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# Evaluating the Environmental Quality of Forest Remnants Using Landscape Metrics

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**Abstract:** Forest remnants are hotspots of biodiversity and play an important role in providing services such as regulating the climate, reducing surface runoff, helping erosion control, protecting and contributing to the balance of ecosystems, and other functions. Despite this, natural vegetation is fragmented and limited to a few remnants, which are gradually suffering from anthropogenic pressures. Assessing the environmental quality of these remnants is therefore vital to understanding their current condition and to provide support for their conservation. This study aims to assess the environmental quality of forest remnants in six water basins in the municipality of Campinas/SP, Brazil. Forest remnants were mapped, and their environmental quality was assessed by applying an analytic hierarchy process (AHP), considering a set of structural landscape metrics previously selected from the literature. Of the 2319 forest remnants evaluated, 4.5% and 30%, respectively, registered high and low environmental quality. The Atibaia and Jaguari basins recorded the highest number of environmentally fragile remnants due to their small size and being predominantly elongated, and to the high erodibility of the soil. In the Anhumas, Capivari, Capivari-Mirim, and Quilombo basins, medium-sized forest remnants predominate. There is a greater distance between them, with a high intensity of land use/land cover in their surroundings, related to the prevalence of urbanized areas. Specific management actions should be taken in each of these basins.

**Keywords:** river basins; environmental quality; forest remnants; landscape metrics



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## 1. Introduction

Remnant forests, i.e., intact forest patches that have persisted through the landscape change process, play a key role in sustainable development, being strategic natural hotspots in anthropic landscapes [1]. In particular, remnant forests are hotspots for maintaining both the ecological functionality and biological conservation of human-dominated landscapes [2]. Such areas preserve many of the ecosystem services delivered by autochthonous landscapes, which disappeared after deforestation and conversion to other land cover types (such as cropland) [1]. Remnant forests provide various ecosystem-regulating services, e.g., water quality [3] and air quality regulation [4], soil retention [5], global and local climate regulation [6,7], provisioning, e.g., timber [8], food production [9] and cultural services [10]. When located in urban areas, forests support or enable multiple co-benefits for city residents and visitors through the ecosystem services they provide, as well as by supporting biodiversity.

These services include reducing potentially harmful exposure (by easing air and noise pollution, reducing urban heat islands, and mitigating the likelihood of floods) and expanding cultural services (spaces for relaxation and opportunities for social interaction and physical activity) [11,12], which in turn enhance wellbeing and health [13]. The above-mentioned benefits contribute to several Sustainable Development Goals (SDGs) (e.g., SDGs 3, 11, and 13) by supporting human wellbeing in terms of risk prevention and mitigation, the green economy, and intangible values.

However, deforestation associated with expanding urbanization, the conversion of forested areas to other land cover types (such as cropland), and the increasing fragmentation of the remaining forest relicts are leading to extraordinary losses in terms of biodiversity and ecosystem services [14,15].

According to Peters et al. [16], approximately one-third of the remaining tropical forests is in poor structural condition or faces human pressure as a result of timber exploitation, the expansion of the farming sector, and climate change. As an example, in the state of São Paulo/Brazil, the Atlantic rainforest decreased between 1854 and 2000 from 80% to 3% [17]. In the municipality of Campinas, in São Paulo State, degradation and fragmentation of forests result from the expansion of urban areas and agricultural activities, mainly for sugarcane cultivation and pastureland [18]. For these remnants to be functional and provide the benefits mentioned above, long-term planning and management are required.

Some authors point out that not only is the composition of the forest remnants important, but its spatial location is, too [19,20]; thus, the first step towards the proper management of remaining forest consists of surveying and mapping these areas. From there, their planning and management can be carried out at regional, municipal, and local (neighbourhood) levels to establish a multifunctional network of inter-connected areas of vegetation that influence the restructuring of the rural–urban landscape mosaic [21,22].

Moreover, since landscape metrics enable the analysis of the relationship between spatial patterns and ecological processes [23–27], the quantification of landscape structure using this method can provide scientific soundness and technical reliability scientific support for assessing the quantity and environmental quality of remnants [28]. As an example, fragment size and shape are used as proxies for high-quality habitats, as well as fragment core area presence, according to typical edge effect distances [29].

In fact, the landscape metrics work as an effective tool for the spatial analysis of landscapes, especially when associated with concepts of sustainable landscape planning, contributing not only to the characterization of the spatial features of a landscape but also to comprehending its ecological functions [30–35]. Furthermore, various authors [36,37] point out that using geoprocessing techniques associated with environmental management criteria helps to implement appropriate environmental planning, thereby enabling wider discussion about forest remnants and identifying priority areas for implementing the most appropriate management and recovery strategies.

This study aims to assess the environmental quality of forest remnants in the river basins of Campinas municipality/SP, Brazil, using a set of structural landscape metrics. To achieve this aim, for each remnant, total and nuclear, the edge index, distance from nearest neighbour, proximity to watercourses, water spring, land use/land cover in the surrounding area, and potential soil erodibility were determined. The environmental quality was assessed by applying an analytic hierarchy process (AHP) to enable the weighting for the relative importance of each criterion to be calculated. We also intended to ascertain whether the current conditions of land use and occupation in the river basins, as well as other factors associated with anthropogenic pressures or natural conditions, have an impact on the current state of these remnants. The final goal was to produce maps that show the environmental quality of each remnant, which can serve as an important tool and support for the management of natural vegetation endorsed by public authorities.

## 2. Material and Methods

### 2.1. Study Area

The municipality of Campinas/SP comprises six basins and is located in the inland of the state of São Paulo (Figure 1). With a total area of 794,571 km$^2$, the average annual temperature is 22 °C and the average precipitation is 1370 mm/year, mainly concentrated in the warmer months between November and March. Located in a transitional region between the Cerrado and the Atlantic Forest biomes, the remaining forest fragments of natural vegetation have phytophysiognomies of the following classes: seasonal semideciduous forest; mixed forest; paludosa forest; and seasonal semideciduous forest with small traces of Cerrado [38]. In the last century (1920–2020) the population of Campina increased by around 1,000,000 inhabitants, recording 1,139,000 inhabitants in 2022 [39]. According to Ribeiro et al. [40] between 1991–2011 the urban area expansion of Campinas was 49%, increasing from 140 km$^2$ in 1991 to 209 km$^2$ in 2011.

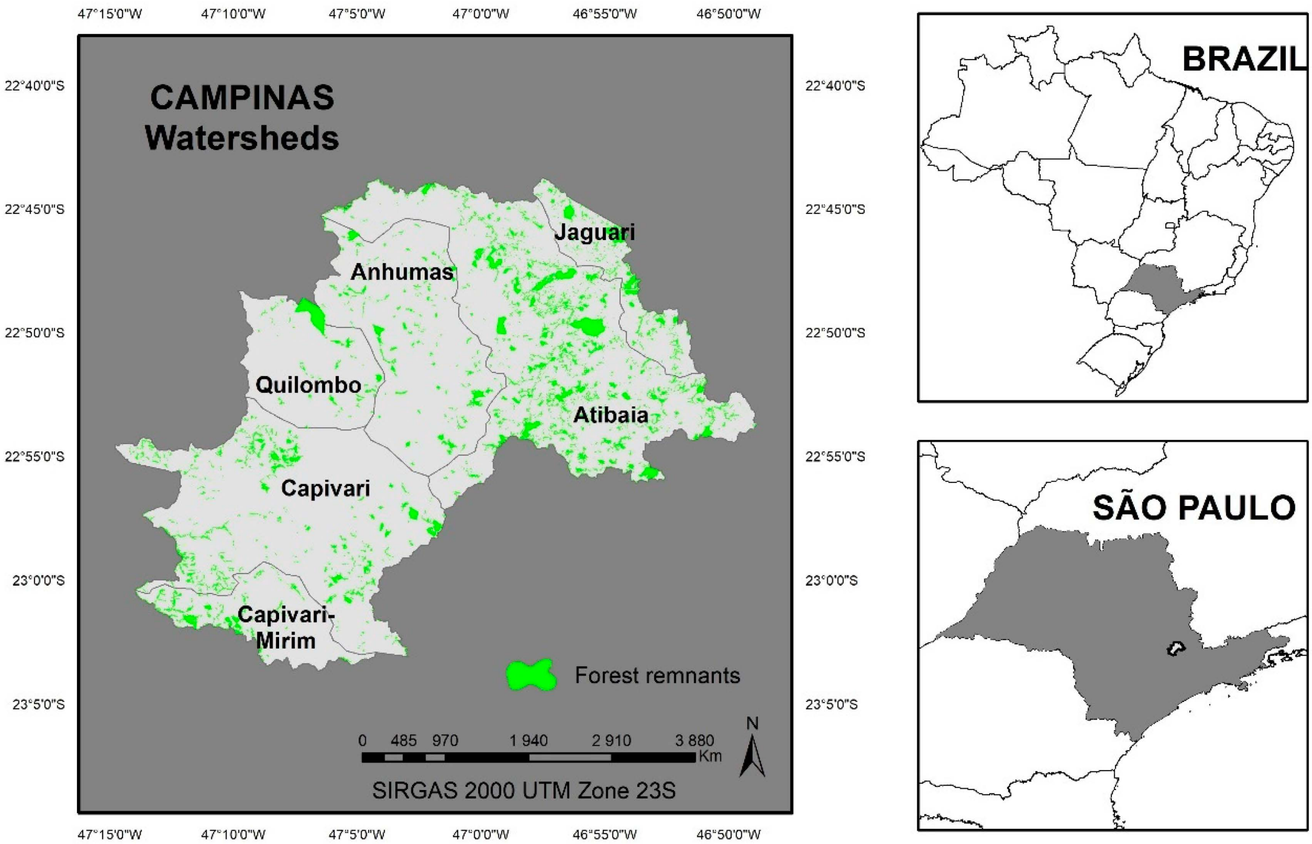


**Figure 1.** Location: municipality of Campinas and river basins.

A total of 2319 forest remnants were identified in Campinas municipality/SP [36,41]. Considering the five basins included in study area (Figure 1 and Table 1), with a total of 1368 (12.8% of its total area), the Atibaia river has the highest number of remnants and also the largest area. The Capivari and Anhumas basins have a very similar percentage of area occupied by remnants, respectively, 5.7% and 5.9%, while the Quilombo basin has the lowest area occupied by forest remnants (2.5%). The remnants of the Capivari-Mirim and Anhumas basins recorded the highest mean areas, 5.8 and 4.9 ha, respectively, whilst in the Atibaia and Jaguari basins, the mean areas of each remnant are 2.4 and 1.9 ha, respectively [41]. The Capivari and the Anhumas basins are the ones with the highest population density.

**Table 1.** Main characteristics of the basins under study.

| River Basins in the Municipality of Campinas/SP | Total Area (ha) | Population Density (inhab./km$^2$) | Altitude Range (m) | Nº of Remnants | Mean Area (ha) | Total Area Covered by Remnants (ha) % | |
|---|---|---|---|---|---|---|---|
| Anhumas | 14,508.0 | 2476.0 | 186.3 | 176 | 4.9 | 865.2 | 5.9 |
| Atibaia | 25,782.7 | 1546.0 | 508.7 | 1368 | 2.4 | 3298.2 | 12.8 |
| Capivari | 21,820.2 | 3776.8 | 209.0 | 323 | 3.8 | 1241.3 | 5.7 |
| Capivari-Mirim | 5544.5 | 1663.5 | 125.8 | 75 | 5.8 | 434.3 | 7.8 |
| Jaguari | 4554.0 | * | 422.6 | 324 | 1.9 | 610.3 | 13.4 |
| Quilombo | 7325.3 | 2271.0 | 149.6 | 53 | 3.4 | 179.6 | 2.5 |

* without population.

### 2.2. Selection of Landscape Metrics

The metrics presented in Table 2 were calculated for each remnant using the Patch Analyst extension to the ArcGIS 10.8 software [42]. They were selected from studies with a similar scope to the present study [17,43–50].

**Table 2.** Landscape metrics calculated for each remnant.

| Metric | Description |
|---|---|
| Fragment area (AREA) | Corresponds to the area of each remnant. It is widely accepted that the richness and the abundance of certain species directly depend on the size of the fragments, so larger fragments have greater diversity [44,49]. According to their size, the remnants can be classified as very small (<0.50 ha); small (0.50–1.00 ha); medium (1.00–5.00 ha); good (5.00–20.00 ha); adequate (>20.00 ha) [48]. |
| Nuclear area/core area (CA) and central area index (CAI) | The core or nuclear area relates to the central area of a forest remnant, taking no account of the marginal strip exposed to the edge effects, where the microclimate changes as a result of its contact with the landscape matrix [44]. According to the literature, the edge effect range can vary from 20 to 100 m [47,49]. In the present work, 60 m value was adopted based on [49].<br>The central area index (CAI) refers to the remaining area and the higher the value, the better the quality of the landscape; conversely, lower values indicate a greater edge effect [43,49]. |
| Circularity index (CI) | CI intends to evaluate the degree of similarity of a circumference to thar the shape of the remnant. According to the equation below, CI is a result of the relationship between the area (A, in m$^2$) and perimeter (L, in m) of forest fragments [45,51].<br>$\mathrm{CI} = \frac{2.\sqrt{\pi.\mathrm{A}}}{\mathrm{L}}$<br>Based on [52], the shape of the fragments is classified as elongated (CI < 0.65), moderately elongated ($0.65 \leq$ CI < 0.85), and rounded (CI $\geq$ 0.85). |
| Distance from the nearest neighbour (DNN) | Indicates the Euclidean distance (in meters) from a forest remnant to its nearest neighbour. This metric is associated to the connectivity of the landscape, i.e., the degree to which the landscape facilitates or impedes movement among resource patches. After a certain degree of isolation, the biological populations of the fragments begin to show losses in terms population dynamics and community structure [43,44]. |
| Proximity to the watercourse (PROXWC) | Euclidean distance estimated from a forest remnant to the nearest watercourse (in meters). |
| Water springs (WS): | WS refers to the springs identified in each remnant according to [38]. |
| Land use/land cover in the surroundings (LULCSUR): | Land use/land cover (LULC) was assessed for the areas in a radius of up to 175 m around each remnant. LULC refers to 2013 and was provided by [38]. The intensity of natural landscape modification around each fragment was classified according to [53]: (i) very low intensity, including natural or almost natural landscapes, such as the Brazilian Cerrado or forest; (ii) low intensity, covering natural vegetation with a small changes; (iii) moderate intensity, including transition areas, such as parks and planted pastures; (iv) high intensity, considerable modification of the natural landscape, such as deforested areas, dirt roads, orchards; and (v) very high intensity, completely modified areas, such as exposed soil, degraded areas, paved streets, buildings, and similar areas. |
| Soil Erodibility (EROD) | Evaluates the predominant soil typology in each forest remnant and the corresponding erodibility degree according to [54,55], where gley soils (very low); red-yellow latosols and yellow latosols (low); heterogeneous Cambisols (high); red-yellow argosols (very high). |

### 2.3. Environmental Quality Index ($EQI_{\_REM}$)

The analytic hierarchy process (AHP), a multicriteria decision analysis (MCDA) method, has been widely used for conservation evaluation and environmental management as well as for forest management planning [56–58]. Developed by Saaty [59], AHP can be defined as an estimation and decision-making method applied when the decision hierarchy can be defined; it incorporates the components' hierarchy for facilitating decision making. Therefore, the AHP method allows a determination of the best decision among various key preferences and the likelihood of parameters considered. In this study, AHP-based pairwise comparison matrices were constructed between distinct thematic layers at each level of the hierarchy. A standard Saaty nine-point scale was applied for assessing the relative importance of each criterion and its respective features, in which "1" implies "equal importance" between the two criteria, and "9" represents the "extreme importance" of one criterion compared to another [59]. In AHP, complex decisions are reduced to a matrix comprising a series of pairwise comparisons, which then generates the results. The weights of each layer were decided using the principal eigenvector of the square matrix of each criterion (Table 3). The normalized relative weight was calculated by dividing each element of the pairwise matrix by the sum of its column (Table 4). The higher the weights, the greater the influence of the criteria on the environmental quality of the forest remnants.

**Table 3.** AHP values of paired comparison between the selected indicators.

| | **AREA** | **CAI** | **CI** | **DNN** | **PROXWC** | **WS** | **LULCSUR** | **EROD** |
|---|---|---|---|---|---|---|---|---|
| AREA | 1.000 | 0.250 | 1.000 | 0.500 | 2.000 | 0.333 | 1.000 | 1.000 |
| CAI | 4.000 | 1.000 | 3.000 | 2.000 | 4.000 | 0.500 | 3.000 | 2.000 |
| IC | 1.000 | 0.333 | 1.000 | 1.000 | 3.000 | 0.333 | 3.000 | 0.333 |
| DNN | 2.000 | 0.500 | 1.000 | 1.000 | 3.000 | 0.333 | 2.000 | 0.500 |
| PROXWC | 0.500 | 0.250 | 0.333 | 0.333 | 1.000 | 0.333 | 0.333 | 1.000 |
| WS | 3.000 | 2.000 | 3.000 | 3.000 | 3.000 | 1.000 | 2.000 | 1.000 |
| LULCSUR | 1.000 | 0.333 | 0.333 | 0.500 | 3.000 | 0.500 | 1.000 | 1.000 |
| EROD | 1.000 | 0.500 | 3.000 | 2.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| Total | 13.500 | 5.166 | 12.666 | 10.333 | 20.000 | 4.333 | 13.333 | 7.833 |

Fragment area (AREA); central area index (CAI); circularity index (CI), distance from the nearest neighbour (DNN); proximity to the watercourse (PROXWC); water springs (WS); land use/land cover in the surroundings (LULCSUR); Soil Erodibility (EROD).

**Table 4.** Weighted values from the paired comparison between the indicators.

| | **AREA** | **CAI** | **CI** | **DNN** | **PROXWC** | **WS** | **LULCSUR** | **EROD** | **Eigen Vector** |
|---|---|---|---|---|---|---|---|---|---|
| AREA | 0.074 | 0.048 | 0.079 | 0.048 | 0.100 | 0.077 | 0.075 | 0.128 | 0.079 |
| CAI | 0.296 | 0.194 | 0.237 | 0.194 | 0.200 | 0.115 | 0.225 | 0.255 | 0.215 |
| IC | 0.074 | 0.064 | 0.079 | 0.097 | 0.150 | 0.077 | 0.225 | 0.043 | 0.101 |
| DNN | 0.148 | 0.097 | 0.079 | 0.097 | 0.150 | 0.077 | 0.150 | 0.064 | 0.108 |
| PROXWC | 0.037 | 0.048 | 0.026 | 0.032 | 0.050 | 0.077 | 0.025 | 0.128 | 0.053 |
| WS | 0.222 | 0.387 | 0.237 | 0.290 | 0.150 | 0.231 | 0.150 | 0.128 | 0.224 |
| LULCSUR | 0.074 | 0.064 | 0.026 | 0.048 | 0.150 | 0.115 | 0.075 | 0.128 | 0.085 |
| EROD | 0.074 | 0.097 | 0.237 | 0.194 | 0.050 | 0.231 | 0.075 | 0.128 | 0.136 |
| Total | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |

Fragment area (AREA); central area index (CAI); circularity index (CI), distance from the nearest neighbour (DNN); proximity to the watercourse (PROXWC); water springs (WS); land use/land cover in the surroundings (LULCSUR); Soil Erodibility (EROD).

Moreover, AHP includes an effective method for weighing the consistency of the decision-maker's evaluations, which helps to decrease bias in the decision-making procedure. An assessment of the consistency index ($CI$) is the first step, and an estimation of the $Cr$ is the second step. Equations (1) and (2) were used to calculate the degree of consistency for this study:

$$\text{Consistency Index } (CI) = \frac{\gamma_{max} - n}{n - 1} = \frac{8.792 - 8}{8 - 1} = CI = 0.113 \quad (1)$$

where $\lambda max$ is the maximum eigenvalue; $n$ = number of criteria.

$$\text{Consistency ratio } (Cr) = \frac{CI}{RI} = \frac{0.113}{1.41} = 0.080 = CR = 8.0\% < 10\% \tag{2}$$

where $RI$ = random inconsistency, according to the values of the Table 5.

**Table 5.** Average random consistency index (*RI*).

| ***n*** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
|---|---|---|---|---|---|---|---|---|---|
| *RI* | 0 | 0 | 0.53 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

As the study applied a total of 8 variables, the value of the random consistency index (*RI*) was 1.41, set by Saaty [59] (Table 5). Based on this value and the result of the consistency index (*CI*) (Equation (1)), the consistency rate (*CR*) was calculated. The value obtained was 8.0% (Equation (2)), which is lower than the 10% limit, reflecting a consistent analysis.

Thus, the Environmental Quality Index (*EQI*) could be calculated from the following equation (Equation (3)):

$$\begin{aligned} EQI_{rem} = 0.079\,AREA + 0.215\,CAI + 0.101\,IC + 0.108\,DNN + 0.053\,PROXWC + 0.224\,WS \\ +0.085\,LULCSUR + 0.136\,EROD \end{aligned} \tag{3}$$

According to the results obtained, the metrics with the greatest weight were, respectively: WS (water springs), central area index (*CAI*), soil erodibility (*EROD*), distance from the nearest neighbour (*DNN*), circularity index (*CI*), land use/land cover in the surroundings (*LULCSUR*), fragment area (*AREA*), and proximity to the watercourse (*PROXWC*).

## 3. Results and discussion

### *3.1. Fragment Area (AREA)*

An assessment of the size of the remnants using the AREA metric shows that in the Anhumas, Capivari, Capivari-Mirim, and Quilombo basins, there is a predominance of forest remnants with an area between 1.0 ha and 5.0 ha, classified as medium size, while in the Atibaia and Jaguari basins, the forest remnants, although greater in number, are very small, predominantly less than 0.5 ha (Figure 2). The predominance of many small remnants may show that large remnants have been divided into a greater number of fragments, but smaller ones, as observed by [44].

This condition is particularly evident in the Jaguari basin, where there were 342 forest fragments, 67% of which were less than 0.5 ha in size, occupying around 6% of the total forest area, while 2% of the remnants, which are over 20 ha in size, account for around 50% of the total forest in this basin. The same situation can be observed in the Atibaia basin. These results were reported by [43], in which fragments in the small size class tended to have a greater number of patches but less representation in terms of total forest area.

This inverse relationship has also been shown by other authors in other locations and on other scales of study. A study of Atlantic Forest remnants in the state of Rio de Janeiro found that approximately 85% of the fragments had an area of less than 100 ha; however, in terms of area, they corresponded to only 20% of the remaining vegetation area. On the other hand, more than 67% of the remaining forest area was distributed in the few remnants of more than 1000 ha [60]. According to [45], an intense process of fragmentation is seen in the presence of a large number of forest remnants or fragments in the landscape; in contrast, it is deduced that an ideal natural landscape would be one where its entire area is occupied by natural vegetation in just one forest massif. The small size of the forest remnants observed in the basins of the municipality of Campinas makes them even more vulnerable to the edge effect, thus intensifying habitat changes and increasingly de-characterizing the natural forest environment [25,61].

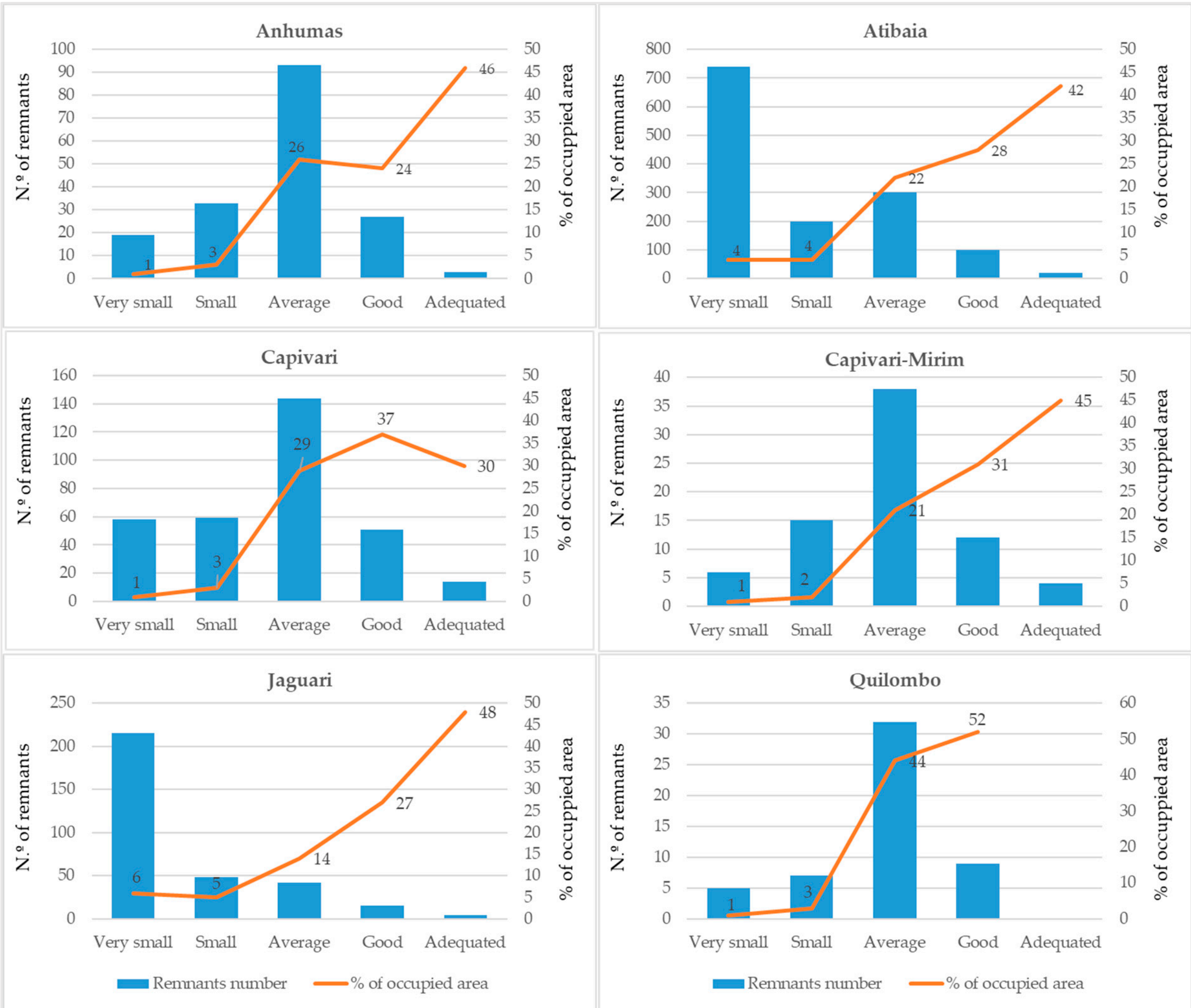


**Figure 2.** Number of forest remnants by size class and the percentage of area they occupy.

### *3.2. Nuclear Area/Central Area (CA) and Central Area Index (CAI)*

The evaluation of the CA and CAI metrics indicated the very low percentage of central area was to the detriment of the high percentage of edge area in the forest remnants of the river basin analysed (Figure 3 and Table 6). In the Quilombo and Capivari basins, the CAI is around 10%, whilst the highest CAI was recorded in the Anhumas basin with 33.4% of the total area. Even so, this figure is particularly low, because in addition to the low percentage of forest vegetation remaining in the basin, more than 60% of this area is classified as border area. If we consider the number of forest remnants that have a central area greater than zero, the highest values occur in the Anhumas and Quilombo basins, with 27 and 28%, respectively, while in the Jaguari and Atibaia basins, only 6 and 9%, respectively, of the forest fragments have remnants with a core area. The remaining remnants are made up exclusively of edge areas. Several authors consider that this condition is associated with the predominant presence of very small remnants and their irregular and elongated shape [40,43,45,62]. De Paula et al. [62], when studying the extent of edge effects in tropical fragmented landscapes, stated that forest fragments suffer from edge effects, which cause changes in ecological and ecosystem processes, undermining habitat quality and the provision of ecosystem services. The green plan for the municipality of Campinas emphasised that the reduction in vegetation cover has led to an increase in forest fragmentation and the edge effect, which can reduce the environmental quality of these areas [44]. Habitat fragmentation and degradation lead to the isolation of communities and are the main threats to species with restricted or endemic distribution, which can also result in their disappearance [38,63].

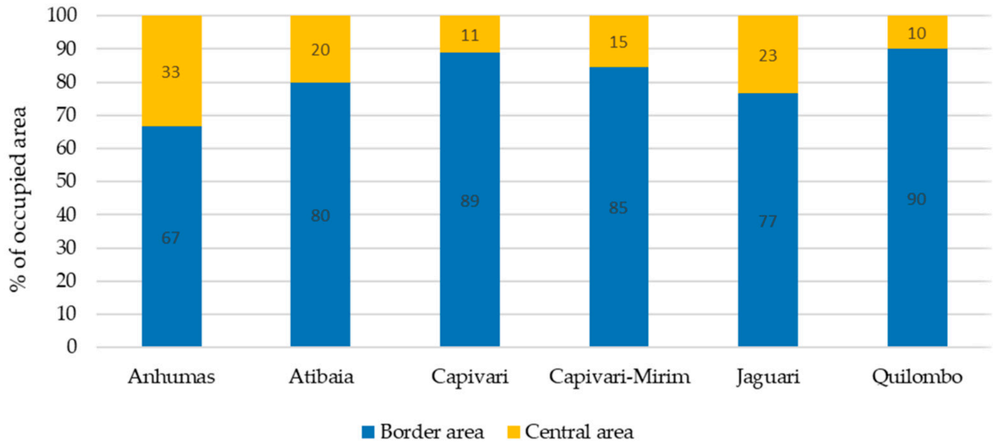


**Figure 3.** Central area versus edge area.

**Table 6.** Central area (CA) and central area index (CAI) of the remnant forests in the watersheds.

| | River Basins in the Municipality of Campinas/SP | | | | | |
|---|---|---|---|---|---|---|
| | **Anhumas** | **Atibaia** | **Capivari** | **Capivari-Mirim** | **Jaguari** | **Quilombo** |
| N. remnants | 176 | 1368 | 323 | 75 | 324 | 53 |
| NDCA | 47 | 126 | 66 | 19 | 20 | 15 |
| Total area (ha) | 862.2 | 3298.2 | 1241.3 | 434.3 | 610.3 | 179.6 |
| Central area (CA) (ha) | 287.6 | 664.9 | 137.2 | 66.9 | 142.2 | 17.6 |
| CAI (%) | 33.4 | 20.2 | 11.1 | 15.4 | 23.3 | 9.8 |

NDCA = number of disjoint central areas; CAI: central area index.

In fact, forest edges are typically hotter, drier, brighter, and windier than interior forest, which can cause higher tree recruitment and mortality, leading to rapid community turnover [64]. Thus, long-term compositional shifts can occur, resulting in taxonomically and functionally distinct tree communities at forest edges [65] and reduced species richness [66], but this does not always happen [62,67,68]. For example, Melito et al. [68] state that the edge effect magnitude is highly variable and can be mediated by structural contrast with the adjacent matrix (i.e., land cover) type.

### *3.3. Circularity Index (CI)*

According to the circularity index (CI), in all the river basins, the forest remnants are predominantly elongated (CI < 0.65), followed by moderately elongated remnants (CI between 0.65 and 0.85), and only a small portion of remnants are classified as rounded, which would be the most ideal shape (Table 7). The highest percentage of remnants with CI > 0.85 was recorded in the Quilombo basin, with 21% of the total.

Recognising that one of the most significant impacts of forest fragmentation is the edge effect, the analysis of indices related to the shape of remnants and CI are essential. In fact, several authors state that forest fragmentation and edge effects related to deforestation have been recognized as among the most prevalent and harmful processes occurring in the tropics [69–71], as they produce changes in ecosystem and ecological processes and undermine habitat quality and the provision of ecosystem services [42].

**Table 7.** CI of forest remnants in river basins.

| Circularity Index (CI) | Shape | River Basins in the Municipality of Campinas/SP | | | | | |
|---|---|---|---|---|---|---|---|
| | | Anhumas | Atibaia | Capivari | Capivari-Mirim | Jaguari | Quilombo |
| <0.65 | Elongated | 53.9% | 69.3% | 59.1% | 62.7% | 75.9% | 41.5% |
| 0.65–0.85 | Moderately elongated | 35.2% | 15.5% | 32.8% | 29.3% | 18.2% | 37.7% |
| >0.85 | Rounded | 10.9% | 15.2% | 8.1% | 8.0% | 5.9% | 20.8% |
| Total | | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| Minimum | | 0.21 | 0.14 | 0.17 | 0.14 | 0.15 | 0.26 |
| Maximum | | 0.96 | 0.96 | 0.94 | 0.92 | 0.97 | 0.96 |
| Average | | 0.63 | 0.54 | 0.59 | 0.59 | 0.53 | 0.67 |
| Standard deviation | | 0.17 | 0.18 | 0.21 | 0.18 | 0.18 | 0.17 |

### 3.4. Distance from the Nearest Neighbour (DNN)

Analysis of the DNN metric revealed different behaviours in relation to the distance from the nearest neighbour of the forest remnants in the river basins analysed. In general, the lowest average distances from other remnants are found in the Atibaia and Jaguari basins (Table 8). In these basins, more than 70% of the remnants are less than 60 m from their nearest neighbour. This could be a positive factor if it indicates the possibility of better gene flow for both fauna and seeds [42].

**Table 8.** DNN among forest remnants in river basins.

| DNN (m) | River Basins in the Municipality of Campinas/SP | | | | | |
|---|---|---|---|---|---|---|
| | Anhumas | Atibaia | Capivari | Capivari-Mirim | Jaguari | Quilombo |
| <60.0 | 52.8% | 80.7% | 52.3% | 58.7% | 75.3% | 32.0% |
| 60.0–120.0 | 14.2% | 11.7% | 19.5% | 14.7% | 14.8% | 18.9% |
| 120.0–200.0 | 10.2% | 4.7% | 11.5% | 9.3% | 6.2% | 17.0% |
| >200.0 | 22.6% | 2.9% | 16.7% | 17.3% | 3.7% | 32.1% |
| Total | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| Minimum | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 | 3.3 |
| Maximum | 1182.5 | 985.4 | 1294.8 | 940.0 | 335.4 | 1767.6 |
| Average | 146.7 | 42.0 | 116.7 | 115.9 | 45.8 | 255.7 |
| Standard deviation | 211.1 | 75.8 | 172.0 | 176.6 | 59.9 | 366.7 |

DNN: distance from nearest neighbour.

Conversely, the highest DNN averages were recorded in the Quilombo, Anhumas and Capivari basins. These are the basins with the highest degree of urbanisation in Campinas, as the dominant LULC: 49%, 55% and 47%, respectively. It is included in the high intensity class where buildings, paved streets, exposed soil, and degraded areas are dominant. Land use and land cover change greatly influence the landscape fragmentation [72,73], leading to a loss of connectivity between natural habitats.

However, it is important to consider that at the fragment level, the degree of isolation of the remnants may not accurately reflect the structural and functional connectivity of a given landscape, since factors such as the permeability of the matrix can be important [74,75].

In this context, indices that only assess structural connectivity may not be regarded as ecologically realistic and should therefore be analysed while keeping other indicators in mind as well, in order to verify not only structural but also functional connectivity between the remnants [47,75,76]. Jesus et al. [36], when analysing the structure of forest fragments of the river basin Poxim-se, Brazil, found a large prevalence of small fragments close together. They note that 85% of the remnants assessed had an area of less than 45 ha, and these were the ones that were closest together. This proximity results from the process of fragmentation of larger patches into fragments that are smaller, but which are close to each other as they originate from the same remnant [44]. This is one of the consequences of fragmentation, especially notable in the process of urbanisation, which is beginning to considerably transform the natural landscape through changes in land use/land cover, increasing anthropogenic action in the environment and putting pressure on natural resources, in this case on forest remnants [77].

Therefore, considering these connectivity conditions and the land use/land cover, there is great potential for establishing ecological corridors, especially in basins such as Atibaia and Jaguari and specific regions of other basins. Establishing ecological corridors is a strategy aimed at reducing the effects of forest fragmentation by connecting forest remnants. It is one of the priorities defined in the Forest Code (Law No. 12.651/2012) [78], which establishes general rules on the protection of native vegetation in Brazil. This would enable a permeable matrix to be built into the landscape that guarantees the movement and dispersal of species of fauna and flora [46,79].

Pereira and Cestaro [79] emphasise that ecological corridors require multidisciplinary perception that integrates physical–natural, biological, and socioeconomic elements and relevant legislation. For this reason, they must start at macro scales and reach scales of detail that allow the possibility of effective connection between forest remnants to be assessed. Crouzeilles et al. [60] comment on the importance of intermediate remnants that enable the flow of fauna and flora as well as the dispersal capacity of species.

In the case of Campinas/SP, the municipality's Green Plan and Master Plan (*Plano diretor municipal*) [80] recognise the current loss of biodiversity of fauna and flora resulting from the fragmentation of natural habitats and propose some guidelines to prevent, among other problems, the uncontrolled deforestation and unplanned urban expansion from causing even more loss to local natural ecosystems. One of these proposals is to promote the rebalancing of the ecosystem through the conservation and recovery of forest remnants and the creation of ecological corridors between them. The marginal areas of the Atibaia River are priority areas indicated for the implementation of these ecological corridors [38,80].

### *3.5. Proximity to the Watercourse (PROXWC)*

The average distance between forest remnants and the nearest watercourse varied from river basin to river basin. The Quilombo basin is where the remnants are furthest from the watercourses, with 22.6% of them more than 200 m away. The lowest average was found in the Capivari basin; however, it was in the Jaguari basin that the lowest maximum PROXWC value was found (Table 9). Remnant forest and other green infrastructure ensure the protection of water sources by preventing erosion and siltation in water bodies, reducing soil compaction due to the effect of rain, increasing rainwater infiltration, and consequent groundwater recharge [8,77,80]. Moreover, proximity to water bodies can supply water resources for the local biota and their ecosystem relationships and it also ensures the protection of water resources in terms of quantity and quality.

**Table 9.** Proximity to the watercourse (PROXWC).

| PROXWC (m) | River Basins in the Municipality of Campinas/SP | | | | | |
|---|---|---|---|---|---|---|
| | **Anhumas** | **Atibaia** | **Capivari** | **Capivari-Mirim** | **Jaguari** | **Quilombo** |
| <60.0 | 81.2% | 87.9% | 93.2% | 81.3% | 88.6% | 67.9% |
| 60.0–120.0 | 5.7% | 6.6% | 3.7% | 6.7% | 7.4% | 5.7% |
| 120.0–200.0 | 2.3% | 3.7% | 2.2% | 8.0% | 3.4% | 3.8% |
| >200.0 | 10.8% | 1.8% | 0.9% | 4.0% | 0.6% | 22.6% |
| Total | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| Minimum | 0.0 | 0.0 | 0.00 | 0.0 | 0.0 | 0.0 |
| Maximum | 833.2 | 354.5 | 316.5 | 499.2 | 274.4 | 795.7 |
| Average | 56.4 | 21.8 | 12.1 | 34.6 | 20.4 | 128.1 |
| Standard deviation | 134.5 | 47.5 | 37.8 | 83.6 | 40.8 | 218.7 |

Several authors [81–83] consider that the impact of forest cover on streams is such that it is expected that fragments of sufficient size within a heavily anthropized basin could alter physical and water quality conditions. Ref. [83] argues that if the fragment is large enough, a "forest reset effect", i.e., a reset effect on a range of water chemistry and in-stream physical conditions, can occur.

It is important to emphasise that the protection of water resources through the presence of vegetation in their surroundings is already provided for in the Forest Code (Law No. 12.651/2012) [78] under the concept of Permanent Preservation Area (APP), considering their relevant environmental functions, i.e., facilitating gene flow and contributing to the preservation of water resources. In view of this, the municipality of Campinas, through its Master Plan, has already highlighted the problem of the lack of riparian forests and the need for investment in the recovery and conservation of APPs around water bodies [84].

The Atibaia, Jaguari and Capivari river basins have high water potential; the Atibaia basin, for example, is the municipality's main water supply source, accounting for 93.5% of the water supply in Campinas [84]. In this basin, the Campinas Master Plan provides for an increase in the flow of water captured in order to improve the municipality's water security. In addition to increasing the flow captured, the proposals include building a reservoir to store water from the Atibaia River when it is in flood, thereby guaranteeing a reserve in periods of drought [79].

### *3.6. Water Springs (WS)*

Regarding water springs, assessed by their presence (or absence) within the forest remnants, it was found that most of the forest remnants in all the river basins do not have springs in them (Figure 4). This is not because of the possible low number of springs in the municipality; on the contrary, despite the high density of watercourses and springs in Campinas' catchment areas, many of the municipality's springs are unprotected.

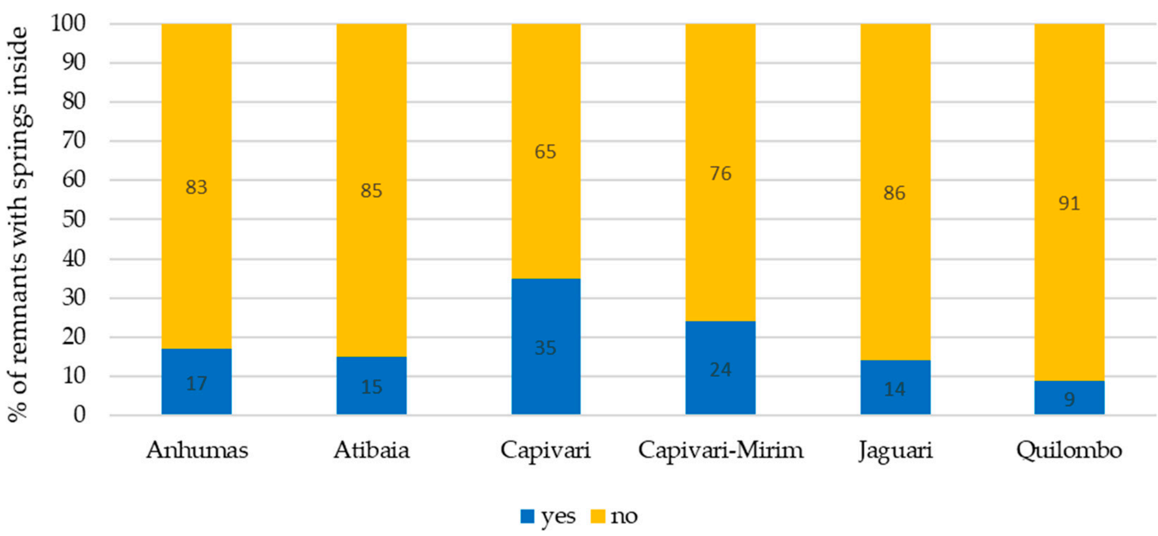


**Figure 4.** Percentage of water-producing forest remnants in the Campinas/SP water basins.

The high potential of the Atibaia and Jaguari basins for water production makes them more sensitive to the process of urbanisation, densification and poor land management, which can affect water availability and cause losses in the quantity and quality of water [85]. On the other hand, the study carried out by Siqueira et al. [86] in Southern Brazil showed that the areas characterized by agricultural and urban activities negatively affect the quality, while the presence of riparian forests within a radius of 50 m improve water quality. Garcia et al. [87] also showed that springs located within an area of environmental preservation and with minimal anthropogenic intervention (e.g., Mata de Santa Genebra, a forest remnant located in the Anhumas river basin) had higher water quality than springs located in areas of strong anthropogenic intervention or without riparian forest in their surroundings.

### 3.7. Land Use/Land Cover in the Surroundings (LULCSUR)

With regard to land use/land cover around the remnants, it was found that in all the river basins except for the Jaguari basin, most of the forest remnants are in contact with areas classified as prone to very-high-intensity LULC change (Table 10), i.e., areas characterized by the presence of exposed soil, degraded areas, paved roads, and buildings [53].

**Table 10.** Intensity of land use/land cover in the surroundings (LULCSUR) of the remnants.

| Intensity of LULC | River Basins in the Municipality of Campinas/SP | | | | | |
|---|---|---|---|---|---|---|
| | Anhumas | Atibaia | Capivari | Capivari-Mirim | Jaguari | Quilombo |
| Very low | - | 0.1% | - | - | - | - |
| Low | 1.2% | 1.5% | | - | 0.6% | - |
| Moderate | 4.5% | 30.6% | 21.3% | 8.0% | 81.5% | 1.9% |
| High | 3.4% | 6.1% | 2.2% | 10.7% | 1.5% | 7.5% |
| Very high | 90.9% | 61.7% | 76.5% | 81.3% | 16.4% | 90.6% |
| Total | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |

The assessment of land use and land cover in the surroundings of these remnants, together with their size and shape, is a very significant factor for the intensity of the edge effect, since different LULC in these surroundings can cause edge effects to manifest in different ways and to different extents [88]. As an example, the Jaguari river basin is the one with the highest percentage of areas classified as moderate LULC, in which rural activities such as grazing and cultivation predominate. It is also the one in which the majority of forest remnants are surrounded by areas classified as transition areas such as parks and planted pastures. This implies an edge effect with distinct characteristics in these remnants, when compared, for example, to the remnants in the Anhumas and Quilombo basins, where the edges of the remnants are in contact with areas highly disturbed by human activities. In these urban areas, the promotion of green infrastructure is clearly not enough to guarantee the conservation of fragile areas of great environmental value, as already highlighted by [13,20]. In these cases of strong urban consolidation, specific planning approaches are needed that include proposals both to promote green infrastructure and to mitigate the impacts of urban growth on these areas [89].

### 3.8. Soil Erodibility (EROD)

The highest degrees of soil erosion susceptibility were identified in the remnants of Atibaia (85.5%) and Jaguari basins (99.4%) (Table 11). These basins are also the ones with the highest percentage of forest remnants and whose predominant characteristic is high water potential.

**Table 11.** Soil erodibility of forest remnants.

| Level of Erodibility | River Basins in the Municipality of Campinas/SP | | | | | |
|---|---|---|---|---|---|---|
| | Anhumas | Atibaia | Capivari | Capivari-Mirim | Jaguari | Quilombo |
| Very low | 55.7% | 14.5% | 33.8% | 44.0% | 0.6% | 96.2% |
| Poor | 0.6% | - | - | 6.7% | - | - |
| High | 2.3% | - | - | 9.3% | - | 3.8% |
| Very high | 41.5% | 85.5% | 66.2% | 40.0% | 99.4% | - |
| Total | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |

Soil susceptibility to erosion is associated with various factors such as climatic conditions, relief characteristics, and historical practices of different social agents, all of which have altered landscapes and the capacity of vegetation as a soil protection agent [90,91]. Considering this last point, the environmental relevance of forest remnants for soil conservation stands out even more, especially in areas where the degree of erodibility is very high, as it is in the Jaguari, Atibaia, Anhumas and part of the Capivari basins.

Moreover, this is an important factor in prioritising expanses for forest recovery and the restoration of riparian areas, especially in mosaics of fragmented tropical forest landscapes dispersed in an agricultural matrix, as highlighted by Chará et al. [92]. Thus, the implementation of appropriate conservation practices will be effective not only for the soil but also for water, by reducing the velocity of surface runoff, increasing infiltration, and therefore preventing soil erosion [92].

### *3.9. The Environmental Quality of Forest Remnants*

The environmental quality of the remnants is shown in Table 12 and Figure 5.

**Table 12.** Environmental Quality Index of forest remnants ($EQI_{rem}$) in the catchment areas of Campinas/SP.

| Environmental Quality | Number of Forest Remnants (%) | | | | | |
|---|---|---|---|---|---|---|
| | Anhumas | Atibaia | Capivari | Capivari-Mirim | Jaguari | Quilombo |
| Very low | - | - | - | - | - | - |
| Low | 28 (15.9%) | 408 (29.8%) | 49 (15.2%) | 10 (13.3%) | 84 (25.9%) | - |
| Medium | 131 (74.4%) | 913 (66.7%) | 252 (78.0%) | 57 (76.0%) | 232 (71.6%) | 51 (96.2%) |
| High | 16 (9.1%) | 46 (3.4%) | 22 (6.8%) | 8 (10.7%) | 8 (2.5%) | 2 (3.8%) |
| Very high | 1 (0.6%) | 1 (0.1%) | - | - | - | - |
| Total | 176 (100%) | 1368 (100%) | 323 (100%) | 75 (100%) | 324 (100%) | 53 (100%) |

According to the results, none of the river basins had forest remnants classified as being of very low environmental quality. In all the basins, most of the remnants were classified as medium quality. In general, the results were average and reflect the fact that despite the pressures and vulnerabilities to which they are subject, most forest remnants are not in such a degraded state that management and recovery actions are impossible. In the Atibaia and Juguari basins, around one third of the forest remnants have a percentage of low quality (29.8% and 25.9%, respectively), whilst in the Anhumas and Capaivari-Mirim basin, around 10% are classified as having high environmental quality.

It is important to note that only two remnants were classified as being of very high environmental quality. These are the A.R.I.E. Mata de Santa Genebra, located in the Anhumas basin, and a fragment of FES at *Fazenda Santa Mariana*—Furnas, in the Atiabaia basin. The Santa Genebra Forest is the largest forest fragment in Campinas and is a Conservation Unit (UC) of the "Area of Relevant Ecological Interest" category, legally established in 1985 by Federal Decree No 91.885 of 5 November 1985. The Santa de Genebra Forest has limited access, only permitted through the main gate, and is under the management of the José Pedro de Oliveira Foundation, which is responsible for its conservation. As it is a Conservation Unit, Mata de Santa Genebra also has a management plan, published in August 2010. The forest is home to approximately 660 species of flora, some of which are at risk of extinction in the country, such as *Euterpe edulis* (juçara palm) and *Ocotea odorifera* (canela-sassafrás) [93]. In the management plan for Mata de Santa Genebra, in addition to presenting the diagnosis of the surroundings and the A.R.I.E., an entire chapter is devoted to planning the forest. In other words, the specific management objectives for the area are listed and the bases for various programmes are established, such as protection programmes, research and monitoring, visitation, recovery, among others [80].

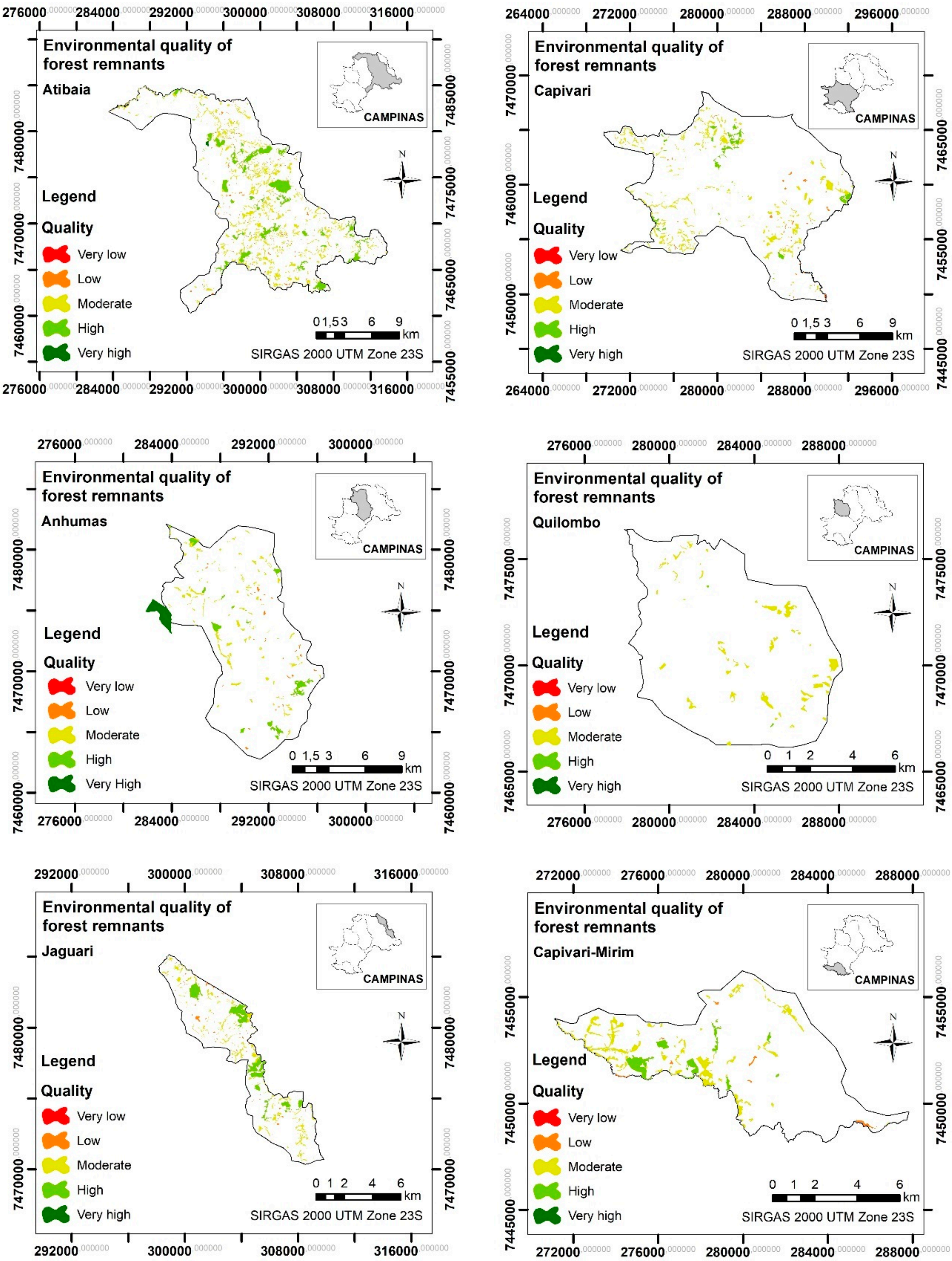


**Figure 5.** Environmental quality of forest remnants in the Campinas/SP catchment area.

## 4. Conclusions

Forests supply crucial ecosystem services vital to sustainable development and human wellbeing and play a chief role in achieving the several Sustainable Development Goals

(SDGs) of the United Nations 2030 Agenda. Remnant forests are natural areas of exceptional ecological value, particularly when located in intensively exploited landscapes, such as the area under study. In this study, a total of 2319 forest remnants were characterized using a set of structural landscape metrics, and their environmental quality was assessed by applying an analytical hierarchy process. Among the indicators analysed, the presence of water springs and the circularity index were the factors that most determined environmental quality. The results show that only a hundred of the remaining areas have high or very high environmental quality. The vast majority have a medium or low environmental quality, which is related to their small size, their elongated shape, and their proximity to highly anthropized areas that exert strong pressure on the remnants.

Evaluating the environmental quality of forest remnants at the hydrographic basin and municipal scale, especially based on spatial analyses, seems to be an effective tool for municipal authorities as it provides useful guidelines to inform urban planning and municipal environmental management. The use of landscape metrics proved to be effective to assess the environmental quality of remnants, and this approach can therefore be recommended as an instrument for the primary evaluation of natural vegetation remnants in different geospatial areas and phytophysiognomic environments.

Although using an Environmental Quality Index proved to be effective for this study, it might be necessary to adjust the selected indicators and the coefficients associated with each indicator considered if it is applied to other regions whose characteristics are significantly different, such as other biomes. The AHP offers a fitting solution for modelling complex problems with its hierarchical structure; however, because of its subjective nature, in future research, the AHP should be combined with some objective methods (such as the entropy weight method) to comprehensively consider the decision of coefficient.

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