Environmental fragility as an indicator of the risk of contamination by human action in watersheds used for public supply in western Paraná, Brazil.

Kelly Krampe Peres (kellyperes13@gmail.com)
UNIOESTE: Universidade Estadual do Oeste do Parana https://orcid.org/0000-0001-7657-5757
Ricardo Guicho
UNIOESTE: Universidade Estadual do Oeste do Parana
Gabriela Medeiros
UNIOESTE: Universidade Estadual do Oeste do Parana
Mailor Wellinton Wedig Amaral
UNIOESTE: Universidade Estadual do Oeste do Parana
Thais Tagliati da Silva
UNIOESTE: Universidade Estadual do Oeste do Parana
Maria Clara Pilatti
UNIOESTE: Universidade Estadual do Oeste do Parana
Maritane Prior
UNIOESTE: Universidade Estadual do Oeste do Parana
Norma Catarina Bueno
UNIOESTE: Universidade Estadual do Oeste do Parana

Research Article

Keywords: slope, geoprocessing, sources, anthropic action

Posted Date: March 22nd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1325192/v1

Abstract

Applying environmental fragility in studies evaluating watershed can guide policy decisions on monitoring and management regarding soil use planning, improving water quality for public supply. The objective of this study is to characterize the environmental fragility as well as to relate it to water quality factors of catchment rivers for public supply in western Paraná, Brazil, in order to evaluate the influence of anthropic actions on catchment sources. Water quality data such as temperature (Temp; C), electrical conductivity (Ec; mS/cm^{-1}), dissolved oxygen (DO; mg L^{-1}), turbidity (Turb; NTU) and pH were measured on site by the multi-parameter probe HORIBA brand, model U-5000. Slope data were obtained from the site of the National Institute of Space Research (INPE). Soil use and occupation was performed in the QGis software, with image obtained from the Sentinel 2A Satelite. Köppen-Geiger classification was used for the climate type. For the environmental fragility maps, the variables slope, climate, soil use and occupation were analyzed using the *QGis raster software* calculator. The intermediate fragility class predominates in the nine municipalities studied, making it necessary to manage them aimed at restoration and conservation, and the municipalities that are the largest areas of high fragility class are: Guaraniaçu, Catanduvas and Cascavel, demanding greater attention. The variation in fragility mainly responded to the pH, E. coli and DQO temperature values, which can be strongly associated with the difference in soil use and slope of the areas evaluated.

Introduction

The scarcity of drinking water in Brazil may be a reflection of management with little planning and based only on emergency measures (ANA 2020). According to the last Ranking on sanitation carried out in Brazil by the *Instituto Trata Brasil*, together with *GO Associados*, almost 35 million people still do not have availability of water supply in Brazil, representing 16.38% of the Brazilian population, and still, more than 100 million Brazilians do not have sewage collection coverage, representing 46.85% of the population (ITB 2018). This panorama is intensified by urban and agricultural growth, which degrade ecosystems through river banks deforestation, irregular occupations, disposal and inadequate treatment of effluents (Malik and Bhat 2014; Johannsen et al. 2016; Tiecher et al. 2017; Karakurt et al. 2019; Lechuga-Crespo et al. 2020), contributing to environmental fragility.

Environmental fragility is defined as the sensitivity and resilience of an ecosystem, being directed by natural characteristics and anthropogenic stressors (Turner et al. 2003; Anjinho et al. 2021). The application of this concept in environmental evaluation studies consists of the fragility arrangement in hierarchical levels within the established territory zoning, portraying degrees of susceptibility of the environment to undergo disruptions in its dynamic balance (Tran et al. 2012). Integrating landscape characteristics in an integrated manner can more accurately point to the level of vulnerability of the studied environment (Sutil et al. 2020). Thus, applying environmental fragility in studies evaluating watershed can guide policy decisions on monitoring and management regarding soil use planning, improving water quality for public supply. (Braga et al. 2017; Abrão and Bacani 2018).

In this scenario, the sanitation sector still demands improvement in its management models, especially those of water supply and sanitation (Rossoni et al. 2020), since the effective evaluation of water quality parameters has a profound impact on the overall quality of a catchment area (O'Grady et al. 2021). Regarding the evaluation of catchment rivers for public supply, it is necessary to consider the spatial interactions among climate, water distribution, relief and geology (Silva et al. 2011; Fraga et al. 2020), using physico-chemical parameters that interfere with potability (Kannel et al. 2007; Tripathi and Singal 2019).

In view of this, geotechnologies are strong allied regarding environmental fragility, since they offer important tools for the characterization, management and monitoring of space, detecting possible impacts on water bodies (Alves et al. 2021; Silva et al. 2021). Among them, the Integrated Management Systems (GIS) aggregate variables and spatial information, facilitating environmental characterization (Storto and Cocato 2018; Sutil et al. 2020; Alves et al. 2021).

Studies evaluating watersheds using data provided through geoprocessing associated with the water physical and chemical parameters are still scarce in Brazil. Among them, it is possible to mention Bilich and Lacerda (2005) who analyzed the Water Quality Index in areas of water spring protection for ten years in Distrito Federal; Lopes et al. (2008) who made a water quality map of Acaraú watershed in the state of Ceará, using the Water Quality Index associated with a Geographic Information System (GIS); Lemke et al. (2012) quantified the influence of soil use and occupation on the water quality of Dourados River Basin in the state of Mato Grosso do Sul; Justos (2012) used GIS's to monitor some physico-chemical parameters of the surface waters of São Pedro River watershed in the state of Paraná; Gomes et al. (2017) used interpolated maps encompassing water quality parameters in Piracicaba River Basin in the state of Minas Gerais; and Dino and Toledo (2020) evaluated the soil use and occupation in two sub-basins, associated with the quality of surface water in the confluence area of Paranapanema and Itapetininga rivers in the state of São Paulo.

Therefore, due to the need of studies which evaluated the water quality for catchment and supply to justify prevention and mitigation measures of anthropic impacts on such environments, the objective of this study is to characterize the environmental fragility as well as to relate it to water quality of 9 catchment rivers for public supply in western Paraná, Brazil, in order to evaluate the influence of anthropic actions on catchment sources.

Material And Methods

Study area

The state of Paraná is divided into 16 watersheds (Resolution number 024/2006/SEMA) of which three, Paraná III, Piquiri and Iguaçu, bathe the western region of the state. This region covers 54 municipalities (AMOP 2018), the most populous being Cascavel, Foz do Iguaçu, Toledo and Medianeira. Although the western region comprises a small population, it stands out for intense agricultural production, with a large part of its extension of monoculture areas, the main power and water stations and tourist centers of the country. All municipalities in western Paraná have some agricultural production and livestock, while only a few have extractive production (PNUD 2018).

Therefore, for this study, 9 water catchment watersheds were selected for public supply in the western region of Paraná. To obtain a representative sample N, nine municipalities were selected: (GUAR), Catanduvas (CTD), Três Barras do Paraná (TBP), Boa Vista Aparecida (BVA), Foz do Iguaçu (FOZ), Medianeira (MED), Santa Tereza do Oeste (STO), Cascavel (CVEL), Toledo (TOL) belonging to the three watersheds that bathe the region (Fig. 1).

Water collections were performed in March 2020, and two points were sampled at the headwater and close to the water collection station of the sanitation company (Table 1). At the same time, the points descriptive characterization was performed as well as the areas photographic recording for further confirmation of terrestrial truth.

Table 1
Geographical location of the sampling stations (headwater and catchment points) superficial for the three watersheds in the western region of Paraná.

Watershed	City	River	Sampling station	Lat/long	Depth (cm)	Width (m)	Average stream flow (m^3/s)
Piquiri	Guaraniaçu	Baú river	GUA_P1	25°40'56"S 52°53'29"O	0.16	5.23	0.08
			GUA_P2	25°40'27"S 52°53'20"O			
Paraná III	Catanduvas	Arroio river Passo Liso	CTD_P1	25°11'13"S 53°08'18"O	0.17	4.1	0.17
			CTD_P2	25°12'38"S 53°07'51"O			
	Boa vista Aparecida	Jacutinga River	BVA_P1	25°25'17"S 53°25'46"O	0.26	5.2	0.22
			BVA_P2	25°25'46"S 53°26'17"O			
	Três Barras do Paraná	Itaguaçu Creek	TBP_P1	25°26'11"S 53°11'17"O	0.32	2.8	0.1
			TBP_P2	25°26'21"S 53°10'50"O			
Baixo Iguaçu River	Cascavel	Cascavel River	CVEL_P1	52°53'29"S 53°26'06"O	0.41	4.25	0.41
			CVEL_P2	52°53'20"S 53°26'19"O			
	Toledo	Toledo River	TOL_P1	24°45'49"S 53°39'50"O	0.44	6.1	1.81
			TOL_P2	24°43'51"S 53°42'40"O			
	Santa Tereza do Oeste	Gonçalves Dias River	STO_P1	25°20'29"S 53°35'20"O	0.2	3.25	0.19
			STO_P2	25°30'47"S 53°36'14"O			
	Medianeira	Alegria River	MED_P1	25°18'35"S 54°30'31"O	0.21	3.3	0.06
			MED_P2	25°17'30"S 54°40'35"O			
	Foz do Iguaçu	Tamanduá River	FOZ_P1	25° 30'26"S 54°31'50"O	0.19	3	0.21
			FOZ_P2	25°32'13"S 54°31'25"O			

Abiotic and biotic variables

Date regarding the sampling of physical and chemical variables such as temperature (Temp; C), electrical conductivity (Ec; mS/cm^{-1}), dissolved oxygen (DO; $mg\ L^{-1}$), pH and turbidity (Turb; NTU) were measured on site by the Multi-parameter probe HORIBA brand, model U-5000.

The following variables were analyzed by the Laboratory of Limnology of GERPEL, Unioeste-Campus Toledo: the oxygen consumption due to the chemical oxidation (DQO; $mg\ L^{-1}$) and organic matter (BOD; $mg\ L^{-1}$) the concentrations of total nitrogen Kjeidahl (TN; $mg\ L^{-1}$), nitrate (N03; $mg\ L^{-1}$), ammonium (NH4; $mg\ L^{-1}$), total dissolved phosphorus (TP; $mg\ L^{-1}$), orthophosphate (P04-; $mg\ L^{-1}$), chlorophyll a (CLa; $mg\ L^{-1}$), total solids (TS; $mg\ L^{-1}$), total coliforms (CT; NMP/100 mL) and *Escherichia coli* (Ec; NMP/100 mL). The analyzes were performed using the standardized methods in Standard methods (APHA 2017). The chemical variables were measured after the material was collected by subsurface immersion of polyethylene bottles, properly refrigerated and kept in the dark until their destination.

Mapping and analysis of environmental fragility

The environmental fragility analysis was performed with the QGis raster calculator, using maps algebra, where a mathematical function is used to weigh values defined for each subclass of the variable considered.

One of the variables analyzed in this study was the slope obtained from the National Institute of Space Research (INPE) website and reclassified into 4 thematic classes, namely: 0 - 3%, 3 - 8%, 8 - 20%, 20% - 45%, according to EMBRAPA (1979).

The second variable was the soil use and occupation, performed by manual classification, in the QGis software, with images obtained from the Sentinel 2A Satelite (04-25-2020, 04-15-2020, and 05-15-2020) with spatial resolution of 10 meters. For the classification of the study area, five main classes were considered: Agriculture and Livestock, Water, Urban Area, Forest and Mining, Based on the Earth use Technical Manual (IBGE 2013), where it has information on what types of use are contemplated in each class.

In addition to slope and soil use, climate type was the third variable considered. For this purpose, the information proposed by Alvares et al. (2013), which provides shapefiles, for the whole country, of the areas that are influenced by the climatic conditions based on the Köppen-Geiger classification were used.

For the performing of the environmental fragility maps, each of the variables analyzed (slope, climate and soil se and occupation) had their weighted subclasses with values from 1 to 5. Where 1 is the lowest and 5 is the highest sign of fragility - "Very Low", "Low", "Intermediate", "High" and "Very High" (Table 2). As a weighting parameter, the determination of subclasses was based on studies by Franco et al.(2012); Souza et al. (2011); Massa and Ross (2012) and Ross (1994).

Table 2
Levels of fragility according to the characteristics

Characteristics	Classes	Weights
[a]Slope	Plan	1
	Gently undulating	2
	Undulating	3
	Strongly undulating	4
[b]Use and occupation	Forest	1
	Water	2
	Agricultural	3
	Urban Areas	4
	Mining	5
[b]Climate	Cwa	3
	Am	2
	Af	5
	Cfa	2
	Cwb	3
	Csb	3
	Csa	3
	Cfb	2
	Bsh	5
	As	4
	Cwc	4
	Aw	4
[a] Franco et al. (2012)		
[b] Souza et al. (2011)		

To perform the simple average mathematical function, for the previously weighted classifications, the QGis software raster calculator was used according to Equation 1.

(1)

$$F = \frac{(D + Us + Cl)}{3}$$

Equation 1: Calculation of average fragility, where: F is the Environmental fragility, D is the slope, US is the soil use and occupation and Cl is the climate.

Thus, pixel-by-pixel is generated, considered all the variables, the results that determine the final environmental fragility. The method was applied in the same way for each of the watersheds of the municipalities studied.

This paper is concerned to be inclusive with color blind people, therefore, for the thematic maps identified by colors, colorimetric scales were used that make their distinctions possible, with the help of the Color Brewer 2.0 (2021) site.

Data statistical processing

Considering the different collection points and the strong influence on water quality, all the variables collected were previously analyzed using descriptive statistics (mean and coefficient of variation) according to their nature. In order to compare possible statistical differences of each variable among the municipalities, the analysis of variance of one criterion (one-way ANOVA) was used to evaluate the variation of factors individually according to the municipality, and, when significant, a posteriori Tukey's test.

The variation of the environmental factors among the sampling stations was verified in a multivariate manner by means of a non-parametric permutational multivariate analysis of variance (PERMANOVA), applied to the Bray-Curtis similarity matrix with 9999 permutations. The environmental variables were also submitted to the principal component analysis (PCA) with the objective of characterizing the stations, identifying the variables with greater power to differentiate them (Wiegleb 1980).

In addition, after the characterization of fragility, a linear correlation was used to evaluate the dependence of environmental variables as a function of the percentage of each class of environmental fragility among the municipalities.

Environmental data were standardized so that they have the same weight in the analyzes (Borcard et al. 2011). All THE analyzes were performed using the language and environment for computational statistics R (R CORE TEAM 2014), together with the Vegan library (Oksanen et al. 2015).

Results

Differences were observed among the evaluated means of the physico-chemical variables among the rivers based on the analysis of variance (ANOVA-one way) and the grouping performed by the Tukey post-test (Table 3). The municipalities of Boa Vista da Aparecida (BVA), Catanduvas (CTD) and Três Barras do Paraná (TBP) presented pH values higher than 7, while the municipalities of Cascavel (CVEL) and Toledo (TOL) presented values close to 5 (Table 3). The municipalities of Três Barras do Paraná and Santa Tereza do Oeste (STO), presented mean values of DQO greater than 70 mg/L (Table 2). Electrical conductivity showed higher values for the municipalities of Boa Vista da Aparecida, Catanduvas, Guaraniaçu (GUAR) and Três Barras do Paraná (0.08 MS/cm^{-1}). The total dissolved solids presented higher values for the municipalities of Três Barras do Paraná (71.75 mg/L), Boa Vista da Aparecida (77.25 mg/L) followed by Catanduvas (71.00 mg/L). The municipalities of Toledo (TOL), Foz do Iguaçu (FOZ) and Guaraniaçu stood out with the highest turbidity values, however Catanduvas presented the lowest value for this variable (Fig. 2).

Table 3
Comparisons of means (one way ANOVA) of environmental variables among the municipalities evaluated. Representative differences ($p < 0.05$) are highlighte bold

Municipalities	BVA	CTD	CVEL	FOZ	GUAR	MED	STO	TBP	TOL	R²	F	p
Temp (ºC)	23.22 ± 1.08	19.45 ± 0.26	20.9 ± 1.00	22.41 ± 0.98	17.93 ± 0.61	21.93 ± 0.42	22.52 ± 1.26	21.04 ± 0.05	20.83 ± 0.20	0.88	9.07	**0.01**
DO (mg L^{-1})	3.43 ± 0.32	4.94 ± 0.35	10.74 ± 0.35	2.58 ± 0.54	4.84 ± 0.22	2.8 ± 0.57	2.53 ± 0.78	4.47 ± 0.35	10.59 ± 0.29	0.95	23.64	< **0.00**
pH	7.41 ± 0.28	7.31 ± 0.01	5.47 ± 0.52	6.32 ± 0.13	6.79 ± 0.44	6.66 ± 0.10	6.64 ± 0.31	7.27 ± 0.09	5.94 ± 0.26	0.9	10.21	**0.01**
Condut (mS/cm^{-1})	0.08± 0.01	0.08 ± 0.01	0.05 ± 0.01	0.05 ± 0.01	0.08 ± 0.01	0.03 ± 0.01	0.01 ± 0.01	0.08 ± 0.01	0.02 ± 0.01	0.92	14.21	**0.01**
prof (m)	0.26 ± 0.02	0.17 ± 0.01	0.41 ± 0.15	0.19 ± 0.15	0.16 ± 0.03	0.21 ± 0.18	0.2 ± 0.01	0.32 ± 0.10	0.44 ± 0.10	0.63	1.9	**0.17**
Tur (NTU)	9.21 ± 0.46	6.07 ± 2.31	9.67 ± 2.31	13.65 ± 3.06	13.25 ± 1.20	8.91 ± 1.20	10.53 ± 1.51	9.61 ± 0.21	22.25 ± 1.90	0.91	11.84	**0.01**
Chlorophyll (µg/L)	0.56 ± 0.01	0.56 ±0.01	2.88 ± 2.72	1.72 ± 1.64	1.00 ± 0.62	0.56 ± 0.01	1.48 ± 1.30	0.76 ± 0.28	1.68 ± 0.33	0.44	0.88	0.56
Ecoli (NMP/100mL)	428.50 ± 78.48	445.00 ± 154.14	663.00 ± 291.32	314. 50 ± 19.09	4695.50 ± 5612.30	2772.5 ± 2600.03	222.5 ± 142.12	250.5 ± 34.64	1118. 00 ± 362.03	0.49	1.09	0.44
Colt (NMP/100mL)	9208 ± 4471.03	17154.00 ± 9958.89	4865.00 ± 3323.40	16999.50 ± 4049.60	10112.00 ± 0.001	17697 ± 50 ± 9190.27	2907.50 ± 764.38	9393.00 ± 8680.44	14833.50 ± 986.41	0.6	1.72	**0.21**
BOD (mg/L)	1.30 ± 0.36	1.00 ± 0. 01	1.68 ± 0.82	1.75 ± 1.06	1.76 ± 0.14	1. 05 ± 0.08	1.45 ± 0.64	1.00 ± 0.01	1.72 ± 0.17	0.42	0.82	0.6
DQO (mg/L)	67.50 ± 3.53	58.33 ± 2.35	41.66 ± 9.42	16.66 ± 11.78	63.33 ± 14.14	61.67 ± 14.14	71.66 ± 2.35	77.50 ± 5.89	25.83 ± 3.53	0.91	11.43	**0.01**
TP (mg/L)	0.02 ± 0.01	0.02 ± 0.02	0.01 ± 0.01	0.02 ± 0.02	0.02 ± 0.05	0.02 ± 0.02	0.01 ± 0.02	0.03 ± 0.06	0.04 ± 0.02	0.69	2.52	0.09
Nitrate (mg/L)	0.09 ± 0.07	1.00 ± 0.42	1.25 ± 0.49	1.25 ± 0.40	0.80 ± 0. 42	1.00 ± 0.01	0.55 ± 0.07	1.75 ± 0.49	1.80 ± 0.14	0.71	2.74	0.07
Nitrogen ammonia (mg/L)	0.001 ± 0.01	0.01 ± 0.01	0.05 ± 0.07	0.17 ± 0.25	0.01 ± 0.01	0.01 ± 0.01	0.02 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.44	0.89	0.55
Orthophosphate (mg/L)	0.01 ± 0.01	0.01 ± 0.02	0.02 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.86	6.81	**0.01**
TS (mg/L)	77.25 ± 6.72	71.00 ± 4.95	40.00 ± 3.53	41.50 ± 6.36	67.50 ± 12.02	48.75 ± 5.30	40.50 ± 8.48	71.75 ± 10.96	21.57 ± 2.47	0.09	13.34	**0.01**
Rainfall (mm)	5.02	3.81	3.81	2.87	2.6	2.54	3.81	5.02	2.84	-	-	-
Stream flow (m³/s)	0.22 ± 0.68	0.17 ± 0.17	0.41 ± 0.18	0.10 ± 0.06	0.08 ± 0.04	0.06 ± 0.03	0.19 ± 0. 04	0.1 ± 0.06	1.81 ± 1.68	0.63	1.91	0.17

The principal component analysis (PCA) for environmental variables summarized 49.77% of the total variability of the data sampled in the first two axes (Fig. 2). The dispersion of the scores of the sites sampled in these axes showed a separation in the diagram of the sampling municipalities, suggesting some similarities among them (Fig. 2). The first PCA axis explained the variability mainly in relation to chlorophyll *a* (correlation value: 0.30) and turbidity (0.32) positively for the municipalities of Cascavel and Toledo; and pH (-0.37), total solids (-0.37) and DQO (-0.32) negatively. This axis is responsible for the samplings of Guaraniaçu, Três Barras do Paraná, Catanduvas, Medianeira and Boa Vista da Aparecida (negatively), due to the similarity of the factors of higher correlation (Figure 2). The second axis is positively related to Ammoniacal Nitrogen (0.51) Total phosphorus (0.37) and Orthophosphate (0.32), and negatively by Dissolved oxygen (-0.38), depth (-0.364) and DQO (-0.25). This axis isolates the sampling site of the municipality of Foz do Iguaçu (5,00) positively and the sampling site of the municipality of Cascavel (-2.55) negatively, highlighting them from the others as a function of discrepant values before the variables with higher correlation (Fig. 2).

When evaluated in a multivariate manner, the environmental variables that characterize water quality indicate a representative difference as a function of the municipalities according to PERMANOVA (Gl: 8; R^2: 0.73; F: 3.10; p-valor: 0.001). This factor effectively confirms the statistical difference in the water quality of the environments as indicated in the ordination represented by PCA (Fig. 2).

Among the watersheds evaluated, there was predominance of the gently undulating (3-8% of slope), being more representative in the municipalities of Foz do Iguaçu (70.86%) (Fig. 3A), Três Barras do Paraná (60.80%) (Fig. 3B), Medianeira (56.20%) (Fig. 4A), Santa Tereza do Oeste (53.17%) (Fig. 3D) and Toledo (52.85%) (Fig. 4B) (see Table 4). Then the undulating class (8 - 20% of slope), with predominance in the municipalities of Catanduvas (58.06%) (Fig. 3C), Cascavel (53.27%) (Fig. 3E), Boa Vista da Aparecida (49,55%) (Fig. 3F) and Guaraniaçu (47.63%) (Fig. 4C) (Table 4). The watersheds with steeper relief, represented by the strongly undulating class (20 - 45% of the slope) were Guaraniaçu (38.43%), Boa Vista da Aparecida (29.65%) and Catanduvas (21.03%). On the other hand, the watersheds with lower slopes, considered flat (0 - 3% of slope) were Santa Tereza do Oeste (29.60%), Três Barras do Paraná (16.40%), Foz do Iguaçu (9.95%) and Toledo (5.02%).

Table 4
Percentage of the slope classes of the watersheds of the municipalities of western Paraná-BR

Slope Classes	**BVA**	**CVEL**	**CTD**	**FOZ**	**GUA**	**MED**	**STO**	**TBP**	**TOL**
	(%)	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**
Plan	0.6	2.42	1.14	9.95	0.53	4.90	29.60	16.40	5.02
Gently undulating	20.20	37.26	19.77	70.86	13.36	56.20	53.17	60.80	52.85
Strongly Undulating	49.55	53.27	58.06	19.13	47.63	37.10	17.00	22.30	41.35
Mountainous	29.65	6.94	21.03	0.06	38.43	1.70	0.23	0.50	0.78
Total	100	100	100	100	100	100	100	100	100

Regarding the soil use and occupation, the most prominent class is agricultural (Fig. 5, Fig. 6, Table 5), being predominant in the municipalities of Boa Vista da Aparecida (70.18%) (Figure 5F), Toledo (68.90%) (Fig. 6B), Catanduvas (62.24%) (Fig. 5C), Foz do Iguaçu (56.64%) (Fig. 5A), Três Barras do Paraná (56.03%) (Fig. 5B), Guaraniaçu (55.48%) (Fig. 6C) and Medianeira (54.31%) (Fig. 6B). Observing the territorial extension of the agricultural class, the watersheds that have the largest areas are: Toledo with 63.62 km², Santa Tereza do Oeste with 45.19 km² and Cascavel with 21.13 km².

As far as the forest class is concerned, the watersheds that present the largest areas are Santa Tereza do Oeste (55.08%) (Figure 5D), Três Barras do Paraná (43.02%) and Guaraniaçu (39.64%), and in the other municipalities, less than 30% of the area was represented by this class. In the context of territorial extensions, the watersheds that have larger forest areas are: Santa Tereza do Oeste (59.15 km²), Toledo (12.65 km²) and Cascavel (12.42 km²).

In the urban area class, the watersheds that have the larger territorial extension are: Cascavel (16.15 km²) (Figure 5E), Toledo (15.70 km²) and Medianeira (9.66 km²). The watersheds that have higher percentages of this class are: Cascavel (32.12%), Medianeira (31.96%) and Foz do Iguaçu (23.26%). On the other hand, the watersheds that have lower percentages of urban area are: Três Barras do Paraná (0.74%), Boa Vista da Aparecida (0.93%), Santa Tereza do Oeste (2.79%), Guaraniaçu (4.69%) and Catanduvas (7.86%).

It is important to emphasize that all the collection points are located in a forest region, however, all the municipalities have at least one of the points located near the agricultural region. Some municipalities have urban areas close to the collection points, namely: Toledo (TOL_P2), Santa Tereza do Oeste (STO_P1 and STO_P2), Medianeira (MED_P1), Foz do Iguaçu (FOZ_P1 and FOZ_P2) and Cascavel (CVEL_P1). It is important to highlight that in Cascavel and Toledo there are mining areas, and that in Cascavel one of the collection points is located near this region (CVEL_P2).

Table 5
Areas and percentage of the Use and Occupation of watersheds classes of the municipalities of western Paraná-BR

Use and occupation	BVA		CVEL		CTD		FOZ		GUA		MED		STO		TBP		TOL
	Km²	%	Km²	%	Km²	%	Km²	%	Km²	%	Km²	%	Km²	%	Km²	%	Km²
Agricultural	20.3	70.18	21.13	41.73	15.10	62.2	10.9	56.6	11.6	55.5	16.4	54.31	45.19	42.07	6.86	56.03	63.6
Water	0.28	0.74	0.40	0.80	0.04	0.14	0.09	0.49	0.04	0.19	0.04	0.15	0.07	0.06	0.02	0.21	0.27
Urban Area	0.33	0.93	16.15	32.12	1.89	7.86	4.41	23.3	0.97	4.69	9.66	31.96	3.01	2.79	0.09	0.74	15.7
Forest	10.2	28.15	12.42	24.88	7.20	29.8	3.72	19.6	8.26	39.6	4.11	13.58	59.15	55.08	5.23	43.02	12.6
Mining	0	0	0.23	0.47	0	0	0	0	0	0	0	0	0	0	0	0	0.07
Total	36.1	100	50.33	100	24.2	100	19.1	100	20.8	100	30.3	100	107.4	100	12.20	100	92.3

The municipalities fit within the same macro-region of the state, with similar climatic characteristics. The predominant climatic type identified, according to the Brazilian climate classification by Köppen, adapted by Alvares et al. (2013) was CFA, characterized as subtropical, with a mean temperature in the coldest month less than 18 ºC and in the hottest month with a temperature higher than 22 ºC. Only the municipality of Catanduvas presented two climatic types, CFA and CFB, classified as temperate itself, with a mean temperature below 18 ºC in the coldest month and in the warmest month, a mean temperature below 22 ºC (EMBRAPA 2012).

The fragility maps indicate that the predominant class is the intermediate class (Fig. 7, Fig. 8, Table 6), being the watersheds with predominance of this Boa Vista da Aparecida (94.94%) (Fig. 7F), Toledo (90.93%) (Fig. 8B), Santa Tereza do Oeste (87.27%) (Fig. 7D) and Medianeira (83.80%) (Fig. 8A). It is noteworthy that areas with very high fragility were not found in all the evaluated watersheds, highlighting that in the watershed of the municipality of Foz do Iguaçu (Fig. 7A) no areas with high fragility were found either.

The classes found with the lowest percentages in the watersheds were very low and high classes. The watersheds with the lowest percentages of very low class are: Toledo (0.05%), Medianeira (0.07%), Boa Vista da Aparecida (0.08%). Whereas, the watersheds with the lowest percentages of very low class are: Três Barras do Paraná (0.49%) Guaraniaçu (0.34%) and Santa Tereza do Oeste (0.21%). Regarding the high class, the watersheds that have the largest areas are: Guaraniaçu (1.34%), Catanduvas (0.33%) (Figure 5B), and Cascavel (0.26%) (Fig. 7E), the watersheds that have lower percentages of high class are: Foz do Iguaçu (0.00%), Toledo (0.02%) and Santa Tereza do Oeste (0.02%).

Table 6
Areas and percentage of the Environmental Fragility of watersheds classes of the municipalities of western Paraná-BR

Fragility	BVA		CVEL		CTD		FOZ		GUA		MED		STO		TBP	
	Km²	%	Km²	%	Km²	%	Km²	%	Km²	%	Km²	%	Km²	%	Km²	%
Very Low	0.03	0.08	0.08	0.16	0.04	0.16	0.02	0.16	0.07	0.16	0.02	0.07	0.23	0.21	0.06	0.4
Low	1.75	4.85	13.68	27.18	4.77	19.69	3.63	19.69	4.33	19.69	4.81	15.90	13.42	12.49	3.27	26.8
Intermediate	34.26	94.88	36.44	72.40	19.34	79.82	15.46	79.82	16.15	79.82	25.35	83.80	93.75	87.27	8.85	72.5
High	0.07	0.19	0.13	0.26	0.08	0.33	0	0	0.28	1.34	0.07	0.23	0.02	0.02	0.02	0.16
Very High	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	36.11	100	50.33	100	24.23	100	19.1	100	20.8	100	30.3	100	107.4	100	12.20	100

Environmental fragility presented significant dependence on temperature and pH variables, and the higher the rate of, the higher temperatures and lower pH are observed (Table 7). Another point to be highlighted is E. coli and COD, which, although not reaching $p < 0.05$, pointed to a tendency toward higher concentrations of E. coli and lower COD for higher fragilities (Table 7).

Table 7

Comparison of limnological variables as a function of the percentage of occurrence of the environmental fragility classes. (T water: Water temperature, DO: D electrical conductivity, Prof.: Depth, Tur: Turbidity, CL-a: Chlorophyll; Eci: *Escherichiacoli*, TC:total coliforms, BOD: biological oxygen demand, COD: chemical c NO_3: nitrate, TN: Total Kjeidahl Nitrogen, PO_4: orthophosphate and TS: Total solids) measured in the eighteen sampling stations of urban rivers in t

standardized coefficient	Temp	DO	pH	Condut	Prof	Tur	Chlorophyll	Ecoli	Colt	BOD	COD	TP	Nitrate
Very Low	0.043	-0.436988	0.7865284	0.272	-0.069	-0.097	-0.392	-0.179	-0.390	-0.322	0.854	-0.118	0.116
Low	2.309	0.8522065	-3.7940966	-2.479	2.034	3.048	2.286	1.325	-1.969	2.684	-1.453	0.567	0.894
Intermediate	2.627	0.4201527	-3.1369079	-2.546	1.890	3.344	1.824	1.347	-2.032	2.614	-0.952	0.433	0.682
High	-0.534	0.0784789	-0.1753511	0.156	-0.206	0.247	0.019	0.753	-0.034	0.400	-0.008	-0.242	-0.351
R²	0.721	0.142	0.606	0.354	0.176	0.256	0.232	0.412	0.191	0.191	0.479	0.095	0.179
F	8.400	0.537	4.993	1.781	0.695	1.119	0.983	2.276	0.770	0.768	2.991	0.340	0.708
P value	**0.001**	0.711	**0.012**	0.193	0.609	0.389	0.450	0.117	0.564	0.565	0.059	0.846	0.601

Discussion

The municipalities have distinct characteristics not only because of the water quality, but also have naturally distinct physical characteristics among the watersheds evaluated, in agreement with the theory of the river continuum concept of Vanotte et al. (1980). However, the environmental variables pointed to different levels of anthropic interference. Initially, the difference among the environments is highlighted mainly due to pH, conductivity, COD, orthophosphate and total solids, variables that interfere directly with water quality and the water supply treatment process (Collares et al. 2021).

The municipalities of Cascavel and Medianeira stand out with low pH values, around 5, being possibly related to the disposal of industrial effluents, domestic sewage and agricultural activities, directly influencing the inferior water quality for these areas (Chen and Lu 2014; Carvalho et al. 2015; Shi et al. 2017). On the other hand, the municipalities of Foz do Iguaçu, Catanduvas and Santa Tereza do Oeste presented mean values of COD greater than 70 mg/L, which may be related to the influence of residential activities and sewage treatment plant (Hua 2017), as well as agricultural activities (Shi et al. 2017).

The environmental variables that characterize the water quality point to a representative difference according to the municipalities. This factor effectively confirms the statistical difference in the water quality of the environments as indicated in the ordination. The municipalities of Boa Vista da Aparecida, Catanduvas and Guaraniaçu presented similarity mainly due to pH, total solids, orthophosphate and conductivity. Concomitantly, these municipalities presented dominance of small agricultural properties, as a result of a relief varying from undulating to strongly undulating of such areas (Biasi 1992; Kawano et al. 2021). The higher the slope, the higher the speed and the capacity to transport water in a liquid state, which is responsible for the erosion processes that these environments are exposed to (Souza and Oliveira 2018). Another factor that reinforces the correlation is that the predominant variables in these municipalities are strong indicative of non-point polluting sources such as fertilizer use (Meneses et al. 2015; Hua 2017; Cheng et al. 2018). The COD levels of water are higher in arable areas, because there is a load of nutrients from the soil to water (Ribeiro et al. 2014; Shi et al. 2017), reflecting the agricultural extension of these regions (PNUD 2018).

What can be observed in general, the municipalities that have higher percentages of forest also have lower percentages of urban area, as well as the municipalities that have higher percentages of urban area also have lower percentages of forest. This trend may be related to the reality that in the urban area, the existing forest regions tend to be deforested to give way to the residences, and the agricultural and livestock regions have predisposition to forest degradation to gain area of planting and livestock breeding. In this context, Carvalho et al. (2016) confirm that the presence of residences close to the watercourse shows the absence of permanent preservation areas (PPA) in that region, which causes environmental damage, as well as irregular runoff, floods, improper disposal of sanitation organic matter, and plumbing harmful to water interaction and human life.

The class of fragility predominantly in this study was the intermediate class. Similar results were found by Anjinho et al. (2021), Abrão and Bacani (2018), Nörnberg and Rehbein (2020) Rehbein (2020), Gouveia et al. (2015), Corte et al. (2015), Bueno et al. (2018), Bisognin et al. (2018), who attribute the areas with intermediate fragility to the steep areas allied to Agriculture and Livestock, due to the inadequate soil management, making the soil susceptible to erosion, as well as to cattle grazing areas close to the watercourses, allowing direct contact of the cattle with water. These factors when combined end up generating the springs contamination.

The variation in fragility mainly responded to the pH, E. coli and DQO temperature values, which can be strongly associated with the difference in soil use and slope of the areas evaluated. Higher temperatures were related to intermediate fragility and lower to high fragility, which may be associated with more intensive slope causing an increase in the flow of the river, since tidal water tends to receive less direct insolation and, therefore, making it colder (Vanotte et al. 1980). Another factor is lower pH and higher concentration of *E. coli* being related to intermediate to high fragility. These factors are indicative of urban densification, as well as temperature, also reflecting on the agricultural extension of the municipality, characterizing a great use of agricultural pesticides that increase the load of nutrients charged to the water bodies, favoring the bacteria development (Esteves 2011; Lötjönen and Ollikainen, 2019).

Thus, the most vulnerable watersheds can be considered those of the municipalities of Cascavel, Foz do Iguaçu, Toledo and Medianeira, due to the fact that they present large urbanized regions close to the collection points, since one of the collection points of Cascavel is close to a mining region (quarry). Anthropogenic activities directly affect the fragility of these environments as well as water quality (Campos et al. 2011; Silva et al. 2016; Pereira et al. 2018).

Generally, areas with steep relief with exposed soil or vegetation are associated with intermediate to high fragility, as well as urban areas, where the human intervention modifies the environment (Silveira et al. 2014; Schiavo et al. 2016; Valle et al. 2016; Belato et al. 2019).

In addition, the watersheds of Boa Vista da Aparecida, Catanduvas, Guaraniaçu and Três Barras do Paraná presented reflections of the large areas of Agriculture and livestock close to the collection points, which may be harmful because the animals are close to the bodies of water and perennial and semi perennial cultures (Campos et al. 2011; Silva et al. 2016). Even some authors having recorded the very low and low fragility class with predominance in areas of low slope relief, this factor is usually associated with areas with dense vegetation and/or reforestation regions, which does not occur in these municipalities (Goncalves et al. 2011; Franco et al. 2012; Bacani et al. 2015; Costa et al. 2015; Storto and Cocato 2018; Periçato and Souza 2019; Souza et al. 2020).

The results indicate that areas with steep slope, together with regions with poor use in soil preservation (agriculture or urban area), are found to have higher rates of environmental fragility, thus more fragile, thus damaging water sources and water quality. However, the need to pay attention to the watersheds with a predominance of intermediate fragility is emphasized, since the watersheds management is necessary for restoration and conservation, aiming to prevent the advance of fragility, added to minimizing the anthropic impacts of the use and occupation of these environments, thus achieving the improvement of water quality in these areas.

Conclusion

The present study showed that the intermediate fragility class predominates in the nine municipalities studied in the west of Paraná, namely: Boa Vista da Aparecida, Catanduvas, Cascavel, Foz do Iguaçu, Guaraniaçu, Medianeira, Santa Tereza do Oeste, Três Barras do Paraná and Toledo. Management of the same is necessary for restoration and conservation, aiming to prevent the advance of fragility added to minimize the anthropic impacts of the use and occupation of such environments. The municipalities that have the largest areas with high fragility class, with the most fragile ones, are: Guaraniaçu, Catanduvas and Cascavel, demanding greater attention, because they are harmful to the water sources and the water quality of the water bodies.

It also pointed out distinct characteristics among the water catchment rivers for public supply, of the west of Paraná, due to the water quality and due to its natural characteristics. The variation in fragility mainly responded to the pH, E. coli and DQO temperature values, which can be strongly associated with the difference in soil use and slope of the areas evaluated.

The use of geoprocessing tools made it possible to make the fragility maps as well as, how to associate it with water quality factors of 9 catchment rivers for public supply in the west of Paraná, Brazil, proving to be an efficient tool for the study of environmental changes, emphasizing the limitation of studies that combine geoprocessing with water quality indices. The results obtained can be used for future decision-making regarding environmental management based on the water quality improvement and restoration of the studied sources.

Declarations

Funding Capes and funding of research through public call 26/2018 – Programa Paranaense de Pesquisas em Saneamento Ambiental (PPPSA) Fundação Araucária/SANEPAR.

Conflicts of interest / competing interests: Not applicable

Data and materials availability: Not applicable

Code availability: Not applicable

Authors' contributions: Not applicable

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Figures

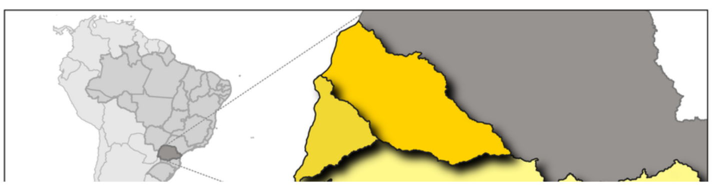

Figure 1

Municipalities in the western region of Paraná, Paraná, Brazil selected to evaluate the quality of the rivers used for water catchment and supply of the population.

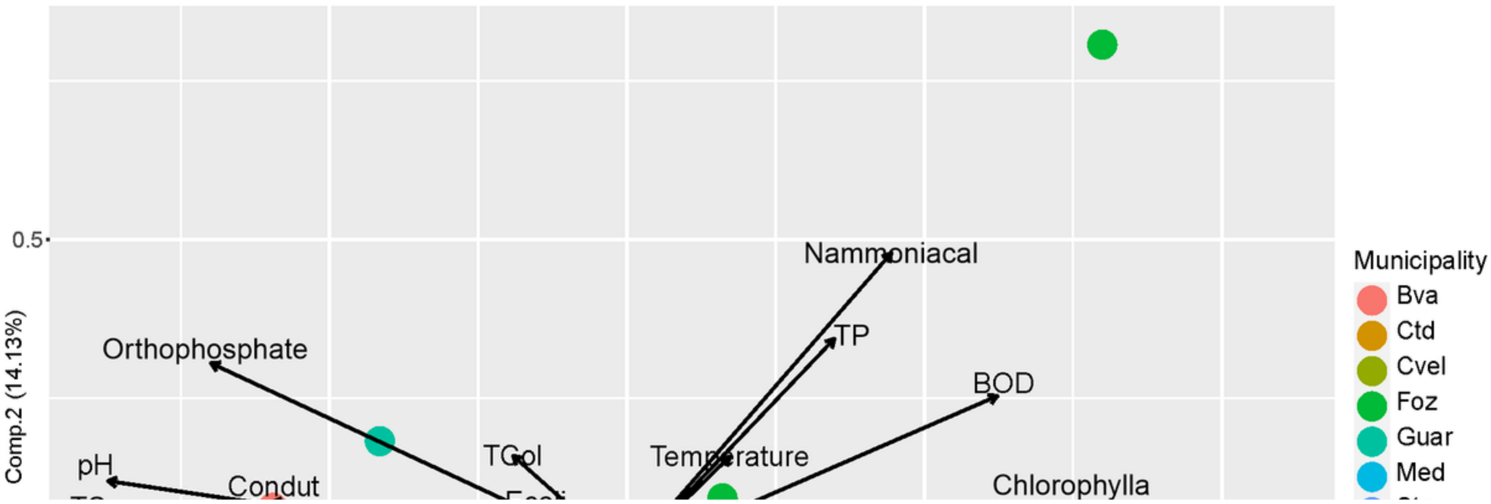

Figure 2

Analysis of the main components (PCA) for physical, chemical and biological data analyzed in the nine municipalities evaluated in western Paraná, Brazil. (Temp: Water temperature, DO: Dissolved oxygen, Condut: conductivity: electrical conductivity, Prof.: Depth, Tur: Turbidity, CL-a: Chlorophyll *a*; Ecoli: *Escherichiacoli*, Colt: total coliforms, BOD: biological oxygen demand, COD: chemical oxygen demand, TP: Total phosphorus, $N0_3$: nitrate, TN: Total Kjeidahl Nitrogen, $P0_4$: orthophosphate and TS: Total solids).

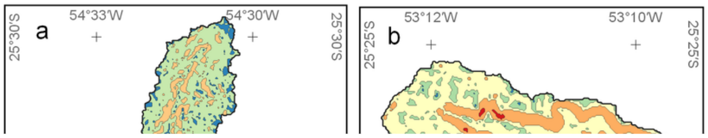

Figure 3

Slope Maps. A - Paraná River (Itaipu Lake), Municipality of Foz do Iguaçu, Paraná-BR. B - Itaguaçu Creek (Trigôlandia), Municipality of Três Barras do Paraná, Paraná-BR. C - Arroio Passo Liso, Municipality of Catanduvas, Paraná-BR. D - Gonçalves Dias River, Municipality of Santa Tereza do Oeste, Paraná-BR. E - Cascavel River, Municipality of Cascavel, Paraná-BR. F - Jacutinga River, Municipality of Boa Vista da Aparecida, Paraná-BR.

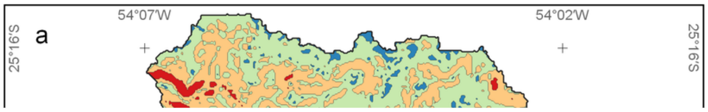

Figure 4

Slope Maps. A - Alegria River, Municipality of Medianeira, Paraná-BR. B - Toledo River, Municipality of Toledo, Paraná-BR. C- Baú river Municipality of Guaraniaçu, Paraná-BR.

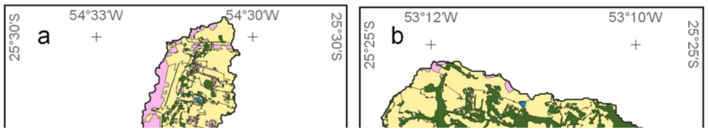

Figure 5

Soil use and Occupation Maps. A - Paraná River (Itaipu Lake), Municipality of Foz do Iguaçu, Paraná-BR. B - Itaguaçu Creek (Trigôlandia), Municipality of Três Barras do Paraná, Paraná-BR. C - Arroio Passo Liso, Municipality of Catanduvas, Paraná-BR. D - Gonçalves Dias River, Municipality of Santa Tereza do Oeste, Paraná-BR. E - Cascavel River, Municipality of Cascavel, Paraná-BR. F - Jacutinga River, Municipality of Boa Vista da Aparecida, Paraná-BR.

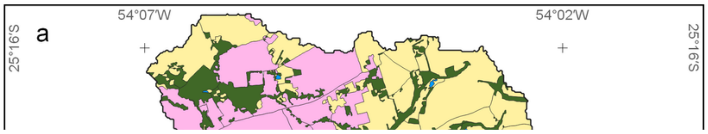

Figure 6

Soil use and Occupation Maps. A - Alegria River, Municipality of Medianeira, Paraná-BR. B - Toledo River, Municipality of Toledo, Paraná-BR. C- Baú river Municipality of Guaraniaçu, Paraná-BR.

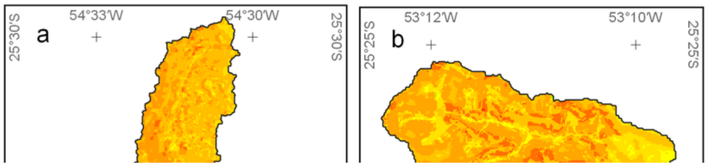

Figure 7

Fragility Maps. A - Paraná River (Itaipu Lake), Municipality of Foz do Iguaçu, Paraná-BR. B - Itaguaçu Creek (Trigôlandia), Municipality of Três Barras do Paraná, Paraná-BR. C - Arroio Passo Liso, Municipality of Catanduvas, Paraná-BR. D - Gonçalves Dias River, Municipality of Santa Tereza do Oeste, Paraná-BR. E - Cascavel River, Municipality of Cascavel, Paraná-BR. F - Jacutinga River, Municipality of Boa Vista da Aparecida, Paraná-BR.

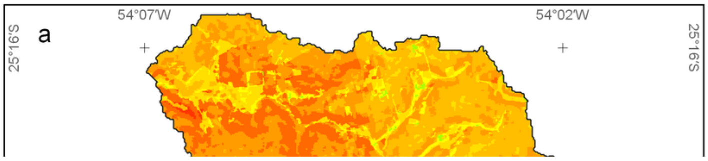

Figure 8

Fragility Maps. A - Alegria River, Municipality of Medianeira, Paraná-BR. B - Toledo River, Municipality of Toledo, Paraná-BR. C- Baú river Municipality of Guaraniaçu, Paraná-BR.