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Delimitation of Permanent Preservation Areas in Watercourses for Management Purposes in Rio Grande Do Sul State: a Regression Model with Hydrological Data and Geoprocessing Techniques

Delimitação de Áreas de Preservação Permanente em Cursos d'água para Fins de Gestão no Estado do Rio Grande do Sul: um modelo de regressão com dados hidrológicos e técnicas de geoprocessamento

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Abstract: This work proposes a regression model to delimit the permanent preservation areas (PPAs) of the marginal strips of watercourses for the hydrographic basins of Rio Grande do Sul based on hydrology and geoprocessing techniques. The methodology consists in determining a regression equation relating the average width of the watercourses with the drainage area and, from the generated equation, estimating an approximation for the PPAs size of the watercourses with geoprocessing software. It was possible to adjust and validate a regression model that delimited the width of PPAs in the marginal strips of all watercourses in RS. The evaluation indicates that the methodology has fast processing and is valid for studies on a regional scale, such as, in hydrographic basin planning studies. Cross-referencing the PPAs generated by the equation in a hydrographic basin with the map of land use and occupation allowed quantifying the proportion of PPAs with adequate and inappropriate uses, being a valid tool for diagnosing the situation of water resources. The limiting factors of the methodology regarding delimited PPA accuracy are: 1- Intrinsic limitations in positional accuracy for the Cartographic Base of Rio Grande do Sul at a scale of 1:25,000, 2) limitations resulting from the regression model 3) errors arising from processing. Thus, the presented method should be used with a caveat in localized situations or for studies and processes that require precise values.
Keywords: Water Resources, Geographic Information System, Hydrographic Basin, Planning, Forest Code.

Resumo: O objetivo do trabalho é propor um modelo de regressão para delimitar as Áreas de Preservação Permanente (APPs) das faixas marginais dos cursos de água para as bacias hidrográficas do Rio Grande do Sul a partir de técnicas de hidrologia e geoprocessamento. A metodologia consiste em determinar uma equação de regressão relacionando a largura média dos cursos d'água com a área de drenagem e, a partir da equação gerada, estimar uma aproximação para o tamanho das APPs dos cursos d'água com softwares de geoprocessamento. Foi possível ajustar e validar um modelo de regressão que delimitou a largura das APPs das faixas marginais de todos os cursos hídricos do RS. A avaliação indica que a metodologia possui rápido processamento e é válida para estudos em escala de âmbito regional, como, por exemplo, em estudos de planejamento de bacias hidrográficas. O cruzamento das APPs geradas pela equação em uma bacia hidrográfica com o mapa de uso e ocupação do solo permitiu quantificar a proporção das APPs com usos adequados e inadequados, sendo uma ferramenta válida para fins de diagnóstico da situação dos recursos hídricos.

Limitações intrínsecas da acurácia posicional da Base Cartográfica do Rio Grande do Sul em escala de 1:25.000, do modelo de regressão e erros oriundos do processamento são os fatores limitantes da metodologia quanto à acurácia das APPs delimitadas. Dessa forma, o método apresentado deve ser utilizado com ressalvas em situações localizadas ou para estudos e processos que exijam valores precisos.
Palavras-chave: Recursos Hídricos, Sistema de Informação Geográfica, Bacia Hidrográfica, Planejamento, Código Florestal.

1 INTRODUCTION

The definition of Permanent Preservation Areas (PPAs) along rivers in Brazil has undergone legal changes over the years. In the case of watercourses, Article 4 of the Federal Law No. 12.651/2012 (BRASIL, 2012) defines PPAs as the marginal strips of any perennial and intermittent natural watercourse, excluding ephemeral ones, from the edge of the regular river bed; minimum PPA widths will vary according to the width:

a) 30 (thirty) meters, for watercourses less than 10 (ten) meters wide;
b) 50 (fifty) meters, for watercourses 10 (ten) to 50 (fifty) meters wide;
c) 100 (one hundred) meters, for watercourses 50 (fifty) to 200 (two hundred) meters wide;
d) 200 (two hundred) meters, for watercourses 200 (two hundred) to 600 (six hundred) meters wide;
e) 500 (five hundred) meters, for watercourses wider than 600 (six hundred) meters.

It is observed that these watercourse widths refer to the regular bed, defined as the *channel through which the watercourse regularly flows throughout the year*. Thus, to define the regular bed, various measurements would be necessary to find the regularity of the watercourses and subsequently define the marginal strip of the PPAs.

The protocol for measuring watercourse flow in Brazil, adopted by the National Water and Basic Sanitation Agency (Agência Nacional de Águas e Saneamento Básico - ANA) and executed by the Geological Survey of Brazil (Serviço Geológico do Brasil - SGB) in the Rio Grande do Sul State, establishes the measurement and recording of width at the time of data collection. Thus, the measurement campaigns present width and corresponding flow data. From the analysis of these data, it is perceived that the width of the watercourse has small variations within a large range of flow values. Therefore, it can be inferred that the width of the regular channel bed of the watercourse can be estimated based on its average flow.

In addition, drainage area is one of the main factors related to the average flow of watercourses, which whose data can be obtained from geoprocessing techniques, without the need for fieldwork measurements. According to Tucci (2002), the average flow shows a strong correlation with the drainage area, usually in a power function.

Several studies have mapped and delimited PPAs through geoprocessing techniques (MAIA et al., 2022; CAVA et al., 2022; NOWATZKI et al., 2021; ROSA; FERREIRA, 2021; PADILHA; CENTENO; FARIAS, 2017; LOUSADA et al., 2016; DOMINGUES et al., 2015; VIEGAS et al., 2014; LEAL et al., 2013; PINHEIRO et al., 2004). Most of these studies applied the 'buffer' tool in a geoprocessing software, which allows delineating an influence zone from the river line quickly and efficiently.

Maia (2022) defined the width of PPAs through fieldwork in the Samambaia Stream, located in the Federal District (DF). Cava et al. (2022) and Pinheiro et al. (2004) used a width of 30 m for the entire study area. Paes et al. (2014) defined 30m width for PPAs for tributaries of the Sapucaí River (which are less than 10m wide) and a width of 50m for the Sapucaí River itself (which is between 10m and 50m wide), based on the Participatory Master Plan of Santa Rita do Sapucaí. Rosa and Ferreira (2021) used images from Google Earth Pro to establish 30 m PPAs for watercourses up to 4th order, and 50 or 100 m for 5th order rivers, as they have widths greater than 10 m, with some river sections reaching approximately 100 m wide.

From the aforementioned studies, it is clear that the criteria for delineating the regular channel and width of PPAs are unequal in their conception, often simplified, laborious (e.g., fieldwork), and sometimes require preliminary work. Therefore, although geoprocessing tools have the capability to apply PPAs delineation quickly, the main question lies in data input, i.e., defining the regular bed of rivers and consequently

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the width of PPAs.

Moreover, most studies have a local scale and applied PPAs delineation to a small number of watercourses. Studies in large river basins, such as Nowatzki et al. (2021), who mapped PPAs in the Paranapanema River Basin, require considerable effort to accomplish and are scarce in the literature.

Using hydrology techniques combined with geoprocessing, Pietzsch (2013) found a relationship between drainage area, flow, and width of watercourses to delineate PPAs in small river basins of the Caverá (1,463 km^2) and Ituim (1,339 km^2) rivers, both in Rio Grande do Sul State. The research demonstrated the applicability of this method that relates two essential hydrological variables and can be expanded to river basins with large drainage areas.

Based on the premises addressed in Pietzsch's research (2013) and moving towards an extrapolation approach for the entire territory of the Rio Grande do Sul State (RS), this study aims to propose a regression model to delineate the width of PPAs of the marginal strips of watercourses in RS using hydrology and geoprocessing techniques. It is also the objective of the study to present the methodology in the context of larger-scale river basins to discuss the limitations of the method and the applicability focusing on water resources management.

2 MATERIAL AND METHODS

The methodology is divided into 3 stages: 1) regression analysis between drainage area and average width of the watercourse; 2) validation of the widths of the watercourses generated by the model; 3) polygon generation for the PPAs.

2.1 A regression model between drainage area and average width of watercourses

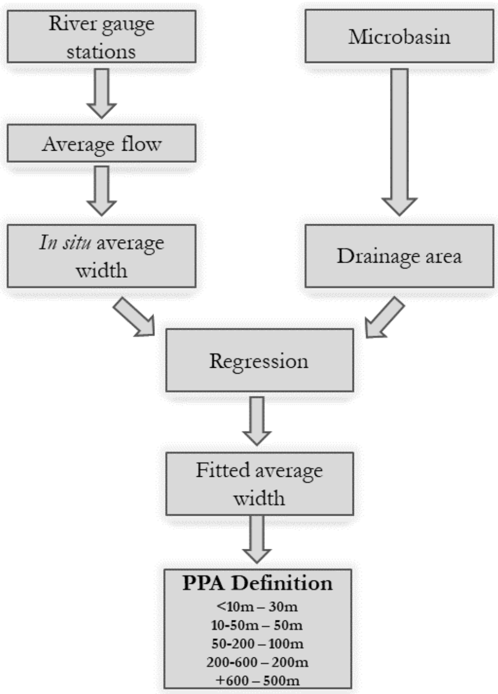
The basic flowchart is depicted in Figure 1. Two types of data were used:

a) Data from 160 ANA/SGB river gauge stations, with field-measured average width and flow data;

b) Vector file of microbasins (or mini basins) from Department of Water Resources and Sanitation / Secretary of the Environment and Infrastructure (Departamento de Recursos Hídricos e Saneamento / Secretaria do Meio Ambiente e Infraestrutura, DRHS/SEMA), containing drainage area information.

Essentially, the methodology consists of determining a regression equation relating the average width of the watercourse provided by the gauge station data with the drainage area, as indicated in the microbasin file. From the generated equation, it is possible to estimate the average width of the watercourses for each location based on the drainage area.

Figure 1 - Flowchart with the research's general conception.



Elaboration: The Authors (2021).

To apply the proposed adjustment, data from 121 randomly selected river gauge stations were used. The data from the remaining 39 stations were used for validation (independent samples). Figure 2 shows a map with the stations used for the application of this methodology. Considering the data from the available stations, the interquartile range (IQR) of the flow measurements was obtained for each station using Eq. (1):

$$IQR = Q_3 - Q_1 \tag{1}$$

where Q_3 and Q_1 are, respectively, the third and first quartiles of the flow measurements, values corresponding to the non-exceedance frequencies of 0.75 and 0.25. The upper and lower limits were obtained using Eqs. (2) and (3):

$$USL = Q_3 + 1{,}5\ IQR \tag{2}$$

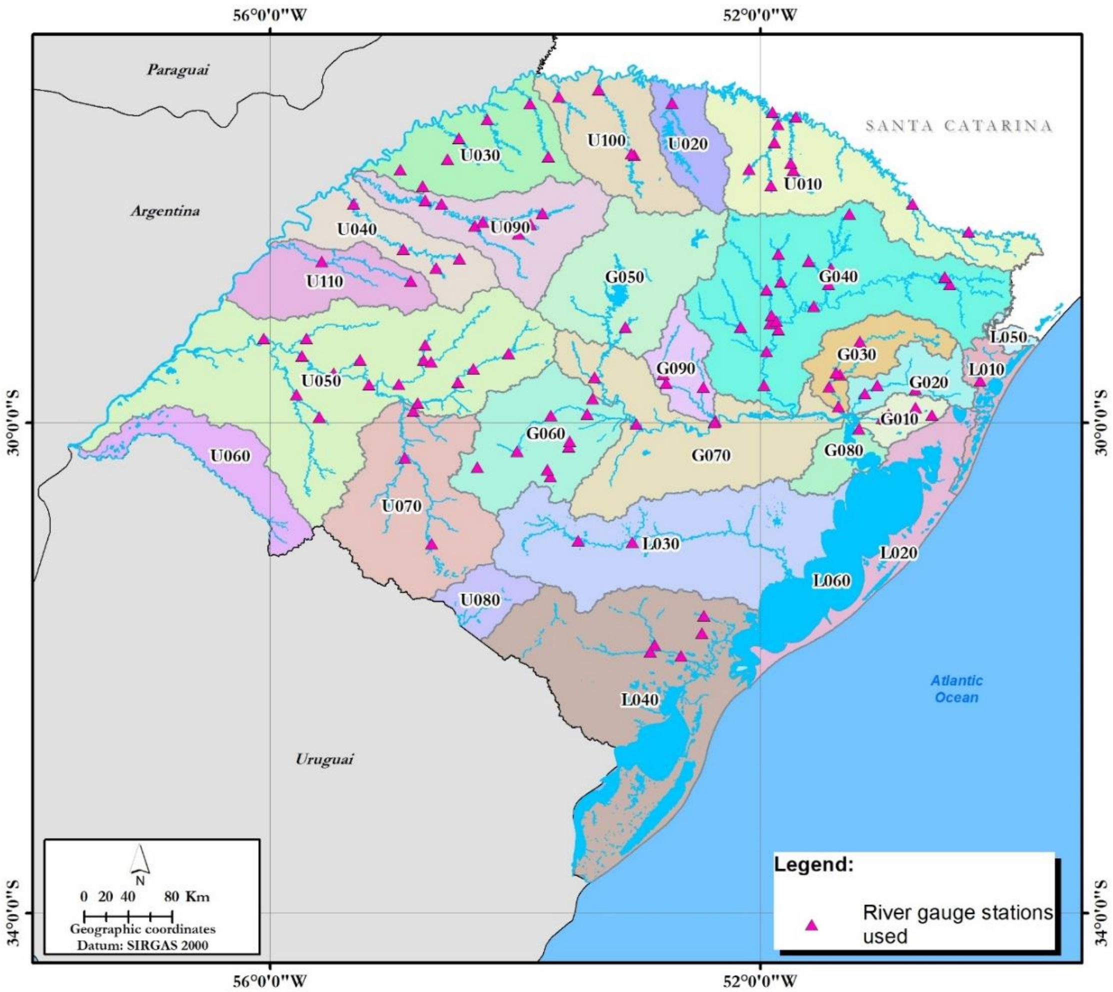
$$LSL = Q1 - 1{,}5\ IQR \tag{3}$$

Measurements that exceeded these limits were ruled out. The width values corresponding to the remaining measurements were used to obtain the average width measured at each station. With the filtered data, a power law was fitted characterizing the average width (A_w), as a function of the contributing area (*A*) through Eq. (4):

$$A_W = a \cdot A^b \tag{4}$$

where the coefficients *a* and *b* were determined using the Ordinary Least Squares. Thus, the estimated average width values of the watercourses for these stations from the equations of the study conducted for RS (SEMA-RS, 2010) were related to the drainage area data provided in the monitoring station database.

Figure 2 - Stations used to adjust the regression model.



Elaboration: The Authors (2022).

2.2 Validation of model-generated watercourse widths

For the validation of the regression model, the remaining 39 stations were used as independent samples. The adjusted average river width by the model was compared with the average width determined by the river gauge station data. The coefficient of determination (R^2) and the root mean square error (RMSE) were used as metrics to evaluate the model.

2.3 Generation of the PPAs polygon in a Geographic Information System software

Based on the generated equation, the widths of the watercourses were defined for the endpoint of each microbasin, using the drainage from the Cartographic Base of the Rio Grande do Sul State (CBRS25), scale 1:25,000 (SEMA-RS, 2018). With this information, the polygons of the riparian zones of the PPAs were generated according to each average width of the watercourse, following the criteria of Article No. 4 of Federal Law No. 12,651/2012, in a Geographic Information System software.

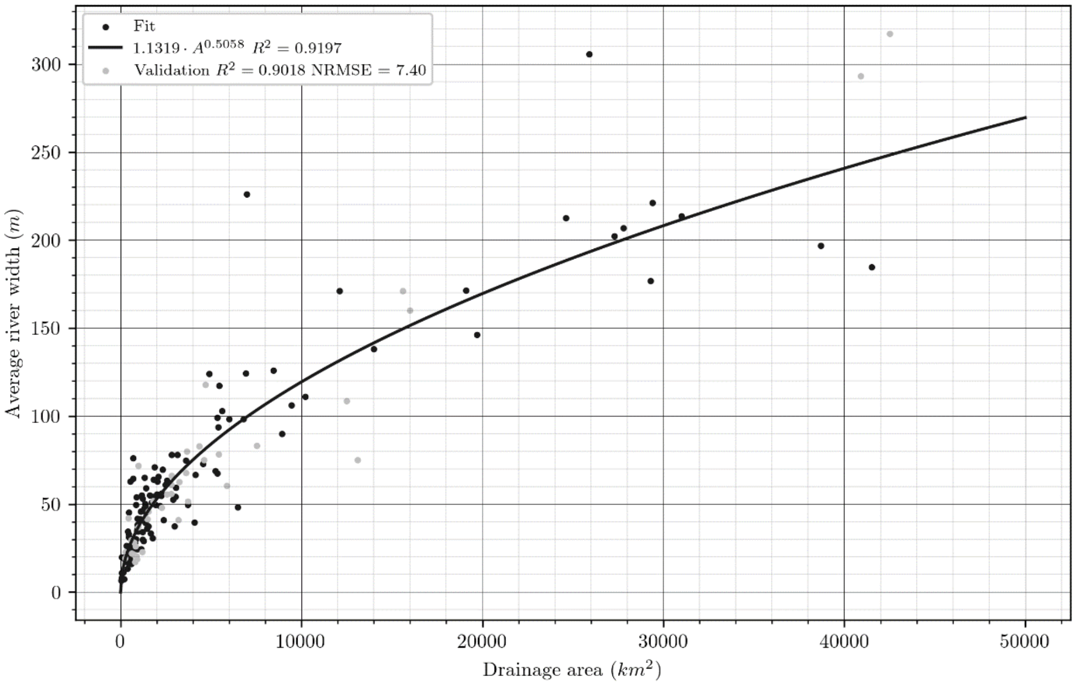
3 RESULTS AND DISCUSSION

Figure 3 presents the data used for fitting, the adjusted function, and the data used for validation. The obtained fit, given by Eq. (5), shows a coefficient of determination (R^2) of 0.9197 with respect to the measured values:

$$A_W = 1{,}1319 \cdot A^{0{,}5058} \tag{5}$$

where Width (A_W) is in meters and Area (A) is in km².

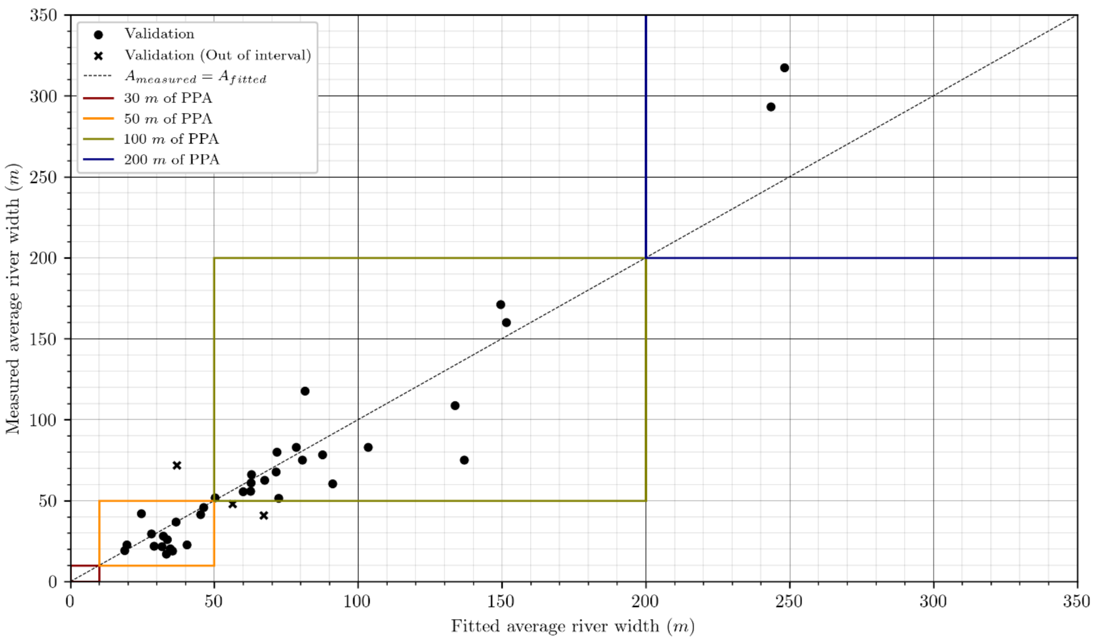
Figure 3 - Relationship between drainage area (contribution area) and average width of watercourses.



Elaboration: The Authors (2023).

For the validation stage, it was possible to correctly classify the PPAs of 36 out of 39 randomly chosen stations for validation, with only 3 stations falling outside the PPA intervals. Figure 4 presents the comparison of each station with the width ranges of the PPAs delimited by the rectangles on the graph. It can be observed that the stations have validation within the 50m, 100m, and 200m PPA ranges. For the proposed validation metrics, an R^2 of 0.9497 and a normalized root mean square error (NRMSE) of 7.4% were considered satisfactory. Therefore, the data from independent stations demonstrate that the fit is considered adequate to validate the regression model.

Figure 4 - Comparison between measured and calculated width values from the general equation.



Elaboration: The Authors (2023).

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Although the fit presents stations outside the range, the method is considered valid for general applications, i.e., the possibility of using only one equation to estimate the PPAs of all watercourses in RS. Local specificities of a watershed, such as geological or geomorphological characteristics, were not considered by this method.

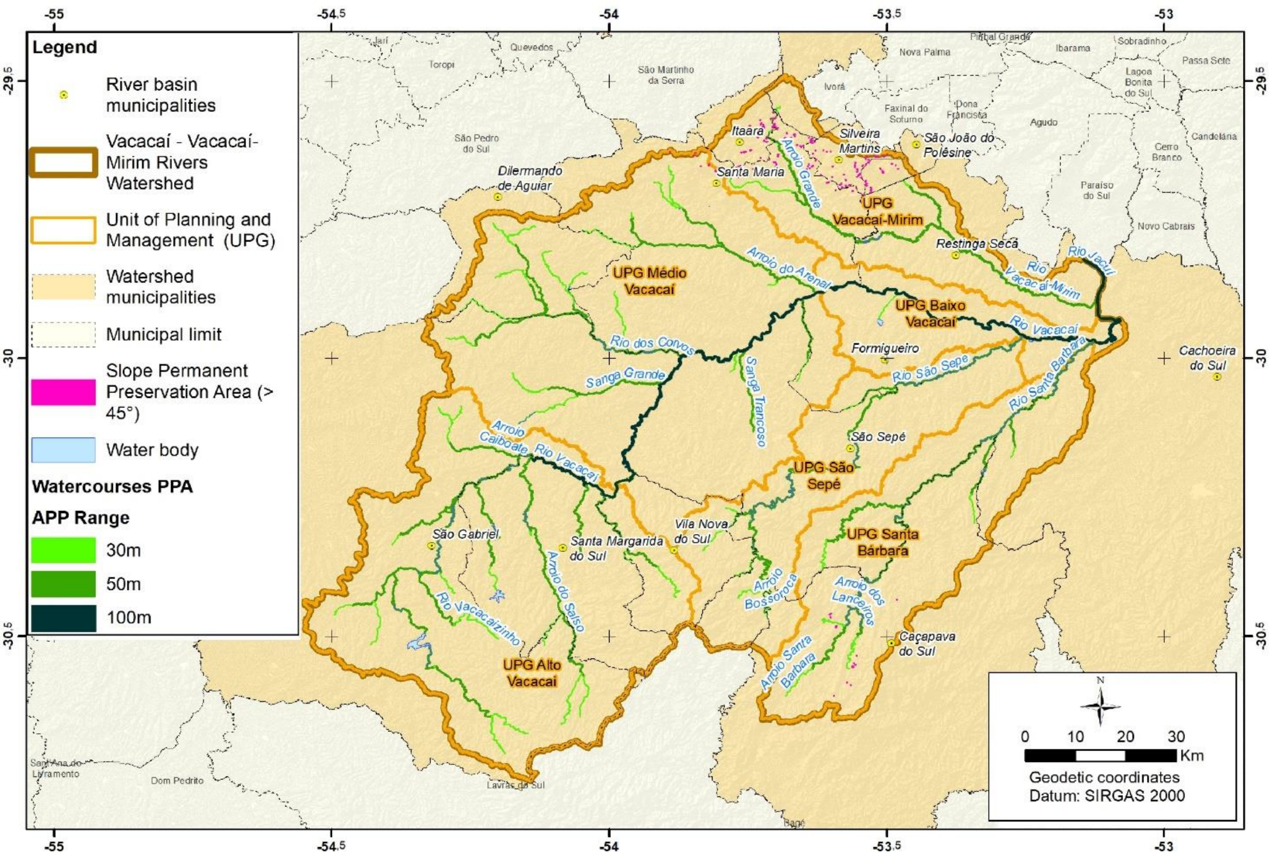
The results were generated for each watershed and deposited in the DRHS/SEMA database. An example of the application occurred in the Vacacaí - Vacacaí-Mirim Rivers Watershed, which has a Basin Plan (corresponding to one of the planning instruments provided for in the National Water Resources Policy - Federal Law No. 9.433/1997) being developed by the technical team of DRHS/SEMA. The application is included in the report of Phase A - Diagnosis of the Water Resources Plan of the Vacacaí - Vacacaí-Mirim Rivers Watershed (SEMA, 2021).

The generated results are presented in Figure 5, which shows the PPAs of the watercourses, used with the proposed method. The PPAs were intersected with the land use and land cover map from MapBiomas Project, Collection 5 (MAPBIOMAS, 2018), for the year 2018, allowing quantification and diagnosis of the proportion of PPAs with suitable and unsuitable uses in the watershed.

Table 1 provides the respective values for the percentage of each type of land use over the calculated PPA area integrated by the Unit of Planning and Management (UPG) in the watershed.

For territorial management purposes at the watershed scale, the proposed methodology is interesting as it allows quantification and spatialization of land uses in preservation areas. In the Vacacaí - Vacacaí-Mirim Rivers Watershed, it was possible to estimate the UPGs with higher or lower rates of forest and grassland formation land use classes in the PPA strips. The Vacacaí-Mirim UPG showed the lowest rate of these classes, which is associated with degradation conditions in water quality (SEMA, 2021). This type of recognition is important at the watershed scale as it promotes a better understanding of the dynamics of interaction with water resources in different portions of the watershed.

Figure 5 - PPAs in the watercourses of the Vacacaí - Vacacaí-Mirim river basin.



Elaboration: SEMA (2021).

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Table 1 - Percentage of area occupied by each land use over the PPA area calculated in each UPG in the watershed.

Land Use	UPG Alto Vacacaí	UPG Médio Vacacaí	UPG Baixo Vacacaí	UPG Santa Bárbara	UPG São Sepé	UPG Vacacaí-Mirim
Forestry	77.20%	63.61%	67.04%	74.03%	79.93%	63.15%
Grassland/Pasture	6.06%	8.19%	5.48%	12.93%	6.32%	3.27%
Planted Forest	0.04%	0.00%	0.00%	0.00%	0.08%	0.07%
Agriculture – Other Crops	10.55%	20.68%	7.48%	11.59%	11.02%	27.11%
Agriculture – Soy	1.79%	1.12%	1.85%	0.46%	1.05%	0.73%
Agriculture and Pasture Mosaic	0.00%	0.93%	0.00%	0.00%	0.00%	1.94%
Urban infrastructure	0.39%	0.68%	0.00%	0.00%	0.00%	0.26%
Water	3.91%	4.39%	14.29%	0.94%	1.50%	3.31%
Other non-vegetated area	0.06%	0.39%	3.86%	0.04%	0.08%	0.15%
Rocky outcrop	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Total	100%	100%	100%	100%	100%	100%

Elaboration: SEMA (2021).

3.1 Discussions and limitations of the method

From the analyses conducted, four limitations that impair the correct delimitation of PPAs stand out:

3.1.1 HYDROGRAPHIC NETWORK AND THE HYDROLOGICAL REGIME

PPAs are mandatory only in perennial and intermittent natural watercourses, excluding ephemeral ones. Ephemeral drainages are characterized by surface runoff occurring shortly after rainfall events. As a result, the construction of the hydrographic network generally does not take into account the hydrological regime, leading to discrepancies between the presence of a watercourse from the hydrographic network in a location of ephemeral drainage, or vice versa. Intermittent and ephemeral rivers are temporary and difficult to map (CAVA et al., 2022).

Disparities between the hydrographic network available from official agencies and the terrestrial reality are common problems in Brazil (e.g., TANIWAKI et al., 2018) and in other parts of the world (e.g., MORISAWA, 1957). Cava et al. (2022) extensively analyzed this issue and recommended field verification, as well as asserting that hydrographic charts should not be treated as absolute truth to guide legal decisions on the scale of rural properties.

3.1.2 POSITIONAL ACCURACY OF THE CARTOGRAPHIC BASE OF THE RIO GRANDE DO SUL STATE - VERSION 1.0 - 2018

The PPAs were generated from the drainage sections of the CBRS25, scale 1:25,000. Therefore, the location of the generated PPAs is a consequence of the scale and also the positional accuracy of the CBRS25 and may vary if another hydrographic network is used.

As indicated in the documentation (SEMA-RS; 2018), in the process of cartographic consistency validation, it was possible to classify the CBRS25, scale 1:25,000, in Class C1 according to the Standard of Cartographic Accuracy of Digital Cartographic Products (SCA-DCP). For class C of the SCA-DCP, an average error of 20m is admitted for the scale 1:25,000.

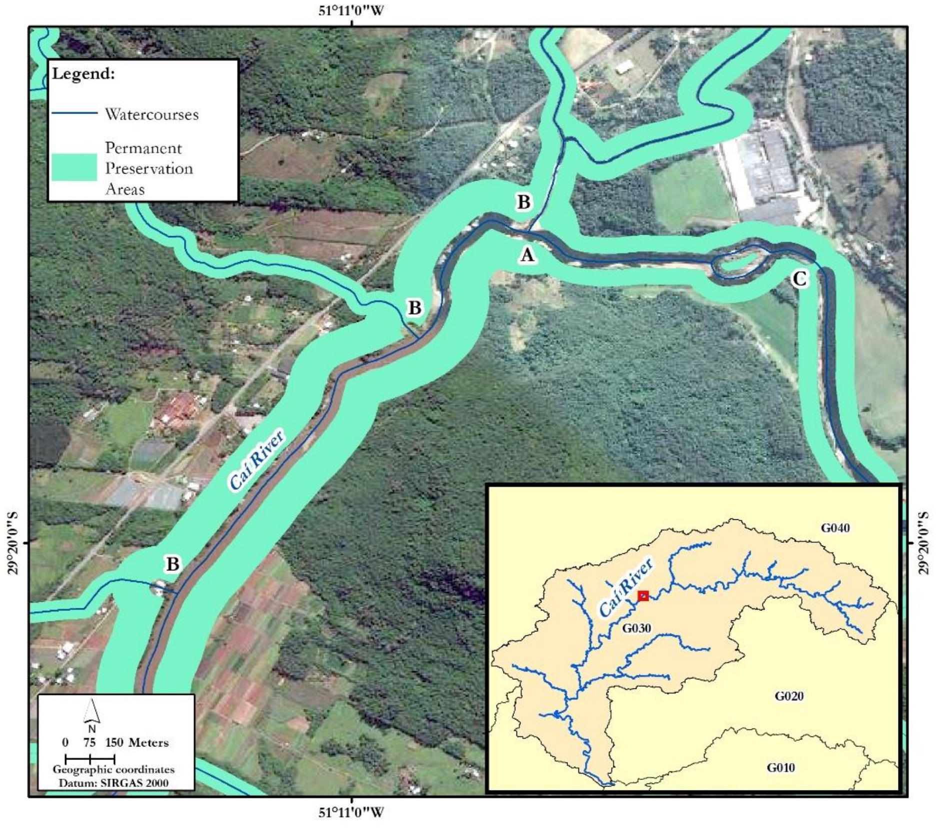
3.1.3 LIMITATIONS IN THE DRAINAGE-AREA-AND-AVERAGE-WATERCOURSE-WIDTH EQUATION

The relationship estimated in the regression model may underestimate or overestimate the mean width of watercourses and consequently the width of the PPA. Since the equation is general for all watercourses in

RS, it is possible to assume that the relationship of the regression model will not be correct for all watercourses, thus producing underestimation or overestimation of PPA widths.

Regression accuracy is important for values close to the boundaries of the PPA delimitation bands, i.e., the change in the width of the PPA when the drainage area reaches a value that corresponds, through the equation, to a width that entails a change in the width of the PPA. This can happen even if in practice the river maintains the same width as upstream (Figure 6 - Point A). For example, the value of 83 km² of drainage area is the threshold between rivers with average width less or greater than 10 m, that is, smaller and larger values of drainage area produce PPAs with widths of 30 m or 50 m, respectively. The same situation occurs for rivers with average widths of 50, 200, and 600 m, which have boundary values related to the drainage area. Therefore, the location of the sudden change in the width of the generated PPA is imprecise because it does not necessarily reflect the reality of the mean width of the watercourse. For planning with a more conservative view of the basin, to reduce this limitation, values of boundary areas slightly lower than those found by the equation could be adopted if approved by the corresponding instances.

Figure 6 - Result of the generated PPAs on the Caí River and tributary rivers of the Caí Hydrographic Basin (G030). Point A - Represents the increase in the width band of the PPA related to the drainage area. Points B - Issues in generating the PPA at river confluences. Point C - Issues in generating the mean width of the river.



Elaboration: The Authors (2022).

3.1.4 SYSTEMATIC ERRORS ARISING FROM PROCESSING IN A GEOGRAPHIC INFORMATION SYSTEM SOFTWARE

Systematic errors were recorded in the results obtained from processing. At the confluence of watercourses, the junction of tributary rivers adopts the main river's average width, consequently increasing the width of the PPA (Figure 6 - Point B). This was the main error of the method and was common to all processed hydrographic basins.

Along some watercourses, there were occasional differences in the average width of the river and consequently in the buffer width of the marginal strip (Figure 6 - Point C). This error was also common for the processed hydrographic basins, although it occurred less frequently than the first error. These two systematic errors limit the delimitation of the PPA for localized cases. Evidently, artificial reservoirs are not represented by the method, requiring the introduction of a specific vector file to correct this inconsistency.

4 CONCLUSION

It was possible to adjust and validate a regression model that delimited the width of the Permanent Preservation Areas (PPAs) of the riparian zones of watercourses in RS using hydrology and geoprocessing techniques. This work has the same approach as Pietzsch's proposal (2013), but the proposed model uses a regression model that enables the estimation of the PPAs for all watercourses in RS.

The methodology has fast processing and is valid for studies on a regional scale, such as watershed planning studies. The intersection of the PPAs with the land use and land cover map allowed quantifying the proportion of PPAs with suitable and unsuitable uses in the watershed, being a valid tool for regional environmental diagnosis linked to water resources.

As it is based on drainage area, the calculated PPA will always have upstream to downstream increments, thus avoiding sporadic reductions in this area due to natural or anthropic conditions. The watershed area is a factor of public and impersonal determination in a geoprocessing software, considering the same cartographic base and methodology. Furthermore, it can be considered immutable and easily auditable.

Intrinsic limitations of the positional accuracy of the Cartographic Base of Rio Grande do Sul State at a scale of 1:25,000, the regression model, and errors resulting from processing are limiting factors of the methodology regarding the accuracy of the delimited PPA. Therefore, the method presented should be used with caution in localized situations or for studies and processes that require precise values.

Authors' Contribution

Conceptualization - F.S.C.M., F.C.S.; Data curation - R.C.S, A.D.K.; Investigation - B.A.S., E.M., R.C.S, A.D.K.; Formal analysis - B.A.S., E.M., F.C.S; Methodology - B.A.S., E.M., F.C.S, F.S.C.M.; Project administration - F.C.S.; Software - B.A.S.; Validation - B.A.S., F.C.S.; Visualization - F.C.S., A.D.K., B.A.S.; Writing - original draft - F.C.S.; Writing - review and editing - All authors.

Conflicts of Interest

The authors declare no conflicts of interest.

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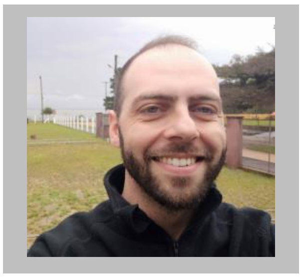
Biography of the main author



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