Brazilian forest code: an intriguing framework for designing worldwide protected areas

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Abstract. The Brazilian Forest Code of 1965 was conceived and written by visionaries. Even without sophisticated mapping technology, its authors managed to create a masterpiece of environmental protection based on solid landscape ecology grounds. Theoretically the law was envisaged to provide protection for biological diversity, watersheds and other environmental resources by prohibiting human activities within key strategic areas. Nevertheless, little was known about the significance of this bill along half century of its existence. In fact, delineation and subsequent enforcement of these spatially complex zones was hampered by the inability to determine their physical bounds. We then developed a methodology that provided a foundation for conducting automated delineation of these boundaries by incorporating a variety of GIS tools and remote sensing data. Using the Shuttle Radar Topography Mission dataset, this methodology enabled us to create the first maps and visual depictions of Permanent Preservation Areas for different Brazilian scenarios, and henceforth to better understand the magnitude of the natural reserves in preserving vital environmental resources. The results of this study confirm that the Brazilian Forest Code of 1965 creates an intriguing mosaic of environmental protection areas strategically distributed over different strata of the watershed topography. We were also able to recognize, in regard to landscape ecology, how deeply integrated the concept of the watershed as the primary planning unit truly is. This framework has an outstanding appeal for the establishment of integrated natural preserves on a continental basis.

Keywords. natural preserves, environmental legislation, hydrographically conditioned digital elevation models, wildlife corridors.

1. Introduction

Being internationally recognized as a country having one of the most advanced environmental legislations, Brazil still has a long way ahead to fully enforce it [1]. The country has a wide-ranging system of protected areas, which form part of the National Protected Areas System (SNUC). The Brazilian Forest Code (BFC) of 1965, law no 4.771, defined two categories of protected forests: 1) legal reserves (LR), which require that every rural property keeps at least 20% of the land to be covered with the natural vegetation (being it 35% for the savannas of the Legal Amazon, and 80% everywhere else in the Legal Amazon region) as depicted on Figure 1, and 2) permanent preservation areas (PPA), whose definitions were based on key geographic watershed features such as divides and riparian areas. While the forests that make up a legal reserve may be managed – but never clear-cut – for timber production, all direct economic uses of the forested area are precluded on permanent preservation areas. Violations to this law are defined as crimes against the environment subject to both imprisonment and fine [2].

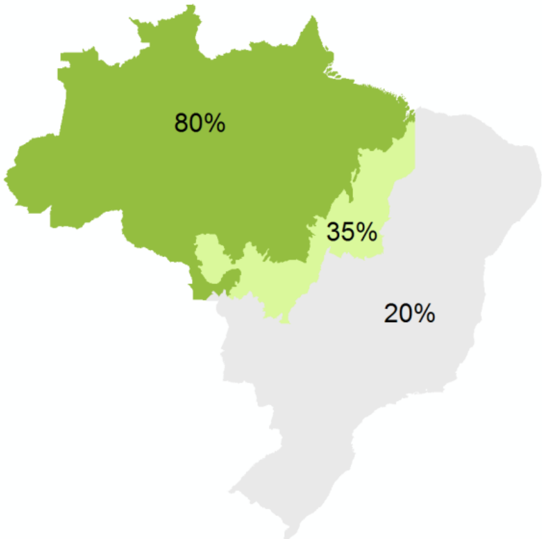

Figure 1. Percentages of native vegetation to be kept within rural properties for different regions of Brazil.

The technical challenges posed to the fulfillment of its constitutional duty to effectively enforce environmental compliance on permanent preservation areas along with the increasing international pressure for stopping deforestation in the Amazon rainforest led the Brazilian government to create the National Protected Areas System in 2000, which was affiliated to the Ministry of Environment and coordinated by the Brazilian Institute for the Environment and Renewable Natural Resources (IBAMA). Paripassu with global environmental awareness, the Brazilian National Council for the Environment enacted resolution nº 303/2002, which instituted the following types of permanent preservation areas:

- on hilltops, comprising the upper-third of hills and mountains;
- along ridge lines, encompassing the upper-third of the hillsides;
- on upland catchments, so defined by the contributing area of any given spring;
- on the margins of natural lakes and lagoons;
- on riparian zones, whose widths depend on the stream's widths;
- on areas with slopes equal to or greater than 100%; and
- on any area situated above 1.800m mean sea level.

The historic lack of appropriate maps depicting the limits of permanent preservation areas [3, 4] along with the shortage of infrastructure and personnel of governmental institutions to perform inspections on remote regions [5, 6] made it virtually impossible to fully enforce this law over the Brazilian territory. In contrast to the permanent preservation areas, the boundaries of protected areas, as stated in the law nº 9.985, are subjectively defined, being much easier to be mapped and thus enforced. The figures for December 2012 show the existence of 548 strictly protected areas spanning over 520,023 km², and 1,214 sustainable-use ones covering 1,007,190 km², created and enforced at federal, state and municipal levels [7]. These values comprise, respectively, 6.1% and 11.8% of Brazil's territory (8,511,965 km²).

An endless polemic on the legality of interfering on permanent preservation areas was settled by the Ministry of Environment of Brazil. In response to the insidious threat posed by invading exotic species to biodiversity and to ecosystem services provided by riparian vegetation, and in order to legalize the necessary actions aimed to eradicating, containing the spread and controlling the numbers of invasive species, CONAMA has enacted resolution nº 369 which introduced regulatory exceptions into the Brazilian Forest Code. This act came into effect on March 28, 2006, instituting a wide range of situations in which the intervention or even the removal of vegetation on permanent preservation areas is imperative and strictly in the interest or for the benefit of the general public.

Although representing a remarkable advance on environmental legislation, these accomplishments remained on paper. The recent technological advances on GIS and high-resolution topographic imagery allowed this issue to be revisited. Our research represents a first step toward automating the delineation of Permanent Preservation Areas for the whole of Brazil.

The main objective of this research was to create visual depictions mapping permanent preservations areas as set by the Brazilian Forest Code of 1965, therefore enabling us to better understand the magnitude of the natural reserves in preserving vital environmental resources.

2. Methods

Using the first seamless global digital elevation model provided by the Shuttle Radar Topography Mission (SRTM) from National Aeronautics and Space Administration (NASA), combined with digital contour lines and hydrography datasets from the Brazilian Institute for Geography and Statistics (IBGE), we have produced high resolution, hydrographically conditioned digital elevation models (HC-DEM) for key watersheds.

2.1. Preprocessing

In order to ensure that the divides of the selected target watersheds would be accurately depicted in the final digital elevation model (DEM), an 8km buffer was defined around the corresponding hydrography. The intersected SRTM tiles were then mosaicked to form a continuous 90m cell-size DEM. To preserve map accuracy during subsequent spatial analyses, the DEMs were projected to UTM coordinates, keeping the same datum (WGS84) of the original SRTM data. The next step was to convert their cells to a point dataset, each point lying in the center and carrying on the elevation value of the respective cell.

Given the requirements for creating a HC-DEM, centerlines were derived for double-line streams and connected to the remaining of the hydrography. The resulting datasets were then checked for connectivity and downstream orientation of all their arcs [8, 9].

The analysis was performed using the software ArcGIS 10.1 SP1 running on Windows 7 Ultimate SP1. However, due to a 512Mb undocumented limit imposed by the Topo_to_Raster routine to the size of the resulting DEM, the interpolation process had to be done in ANUDEM version 5.2 and the results were then imported back into ArcGIS as geodatabase raster datasets.

2.2. Postprocessing

The removal of spurious sinks was performed on the DEM generated by ANUDEM using the Fill command, available in ArcToolbox, to get rid of any eventual depression that would otherwise block downstream flow. Even using ANUDEM with drainage enforcement, the digital hydrography does not always coincide with the bottom of the valley, creating peaks and sinks on the vertical profile of the stream network. Drastic changes in elevation values may occur as a result of applying the traditional stream burning techniques to correct the vertical profile of the rasterized stream network [9]. In order to minimize the changes in the original DEM surface values along the hydrography cells, we modified the method proposed by Hellweger [10].

Initially the vector hydrography was rasterized and the resulting grid was thinned to 1-cell wide using the shortest path algorithm to connect the cells associated to the springs to the cell of the basin's outlet. Next, the vertical profile of this raster hydrography was extracted from the depressionless DEM and then inverted. The cells associated with the springs were assigned NODATA and a 1-cell buffer along all the hydrography received zero as elevation value. This raster was then filled to remove any spurious sinks which, in fact, promoted the removal of eventual spurious peaks along the stream network because of its inversion. The resulting hydrography profile was inverted again, bringing it back to the correct vertical position. The spring cells received their original elevation values and a large value (5,000m) was subtracted from all stream cells. The fill procedure was executed once more, this time getting rid of the spurious sinks. The maximum difference between these results and the previous stream profile, minus 0.5m, was calculated and added to all the stream cells, assuring that none of them would be higher than the bordering ones.

The DEM surface within a 5 cell buffer along each side of the hydrography was then replaced by ramps mathematically created between the borders of the buffer and the stream network's cells. The overlapping of some buffers occurred whenever the distance between any two streams was less than 10 cells. Such situations, not contemplated in the Hellwerger's method, are usually found in meandering rivers, leading to miscalculation of the elevation values for the associated ramps. To avoid this problem, it was necessary to identify the centerlines of the areas of superimposition, keeping their original elevation values.

Flow direction is vital for deriving subsequent hydrographic information about a surface and therefore, this dataset should be as accurate as possible given the input data. The derivation of the flow direction grid for the reconditioned DEM required three steps, each one for a different region: (1) for cells lying outside the buffer, the flow direction was derived using the depressionless DEM values converted to millimeters and then to integer, (2) for cells inside the buffer but not belonging to the hydrography, their flow directions were imposed towards the closest river cell using the CostBackLink command, and (3) for cells belonging to the stream network, their directions were forced to follow the shortest path to the basin's mouth, also using the CostBackLink command. This strategy was conceived to guarantee that the surface runoff within the buffer would converge to the stream cells and, once there, it would flow towards the outlet.

2.3. Analysis approach

For purposes of organization and efficiency, we separated the spatial characteristic of the Permanent Preservation Areas into seven denominations. Then we created specific routines for automatically mapping each one the seven subtypes of protected areas. The following descriptions highlight each of the processes:

1. **On hill tops**: the hills were isolated by inverting the reconditioned DEM. The cell associated with the peak of each hill was a sink and the basis of its hill was defined by the boundary of respective watershed. The minimum and the maximum elevation values of each hill were calculated and the cells corresponding to its upper third were flagged as protected areas, as illustrated on Figure 2.

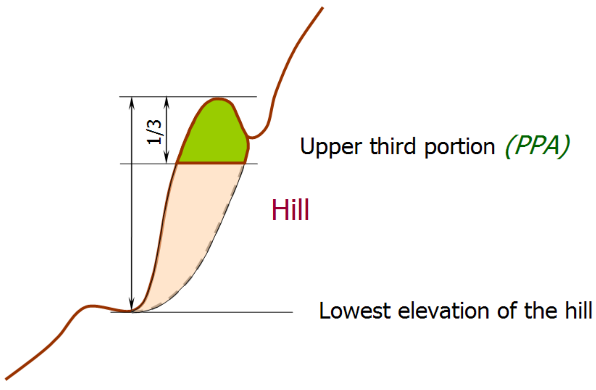

Figure 2. Delineation of Permanent Preservation Areas on hilltops.

2. **Along divides**: the areas to be protected encompass the upper third of the hillsides. In order to map them, for every cell in the landscape one needs to know what is the elevation of its closest cell to the divide (upper bound) and also what is the elevation of its closest cell to the hydrography (lower bound). These three cells must lie along the same flow path in order to find the relative vertical position of a given cell in respect to its base. Only after is it is possible to select the cells belonging to the hillside's upper third (Figure 3).

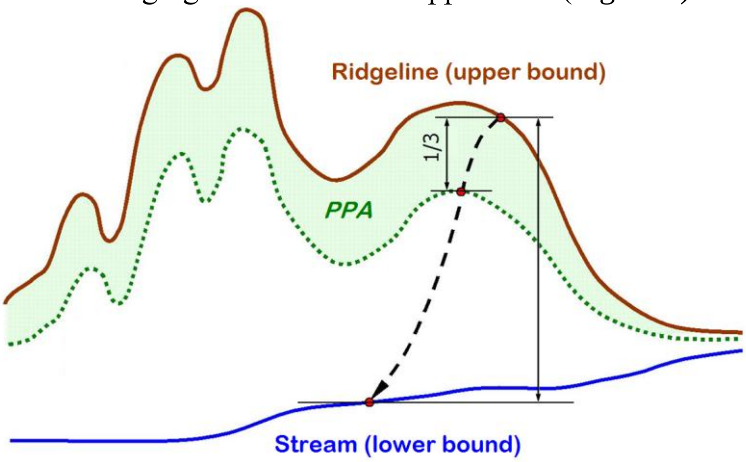

Figure 3. The upper third portion of a hillside.

3. **On upland catchments**: this category of permanent preservation area combines the area within a minimum radius of 50m of each spring with the respective contributing area, as shown on Figure 4. A grid containing only the cells associated to the springs was used as input to the WATERSHED command in order to derive the contributing area as well as to define a 50m-radius buffer around them.

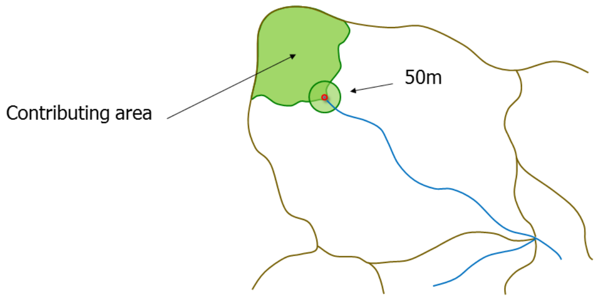

Figure 4. A 50m-buffer around a spring overlaid on its drainage area compose the area to be protected.

4. **Bordering natural lakes and lagoons**: the extent of the protection zone adjoining lakes and lagoons varies according to their area, being it 50m for areas up to 20 ha (200,000m²) and 100m otherwise.

5. **On riparian zones**: the delineation of protected areas along streams relies on determining the width of the floodplains associated to their highest water levels reached at the peak of the raining season.

   The challenge of finding the floodplain's width lies in the delineation the centerline of the inundated area. Our approach can be summarize in the following steps: **(1)** identify the floodplain's extent either from radar imagery interpretation or by comparing the DEM surface elevations with simulated water levels from hydraulic models developed for the stream network under analysis, **(2)** identify the cells lying on the borders of the floodplain and convert them to a point dataset, **(3)** create a Thiessen polygon dataset for those points, **(4)** clip the Thiessen lines with the polygon portraying the floodplain extent, **(5)** remove the Thiessen lines touching the border of the floodplain polygon, to further reduce the amount of lines to work with, **(6)** manually select the centerlines and save them into a separate dataset (we suggest to use the shortest path algorithm to connect the initial segment to the final one of each major centerline to speed up this process, which tends to be very tedious and labor intensive), **(7)** rasterize the centerline dataset and generate an Euclidean-distance surface from these cells, **(8)** extract the distance of each borders' cell to the closest cell of the centerline and multiply the results by two, **(9)** reclassify the resulting grid using the ranges shown in Table 1, **(10)** convert those cells to a point dataset and create buffers for them according to the respective riparian width values, **(11)** rasterize the buffer polygon dataset and finally merge the resulting grid with the floodplain one in order to produce the map of the Permanent Preservation Areas.

Table 1. Riparian zone's width according to the extent of the floodplain.

Floodplain's width (meters)	Riparian zone's width (meters)
< 10	30
10 – 50	50
50 – 200	100
200 – 600	200
> 600	500

The main steps of this process are depicted on

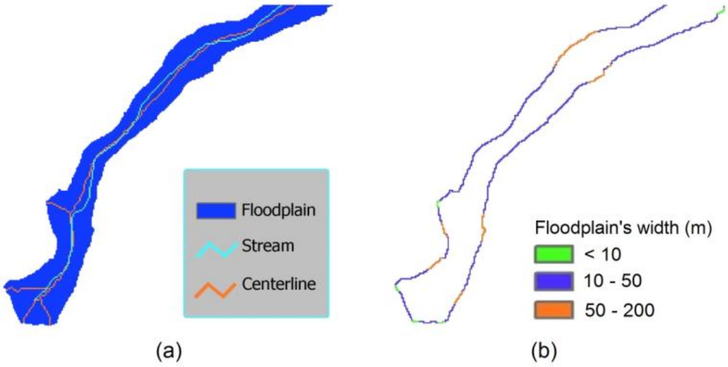

Figure 5 and Figure 6.

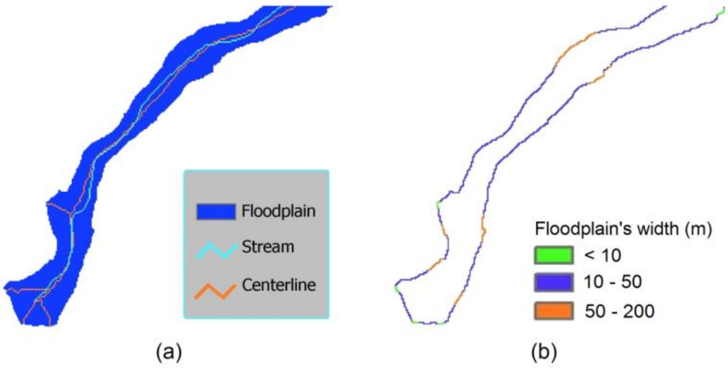

Figure 5. (a) Comparison between the original stream location and the centerline derived for its floodplain, (b) buffer's width as a function of the floodplain's width.

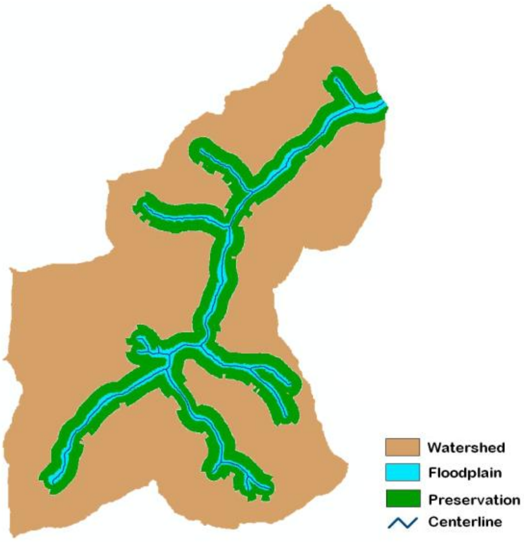

Figure 6. Outline of the riparian zones to be protected bordering the floodplains.

6. **On steep slopes**: any portion of the terrain whose slope is greater than 100%, which is equivalent to an angle of 45°, is protected under the Brazilian Forest Code. One must ensure that the Z units match the dataset coordinates in order to generate the correct results when applying the SLOPE command; if not, a proper Z factor must be applied.
7. **On high elevations**: any area situated at more than 1,800m above sea level constitutes a protected area.

The final map for each case study was generated by compiling each of the seven subtypes. Once the map was created, the implication and significance of the spatial arrangement of the Permanent Preservation Areas over the target watersheds became obvious.

2.4. Case studies

In order to highlight the effectiveness of the Brazilian Forest Code of 1965 in providing suitable ecosystems protection for a variety of topographic conditions, we had developed three case studies encompassing four biomes: (1) *Amazônia* - Amazon rainforest; (2) *Pantanal* - the largest wetland in the world and declared a UNESCO Biosphere Reserve and a World Heritage Site; (3) *Cerrado* - savanna woodlands, a highly threatened Brazilian ecosystem that rivals the rainforest for biodiversity, and one of the two Brazilian biodiversity hotspots (the other is the Atlantic Forest); and (4) *Mata Atlântica* - Atlantic forest, the most fragile and devastated Brazilian ecosystem (currently its fragments represent less than 7% of its original extension). The locations of the target watersheds are shown on Figure 7.

Figure 7. Locations and names of the three case studies watersheds.

2.4.1. Case study 1: Amazon rainforest

The Crepori river basin, a major tributary of the Tapajós river, which in turn belongs to the Amazon basin, was selected for an in-depth study because of the recent land use change toward the expansion of soybean cultivation and its history of gold mining along the river banks [11]. Located in the southwest region of the State of Pará, Brazil, the Creopri river drains an area of 13,578 km², equivalent to one third of Switzerland (Figure 8).

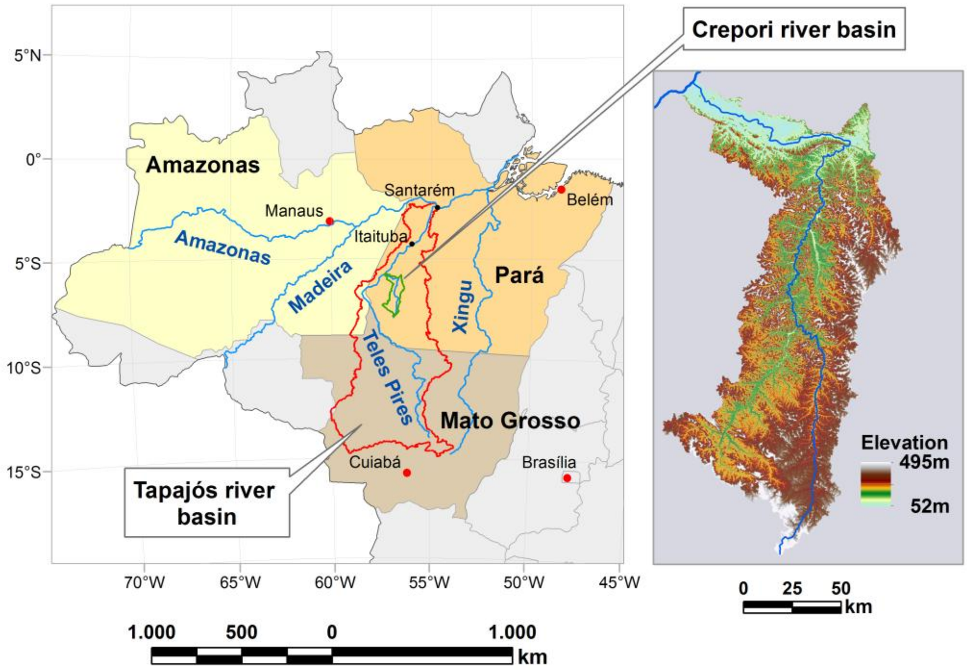

Figure 8. Location of the study area in the State of Pará, Brazilian Amazon, and its DEM.

Elevations range from 52m on its confluence with the Tapajós river to 495m above sea level in the uplands to the south, having an average elevation of 250m (±68m). Its terrain consists of a highly complex network of numerous small rivers that cut through ground with slopes ranging from 0% to 250%, with an average value of 13% (±9%). Annual rainfall in this area is just over 2,000 mm and the average temperature is 28^{o}C.

The intricate stream network along with the complex relief of this watershed pose considerable challenge to mapping its permanent preservation areas, making it an ideal candidate to evaluate the methodology of automatic delineation of PPAs in the Amazon rainforest. The HC-DEM for this basin was generated by adopting a cell size of 30m.

2.4.2. Case study 2: Amazon rainforest/Savanna/Wetland

The Sepotuba river basin, a tributary of the Upper Paraguay and located within the Paraná basin, was also selected for this study because of the recent expansion of soybean cultivation in an area of rich biodiversity, home to the transition between the Amazon rainforest, savanna *(cerrados)* and wetland (pantanal). The Sepotuba watershed encompasses an area of 9,845 km² in the southwest of the State of Mato Grosso (Figure 9).

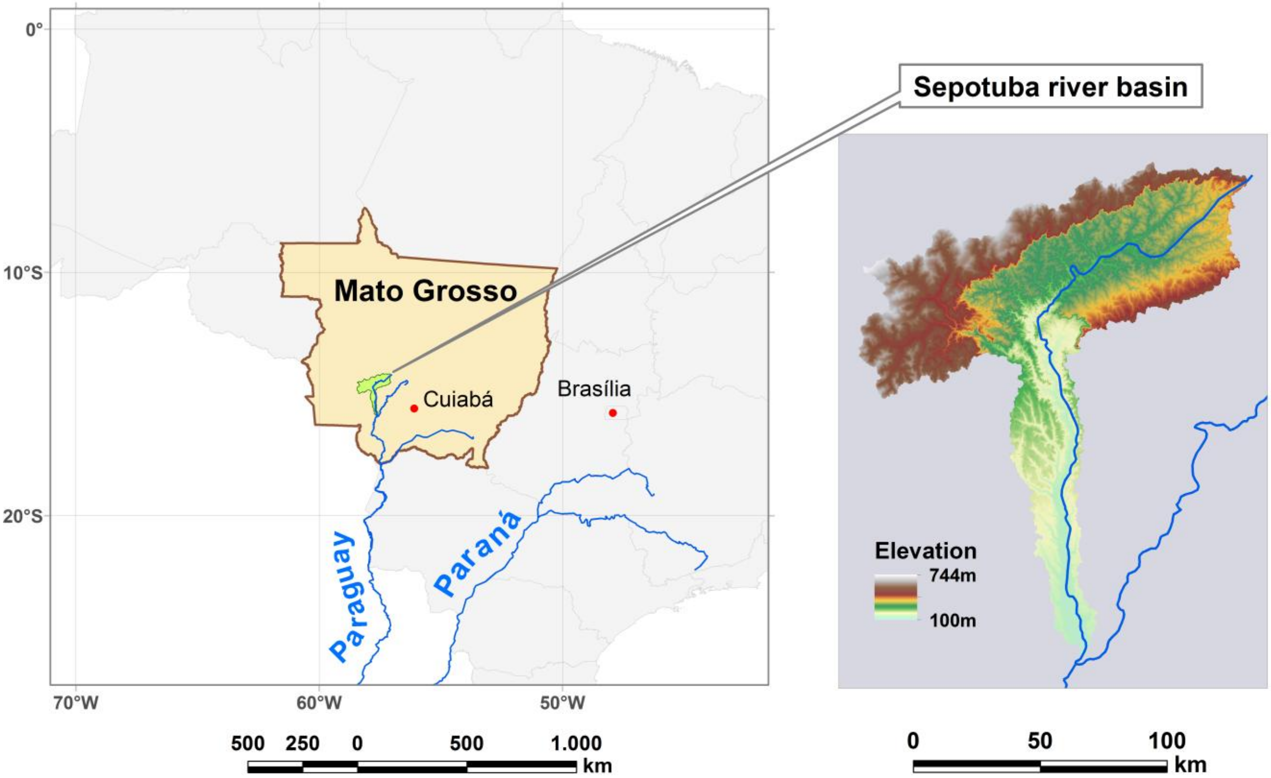

Figure 9. Location of the Sepotuba river basin and its respective DEM.

Although the area of the State of Mato Grosso (906,068 km²) represents only 18% of the Legal Amazon, there is concentrated 40% of all deforestation in the Amazon rainforest. The HC-DEM for the Sepotuba river basin was generated using a cell size of 20m.

Elevations within this watershed range from 100m on its confluence with the Paraguay river to 744m above sea level in the plateaus of the northwest, with an average of 366m ± 152m. Its terrain has slopes ranging from 0% to 101%, presenting an average of 6% ± 5%. The upper portion of its border establishes the divide between the Amazon and Paraguay basins.

2.4.3. *Case study 3: Savanna/Atlantic forest*

The site chosen for the third case study was the watershed upstream of the dam of the Tres Marias hydroelectric power plant, located in the Upper São Francisco region, covering an area of approximately 51,000 km². The two major rivers that flow into the Tres Marias reservoir are São Francisco and Paraopeba (Figure 10).

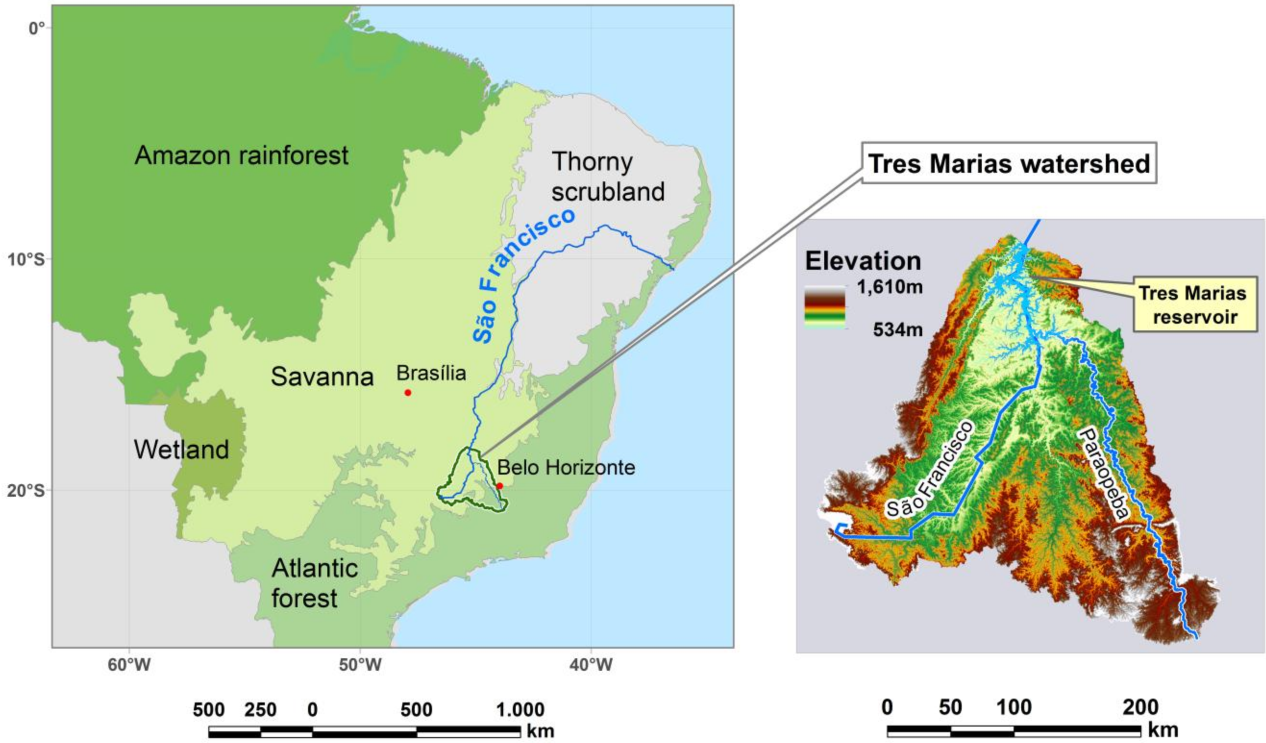

Figure 10. Brazilian biomes, along with the location of the Tres Marias watershed and its DEM.

Given the availability of both contour line and hydrography datasets from IBGE for the whole area at 1:50,000 scale, the HC-DEM for the Tres Marias watershed could be generated adopting a cell size of 10m. The relief of this region presented elevations between 534m and 1,610m, with an average of 795m ± 150m. Its slopes ranged from 0% to 472%, having an average value of 11% ± 10%.

3. Results

We found that at least 30% of the extent of each selected watershed falls under the Permament Preservation Area legal definition. In order to portray the spatial arrangement of this environmental protection across different strata of the landscape, a 3D depiction of the extents of the overall protection provided by the Brazilian Forest Code of 1965 for a small portion of the Crepori river basin is illustrated in Figure 11.

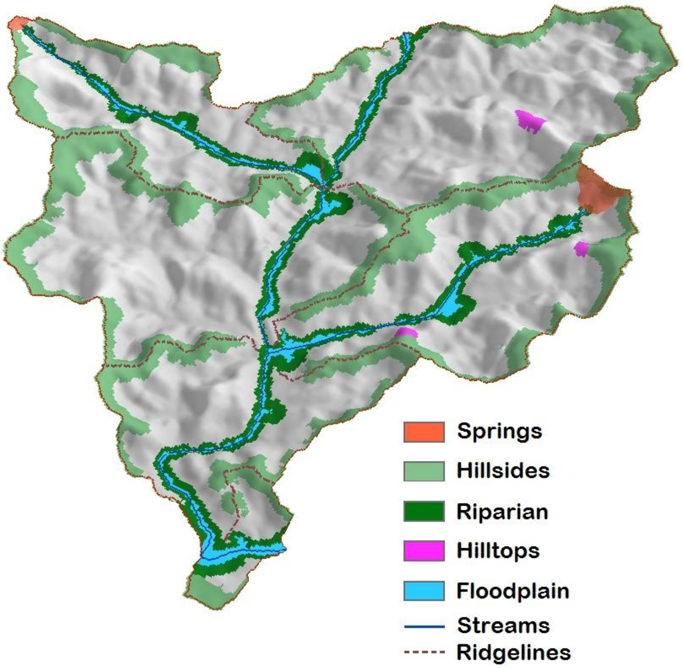

Figure 11. 3D example of natural corridor structures for a sample watershed, stemmed from the spatial nature of the different categories of Permanent Preservation Areas.

The figures for the all of three case studies are summarized in Table 2.

Table 2. Relief characteristics and extent/percentage of permanent preservation areas for the target watersheds.

	Crepori (Amazon)	**Sepotuba** (Amazon/Savanna/Wetland)	**Tres Marias** (Savanna/Atlantic forest)
Elevation	52..495m (0 = 250 ± 70m)	100..744m (0 = 366 ± 152m)	534..1,610m (0 = 795 ± 150m)
Slope	0..250% (0 = 13 ± 9%)	0..101%(0 = 6 ± 5%)	0..472% (0 = 11 ± 10%)
PPA category			
Upland catchments	289 km² (2%)	961 km² (10%)	3,487 km² (7%)
Along ridgelines	2,273 km² (17%)	1,464 km² (15%)	12,344 km² (24%)
Riparian zones	3,060 km² (23%)	552 km² (6%)	5,803 km² (11%
Hilltops	4 km² (---)	206 km² (2%)	6,617 km² (1%)
Steep slopes	1 km² (---)	0,004 km² (---)	39 km² (---)
Watershed area	13,578 km²	9,845 km²	50,830 km²
Overall protection*	5,383 km² (40%)	2,968 km² (30%)	19,773 km² (39%)

4. Conclusions

The results of the present study confirm that the Brazilian Forest Code of 1965 creates an intriguing mosaic of environmental protection areas strategically distributed over different strata of the watershed topography. Even for gently undulated landscapes, such as those of the Sepotuba river basin, the Permanent Preservation Areas would account for nearly 1/3 of the watershed's total area. Furthermore, we are also able to recognize, in regard to landscape ecology, how deeply integrated the concept of the watershed as the primary planning unit truly is.

* The fact that the total area protected is less than the sum of the area values indicates the occurrence of some overlapping among different categories of PPAs.

Two major natural corridors stem directly from the sole enforcement of this law: one formed by the protected areas along ridgelines, which is crucial to assure connection between adjacent subbasins; another one, created by the buffer zones bordering floodplains which are aquatic-terrestrial ecotones. These also play a major role in protecting water bodies from silting. As can be seen, spring protection is of paramount importance to connect these two categories of wildlife corridors. These areas provide a complex ecological network throughout the landscape and can be applied to any country, thus establishing strategically located corridor structures and effectively shielding biodiversity.

Acknowledgements

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