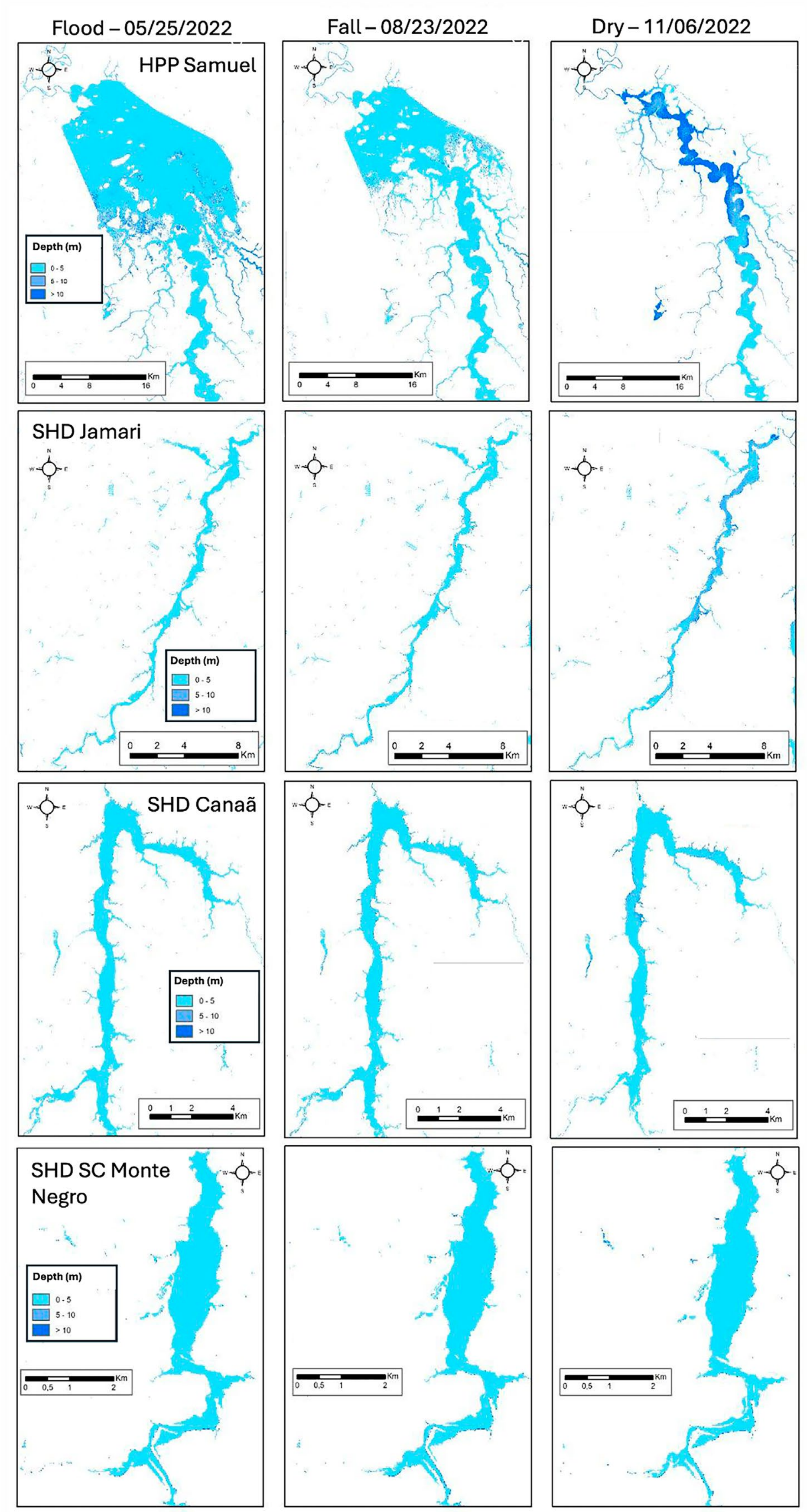

FIGURE 2 | Maps illustrating temporal variation in the Total Water Surface Areas (TWSA) of four reservoirs: HPP Samuel, SHD Jamari, SHD Canaã, and SHD SC Monte Negro, across three stages of the hydrological cycle of the Jamari River: 25 May 2022 (flood season), 23 August 2022 (fall-dry season), and 6 November 2022 (dry season).

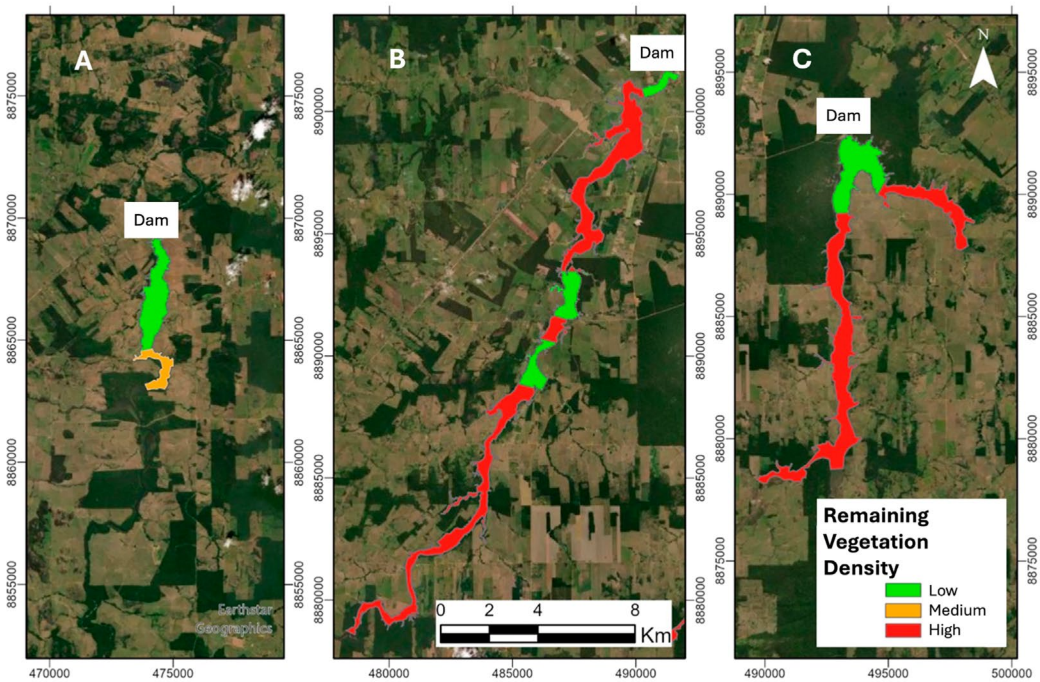

FIGURE 3 | Remaining vegetation density within the three SHD reservoirs of the Jamari River basin, Western Brazilian Amazon, Rondônia State: (A) SC Monte Negro SHD; (B) Jamari SHD; and (C) Canaã SHD.

TABLE 2 | Total Water Surface Area (TWSA) and Water Surface Areas (WSA) free of remaining vegetation in the three reservoirs of SHDs (Small Hydroelectric Dams) of the Jamari River, in the Western Brazilian Amazon (Rondônia State).

SHD Reservoir	TWSA (km^2)	WSA free of remaining vegetation (km^2)	(WSA_{free}×100)/TWSA
SC Monte Negro	4.05	3.18	78.5
Jamari	15.56	3.25	20.9
Canaã	13.25	2.54	19.2

Table 4 summarises the mean, standard deviation, and minimum and maximum values for each parameter, facilitating direct comparison with Brazilian water quality standards for aquaculture.

Water quality profiles varied among the three reservoirs. In SC Monte Negro, Chl-*a* levels ranged from 0.48 to 9.55 mg L^{-1}, with a mean BOD of 1.35 mg L^{-1} and consistently low phosphorus concentrations. The Jamari reservoir displayed higher Chl-*a* values, ranging from 3.69 to 10.85 mg L^{-1}, and recorded a peak phosphorus value of 10.70 mg L^{-1} in November 2018. In the Canaã reservoir, Chl-*a* ranged from 1.09 to 10.19 mg L^{-1}, while phosphorus levels were below the detection limit for most of the period. Across all reservoirs, DO concentrations generally exceeded 5.0 mg L^{-1}.

When compared with CONAMA standards, most parameters remained within acceptable thresholds. Chl-*a* levels across all reservoirs were well below the 30.0 mg L^{-1} maximum. BOD levels also complied with the 5.0 mg L^{-1} limit. Phosphorus concentrations exceeded the 0.03 mg L^{-1} threshold only in the Jamari reservoir. DO levels met the minimum requirement of 5.0 mg L^{-1} in nearly all samples, with only occasional deviations. These exceedances—particularly in phosphorus for Jamari—are highlighted in Table 4.

TABLE 3 | Numerical values of Total Water Surface Areas (TWSA) and water surface areas (WSA) with depths for the installation of aquaculture net-cages with two different heights (2.0 and 1.5 m) in the three SHD reservoirs of the Jamari River, in the Western Brazilian Amazon.

SHD Reservoir	TWSA (ha)	WSA for 2.0 m height net-cages (ha)	($WSA_{2.0}$×100)/TWSA	WSA for 1.5 m height net-cages (ha)	($WSA_{1.5}$×100)/TWSA
SC Monte Negro	405.0	3.66	0.88	27.19	6.71
Jamari	1556.0	619.17	39.80	774.26	49.75
Canaã	1325.0	206.91	15.61	212.26	16.01

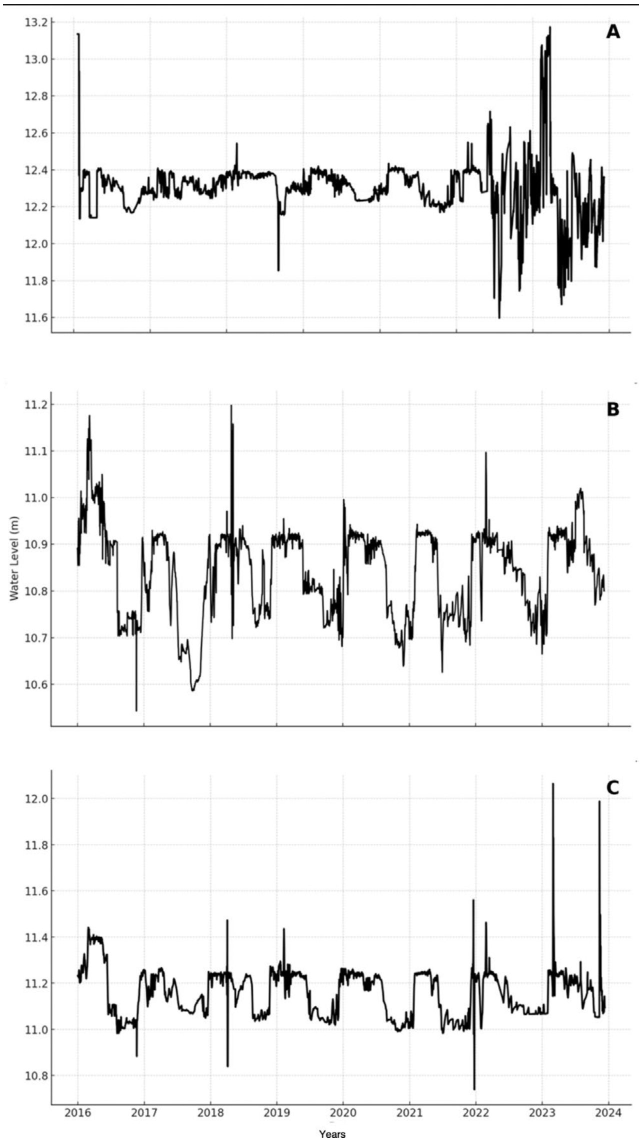

FIGURE 4 | Historical water level data (m) for three SHD reservoirs from their inception to the end of 2023: (A) SC Monte Negro Reservoir—lowest recorded level: 11.597 m on 25 July 2022; (B) Jamari Reservoir—lowest recorded level: 10.543 m on 21 November 2017; and (C) Canaã Reservoir—lowest recorded level: 10.749 m on 23 December 2021.

3.6 | Potential Aquaculture Sites (PAS): Intersection Between WSA Free of Remaining Vegetation and WSA With Appropriate Depth in SHD Reservoirs of the Jamari River

The spatial intersection of WSAs free from submerged tree remnants and those meeting appropriate depth thresholds—(1) 3.5 m and (2) 2.62 m—for each of the three SHD reservoirs on the Jamari River is presented in Figure 5 as PAS. So, his figure displays a spatial overlay of two essential criteria: absence of remaining vegetation and compliance with the minimum depth required for net-cage installation under Brazilian legislation.

Although the SC Monte Negro SHD reservoir is almost entirely free of submerged vegetation, its depth does not meet the regulatory requirement for cages with a height of 2.0 m across most of its area. Consequently, the recommended configuration for this reservoir is the use of net-cages with a maximum height of 1.5 m. Figure 5 highlights these suitable zones, which, despite being limited in surface area, satisfy the minimum required depth of 2.62 m.

The Jamari SHD reservoir presented a more favourable depth profile. Areas free of vegetation with depths exceeding 3.5 m cover 1.47 km^2 (147 ha), while areas exceeding 2.62 m in depth expand to 1.92 km^2 (192 ha). Both zones are deemed suitable for cage aquaculture.

In the Canaã SHD reservoir, the area free of vegetation with depths exceeding 3.5 m totals 2.06 km^2 (206 ha), and for depths above 2.62 m, the area extends slightly to 2.12 km^2 (212 ha). These zones are spatially contiguous and located near the dam, providing ease of access and infrastructure compatibility. The overlap between depth and vegetation suitability is visualised in Figure 5, allowing comparative analysis of aquaculture potential across the three SHD reservoirs.

Table 5 presents a summary of the numerical values for WSA potentially available for net-cage installation at both 2.0 and 1.5 m cage heights. The table details the total WSA of each SHD reservoir, the calculated PAS in hectares, and its percentage share, providing a clear comparative overview between reservoirs and cage configurations.

3.7 | Fish Production Estimate in Potential Aquaculture Sites (PAS) for Net-Cages in the Three SHD Reservoirs of the Jamari River

Table 6 summarises the estimated fish production potential in the PAS identified within the three SHD reservoirs, based on two net-cage configurations. The first configuration utilises Large Volume, Low Density (LVLD) cages, each with a volume of 18.0 m^3 (9.0 m^2 base area and 2.0 m height), and a stocking density of 40.0 kg/m^3. The second configuration employs Small Volume, High Density (SVHD) cages, with a volume of 6.0 m^3 (4.0 m^2 base area and 1.5 m height), and a stocking density of 80.0 kg/m^3.

The estimated production values were calculated for each reservoir's PAS under the regulatory guidelines of Ordinance SAP/MAPA no. 412/2021, which stipulates minimum and maximum spatial ratios of 1:10 and 1:20, respectively, for the dilution of organic load resulting from aquaculture operations. Both scenarios incorporate a 10% deduction in usable cage area to account for the mandatory spacing between cages, as established by the ordinance.

These estimates provide a baseline for evaluating the productive potential of the reservoirs under legally permissible environmental loading and stocking densities, offering guidance for practical and sustainable aquaculture planning within this SHD reservoirs.

4 | Discussion

Hydroelectric reservoirs originating from SHDs have been increasing in number across Brazil and globally (Couto and Olden 2018). Currently, Brazil has 1481 SHDs registered in the ANEEL database, of which approximately 425 are operational,

TABLE 4 | Summary of water quality parameters (mean, standard deviation, maximum and minimum) for SHD (small hydroelectric dam) reservoirs of the Jamari River compared to CONAMA Resolution no. 357/2005 standards. All values are in $mg\,L^{-1}$.

SHD Reservoir	Parametric measures	Chl-*a*	BOD	P	DO
SC Monte Negro	Mean (standard deviation)	4.18 (±2.79)	1.35 (±0.58)	0.01 (±0.02)	6.08 (±1.12)
	Maximum–minimum	9.55–0.48	2.58–0.45	0.05–0.00	8.99–4.25
Jamari	Mean (standard deviation)	6.77 (±1.96)	1.42 (±1.47)	0.82 (±2.9)	5.93 (±0.86)
	Maximum–minimum	10.85–3.69	6.18–0.40	10.70[a]–0.00	7.20–4.83
Canaã	Mean (standard deviation)	5.19 (±2.76)	1.48 (±0.80)	0.00 (±0.00)	5.48 (±0.50)
	Maximum–minimum	10.19–1.09	3.82–0.40	0.01–0.00	6.75–5.03
CONAMA[b] Resolution no. 357/2005		Up to 30.0 $mg\,L^{-1}$	Up to 5.0 $mg\,L^{-1}$	Up to 0.05 $mg\,L^{-1}$	Not less than 5.0 mg/L

Abbreviations: BOD—biochemical oxygen demand; Chl-*a*—chlorophyll-*a*; DO—dissolved oxygen; P—total phosphorus.
[a]Outlier.
[b]Brazilian National Environmental Council (CONAMA).

providing a combined generation capacity of around 5800 MW (ANEEL 2024). However, the total area flooded by SHDs in Brazil remains unquantified, raising concerns about potential reductions in freshwater biodiversity and fisheries productivity in numerous Brazilian river basins and elsewhere (Zeleňáková et al. 2018; Freitas et al. 2022).

Public policies aimed at income generation for riverside, fishing, Indigenous, and rural communities affected by hydroelectric projects are essential, as fish represent the primary source of animal protein for these populations (Begossi et al. 2019). Moreover, safeguarding the livelihoods of these communities is a crucial component of impact mitigation, as their daily lives encompass cultural, folkloric, linguistic, and traditional expressions that may be lost due to hydroelectric-related displacement (MAB 2024). As a mitigation strategy, fish farming in hydroelectric reservoirs may help support the income of communities affected by such projects, particularly in light of the nearly irreversible impacts of dams on migratory fish species, which are highly valued in Brazilian inland fisheries (Campos et al. 2019; Couto et al. 2021). A critical initial step in implementing aquaculture in these artificial environments is to evaluate their environmental suitability for fish cultivation.

Within the Jamari River basin, the reservoir of the Samuel HPP has exhibited substantial variability in water level and, consequently, in TWSA, strongly influenced by seasonal hydrological cycles in the Amazon (Bittencourt and Amadio 2007; Barthem and Goulding 2007). During the rainy season, extensive areas are inundated, whereas the dry season results in markedly reduced water levels. These fluctuations hinder logistical operations such as transportation and feeding, increasing the risk of complete or partial production losses due to insufficient water depth in large portions of the Samuel HPP reservoir during the dry period.

In contrast, the SHD reservoirs of the Jamari basin—SC Monte Negro, Jamari and Canaã—demonstrated relatively low water level fluctuations during the study period, indicating greater environmental stability. All three utilise Kaplan S turbines (ANEEL 2024), operating under a run-of-the-river system with a horizontal configuration and minimal water storage, thereby generating electricity based on natural river flow (Casadei et al. 2019; Martinez et al. 2019).

Furthermore, a study in the Tocantins–Araguaia River system in the eastern Brazilian Amazon revealed that temporal TWSA variation in seven HPP reservoirs, including four run-of-the-river types, was positively correlated with land use and land cover. Greater anthropogenic activity was associated with larger fluctuations in water surface area (Valadão et al. 2023). Although the Jamari River basin encompasses municipalities and agricultural activities, its headwaters remain protected by conservation units and Indigenous territories, which may help stabilise river discharge and consequently reduce water level fluctuations in the SHD reservoirs analysed.

Remaining vegetation is another key factor with several ecological implications for hydroelectric reservoirs. Decomposition of submerged vegetation contributes to greenhouse gas emissions (Lu et al. 2020), impedes navigability (Ploskey 1985), and provides habitat for aquatic fauna, potentially affecting fishing activities and bird foraging patterns (Agostinho 2007). In aquaculture, residual vegetation poses operational risks: net-cages—typically composed of mesh netting—can become entangled with submerged branches, causing structural damage, fish escapes, production loss and unintentional release of cultivated species into natural habitats (Bueno et al. 2015). Canzi et al. (2017) identified submerged vegetation as an exclusionary criterion for aquaculture site suitability in the Itaipu Reservoir on the Paraná River (Southern Brazil), underscoring the importance of mapping and assessing vegetation remnants as a prerequisite for aquaculture development.

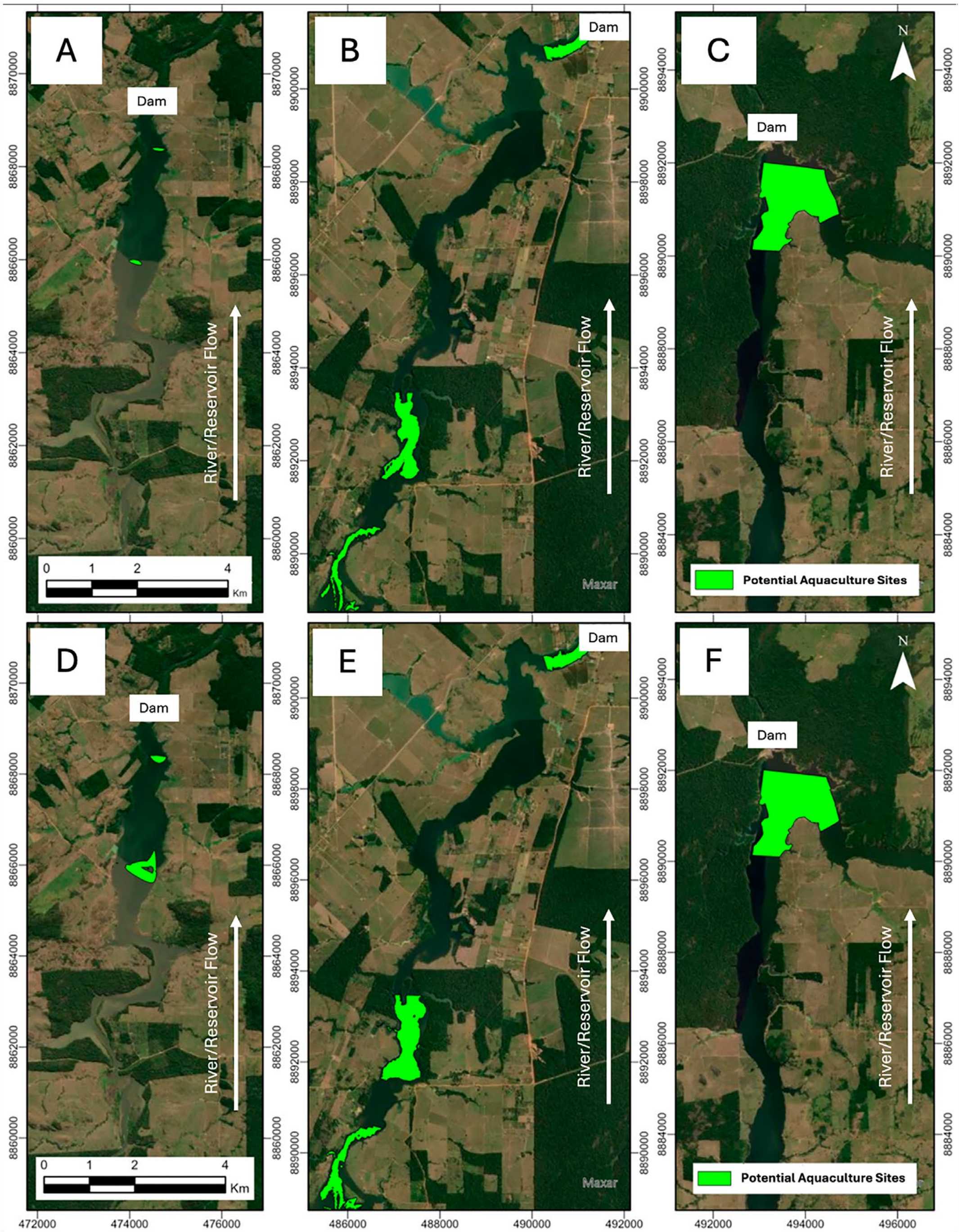

FIGURE 5 | Potential Aquaculture Sites (PAS) with depths exceeding 3.50 m (A–C) and 2.62 m (D–F), corresponding to net-cage systems with maximum heights of 2.0 and 1.5 m, respectively, in three SHD reservoirs of the Jamari River: (A, D) SC Monte Negro; (B, E) Jamari; and (C, F) Canaã.

Thus, considering that: (1) the three SHD reservoirs exhibit low variation in TWSA, corroborated by historical water level data; and (2) the field survey conducted during the dry season (November 2022) under environmentally arid conditions was optimal for detecting remaining vegetation and measuring reservoir depths, it can be concluded that these indicators designate the PAS in these reservoirs as high-potential environments for implementing net-cage aquaculture.

Due to the shallow depth of the SC Monte Negro reservoir, there is an almost complete lack of suitable areas for net-cage aquaculture. This highlights the importance of overlaying two critical variables—remaining vegetation and reservoir depth—to define areas with actual aquaculture potential. It is noteworthy that the procedures for SHD construction and reservoir licensing vary across Brazilian states. In some, vegetation clearance prior to flooding is mandatory, whereas in others, it is not a regulatory requirement (Agostinho 2007).

Water quality is also a critical factor in aquaculture planning, especially for open-water production systems (Simões et al. 2008; Boyd and Tucker 2014). According to CONAMA Resolution no.

TABLE 5 | Numerical values of Total Water Surface Areas (WSA) and total area of Potential Aquaculture Sites (PAS) for net-cages in the three hydroelectric reservoirs of Small Hydropower Dams (SHDs) located on the Jamari River basin (Western Brazilian Amazon), based on two minimum depths (3.50 and 2.62 m). The potential percentage in relation to the total areas of these reservoirs is also presented.

	Intersection of remaining vegetation and depth data > 3.50 m			Intersection of remaining vegetation and depth data > 2.62 m		
SHD Reservoir	**Total WSA (ha)**	**Total area of the PAS (ha)**	**(PAS × 100)/WSA**	**Total WSA (ha)**	**Total Area of the PAS (ha)**	**(PAS × 100)/WSA**
SC Monte Negro	405.00	3.4	0.83	405.00	26.9	6.64
Jamari	1556.00	146.9	9.44	1556.00	191.8	12.32
Canaã	1325.00	206.9	15.61	1325.00	212.2	16.01

357/2005, freshwater intended for aquaculture in Brazil must comply with specific environmental standards. The parameters analysed in this study—Chl-*a*, BOD, P and DO—were predominantly within permissible thresholds. Nonetheless, localised BOD peaks and occasional deviations in phosphorus were observed. These findings suggest that, in general, the water quality in the SHD reservoirs complies with Brazilian aquaculture standards, although some caution is warranted in site-specific assessments.

In 2022, total fish production in Rondônia was 57,200 t, across 15,800 ha of fishpond area (IBGE 2024), positioning the state as Brazil's leading producer of native fish. However, average productivity remains modest at 3.62 t/ha, which is well below the state's estimated potential. Net-cage aquaculture in the SHD reservoirs of the Rondonia State could significantly increase this productivity, given the more intensive characteristics of this production system (Beveridge 2004).

Considering the socioeconomic challenges currently faced by fish farmers in the Amazon—particularly those reliant on excavated ponds—the development of alternative aquaculture models is both urgent and strategic. As reported by Hungria et al. (2024), a substantial number of aquaculturists have abandoned production due to high feed costs, technological stagnation and insufficient institutional support, all of which disproportionately affect traditional pond-based systems. These systems often require extensive land clearing and complex water infrastructure. In contrast, net-cage aquaculture in SHD reservoirs presents an opportunity to reduce deforestation pressure, optimise water usage, and improve production logistics. Consequently, a shift in public policy and research priorities is needed to support reservoir-based aquaculture models in the western Amazon, where environmental protection and rural development must be reconciled (Pacheco et al. 2025).

The severe drought that has recently affected large portions of the Brazilian Amazon raises serious concerns regarding the resilience of pond-based aquaculture systems. Widely adopted in rural and peri-urban settings, these systems have proven vulnerable to prolonged dry seasons and irregular rainfall patterns. As a result, many operations have experienced water shortages, fish mortality, and eventual abandonment (Hungria et al., 2024). These circumstances further underscore the need to explore alternative aquaculture systems adapted to evolving hydroclimatic conditions.

In the specific case of the SHD reservoirs in the Jamari River basin, the modest variability in water levels, as recorded in historical time series, positions them as promising sites for sustaining aquaculture even during dry periods. These reservoirs may serve not only as adaptive platforms but also as efficient systems for fish production, especially when utilising native species such as *Colossoma macropomum*, already familiar to local producers and well adapted to Amazonian environments.

In the broader Amazonian context—where deforestation must be avoided—net-cage aquaculture in SHD reservoirs offers a low-impact, bioeconomy-compatible alternative. Long-term environmental planning, as demonstrated in this study, is essential to guide sustainable decision-making (Silva et al. 2018). The next steps for implementing aquaculture in the SHD reservoirs of the Jamari River include: (1) conducting detailed carrying capacity assessments using hydrodynamic modelling (Asmah et al. 2021); (2) evaluating road and riverine logistics and production outflow (Yakubu et al. 2025); and (3) establishing a Demonstration Aquaculture Unit for research and extension focused on net-cage aquaculture in Amazonian reservoirs.

Finally, fostering partnerships with institutions dedicated to the development of sustainable bioeconomies will be key to strengthening the production chain of native Amazonian fish, with a particular emphasis on no-deforestation approaches.

5 | Conclusion

The findings of this study demonstrate that the Jamari and Canaã SHD reservoirs exhibit favourable environmental conditions for net-cage aquaculture, with extensive PAS that comply with both legal and technical standards. In contrast, the SC Monte Negro reservoir presents limited suitability, primarily due to insufficient depth.

Water quality data for all three reservoirs were generally within the thresholds defined by CONAMA Resolution no. 357/2005. Nonetheless, occasional deviations in phosphorus and BOD levels highlight the importance of establishing robust water monitoring protocols prior to aquaculture deployment.

This study advances the field of spatial aquaculture planning in hydroelectric reservoirs, particularly within the Amazon, where SHDs are increasingly common yet remain underexplored. By

TABLE 6 | Production estimate of Potential Aquaculture Sites (PAS) in three SHD reservoirs of the Jamari River (Western Brazilian Amazon), considering LVLD net-cages of 18.0 m^3 (area of 9.0 m^2; height of 2.0 m and a stocking density of 40.0 kg/m^3) and SVHD net-cages of 6.0 m^3 (area of 4.0 m^2; height of 1.5 m and a stocking density of 80.0 kg/m^3), respectively. Two dilution area ratios are presented: (1) 1:10 and (2) 1:20 (i.e., for one unit area of effective fish production: 10–20 units of dilution area).

SHD Reservoir	Total Area of PAS (ha)	Use area:dilution area (ha)		Number of net-cages for 1:10 dilution (LVLD/SVHD)	Number of net-cages for 1:20 dilution (LVLD/SVHD)	Production estimate with 1:10 dilution (Tons) (LVLD/SVHD)	Production estimate with 1:20 dilution (Tons) (LVLD/SVHD)
		1:10	1:20				
SC Monte Negro	0.34	0.034	0.017	38/85	19/43	27/41	14/20
Jamari	1.47	0.147	0.074	163/368	82/184	118/176	59/88
Canaã	2.07	0.207	0.104	230/518	115/259	166/248	83/124
Total	3.88	0.388	0.195	431/970	216/485	310/466	155/233

integrating remote sensing, depth data and regulatory criteria, the methodology presented offers a replicable and scalable model for evaluating aquaculture viability in tropical reservoirs.

From a policy and practical perspective, the results support the implementation of low-impact aquaculture systems that align with zero-deforestation commitments while enabling income generation for riverine and rural populations affected by dam infrastructure.

Future research should focus on coupling this spatial analysis with hydrodynamic modelling, ecological carrying capacity assessments, and socio-economic viability studies. Establishing demonstrative aquaculture units in selected SHD reservoirs will be vital for validating the findings presented here and for consolidating aquaculture as a sustainable bioeconomic pathway in the Amazon region.

Acknowledgements

The authors thank the Foundation for the Support and Development of Scientific Actions and Research of Rondônia State (FAPERO) for financial support and the provision of scholarships. We also acknowledge Luiz Fontes Machado Neto and Jakson do Rosário Alves for their valuable assistance during the technical fieldwork. Special thanks are extended to the Federal Institute of Rondônia (IFRO) for supplying essential field equipment, including the boat, engine and trailer. The Article Processing Charge for the publication of this research was funded by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) (ROR identifier: 00x0ma614).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Periódicos CAPES at https://www.periodicos.capes.gov.br/.

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