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Assessing ecological risk through automated drainage extraction and watershed delineation

Luiz Rogério Mantelli *, Jomar Magalhães Barbosa, Marisa Dantas Bitencourt

Ecology Department, Institute of Biosciences, University of São Paulo, Rua do Matão, 321, Trav. 14, 05508-900, São Paulo, Brazil

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ABSTRACT

Decision makers are frequently involved in projects requiring ecological risk definition, which are inherent to biological conservation process. It is important to recognize these risks in order to invest wisely in the management and protection of biological resources. In this matter, Geographic Information System tools and remote sensing data have been used frequently as important components in planning and management of conservation units, Rabus et al. (2003), Valeriano et al. (2009) and Valeriano et al. (2010) stressed the advantages of using data that were gathered during the Shuttle Radar Topographic Mission (SRTM) for biological and geomorphologic purposes. For Brazil's national territory, the SRTM data were refined (Valeriano, 2008) and offered as free access on the TOPODATA Project website (http://www.dsr.inpe.br/topodata) where geomorphometric information (including elevation data) at a resolution of 30 m are provided. The aim of this paper is to demonstrate an example of how TOPODATA products have been applied in order to determine the ecological risk of the border of a Conservation Unit, located in the State of São Paulo—Brazil, in the Brazilian Atlantic Forest, using automated drainage network and watershed extraction. A comparison between SRTM, TOPODATA, and ASTER DEM was carried out, showing an advantage of TOPODATA drainage network product. The vectors generated using this data are more similar to the official drainage network vectors than the drainage network extracted using ASTER-DEM or SRTM. The network product generated using ASTER-DEM produced many commission errors and the one generated using SRTM produced a poor network, with generalized vectors, less detailed than the others. The results showed that using the TOPODATA Project's Digital Elevation Model (DEM) can provide important data for ecological analysis and significant additional information for decision making, regarding drainage networks and watershed features. The produced map for border ecological risk showed to fit perfectly to the field work analyses, produced in other works. Furthermore, the extracted watershed polygons might furnish important information unrevealing best conservation unit boundaries, which means more efficient management and best biological conservation results.

1. Introduction

Conservation measures may be discussed with the concept of ecological risk assessment. The United States Environmental Protection Agency (U.S. EPA, 1992) defined that 'Ecological risk assessment evaluates the likelihood that adverse ecological effects may occur or are occurring as a result of exposure to one or more stressors' (U.S. EPA, 1992). Gentile et al. (1993) define risk assessment as a process that determines the probability of a particular event occurring and can play an important role in decision-making.

In the ecological sphere, risk assessment has become potentially favorable as a management tool (Hope, 2006). Although ecological risk assessment is a controversial issue (Tannenbaum, 2010), many points can be considered during decision making, such as weighing up the probable risks in landscape analysis and other important factors, such as social, legal, political and economic (U.S. EPA, 1998).

Therefore, in order to continue improving the interpretation of local and regional ecological risks to the landscape, automatic watershed delimitations can be used to evaluate the exposure of a protected area to possible stressors. It must be done especially in the border lines, where the management and conservation depend on external factors such as land use and landscape integrity (Huang et al., 2007).

Some researchers agreed that ecological risk assessment are usually related to chemical dispersion (Hayashi and Kashiwagi, 2011; Kramer et al., 2011). Along the conservation unit border lines the risk must be provided and controlled in order to foment adequate conservation actions. It is possible only when the ecological risk assessment tools are considered during the protection area planning and delimitation. These tools are essential for management too, after the conservation unit creation.

In this way, the ecological risk assessment of the protected area borders must be a procedure that takes into account the landscape as

* Corresponding author. Tel.: +55 11 76416345.
E-mail address: luizmantelli@gmail.com (L.R. Mantelli).

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a whole, necessarily implying the usage of different remote sensing products. Some example, may be Digital Elevation Model (DEM), drainage network and vector watershed, along with data processing techniques already known.

A DEM is one of the many products available for public use that provide information regarding new datasets for drainage extraction and watershed delineation (Hancock et al., 2006). In areas with complex drainage and huge catchment basins, it is desirable to have products that are easily accessible and efficient at characterizing these networks. Hydrological modeling of small and large geographical domains, such as river channels and drainage areas, is essential to identify areas with current and future water problems related with human occupation (Coz et al., 2009). The combination of remote sensing products with advances in Geographic Information System (GIS) techniques is a tool that can be used for recommending conservation measures (Biswas et al., 2002).

DEMs that are obtained by remote sensing are extremely effective in extracting drainage networks (Martz and Garbrecht, 2007). In Brazil, this type of data has been widely used and can provide information where data accessibility is often limited. Different algorithms and models for automated drainage extraction and watershed delineation have been in use since the mid-eighties. These tools are available from various GIS (Garbrecht and Martz, 1999) and follow a similar processing scheme, including flow direction and accumulation determination, drainage network deviation and ordering, and watershed delineation (Jenson, 1991).

Studies such as Rabus et al. (2003) and Valeriano (2004) have stressed the advantage of using data from the remote sensing products known as Synthetic Aperture Radar (SAR) and Interferometric Synthetic Aperture Radar (InSAR) that were gathered during the Shuttle Radar Topographic Mission (SRTM). The original SRTM took place in February 2000, and successfully recorded the first almost global (from 60° N to 57° S) elevation dataset using interferometric synthetic aperture radar (InSAR). It provided data in C- and X-bands at 1 arc-sec resolution. For South America, C-band data, processed by NASA-JPL, were released in the form of a seamless DEM at a degraded resolution of 3 arc-sec (~90 m), and have been available on-line since 2003.

However, insufficient contrast in some parts of SRTM-3 radar imagery tends to produce an average slope gradient that is too high in flat areas and too low in high-relief areas (Hayakawa et al., 2008). These characteristics can provide a range of vectors and polygon features for automatic drainage network and watershed delimitation.

Another DEM data that is available nowadays is TOPODATA. TOPODATA is a project which offers free access to local geomorphometric variables yielded by SRTM data, available throughout the whole of Brazil. The data have been refined from 3 arc-sec (~90 m) resolution to 1 arc-sec (~30 m) through kriging and are constantly reprocessed in order to enhance the quality of data. This resample procedure has resulted in the improvement of SRTM data, with better resolution of data processing when compared with the original 90 m data.

An additional data that is available is the ASTER-DEM, based on satellite imagery from the Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER). As with TOPODATA, ASTER also has a 1 arc-sec resolution and is freely distributed worldwide.

All these products undergo different processing alterations before they are released. This may cause significant differences in relation to extracting information (Andrades Filho et al., 2009). Thus, three types of DEM were used for automatic drainage and watershed extraction and the data were compared with official Brazilian cartographic drainage maps. Two of the DEM sets (SRTM and TOPODATA) were obtained from InSAR, and one (ASTER-DEM) was obtained from optical data. The official Brazilian cartographic drainage maps were provided by the Brazilian Institute of Geography and Statistics (IBGE), mostly obtained through RADAM Brazil data interpretation. This drainage was adopted as a ground truth.

It is important to consider that the scale of IBGE drainage network (1:50.000) is compatible with this work purpose. This drainage network is the only official map for some areas of the country which was adopted due to its large use in many scientific works and environmental projects in Brazil. Furthermore, the cartographic error is classified as “Class A” after cross-validation. Considering a 1:50.000 scale, it means that the error is less than 15 m (Decreto-Lei No 89.817, 1984). With respect to the different DEM comparisons, many works were developed and various methods were applied to achieve this purpose. For example, Guth (2003) evaluated more than 35 parameters in geomorphological SRTM and ASTER through correlation matrices. Other methods of comparison as variogram analysis, Fourier, and fractal methods have been resistant to automation, because they require special pre-processing, or subjective determination of linearity or periodic trends in noisy data. Koch and Lohmann (2000) used spatial transformation tool to evaluate even parameter descriptors of position, orientation and the scale of the SRTM, compared with the reference date. Jarvis et al. (2004) used map algebra and cross tabulation technics to evaluate the correlation between different DEM data, based on cartographic maps and GPS control points.

Those methods are commonly applied to raster data and cannot be used to drainage network vector comparison. Vectors and polygons are usually analyzed in a qualitative way, through visual interpretation. According to Wechsler (2007), errors are a fact of spatial data and often cannot be avoided. Nevertheless they must be understood and accounted for. As ecologists that use DEM data for biological purposes, our mission is to search for, recognize and accept the error, working to point out the advantages of using different DEM sources and trying to minimize the uncertainties found in the analyses. Following the automatic drainage and watershed extraction trends, the aim of this study was to discuss the application of DEM derived products, drainage networks and watershed limits, in conservation biology and protected area management through the border ecological risk assessment. Also, these will demonstrate the differences between the mentioned DEM products, generated from three different DEM data sources, SRTM, TOPODATA and ASTER-DEM.

2. Material and methods

The study area is the state park known as “Alto do Ribeira” (PETAR), in the south of São Paulo State, Brazil, as shown in Fig. 1. This region has a rugged landscape which comprises the Brazilian Atlantic Forest (Mata Atlântica Biome). According to Capobianco (1989), the São Paulo Vale do Ribeira (São Paulo Ribeira Valley) can be divided into three main geomorphologic zones: a mountainous area, a coastal lowland area and a pre-mountainous area. This study was conducted in the mountainous portion, also known as the Alto do Ribeira. This mountainous region covers an area of about 9000 km^2, inside the Mata Atlantic Biosphere Reserve.

Regarding the determination of the border ecological risk, three different types of DEM (SRTM, ASTER and TOPODATA) were processed using ArcGIS 9.3 and IDRISI Andes. Both softwares were used to provide automated drainage network and watershed extraction. Regardless of the ecological subject, this procedure was very important because it shows the advantages of each DEM, and supported the previously mentioned automated generation of drainage networks and watershed.

Some adjustments, such as corrections and transformations, were previously carried out in order to obtain better DEM input data. The first step was to adjust the SRTM DEM by removing data failures with the free software SRTM-Fill. The original data contain several gaps, inappropriate for this study's purposes. The second procedure was to convert all the products into the same coordinate system. In this case, UTM-WGS84 (zone 22S) was applied using Global Mapper. The next steps were carried out using ArcGIS tools.

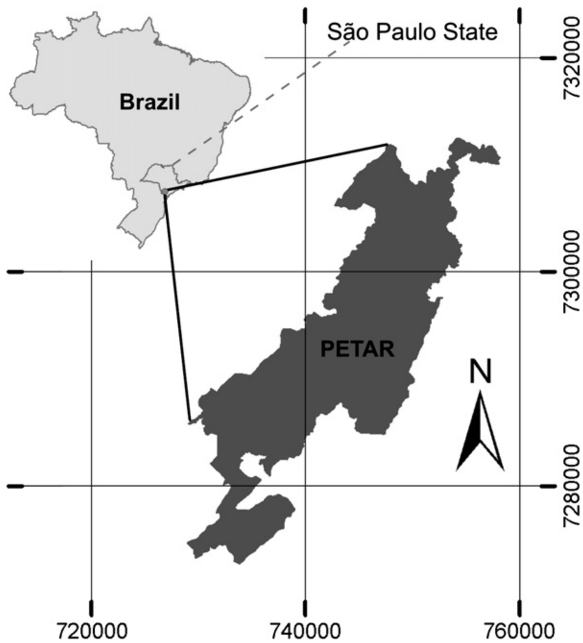

Fig. 1. Studied area location.

The Conditional tool (Spatial Analyst Tool extension) was also used to make corrections. Negative elevation values were removed from the DEMs. Subsequently, automated extraction was carried out using the Hydrology Spatial Analyst Tool. Two secondary raster products were obtained for each DEM input: Flow direction and Flow length. The extracted drainages were classified into stream order and refined to purge excess vectors. All stream vectors were converted into ArcGIS shapefile format. The watershed polygons were extracted using the Watershed IDRISI algorithm.

For comparison purposes, a total of 11,581 points were randomly picked from the IBGE official drainage network and produced on a 1:50.000 scale, which is compatible with the generated vector scale. The mean distances between each IBGE drainage point and the nearest point to an extracted vector were calculated as shown in Fig. 2 example.

ANOVA and Student's *t*-Test were used for statistical comparison. The watershed extraction results were compared in terms of area and also visually compared. These two methods were necessary to assess the precision and accuracy.

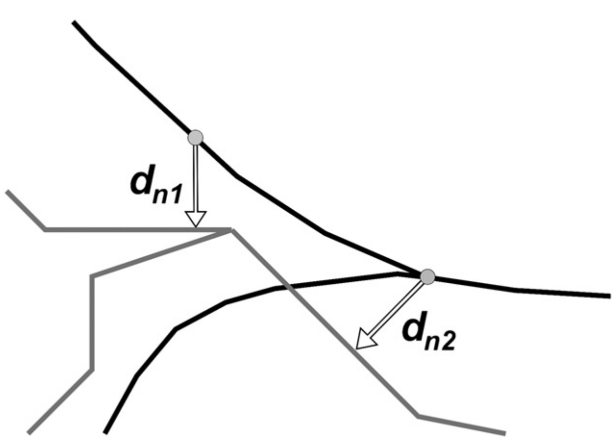

Fig. 2. Mean distances between each IBGE drainage point and nearest point to extracted vector.

Ecological border risk was delimited using an official PETAR border line. This polygon was analyzed by taking into account the TOPODATA extracted drainage network and watershed polygons.

The interpretation was carried out by observing the positions of springs and topographic ridges. Three risk levels were considered: low, medium and high. When the border line was located on top of the ridges, it represents a low ecological risk to the State park, because it suffers no external influence. However, if the border was positioned along a river or drainage course, ecologically it represents a medium risk due to the possibility of external influence. High risk is defined as watersheds that are subject to external influence. This means that drainage flows from external to internal areas.

3. Results and discussion

The resampling procedure provided by the TOPODATA project resulted in improved SRTM data with a better resolution (at 30 m) when compared with the 90 m of the original data. (Valeriano, 2008; Valeriano et al., 2009; Valeriano and Albuquerque, 2010). Fig. 3 shows the spatial resolution differences between all DEM products adopted as baseline data for this study.

Although ASTER-DEM exhibited a similar resolution when compared with TOPODATA-DEM, differences related to altitude representation are clearly discernible in the selected data sample (Fig. 3A and C). Hayakawa et al. (2008) have also taken into account the advantages of using ASTER-DEM over SRTM-3. This work showed that ASTER-DEM has better topographic representation of low-altitude hilly lands, for which SRTM-3 tends to overestimate the height of valley floors. In adition, ASTER-DEM accurately represents such topography, and tends to show slopes having near-zero curvature except at the boundary of the slope. The less detailed representation of valleys in SRTM-3 shows as concave slopes near the valley floor, and convex slopes near ridges.

On the other hand, there was an improvement when these variables were generated using TOPODATA-DEM (Valeriano et al., 2009). To permeate the use of this product application it is important to consider that some failures (gaps) in SRTM-DEM were corrected during the resampling process. Future studies should carry out an absolute comparison between morphometric variables generated using ASTER and TOPODATA-DEM.

When analyzing the drainage networks we found a different result to the one pointed out by Hayakawa et al. (2008). For automated extracted drainage network the vectors created using interferometric-based data produced better results. The comparison of the three drainage networks (SRTM, TOPODATA and ASTER) and the official drainage (IBGE), indicates a smaller mean distance between vectors for SRTM × IBGE (Table 1 and Fig. 4). ANOVA analysis of all the databases suggests that the means are sufficiently different ($F2, 34{,}240 = 19.4$; $p < 0.05$). The other drainage networks, ASTER and TOPODATA, were statistically equal ($p > 0.05$ in *t*-Test analysis), with low mean differences between them.

Found standard deviation values occur due to the methodology adopted to measure the mean distances to the official drainage vectors. It is inherent to commission and mainly omission error (when some real drainage vectors remained to be extracted). With some missing drainage vectors it is more difficult to match the official drainage network and consequently, an increase on standard deviation is commonly verified.

TOPODATA produced the best results, and many regions perfectly matched the IBGE drainage. SRTM vectors, on the whole, seem to be linearized, and lack important small drainages. This occurs because of the larger working scale, determined by poor spatial resolution. The ASTER vectors are also a good match with official vectors. However, in many areas the algorithm generated excessive artifacts (higher commission error), mainly in higher order drainages. It seems that the ASTER-DEM could not be properly interpreted in large valley areas, so

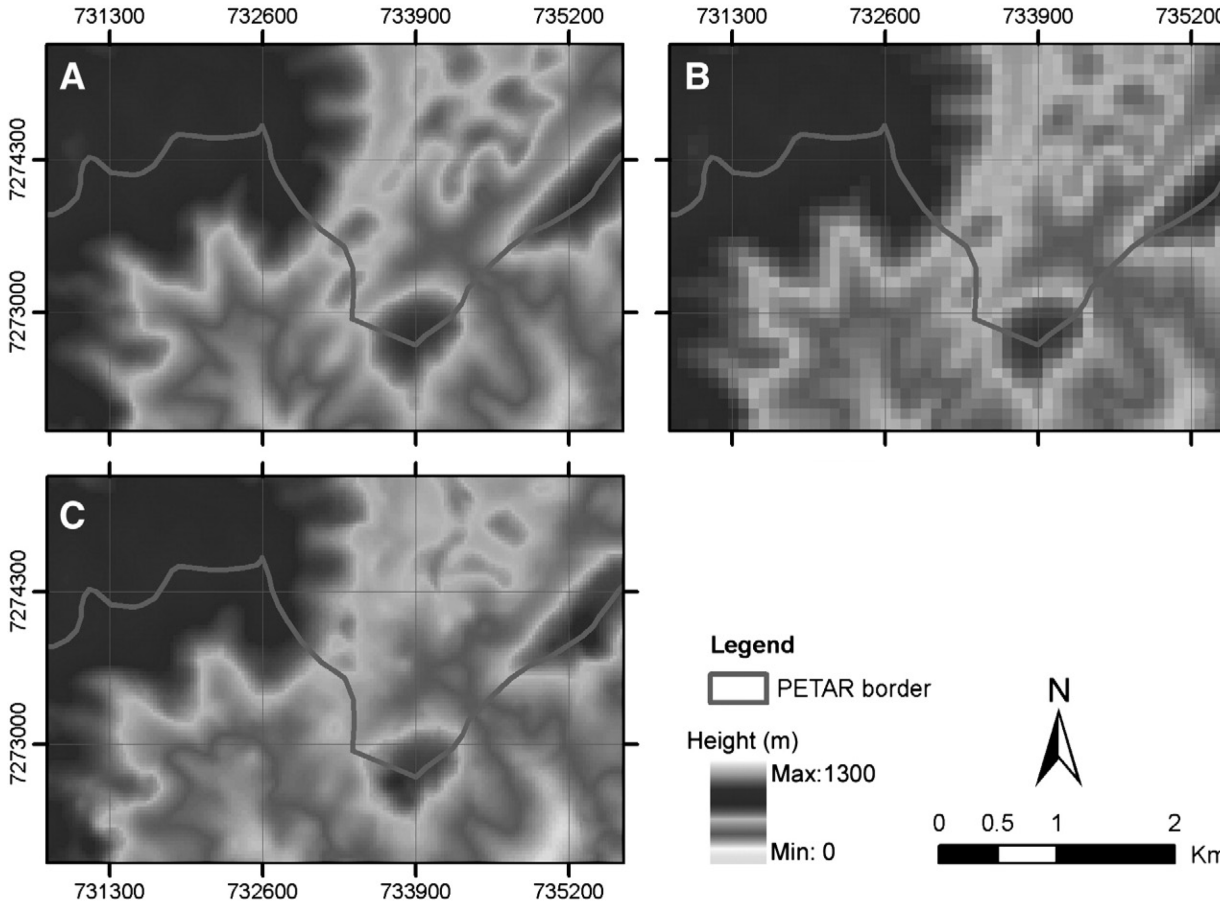

Fig. 3. Spatial resolution comparison among the DEMs adopted for this work. A) TOPODATA-DEM; B) SRTM-DEM; and C) ASTER-DEM.

usage of this product is inadequate for certain purposes. Moreover, the GIS package did not provide options to minimize the errors, depending on the surface type that was analyzed (Wechsler, 2007).

Despite the fact that SRTM has the largest pixel size, comparison with TOPODATA and ASTER highlights that the drainage network obtained from SRTM product was the closest to the official drainage network (IBGE).Some authors have used different methods to show the low level of conformity between automatically extracted drainage vectors and official bases (Andrades Filho et al., 2009). Because the analyses were pixel-based, this inconformity was associated with the spatial displacement or the working scale. This was one of the reasons why we adopted other methods to compare the generated vectors. Higy and Musy (2000), Wechsler (2007), and Zwenzner and Voigt (2009) also highlighted the influence of the size of the grid cell on hydrologic model parameters.

When analyzing the automatic watershed delineation inside a 10 km buffer zone, a comparison of the generated products presented a difference of 5% between the TOPODATA and ASTER watershed polygons. This means that when the watershed polygons are overlapped, there is 95% similarity.

Table 1
Mean distance of extracted drainage to official drainage network (IBGE).

Product type	Mean distance (m)	Standard deviation
SRTM	93.06a	± 103.05
TOPODATA	99.59b	± 114.52
ASTER	101.56b	± 108.00

Means followed by same letters (gray cells) are not significantly different (P = 0.05).

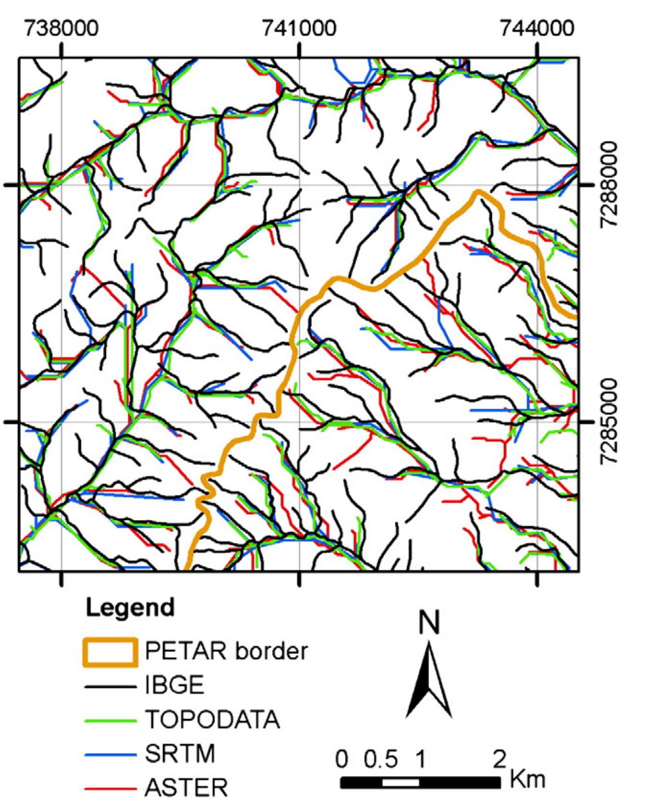

Fig. 4. Comparison between the three automatic extracted drainage networks and the official one.

Even considering this difference of 5%, some serious errors were verified. Drainage extraction based on ASTER-DEM processing seems to be susceptible to smooth topographic variations and sink areas, and in this way produces commission errors (generate many inexistent drainage vectors). Fig. 5 shows these differences clearly. The results show larger difference areas (areas where polygons don't match each other) occurred as a result of ASTER commission errors. These larger polygons are similar to a split TOPODATA watershed. This characteristic is mainly seen in drainage sink locations.

An analysis of the automatic extracted drainage and watershed limits shows that 54.3%, 36.6% and 9.1% of the PETAR park border present Low, Medium and High risks, respectively (Fig. 6). Thus, a substantial ecological risk to the integrity of the Conservation Unit can be interpreted as a threat posed by an alteration or fragmentation of habitat, richness species loss, introduction of exotic species, and accessibility by human communities.

A low risk means that the border is located over the ridges, and does not intersect the watershed limits. The low risk border indicates that the watershed is totally inside the protected area's conservation unit, which reduces the influence of the external environment.

High risk means that the border has watershed partly inside and partly outside the Conservation Unit and the drainage flows towards the park (Fig. 7). This feature indicates that human activities outside the park can negatively impact the local biological characteristics.

Medium ecological risk occurs when the park limit is exactly over a river, with half of the drainage inside the park along the river and the other half outside the park. These border portions also intersect the watershed limit but the drainage network flows away from the protected area or along the limit line. In this case, we can expect intermediate interference of the outside environment. However, this depends on the management of human activities.

All the ecological risks assessed with the drainage analysis must include other information such as land use and land cover changes, local biological threat and public policies. For example, Moraes et al. (2003) showed that aquatic organisms living in PETAR rivers are exposed to different pesticides dissolved in water or bound to suspended particles or sediment. Two of three studied sites, located near high ecological risk line, presented pesticide concentrations above the regulatory concentrations for protection of aquatic life. The other site presented similar concentrations, but this one was located near medium risk line, according to our results. These patterns corroborate with the border ecological risk analyses performed, showing high pesticide concentrations near the determined high ecological risk borders. It means that the border ecological risk assessment could be used as a helpful tool for the decision-making process.

This statement becomes even more relevant if taking account of the fact that decision makers are frequently asked to define the risk associated with biological conservation. The determination of the potential ecological risk areas or, in this case, border ecological risk, has important implications for direct management and investments related to conservation biology (Anderson et al., 2010). It is very important to reserve efforts and financial resource to priority areas, such as high ecological risk ones.

In addition, border ecological risk assessment improves the creation and management processes of buffer zones, defining differentiated land use constraints or buffer zone size.

4. Conclusions

The application of TOPODATA Project data might provide significant additional information to characterize drainage networks and watershed limit polygons. Although SRTM has shown slightly better

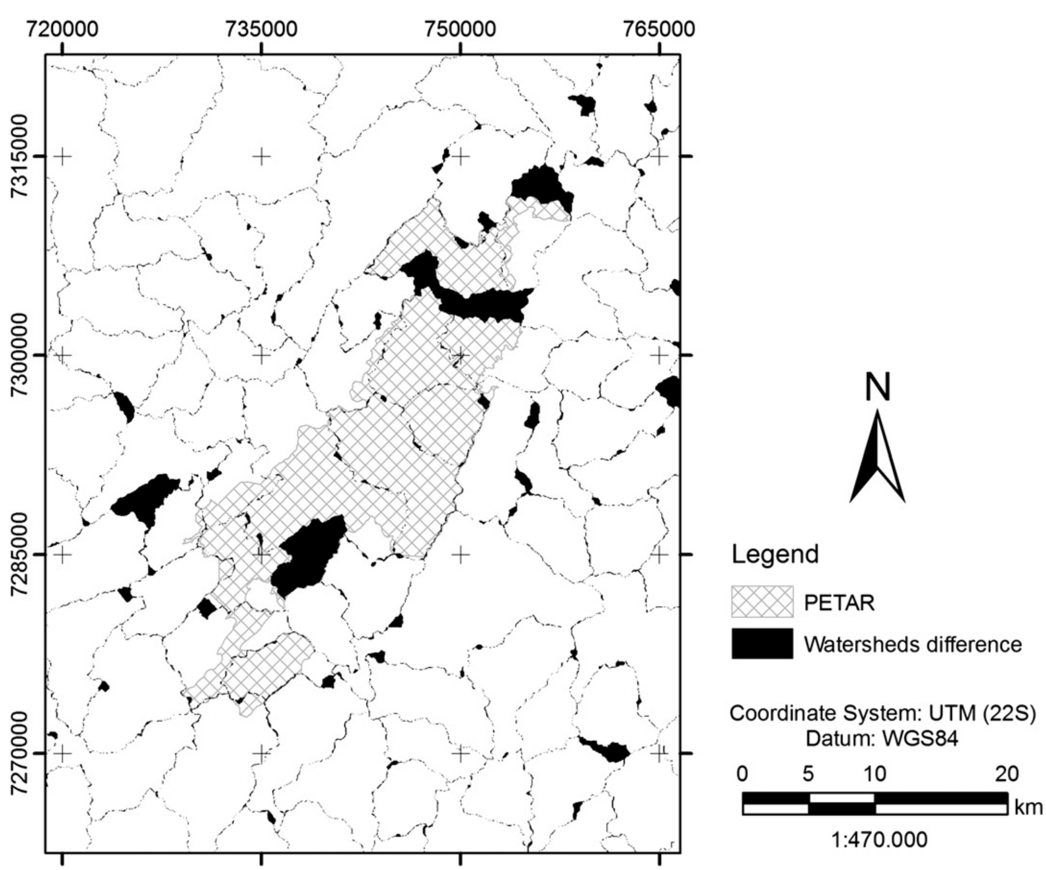

Fig. 5. Difference between the watershed polygon vectors generated with TOPODATA and ASTER DEM.

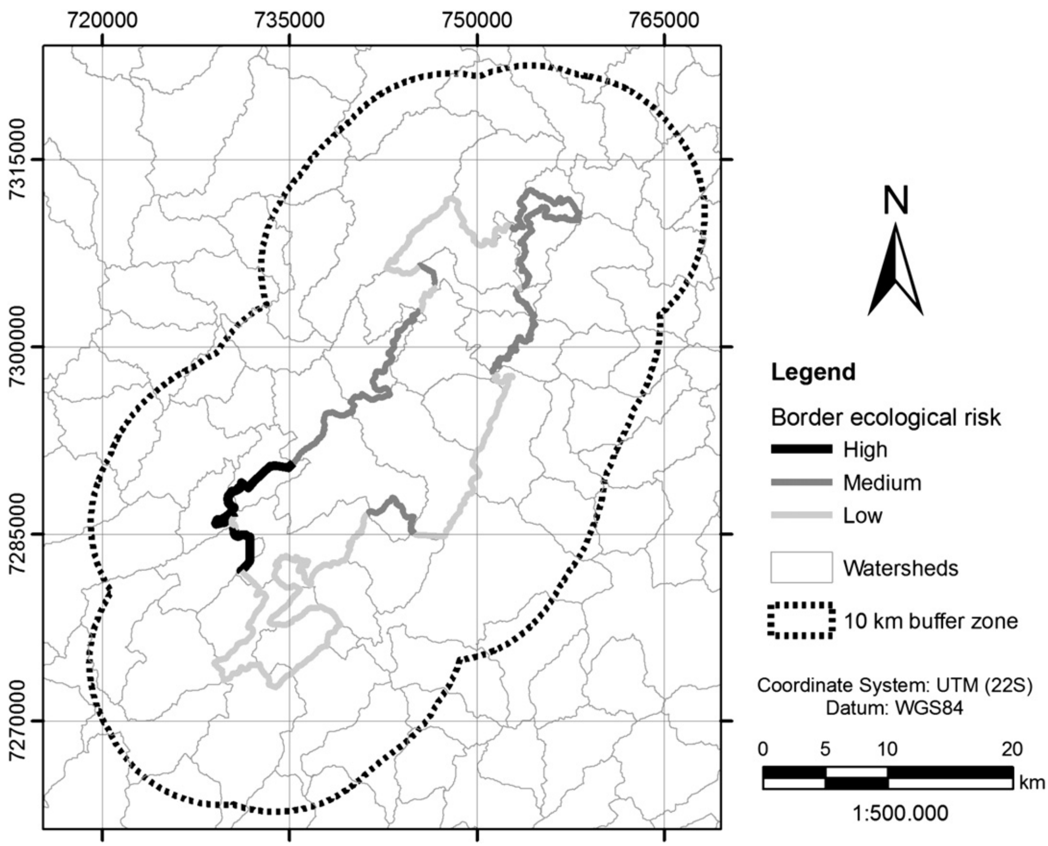

Fig. 6. PETAR park border ecological risk.

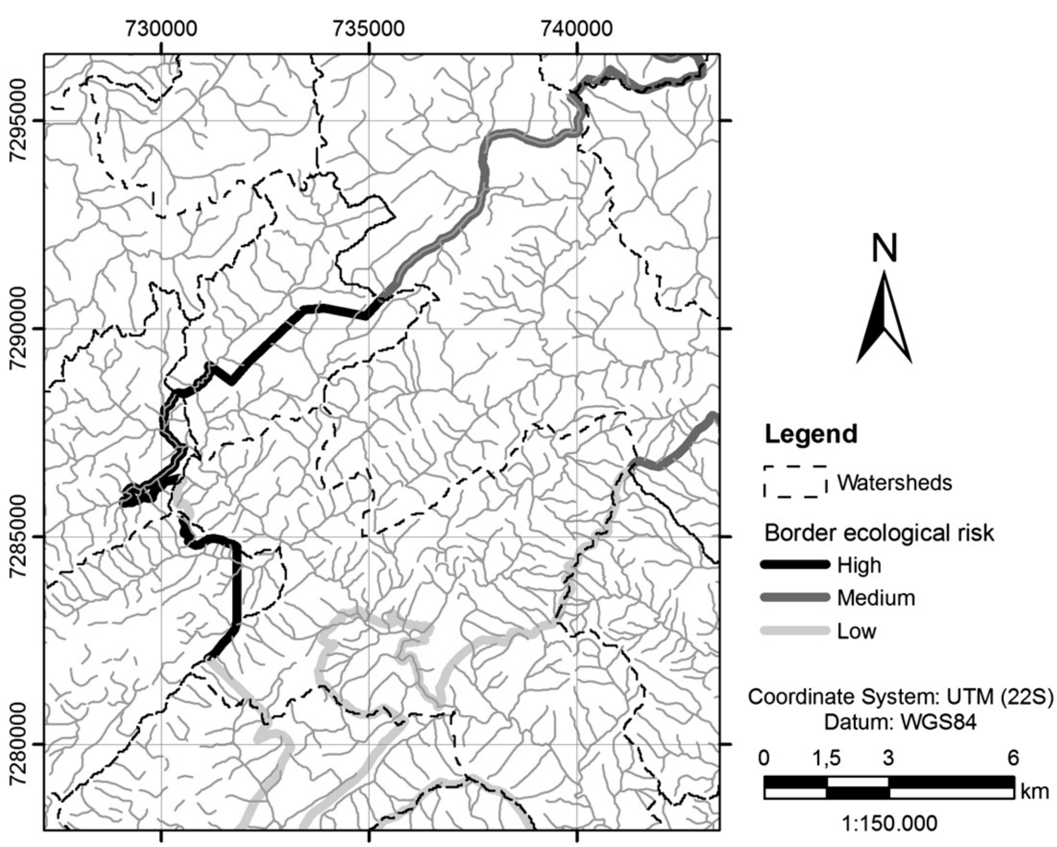

Fig. 7. Border ecological risk determination.

results than TOPODATA, the difficulties in processing SRTM means that TOPODATA is more useful in the Brazilian context, especially considering its free access and ease to download. Furthermore, the refined resolution of TOPODATA data proved crucial during the creation of higher quality drainage network and watershed vectors. In addition, SRTM usage requires more correction steps before drainage and watershed extraction.

The use of DEM can help decision-makers when planning biological conservation. Automatic watershed extraction is an important assessment tool for the spatial delimitation of the ecological risk in protected areas and can provide importat information that may be used for management planning. Information about flow direction and the catchment area of a watershed can help in monitoring programs to maintain essential ecosystem services in protected area. Future studies should analyze the responses of ecosystems to different ecological risks in the borders of protected areas. It is also possible to analyze the association of these areas with watershed position and drainage flow direction.

The method proposed for border ecological risk assessment showed positive results, corresponding to other study that analyzed the pesticide concentration in PETAR. High concentrations were verified in areas where borders were classified as high ecological risk. It means that the proposed ecological risk assessment is a helpful planning and management tool. Researches and decision makers would encourage themselves and recognize the method proposed in this work.

The ecological results of this work were based only on remote sensed data. It is important to consider that better SAR data should improve the results, providing greater accuracy on ecological border risk assessment. Also, field work is recommended in order to avoid miss interpretations. Ecological border risk assessment is a new methodology, with a great potential to help decision makers and public managers.

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