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Geographic information system as a tool for assessing ponds and the potential for environmental impact caused by fish farming

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ABSTRACT

The hydrographic basin of Arroio Marreco (Paraná State) concentrates a productive chain of fish farming and great intensification of tilapia farming. In this study, we aimed to monitor the quality of effluent water and organic and inorganic elements released by fish farming in ponds, using geomorphological and land-use and occupation data. The Terrain Analysis Using Digital Elevation Models, Digital Elevation Model software was used to delimit watersheds in the software Quantum geographic information system version 3.6.3. A total of 1,457 production units (water slides) were identified across the study area. This represented an occupied area of 160.2 ha. Analyzing the sub-basins, it was found that High Marreco is the sub-basin with the most developed logistical chain. Low Marreco does not yet have an integration of its fish farming with the region's logistics chain. Medium Marreco does not have fish farming as its main activity, only using it to reuse inputs from other agricultural activities. There is a large input of nutrients from aquaculture in all the sub-basins. To reduce them, it is recommended to implement decantation and/or reuse of wastewater systems. The results of this study show how important it is to know the dynamics of nutrients in the fish farms and the physical characteristics of the drainage basin to determine the support capacity of the environment, so as not to allow licenses that promote impacts above the self-cleaning capacity of the courses water.

Key words: Aquaculture, eutrophication, TauDEM, ponds.

Sistema de informação geográfica como ferramenta de avaliação de viveiros escavados e potencial de impacto ambiental causado pela piscicultura

RESUMO

Na bacia hidrográfica do arroio Marreco, no estado do Paraná, concentra-se uma cadeia produtiva de piscicultura com intensa criação de tilápias. Neste estudo, foi monitorada a qualidade da água do efluente e dos subprodutos (fósforo e nitrogênio) da piscicultura em viveiros escavados, utilizando-se dados geomorfológicos e de uso e ocupação do solo. O *software* Análise de Terreno com Modelos Digitais de Elevação, Modelo Digital de Elevação, foi utilizado para delimitar bacias hidrográficas no *software* Quantum sistema de informação geográfica v. 3.6.3., o qual identificou 1.457 unidades de produção em toda a área de estudo (160,2 ha de lâmina d'água). Analisando as sub-bacias, constatou-se que o Alto Marreco é a sub-bacia com a cadeia logística mais bem desenvolvida. No Baixo Marreco, ainda não existe integração de sua piscicultura com a cadeia logística da região. Já no Médio Marreco, a piscicultura não é a atividade principal, serve apenas para reutilizar insumos de outras atividades agrícolas. Ocorre em todas as sub-bacias grande aporte de nutrientes da aquicultura, e para reduzi-los, recomenda-se implantar sistemas de decantação e/ou reaproveitamento de águas residuárias. Os resultados deste estudo mostraram a importância de conhecer a dinâmica dos nutrientes na piscicultura e as características físicas da bacia hidrográfica para determinar a capacidade de suporte do meio ambiente de forma a não permitir licenças que resultem em impactos superiores aos da autodepuração.

Palavras-chave: aquicultura, eutrofização, TauDEM, lagoas.

INTRODUCTION

Geographic Information System (GIS) is recognized as an ideal tool for cost reduction in aquaculture because it characterizes aquaculture environments, evaluates its potential, and helps in choosing suitable areas for aquaculture (Salam and Ross, 2000).

In the Paraná Hydrographic Basin 3 (PB3), the main hydrographic sub-basins are those of the São Francisco rivers (center) and the tributaries Arroio Marreco, Guaçu and Dezoito de Abril (to the north), and Santa Quitéria (to the south). The Marreco River is one of the most important tributaries on the right bank of the São Francisco River, covering approximately 75 km between its source (in the urban area of Toledo) and its mouth on the São Francisco River (border between the municipalities of Pato Bragado, Entre Rios do Oeste, and Marechal Cândido Rondon) (IAT).

Bernardi et al. (2012) highlighted the importance of the hydrographic basin as an environmental management unit, and it is necessary to analyze agricultural activities with modern technological tools such as geotechnologies, as these help obtain technical information that can serve as a decision-making tool for monitoring impacts caused by intensified production.

Macedo and Sipaúba-Tavares (2010) affirmed that aquaculture activity causes a nutrients increase in the aquatic environment, increasing the phytoplankton production, leading to changes in the aquatic system, which was confirmed by Coldebella et al. (2020). Analyzing the fishery in several fish farms in the western region of Paraná, the results indicated that the concentrations of total solids, chemical oxygen demand (COD), and total phosphorus (TP) increased significantly in the harvest, causing a deterioration of the effluent released into the environment. Fish farming practices, when carried out intensively, can compromise the quality of water resources in the form of eutrophication (high concentrations of phosphorus from the feed used in fish feed), in addition to affecting biodiversity by escaping fish and launching chemical and biological contaminants, which can compromise the quality of water resources downstream from their site production (Veiga, 2011).

Brazilian agricultural production has shown high growth rates and intensified production in several production chains, with an emphasis on the production and industrialization of products from the soy and animal protein complex, notably in the south and midwest of the country, and has a high demand from Arab and Asian countries, notably China (Escher and Wilkinson, 2019).

Paraná is one of the highlights in the agro-industrialization of meat products, notably in the production chains of swine, poultry, and fish farming, and its western region concentrates a large part of animal production, with emphasis on the county of Toledo, which has the largest gross value of agricultural production (VBP) in Paraná, with R$ 2,162,263,535.01 (when converted to average U.S. dollar=$ 375,392,974.82) (SEAB, 2017; BCB, 2021), with emphasis on the production of swine, poultry, milk, tilapia, and fingerlings of tilapia. In 2020, Toledo and its neighbors Marechal Cândido Rondon and Quatro Pontes produced 10,628 t, 5,054 t, and 3,511 t of tilapia, respectively, with Toledo being the fourth largest producer of cultivated fish in Paraná (IBGE, 2021). Feiden et al. (2018) described that the western region concentrates a local productive arrangement (LPA) of the fish farming production chain, and the growth in activity has caused an intense activity and a great intensification of tilapia farming, which also has more impacts on the environment, such as eutrophication of water bodies. Areas in ha (10,000 m²) of ponds and an average depth of 1 m were used for this study. Thus, it is possible to calculate the eutrophic loads of nutrients released by the fish farm effluent per hectare and to estimate values for a small or large area. Based on the study by Coldebella et al (2020), the quantification of nitrogen (N) and phosphorus (F) in ponds for fish farming is important to evaluate the management of the quality of water and effluents released into water bodies.

The objective of this study was to use GIS to carry out the design of the hydrographic basin, the mapping of the ponds used for fish farming, the determination of its area, and the calculation of the eutrophication potential of the receiving water bodies.

MATERIALS AND METHODS

Study area

In the PB3, the main tributaries of the São Francisco River sub-basin are Arroio Marreco, Arroio Guaçu and Dezoito de Abril (to the north), and Santa Quitéria (to the south). For this study, the territory comprised by the hydrographic sub-basin of Arroio Marreco, a region of high fish production and productivity, which is in the western region of the state of Paraná, between the geographical coordinates 53°40′ and 54°10′ W and between 24°34′ and 24°45′S. The Arroio Marreco has its source in the urban area of Toledo, runs west, and its mouth is on the São Francisco River, in the county of Marechal Cândido Rondon, and crosses intensely anthropized areas, with great agricultural production, until it ends at Itaipu hydroelectric plant.

The soils that make up the hydrographic basin are not erodible (Purple Latosol and Structured Rock Earth), the soil classification is proposed by EMBRAPA (2006), and the most abundant soils are the Eutroferric Red Latosols, the Eutroferric Red Nitosols, and the Dystroferric Red Latosols. These soils are predominantly formed by alteration of the basalts of the Serra Geral Formation (SANTOS et al., 2006).

Its natural vegetation is classified as Semideciduous Seasonal Forest or Subcaducifolia River Forest, in a transition area with Mixed Ombrophylous Forest or Araucaria Forest in the case of an ecotone (IBGE, 2004).

Standardization of spatial data

Spatial data have been redesigned for the official DATUM of Brazil, the geocentric reference system for the Americas (SIRGAS 2000), UTM projection, and South 22 time zone, established by the IBGE. All raster files were converted into a single configuration: spatial resolution with a 30-m pixel, 8-bit unsigned data type, and no data value through operations carried out in QGIS (Hossain et al., 2007; Rezende et al., 2017; Francisco, et al., 2019).

Data acquisition

For the delimitation of the hydrographic basin, it was necessary to install the *Terrain Analysis Using Digital Elevation*

Models (TauDEM) software in QGIS so that the hydrological analysis based on the DEM could be carried out. Subsequently, the ponds were mapped, the flooded area was determined, and the production was quantified. For this, the *QuickMapServices* complement, installed in the QGIS software, was used, in which it was possible to view satellite images to perform the vectorization of water slides by means of remote sensing. According to Francisco et al. (2020), this add-on allows the loading of satellite images produced by various providers (using the *Wharehouse Management System* [WMS] service), thus allowing their online viewing.

With all georeferenced polygons, a database was created, with necessary parameter for calculating the water depth area. The ponds were divided into three size categories as follows: Small, with an area of water depth of less than 3,000 m^2; Medium: area between 3,001 and 5,000 m^2; and Large, with an area greater than 5,000 m^2, as proposed by Francisco et al. (2020), with adjustments, such as the inclusion of all smaller ponds than 1,000 m^2, since in small family farms there are many ponds of these dimensions. The vector analysis was performed manually, and it is not possible to perform it in a semi-automatic or automatic way. According to Francisco et al. (2019), the separation of spectral bands is not possible when we use Google Earth as a tool to make these images available, which would be feasible if it were performed using images from a multispectral sensor.

For better territorial analysis, the drainage area of Arroio Marreco was divided into three sub-basins: High, Medium, and Low Marreco, considering the topographic aspects, land use and occupation, rural infrastructure, and logistics, according to Lira et al. (2022).

Automatic delimiting with TauDEM software

After performing the mosaic referring to the two SRTM scenes, two procedures were carried out during the raster clipping process in relation to the study area, selecting the data type for Signaled Integer 16 Bit and assigning the value -999 to the area no data. After that, we proceeded with the correction of the MDE to remove all the lower cells surrounded by a higher relief using the TauDEM tool installed in the QGIS software version 2.18.28, using the command “Pit Remove” to remove possible altitude inconsistencies in the image. Next, some TauDEM algorithms were used to delimit the basin, such as “D8 Flow Directions” to define the flow direction, “D8 Contributing Area” to delimit the catchment, “Stream Definition by Threshold” to generate the raster of the drainage network, and “Stream Reach and Watershed” to generate the drainage vector and the raster of the basin area. The “D8 Contributing Area” and “Stream Definition by Threshold” algorithms were used in two stages. In the second stage, the commands were used as follows: Exutory identification (plugin *openlayersplugins* in QGIS Wien 2.8); D8 Contributing Area with shapefile outlets (Delimitation of the Arroio Marreco river basin); and Conversion from raster to vector.

Software

The development of the methodology started with the acquisition of two images (i.e., SRTM1S25W054V3 and SRTM1S25W055V3) using the DEM derived from the Shuttle Radar Topography Mission (SRTM), with a spatial resolution of 1 arc-second equivalent to 30 m. Scenes were downloaded directly from the website (https://*earthexplorer.usgs.gov*/) and processed in QGIS Zanzibar software.

Eutrophication potential of fish activity

The potential environmental impact of fish activity in the basin was based on a study by Coldebella et al. (2020), in which the values of total nitrogen (TN) and TP that remain in the environment and what is discharged into the crop effluent, considering the area of the ponds mapped.

RESULTS

The hydrographic basin of Arroio Marreco (Figure 1) is in a region of low altitudes, with 592 m on its spike and 226 m on its mouth, that is, it presents a variation of 366 m; without this variation in altitude interfering with the regional thermal gradient, as it forms a homogeneous climate group (Fritzsons et al., 2008). It has a drainage network with 464.61 km in length, with tributaries distributed in a similar way on the right and left margins, with almost half the extension (46.76%) of this network consisting of the first-order rivers. In addition to the 303 first-order rivers, 89 second-order rivers, 24 third-order rivers, 5 fourth-order rivers, and 1 fifth-order river were mapped.

We identified 1,457 ponds (Table 1), which totaled an occupied area of 162.2 ha of water depths, throughout the drainage area. These ponds were predominantly small and occupy 145.8 ha, that is, 91.0% of the total area. The highest concentration of ponds and water depths occurred in High Marreco (38% of the units), followed by Medium (35%) and Low (27%), with 61.0, 54.2, and 45, 0 ha, respectively.

The High Marreco (Figure 2) has an average altitude of about 480 m, a simple and not very extensive drainage network (±107 km in length), and no fifth-order rivers, and its third- and fourth-order rivers are not very long. This sub-basin has the largest area for fish farming, as located around the city of Toledo, including springs in the northwestern portion of the urban perimeter and the concentration of four fry production units in the region, in addition to close to fish warehouses and the consumer market. As a result, the elements that make up the existing supply chain become stronger (Franco et al., 2017).

In the Medium Marreco sub-basin (Figure 3), there is a change from the urbanized scenario to agricultural areas, although there are urban areas in the headquarters of the districts of Dez de Maio, Vila Ipiranga, and Dois Irmãos. The sub-basin has a complex and extensive drainage network (±202 km in length),

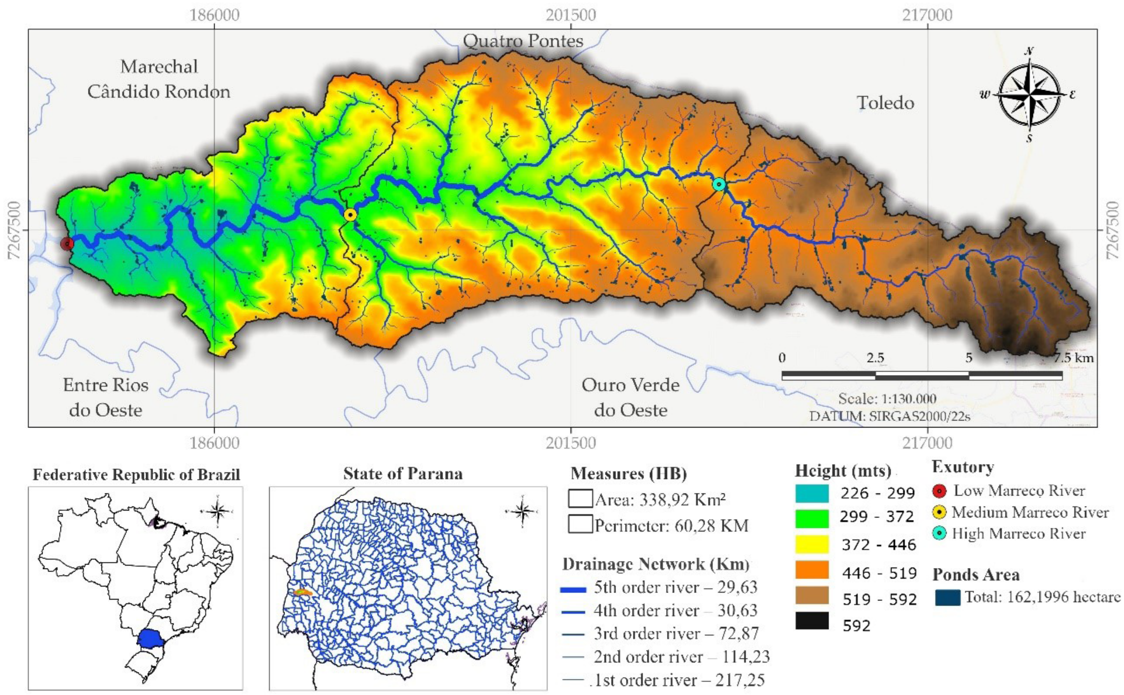

Figure 1. Arroio Marreco hydrographic basin, belonging to the Paraná Hydrographic Basin 3, in the western region of Paraná, with altitude, topography, hydrography, and the exutory that divide the sub-basins, as well as location of the excavated ponds used for fish farming.

Table 1. Distribution of the ponds in the Arroio Marreco hydrographic basin, belonging to the Paraná Hydrographic Basin 3, in western Paraná, according to the size and drainage area.

Ponds (*)	Drainage area (km²)	Size areas (ha)
High Marreco		
Small	98.02	55.6
Average	6.69	3.8
Large	2.82	1.6
Total	107.54	61.0
Medium Marreco		
Small	183.63	49.3
Average	13.03	3.5
Large	5.21	1.4
Total	201.89	54.2
Low Marreco		
Small	112.16	40.9
Average	7.86	2.8
Large	3.56	1.3
Total	123.41	45.0
Sub-basins (total)	432.84	160.2

*Small, with a water area of less than 3,000 m²; Medium, area between 3,001 and 5,000 m²; and Large, with an area greater than 5,000 m², according to Francisco et al. (2020). Prepared by the authors (2021).

almost twice than High Marreco, with first-order rivers totaling 93.83 km in length and with the presence of second-order rivers (44.16 km). Despite the greater concentration of forests and areas of permanent preservation, the supply of nutrients in the drainage network can be considered high if compared to the other sub-basins (Schiemer et al, 2001).

The Low Marreco has an extensive hydrological basin (123.41 km), composed mostly of first- and second-order rivers (Figure 4).

DISCUSSION

According to Little and Muir (1987), land use should be considered when selecting a location for aquaculture and agricultural activities in adjacent areas. It was observed that most ponds are close to pig farming and pastures, as the conditions of incentive to livestock production in the region favored the implantation of aquaculture activity in consortium with other livestock, mainly pig farming. Thus, agriculture can be used as a good indicator of suitable areas for aquaculture enterprise (Edwards, 2015).

The High Marreco region (Figure 2) has added contacts and relationships with other links that make up the production chain, such as cooperatives, educational institutions, research and extension, suppliers of goods, inputs, and services, which are essential and bring market information, innovative, and new technologies to the network, business possibilities. According

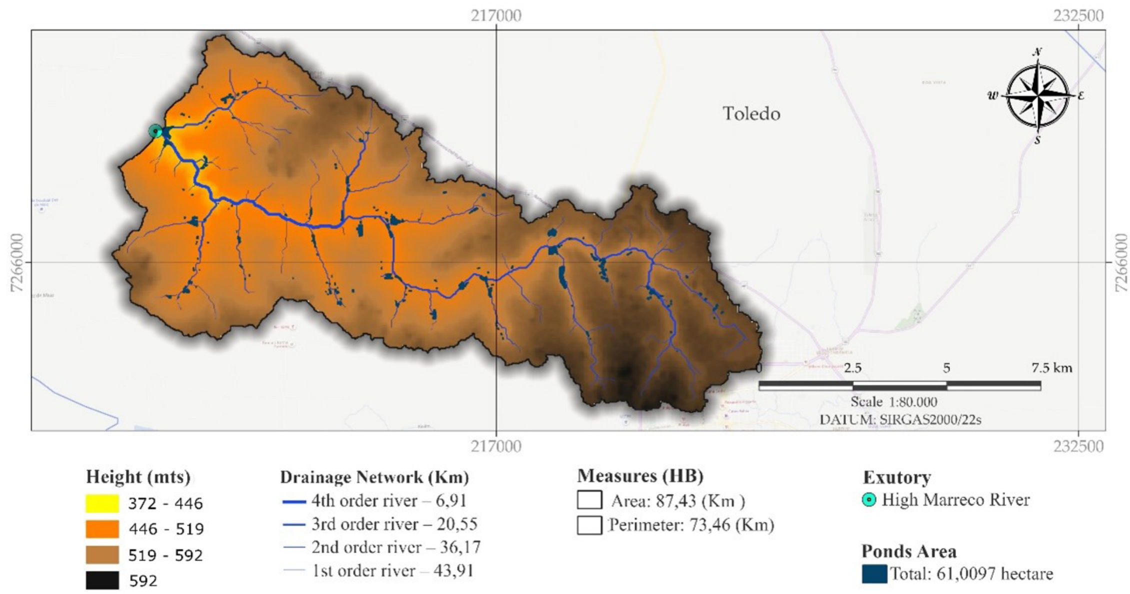

Figure 2. High Marreco hydrographic sub-basin, part of the Arroio Marreco basin, with altitude, topography, hydrography, and location of the ponds used for fish farming.

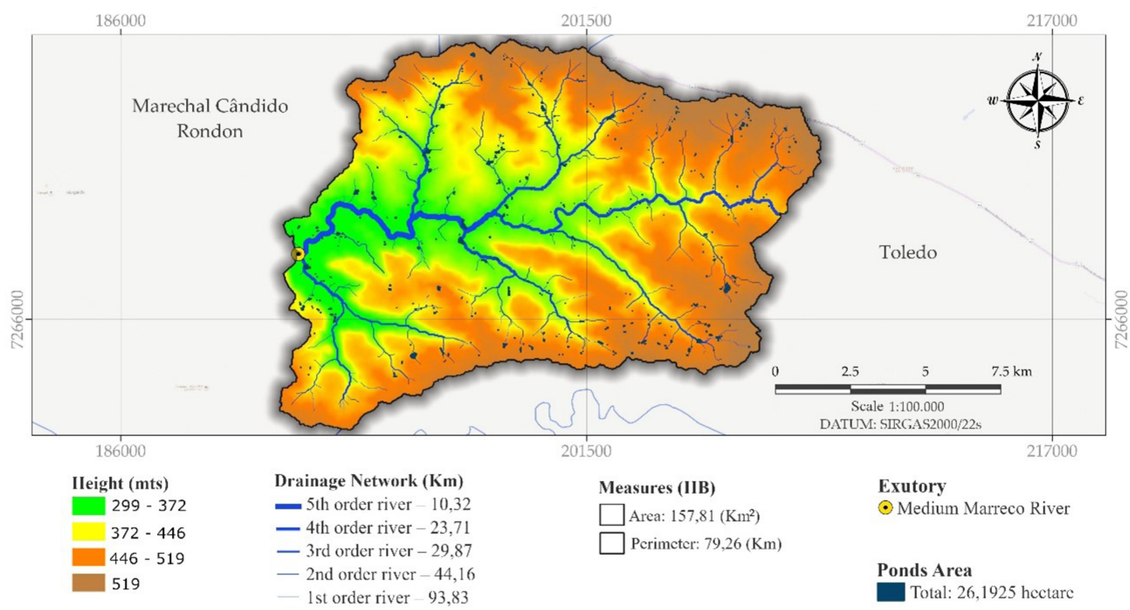

Figure 3. Medium Marreco hydrographic sub-basin, part of the Arroio Marreco basin, with altitude, topography, hydrography, and location of ponds used for fish farming.

to Chidichima et al. (2018), the study region has specialized establishments (slaughterhouses) for the slaughter and processing about 80 t of tilapia/day. Among these establishments, a significant part operates in the cooperative model and the others are privately owned with family management characteristics.

The ponds areas are close to first-order rivers, which can be explained by the fact that it saves expenses related to water derivation and use of water courses, practices that are currently prohibited (Maranhão, 2013). It is also characterized as a possible scenario for a cascade effect up to the exutory between the High Marreco and the Medium Marreco, as the nutrient load from urban effluents flows easily, as first-order rivers tend to be less deep, but with intense hydrological movement, according to Georgin et al. (2015).

In Medium Marreco (Figure 3), the implementation of fish farming in this area was initially based on the consortium

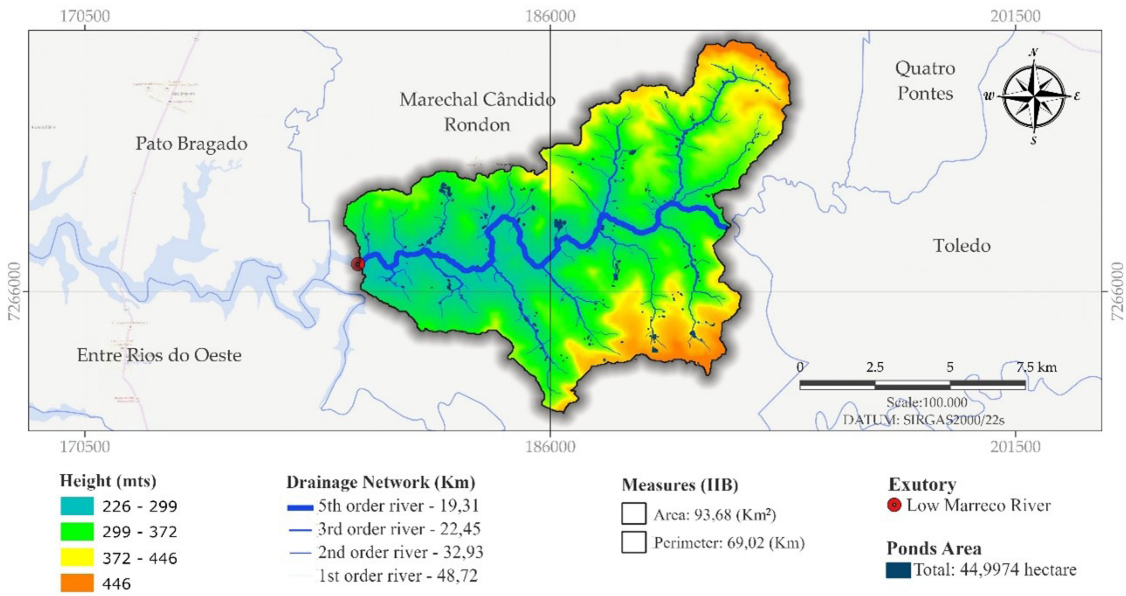

Figure 4. Low Marreco hydrographic sub-basin, part of the Arroio Marreco basin, with altitude, topography, hydrography, and location of the ponds used for fish farming.

of fish production to use the residues of agricultural products produced and reused as raw material, such as poultry and pig manure for fertilizing the ponds. This consortium adds value to these residues, transforming them into new products of animal origin and income supplement; however, this is not recommended in the agro-industrial fish production process, as balanced feeds are used for each breeding phase.

The region of the Medium Marreco, even with its greater environmental fragility but with greater slope, greater concentration of first-order rivers, and greater presence of riparian vegetation, as shown by Lira et al (2022), makes the distribution of ponds located close to first-order rivers and allows the metabolites released by the effluents to be self-purified with greater efficiency.

In Low Marreco (Figure 4), there is a greater agglomeration of production units in areas located with first- and second-order streams close to urban centers, such as in the vicinity of the districts of São Roque and Vila Margarida, reference in the 1990s as an innovator in the sexual inversion process of tilapia, with production of monosex fry, which stimulated the implantation of new nurseries at the time (Boscolo and Feiden 2007).

It is a sub-basin that presents a different situation from the others, because as observed in High Marreco, despite presenting urban areas of two district headquarters, it does not present significant effluent discharge in the water network and allowed the implantation of small ponds with smaller costs. According to Lari et al. (2014), this characteristic is one of the main determinants in the selection of areas for the fish farming enterprise in ponds. Despite being the region that brings together the best conditions for fish farming, it still has logistical restrictions that provide rural producers with greater access to the market for their products (Ploeg, 2000).

Environmental impact

The residual load of the ponds in the concentration of phosphorus (P) and nitrogen (N) in the water, if not controlled, compromises its quality (Cyrino et al., 2010). Good management practices in aquaculture are fundamental for the activity to be promoted with environmental sustainability.

As shown in Table 2, it is possible to verify that the nitrogen supply retained in the ponds is less than that released in the receiving body by the effluents, and this causes the eutrophication of the aquatic environments. As demonstrated by Coldebella et al. (2020), when analyzing the dynamics of nitrogen (N) and phosphorous (F), their low retention in the pond sediment causes the effluents to receive most of the inputs from the entry of these nutrients into the system, causing the eutrophication of the water bodies. According to Correl (1998), this occurs due to the use of feed and fertilizers, and in all the Arroio Marreco basin, most rural properties have ponds in conjunction with other agricultural activities (e.g., poultry, swine, and dairy cattle). The High Marreco basin stands out for diffuse pollution caused by urbanization and fish concentration.

In Table 2, when analyzing the eutrophic impact of the effluents from the ponds, the Medium Marreco sub-basin, despite having a drainage area (201.89 km^2) almost double the others, presents the least potential, both for TN and TP, because the elimination of nutrients in the effluents is 2,072.1 kg of TN and 223.4 kg of TP per hectare of ponds, while in High Marreco it is 2,071.1 kg of TN and 223.4 kg of TP for a drainage area of only 107.54 km^2, and in Low Marreco it is 2,182.2 kg of TN and 223.4 kg of TP for a drainage area of 123.41 km^2. As phosphorus is an important source for the microalgae growth (Lambers et al., 2008; McDowell et al., 2015; Ni and Wang, 2015), its excess promotes eutrophication (Conley

Table 2. Supply of residual nutrients by the ponds of the Arroio Marreco hydrographic basin, belonging to the Paraná Hydrographic Basin 3, in the western region of Paraná, according to the size and productivity.

Ponds (*)	Fish biomass (kg)	Ponds area (ha)	Nutrients TN (kg)	Nutrients TP (kg)	Effluents TN (kg)	Effluents TP (kg)
High Marreco						
Small	278.0	55.6	28,879.75	21,124.66	115,150.38	12,421.59
Average	19.00	3.8	1,973.79	1,443.77	7,869.99	848.95
Large	8.000	1.6	831.07	607.90	3,313.68	357.45
Total	305.00	61.0	31,684.62	23,176.34	126,334.05	13,628.01
Medium Marreco						
Small	246.300	49.3	25,607.40	18,731.04	102,102.76	11,014.11
Average	17.500	3.5	1,817.97	1,329.79	7,248.67	781.93
Large	7.100	1.4	727.18	531.91	2,899.47	312.77
Total	270.900	54.2	28,152.56	20,592.74	112,250.91	12,108.22
Low Marreco						
Small	204.500	40.9	21,244.27	15,539.54	84,705.94	9,137.46
Average	14.100	2.8	1,454.37	1,063.83	5,798.94	625.54
Large	6.400	1.3	675.24	493.92	2,692.36	290.43
Total	225.000	45.0	23,373.90	17,097.30	93,197.25	10,053.45
Sub-basins (total)	800.900	160.2	83,211.08	60,866.38	331,78.21	35,789.68

*Small, with a water area of less than 3,000 m^2; Medium, area between 3,001 and 5,000 m^2; and Large, with an area greater than 5,000 m^2, according to Coldebella et al. (2020) and Francisco et al. (2020). Prepared by the authors (2021).

et al., 2009) and, with its flow in hydrographic basin related to geochemical processes (Imberger, 1994), its self-purification is dynamic on the spatial scale, depending on factors such as topography and river currents. In the Arroio Marreco Basin, its quantification is important because it represents a way to assess environmental pollution. In aquaculture, feed is the main factor of phosphorus input in production systems (David et al., 2017). Thus, productive management is essential to promote sustainability to the environment (Patel and Yakupitiyage, 2003). The erroneous practice promotes the negative impact on the aquatic environment (Pillay, 2007; Bhujel, 2013).

A large concentration of small ponds, smaller than 3,000 m², was identified in the basin, which confirmed that fish farming is mainly exploited by small farmers, as business ventures have the characteristic of implanting large ponds to facilitate automated management. It allows only a low volume of production per excavated nursery, and therefore, there is a need for future adjustments of production structures for more modern industrial production systems (Barroso, 2018).

The greatest potential for eutrophic impact is in High Marreco, because in this sub-basin, there is a smaller drainage area and it is in the upstream of the basin where water bodies have a lesser capacity for dilution and self-purification. In the Medium Marreco, this potential impact is the smallest of the sub-basins, as the configuration of land use and occupation presents many non-aquaculture activities, originating from other activities and consortium with other productions. Thus, to minimize the potential for eutrophication, it is recommended to implement mechanisms for the treatment and control of effluents in fish farms, as required by the new legislation for the environmental licensing of fish farming (Brasil, 2020).

CONCLUSION

GIS and the use of TauDem in the delimitation of hydrographic basins are important tools for the correct mapping of the ponds and for the environmental management of fish farming. This analysis showed the predominance of small ponds located in low-order streams and concentrated close to urbanized areas, which in the future need to be adjusted for agro-industrial production that can use automation mechanisms in the management processes of creation.

Regarding the environmental impact, it is concluded that the eutrophication potential in Arroio Marreco is greater in High Marreco and concentrated in small ponds.

The results of this study show the importance of knowing the distribution of ponds and the physical characteristics of the drainage basin. With that, determine the support capacity of the basin, so as not to allow licenses that promote impacts above its self-purification capacity and, finally, demand that fish farmers implement mechanisms to control the release of effluents and the reuse of water from the ponds.

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None

CONFLICT OF INTERESTS

Nothing to declare.

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AUTHORS' CONTRIBUTIONS:

Morsoleto, F.M.S.: Conceptualization, Data curation, Formal Analysis, Investigation, Writing – original draft, Writing – review & editing. Lira, K.C.S.: Data curation, Investigation, Methodology. Silva, J.F.M.: Data curation, Software. Francisco, H.R.: Data curation, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. Bittencourt, F.: Resources. Feiden, A.: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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