Latin American Journal of Aquatic Research, 52(4): 563-574, 2024
DOI: 10.3856/vol52-issue4-fulltext-3163

Research Article

Sustainable planning geotechnologies for fish farming expansion in small municipalities: a case study of Pato Bragado/PR-Brazil

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ABSTRACT. Using geotechnologies has become fundamental for planning the sustainable expansion of agricultural activities, especially fish farming. The objective of this work was to map and carry out the morphological characterization of the hydrographic micro-basins and their physical aspects, such as slope, altimetry, and land use and occupation, and also to quantify and locate the existing excavated ponds in the municipality of Pato Bragado, in Paraná State. Geotechnology tools and images generated by the free software QGIS and Google Earth were used to create maps of the excavated ponds' physical aspects, quantification, classification, and location. The predominant slope in the municipality is gently undulating, and soy plantation uses 42.99% of the municipality's entire area. The mapping located 190 excavated ponds. Depth measurement was not carried out, but rather mapping concerning water depths representing a total area of 47.86 ha of water blade and nine micro-basins within the municipality of Pato Bragado, with only the Arroio Fundo micro-basin covering 47.37% of all existing excavated ponds. The morphometric indicators concluded that the micro-basins present a minimum risk of flooding, which is ideal for use in fish farming. Making the results of this work available to public managers and fish farmers aims to demonstrate the importance of using geotechnologies for sustainable planning to expand aquaculture activities, which, in this case, are focused on fish farming.

Keywords: *Oreochromis niloticus*; georeferencing; micro-basins; aquaculture; Pato Bragado; Brazil

INTRODUCTION

Fish farming is gaining more and more space and importance in the economic sector of municipalities. During the last decades, its importance for society in producing protein-rich foods has increased (Feiden et al. 2022). The demand for nutritional foods, including fish, increases the need for new aquaculture enterprises. Thus, the use of Geographic Information Systems (GIS) has become an essential tool for use in the field to measure the aquaculture potential (Nath et al. 2000). Currently, new georeferencing technologies allow multiple parameters to be analyzed, such as physical and biological characteristics that make it possible to find the most favorable areas for the expansion of fish farming (Kapetsky & Aguilar-Manjarrez 2007). Using georeferencing technologies makes it possible to create maps of a region's physical aspects to find the areas with the lowest financial and environmental costs (Lira et al. 2022).

The western region of Paraná State in Brazil has small municipalities with great potential for the practice

Associate Editor: Sandra Bravo

of fish farming. According to IPARDES (2022), the municipality of Pato Bragado, since 2013, has stood out in fish production of tilapia (*Oreochromis niloticus*) (Table 1). The municipality has shifted its commercial fish production to tilapia due to the technological advantages this species currently offers, favoring it over other species. The quantification and characterization of the pre-existing excavated ponds in the municipalities favors the planning and efficiency of the expansion of the logistic chain, allowing the adequate use of water resources, avoiding additional costs in the implantation of new production plants, avoiding environmental impacts resulting from the bad use of natural resources (Bernardi 2014, Feiden et al. 2018). Knowing the exact location of excavated ponds helps demarcate Permanent Protection Areas (PPAs), facilitating the environmental licensing process. With georeferencing, water courses can be mapped to help properly measure the self-purification of water bodies (Francisco et al. 2019). The slope and quality of the soil and the simple access to the nearest water body make fish farming viable and attractive to new entrepreneurs (Nath et al. 2000, Oviedo et al. 2013, Nayak et al. 2018, Teixeira et al. 2018).

For authorities and public bodies, GIS and Remote Sensing (SR) are efficient tools for long-term planning of agricultural activities (Burrough 1986, Jayanthi et al. 2018). Using these technologies, Francisco et al. (2020) and Morsoleto et al. (2022a) developed methodologies to locate and quantify the excavated ponds and weirs used in fish farming. In the geographic areas belonging to the municipalities, there are different hydrographic micro-basins, which are the planning units. Knowing the morphometric characteristics of these micro-basins helps to understand the water capacity of a given region or municipality, and based on this knowledge, new fish farming projects can be executed without exceeding the hydrological capacities.

The objective of this work is not just to select areas suitable for fish farming but rather to map areas already installed and which can be used for fish farming with appropriate geotechnology tools to assist in the development of fish farms in inland (or continental) waters, regardless of the physical and natural aspects of the municipalities, and regardless of the size of the chosen municipality, serving municipal managers and bodies responsible for promoting fish farming as a facilitating mechanism for the development of possible fish logistics chains and the application of these techniques.

MATERIALS AND METHODS

Area of study

The municipality of Pato Bragado is located in the southern region of Brazil (24º37'35"S, 54º13'29"W), in the western region of the Paraná State (Fig. 1), between the municipalities of Marechal Cândido Rondon and Entre Rios do Oeste (IBGE 2022a).

Delimitation of the municipality of Pato Bragado

The delimitation of the area of the municipality of Pato Bragado was carried out by downloading the files on the IBGE website (IBGE 2022a), and later, they were designed for the DATUM, SIRGAS 2000 UTM for the 21 south zone. The images were processed in the QGIS software, version 3.18.2 Zurich.

Land use and occupation in the city of Pato Bragado

Land use and occupation data were obtained from the Mapbiomas Project in raster format (GeoTiff), scale 1:100,000, and with a spatial resolution of 30 m (MAPBIOMAS 2019). This tool is intended to produce land cover and land use maps in Brazil and provide statistical information at various scales (Neves et al. 2020). The maps produced make it possible to identify different land use types, such as urban areas, forestry, agricultural areas, pastures, and reforestation. Its creation came from the need for updates on the constant changes in land use dynamics in the national territory.

Slope and altimetry of the municipality of Pato Bragado

The Digital Elevation Models (DEMs) of the slope and altimetry maps were acquired from the Instituto Nacional de Pesquisas Espaciais website (INPE 2023), merged, and projected for the DATUM, SIRGAS 2000 UTM for the 21 south zone, and cut with the mask of the limit of the municipality of Pato Bragado. The slope was performed through the tabs raster, analysis, and slope. Altimetry was performed using raster tabs, analysis, orientation, shading, and roughness. All the information was processed in QGIS software, version 3.18.2 Zurich. Table 2 presents the classification of altimetry defined by Embrapa (2013).

Delimitation of the micro-basin and morphometric indices

For the delimitation of the micro-basin, a DEM was used to obtain images from the INPE website (INPE 2023) through the Shuttle Radar Topography Mission (SRTM) with a configuration of 30 m and 8 bits. Muni-

Table 1. Annual tilapia (*O. niloticus*) production (t) in the municipality of Pato Bragado during the years 2013 to 2021. Source: IBGE (2022b).

Species	2013	2014	2015	2016	2017	2018	2019	2020	2021
O. niloticus	218	250	400	680	620	860	850	858	750

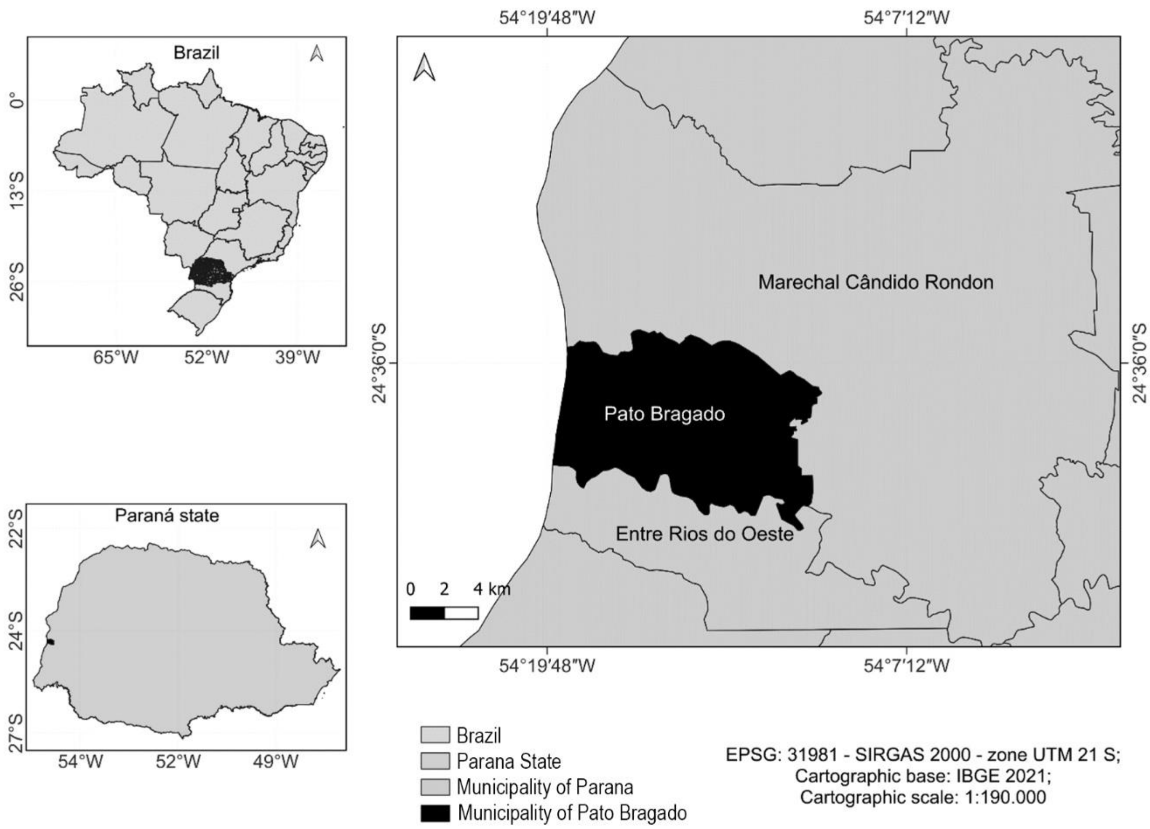

Figure 1. Maps show the Municipality of Pato Bragado's location in Paraná.

cipality vectors were acquired from the IBGE website (IBGE 2022a) and redesigned for DATUM, SIRGAS 2000 UTM 21S. The DEM was processed using the QGIS software - Free and Open Geographic Information System, version 3.18.2 Zurich. The r.fill.dir is a procedure performed to remove all holes in the DEM. In the raster, these pits are the lowest cells surrounded by higher slopes. The delimitation of the basin and information on the hydrography was carried out by capturing the coordinates of the main river outlet with the help of OpenStreetMap. The r.watershed algorithm delimits river basins and drainage networks, while r.water.outlet delimits the drainage point, which is only possible after the slope map is generated; that is, the basin's drainage network is obtained using the r.watershed algorithm, using r.to.vect to convert the raster files to vector format, making it possible to have the basin data and its hydrology vectorized. All these algorithms belong to the GRASS module of QGIS.

Table 2. Percentage of slope classes and their classification. Source: Francisco et al. (2020).

Values (%)	Slope class
0-2	Flat slope
2-5	Gently wavy slope
5-10	Wavy slope
10-15	Strongly wavy slope
15-45	Mountainous slope
45-70	Strongly mountainous slope

To better evaluate the water capacity of the micro-basin, morphometric data were used, which, according to Menezes et al. (2014), facilitate the choice of areas for the activity, in addition to helping the work of public managers. The indices used were form factor (Kf), compactness index (Kc), drainage density (Dd), circularity index (Ic), and sinuosity index (Is), and they were all calculated with the QGIS calculator tool. The shapefile file was used to delimit the hydrography of the basin.

Acquisition of pond data

According to Francisco et al. (2020), the identification and quantification of the structures of the excavated ponds in the micro-basin region were carried out using images from the provider Digital Globe, an American company that licenses the Google Earth high-resolution satellite images on the Google Earth software program.

The excavated ponds were classified according to the traditional arrangement used by fish farming in the region and also adopted by large fish cooperatives due to its logistical ease (Morsoleto et al. 2022a):

- Class I (small ponds) - areas from 300 to 3,000 m^2
- Class II (medium ponds) - areas from 3,001 to 5,000 m^2
- Class III (large ponds) - areas from 5,001 to 10,000 m^2
- Class IV (very large ponds) - areas greater than 10,001 m^2

Ponds with areas smaller than 300 m² were not demarcated, being used for animal watering, according to Coldebella et al. (2020) and Morsoleto et al. (2022a).

RESULTS

Delimitation of micro-basins and soil formation

Several micro-basins had to be included within the municipality of Pato Bragado, so a more detailed analysis can be seen in Figure 2. Eight micro-basins were observed: São Francisco Verdadeiro River, Branco River, Arroio Fundo, Coqueiro Stream, Limeira Stream, Naragito Stream, Petronio Stream, and Sergeant Stream. The micro-basins of the Arroio Fundo, Branco, and São Francisco rivers extend to other municipalities.

The soil formation in the study area (Fig. 3) is mostly composed of latosol (when used for fish farming, requires prior fertilization) in the flat areas, nitosoil in the southern region of the municipality, and around the water body in the eastern portion.

Land use and occupation maps

The municipality has a total area of 12,976.20 ha, distributed according to Table 3. Most of the area is being used for planting soybeans, with 41 fragments totaling 5579.36 ha, covering 42.99% of the municipality's total area. The configuration of land use and occupation in Pato Bragado is shown (Fig. 4).

Slope and altimetry maps

Figure 5 visualizes the slope class obtained. The hydrographic micro-basins incorporated in the municipality of Pato Bragado are suggested to have a gently undulating slope. The municipality's altimetry varies from its lowest point, at 192 m, to its highest point, at 323 m. Figure 6 shows the hypsometry map of Pato Bragado.

Morphometric classification of micro-basins present in Pato Bragado

All morphometric indices of the micro-basins belonging to the municipality of Pato Bragado were analyzed (Table 4). It is noted that among all the micro-basins, only the form factor related to the Branco River watershed has a more circular shape within the municipality.

The morphometric indices indicate that the municipality has large areas suitable for implementing new fish farms, and there are still micro-basins within Pato Bragado's limits without excavated ponds.

Mapping of excavated ponds

Figure 2 shows the location of the excavated ponds. The biggest occupation of ponds is found close to water bodies.

Table 5 summarizes the results of classifying ponds excavated for the municipality of Pato Bragado. In total, 190 excavated ponds were located and classified, representing an area of 47.86 ha of water depth. The Arroio Fundo micro-basin has the largest number (90) of ponds, representing 47.37% of the total. The most abundant class of excavated ponds in the micro-basins was the small one, class I.

DISCUSSION

Knowledge of the characteristics and soil type is fundamental for the adequate choice to implant excavated ponds, as they interfere with porosity and density. The texture, for example, reflects the ease of soil excavation and water retention, and this factor impacts the water balance of aquaculture systems, according to Coche (1985) and Biggs et al. (2005). Soils with higher proportions of clay are better at retaining water (Assefa & Abebe 2018).

Latosol is the predominant type of soil in Pato Bragado, interspersed with nitosoil in areas with higher

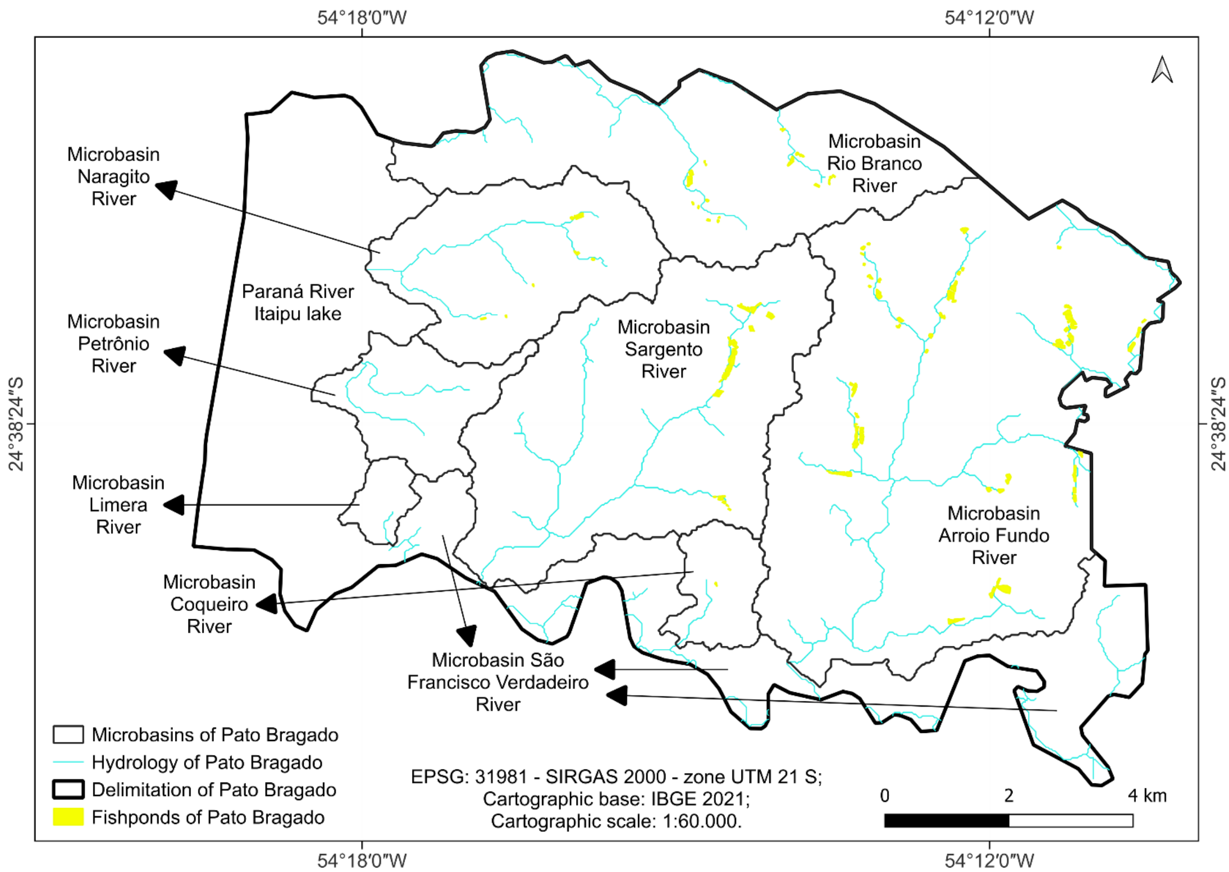

Figure 2. The map shows the delimitation of micro-basins that belong to the municipality of Pato Bragado and the location of the excavated ponds.

altitudes. Both soils are suitable for aquaculture and agricultural activity, as they are homogeneous and present high compaction, an essential quality in the construction of excavated ponds because it makes them less susceptible to erosion by the action of time (Boyd 2015). The low permeability of the soil prevents the use of geomembranes, which makes the aquaculture enterprise more expensive. The excavated ponds need to be properly fertilized; that is, they receive the input of nutrients so that plankton can grow to feed the initial phases of fish farming because the latosol is not rich in organic matter (pH 4-5.5). For aquaculture, a pond with low chemical fertility is not ideal (Lazur 2007). Soil pH outside the range of 6 to 8 decreases nutrient input, decreasing the presence of microorganisms affecting water pH and productivity (Salam 2000, Tapader et al. 2017).

The topographical conditions minimize the costs of aquaculture implementation, maintenance, and productivity (Coche 1985). According to De Oliveira et al. (2016), earthmoving costs and adaptation of areas are some of the biggest obstacles for producers in small municipalities to implement a fish farming system in excavated ponds. The municipality of Pato Bragado has a relatively undulating slope, which makes up a large part of its territory (51.88%) and does not require high costs for the implementation of excavated ponds due to the low slope because in addition to the influence it exerts on the construction of improvements also affects drainage, water runoff, soil movement/erosion and the water retention rate (Falconer et al. 2016) tampering with natural drainage and placing the site under the direct effect of erosion according to Pereira & Silva (2012) and Ssegane et al. (2012). The study area has a flat slope and does not require heavy machinery to implement structures for aquaculture activities. Areas with more than 5 degrees of inclination require structural adaptation (Hossain et al. 2007, Hossain & Das 2010).

Pato Bragado is a relatively flat municipality, and within its limits, it has a large amount of water, as it is contemplated with eight micro-basins, all well supplied

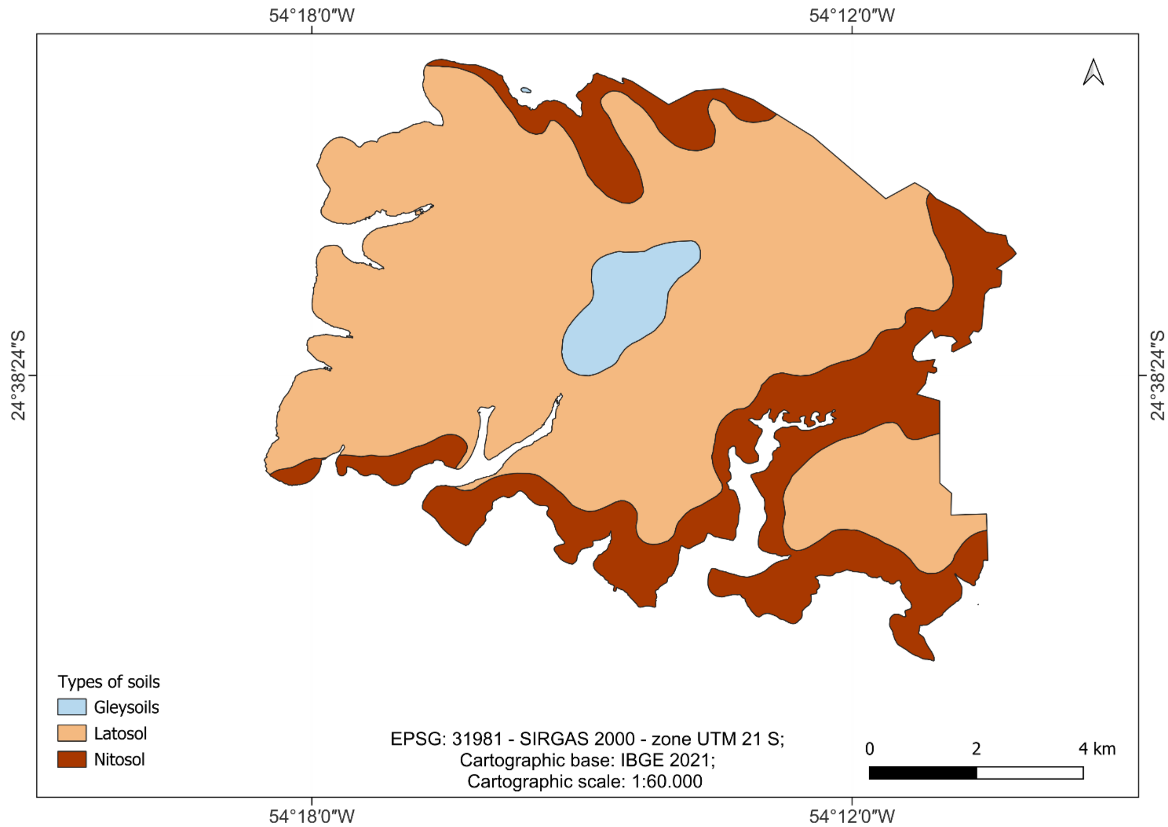

Figure 3. The map shows the Pato Bragado soil formation.

Table 3. Land use and occupation, with area and percentage occupied.

Classes	Fragments	Areas (ha)	(%)
Training forest	118	2313.51	17.829
Forestry	2	0.59	0.005
Flooded fields and swampy area	2	1.76	0.014
Pasture	85	102.77	0.792
Mosaic of agriculture and pasture	360	1807.22	13.927
Urbanized area	2	242.80	1.871
Non-vegetated areas	52	54.00	0.416
Rivers and lakes	33	2834.08	21.841
Soy	41	5579.36	42.997
Temporary crops	47	40.11	0.309
Total	742	12,976.20	100

by their tributaries. The availability of good quality water is essential for the success of fish farming (Ono & Kubtiza 2005). This way, local aquaculture uses a nutrient-rich water source, providing a high nitrogen and phosphorus content (Pereira & Silva 2012).

Altitudes below 700 m are highly conducive to fish activity (Francisco et al. 2019). The municipality of Pato Bragado does not have large depressions and valleys, and its altitude is at most 340 m, which is viable for aquaculture activity. Altitudes greater than 700 m risk flooding due to sudden precipitation (Cardoso et al. 2006). Regarding the distance between water bodies and aquaculture enterprises, the municipality of Pato Bragado has an average distance of 0.5 to 0.9 km. Distances smaller than 1 km are suitable for fish farming (Völcker & Scott 2008).

The city's road network is an important factor in implementing fish farming; however, it has not recei-

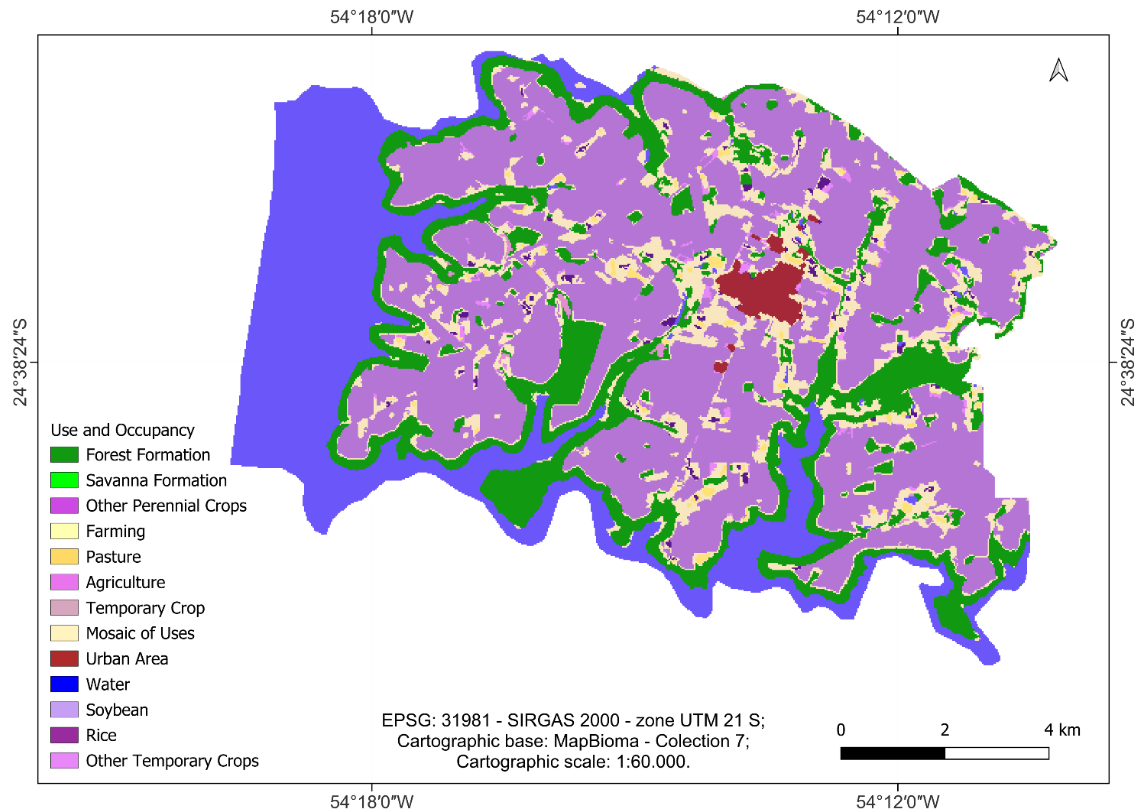

Figure 4. The map shows the types of land use and occupation in the municipality of Pato Bragado.

Table 4. Morphometric indices of the micro-basins in the Municipality of Pato Bragado/PR. *Micro-basins that have stretch in the municipality.

Micro-basins	Morphometric indices				
	Form factor - *f*	Compactness ratio - *kc*	Drainage density - Dd (km km^{-2})	Circularity ratio - *Ic*	Sinuosity ratio - *Is* (%)
Arroio Fundo*	0.45	1.74	2.35	0.32	67.06
Sanga Limeira	0.48	1.63	1.47	0.37	64.76
Sanga Coqueiro	0.49	1.76	0.11	0.32	66.29
Sanga Naragito	0.37	1.71	0.92	0.34	63.47
Sanga Petronio	0.63	2.05	0.25	0.23	71.74
Sanga Sargento	0.36	1.88	1.96	0.28	65.36
Rio Branco*	0.90	1.94	1.23	0.26	69.93
São Francisco Verdadeiro*	0.21	1.81	0.40	0.22	73.77

ved attention from public managers. Well-connected roads with easy flow of inputs (fingerlings, fertilizers, and feed) and especially the harvest must be transported quickly and efficiently, avoiding mortality (Nayak et al. 2018). Pato Bragado has single roads, mostly paved, which does not match the ideal standard of logistical arrangement. Fish warehouses facilitate fish disposal within a less than 50 km radius, which absorbs practically all municipal production. The municipality has a local market developed to meet the needs of aquaculture activities.

When assessing agricultural activities, anthropogenic disturbance modifies the original structure (forest zones and endemic biomes) and replaces them with pastures or plantation areas (Foley et al. 2005). An analysis of land use and occupation helps in choosing the best regions for the installation of excavated ponds, avoiding the use of inappropriate areas that could cause

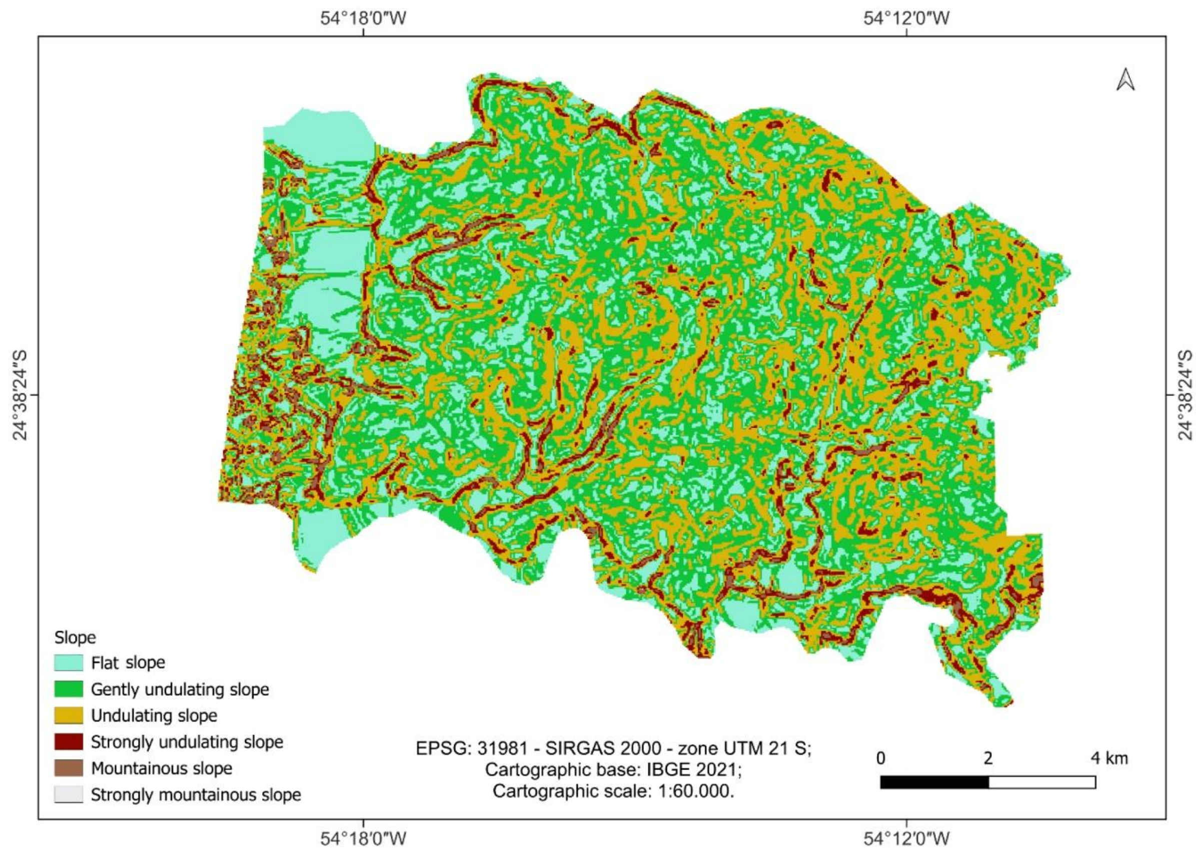

Figure 5. Slope in the municipality of Pato Bragado.

irreparable environmental disasters and conflicts in public management, and also affecting the development of socio-environmental policies (Zak et al. 2008).

Pato Bragado has extensive areas with forest formation, silviculture, and pastures, that is, many fragments, indicating that the municipality has large areas of forest formation (INFOSANBAS 2022). The natural topography of the area chosen for implementing fish farming is always relevant to all the dynamics and cycling of nutrients (Ross et al. 2013). The Kf of the micro-basins present in the municipality of Pato Bragado (between 0.3 and 0.7) indicates a low risk of flooding. Compaction indices (Kc) of the micro-basins between 1 and 1.25 indicate a risk of flooding (Silva et al. 2016); however, no micro-basins presented an index that would indicate a risk of flooding. Regarding Dd, all micro-basins had low rates, except for the Arroio Fundo River micro-basin, which was classified as having medium drainage. Low values are explained by more permeable rocks associated with a rainy regime of low rainfall (Tonello et al. 2006). In the analysis of the circularity ratio of the micro-basins, the highest value was 0.37, which indicates that all the micro-basins have an elongated shape and low risk of flooding. The values of this parameter were similar to those obtained by Simonetti et al. (2022), who compared morphometric indices of the Pirajibu-Mirim River micro-basin for fish farming. All micro-basins that belong to the municipality or occupy part were classified as very sinuous. That is, the drainage of water from the municipality takes time to reach the main channel due to the soil of the region being homogeneous and old (Veloso 2016).

The use of morphometric indices to characterize areas suitable for fish farming and the indication of geotechnologies as tools to assist regulatory agencies in the sustainable planning of the use of water resources were demonstrated in Werneck et al. (2023a). In the early days of aquaculture activities developed in municipalities, managers used the proximity of the water body as a determining factor (Kubitza 2015). The excavated ponds are in the Arroio Fundo, Branco River, Sangas Coqueiro, Naragito, and Sargento micro-basins. This characteristic suggests that small rural properties are important for fish farming in municipalities with a smaller geographical area, as observed by Talau et al. (2021) and Werneck et al. (2023b).

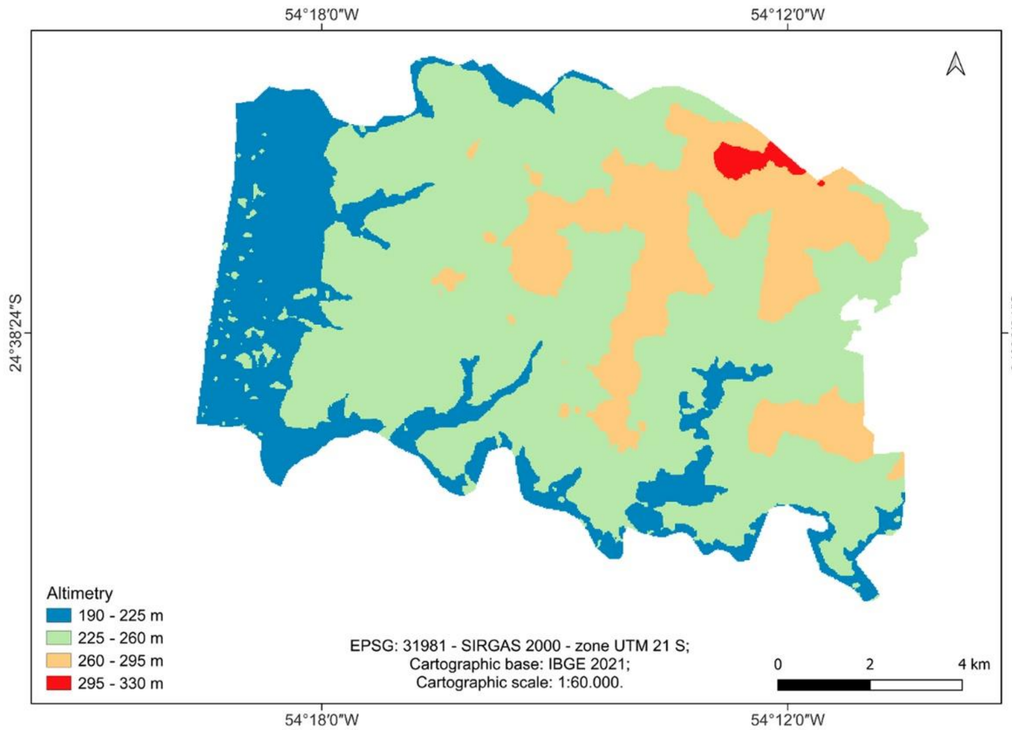

Figure 6. Hipsometry of the municipality of Pato Bragado.

Table 5. Classes of excavated ponds in the micro-basins of the municipality of Pato Bragado. Source: adapted from Francisco et al. (2020) and Morsoleto et al. (2022b).

Classes	Size (m²)	Fishponds	Fishponds (%)	Area (ha)	Area (%)
Arroio Fundo micro-basin					
I - Small	300 to 3000	62	61.40	8.4	28.47
II - Medium	3001 to 5000	26	25.74	10.31	34.95
III - Large	>5000	13	12.86	10.79	36.58
Subtotal		101	100	29.50	100
Rio Branco micro-basin					
I - Small	300 to 3000	19	86.36	2.77	63.97
II - Medium	3001 to 5000	1	4.54	0.37	8.55
III - Large	>5000	2	9.10	1.19	27.48
Subtotal		22	100	4.33	100
Sanga Coqueiro micro-basin					
I - Small	300 to 3000	1	100	0.17	100
II - Medium	3001 to 5000	0	0	0	0
III - Large	>5000	0	0	0	0
Subtotal		1	100	0.17	100
Sanga Naragito micro-basin					
I - Small	300 to 3000	11	91.67	1.99	85.80
II - Medium	3001 to 5000	1	8.33	0.33	14.20
III - Large	>5000	0	0	0	0
Subtotal		12	100	2.32	100
Sanga Sargento micro-basin					
I - Small	300 to 3000	27	72.97	4.66	47.46
II - Medium	3001 to 5000	6	16.22	2.04	20.77
III - Large	>5000	4	10.81	3.12	31.77
Subtotal		37	100	9.82	100
Total (ponds/area)		173		46.14	

CONCLUSIONS

The municipality of Pato Bragado can potentially expand fish farming production with sustainability. The physical characteristics of altimetry and gently undulating slope favor the construction of excavated ponds. The greater number of class I ponds indicates that fish farming is still dominated by family farming, leading us to estimate that when cooperatives enter the region, the logistical arrangement will change to accommodate larger quantities of fish. Although the municipality has several micro-basins in its territory, the Arroio Fundo micro-basin is widely used, which indicates that new enterprises may emerge and expand production in the other micro-basins. The methodology used was very assertive in the characteristics of the study area.

ACKNOWLEDGMENTS

To the Coordination for the Improvement of Higher Education Personnel CAPES for granting the scholarships. To the Aquaculture Management Studies Group - GEMAq, and the Municipality of Pato Bragado for financing CV 01/2022.

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Received: October 20, 2023; Accepted: May 6, 2024