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Hazard Mapping in Urban Environmen-talProtected Areas: Tijuca National Park

Mapeamento de Risco em Áreas Urbanas Ambiental Protegidas: Parque Nacional da Tijuca

Rodrigo B. Santos [a]
Belo Horizonte, MG, Brasil
[a] Universidade do Estado do Rio de Janeiro (UERJ), Centro de Pesquisas e Estudos sobre Desastres (CEPEDES), : Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio)

Francisco Dourado [b]
Rio de Janeiro, RJ, Brasil
[b] Universidade do Estado do Rio de Janeiro (UERJ), Centro de Pesquisas e Estudos sobre Desastres (CEPEDES)

Leonard Schumm [c]
Rio de Janeiro, RJ, Brasil
[c] Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio)

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Abstract

Tijuca National Park (Parque Nacional da Tijuca - PNT), in the Carioca Hills, Rio de Janeiro, faces often landslides. This threatens the environment and the infrastructure, such as Estrada do Redentor, which connects the Paineiras Visitor Center (CVP) to the Floresta Visitor Center Sector. Due to the lithological-structure characteristics and the status of urban protection area, many methodologies are not suitable for risk mapping and management. Therefore, a methodological adjustment was developed to identify

RBS is a Geologist, PhD in Geology, e-mail: rodrigobrusts@gmail.com
FD is a Geologist, Associate Professor, PhD in Geology, e-mail: fdourado@cepedes.uerj.br
LS is a Environmental Analyst, Master in Plant Diversity, e-mail: leonard.schumm@icmbio.gov.br

landslide-prone areas by quantifying, understanding, and spatializing events and conditioning factors. Using GIS tools, we collected data on geological structures and infrastructure to assess risk. As a result, a concentration of high-risk areas was identified near the CVP. Medium risk areas are centralized, while from the middle of the road to Alto da Boa Vista, the predominant areas range from low to medium risk. The most common factors are cracks in the road, loose blocks on the slopes, and cuts in the road. Therefore, on Redeemer Road, there is a combination of factors affecting safety, such as lithological-structure and geomorphological aspects, rainfall, slope and lack of maintenance of existing structures.

Keywords: Landslides. GIS. Risk Assessment.

Resumo

O Parque Nacional da Tijuca (PNT), na Serra da Carioca, Rio de Janeiro, enfrenta deslizamentos frequentes. Isso ameaça o meio ambiente e a infraestrutura, como a Estrada do Redentor, que conecta o Centro de Visitantes das Paineiras (CVP) ao Centro de Visitantes do Setor Floresta. Devido às características geológicas e ao status de área de proteção urbana, muitas metodologias não se adequam ao mapeamento e gerenciamento de riscos. Por isso, foi desenvolvida uma adaptação metodológica para mapear com ultra detalhes áreas propensas a deslizamentos, por meio da quantificação, compreensão e espacialização de eventos e fatores condicionantes. Usando ferramentas SIG, coletou-se dados sobre estruturas geológicas e infraestrutura para avaliar o risco. Como resultado, identificou-se uma concentração de áreas de alto risco próximo ao CVP. As áreas de risco médio estão centralizadas, enquanto do meio da estrada até o Alto da Boa Vista, as áreas predominantes variam de baixo a médio risco. Os fatores mais comuns são fissuras na pista, blocos soltos nas encostas e cortes na estrada. Portanto, na Estrada do Redentor, há uma combinação de fatores que afetam a segurança, como aspectos geológicos, geomorfológicos, pluviosidade, declividade e falta de manutenção nas estruturas existentes.

***Palavras-chave**: Deslizamentos. GIS. Avaliação de risco.*

Introduction

The Tijuca National Park (Paque Nacional da Tijuca – PNT) is the most visited and the smallest terrestrial national park in Brazil. In 2018, received 2.7 million people (ICMBio, 2018) (Figure 1), with a high influence of the Christ the Redeemer monument, located inside PNT's borders. Besides the monument, there is Redentor Road located in the Carioca Hills sector, connecting the Paineiras Visitor's Center (CVP) to the Floresta Sector Visitor's Center in Alto da Boa Vista. Also, it is a popular destination for tourists and locals who practice hiking and biking.

This green heart inside the second largest metropolitan area of Brazil is one of three coastal massifs that surround Rio de Janeiro city. The one that makes up part of this study, called Maciço da Tijuca, receives a lot of yearly rainfall when compared to the lowlands in the vicinity. A study done by Lima & Armond (2022) confirms that the pluviometric stations near the PNT (Rocinha and Jardim Botânico) have the highest values for precipitation. Also, this factor added to the natural conditions such as high slope, brings high levels of hazard to the population living nearby.

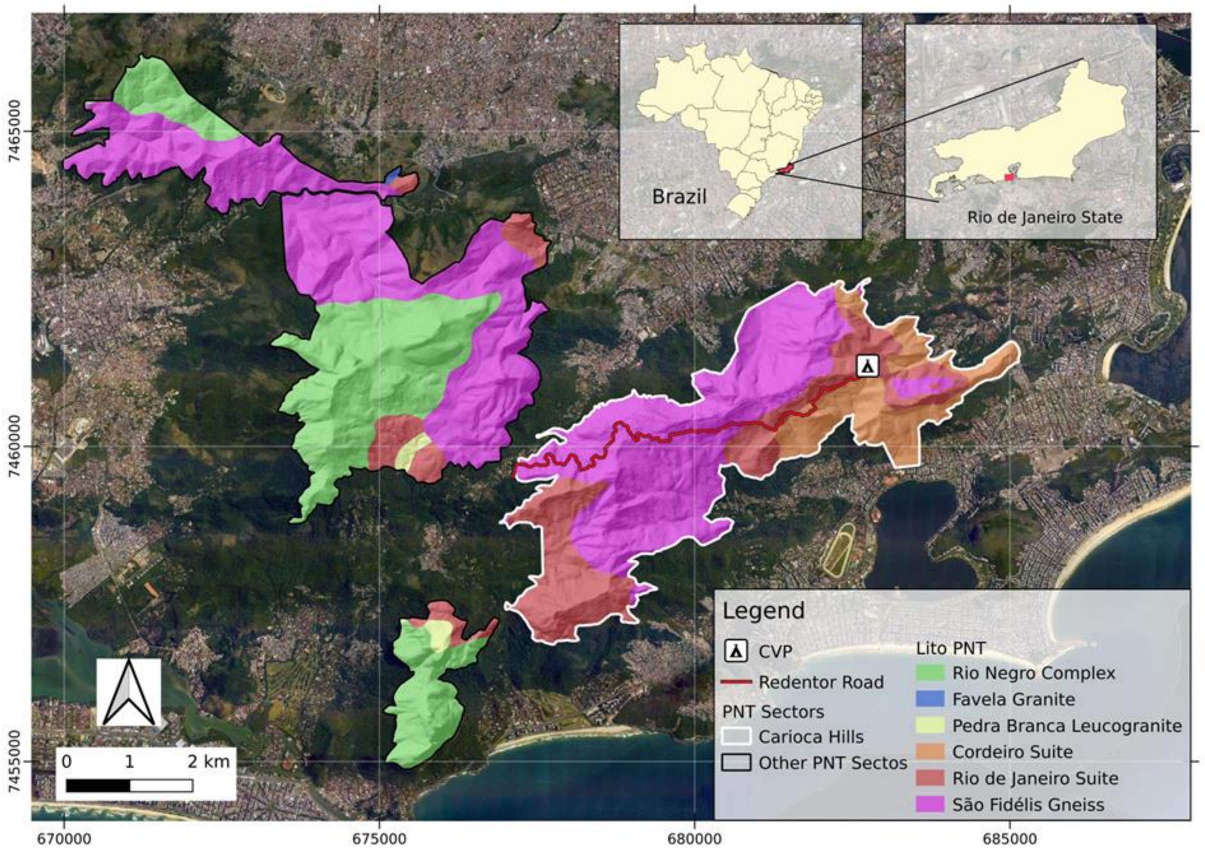

Figure 1 – Location of Parque Nacional da Tijuca (PNT) in the middle of Rio de Janeiro city and its geology. Outlined in white is the area of study: Carioca Hills Sector; in black are the other PNT's sectors; the red line is the Redentor Road. Within PNT borders, there are 6 units, and especially in the Carioca Hills Sector, there are only 3: Suíte Cordeiro, Suíte Rio de Janeiro and Unidade São Fidélis. Source: Authors (2022), adapted from CPRM (2001).

This area is marked by landslides and several occurrences of mass movements that pose danger to users of this recreational area, to fauna and flora, and to the road infrastructure itself. The roadway is frequently closed due to falling blocks and/or landslides which impacts the activities inside PNT's borders, causing access restrictions to the leisure areas and environmental impact, besides an indirect economic one.

According to Highland & Bobrowsky (2008), water is one of the three main natural triggers of landslides, whether it comes in the form of heavy and/or prolonged precipitation or by a flood. In addition, there are still natural causes, such as geological faults, terrain slope, unconsolidated materials, stratification, and rock schistosities; and human causes, such as vegetation removal, drainage detour, and water leakage from infrastructures.

Taking in account all these characteristics of PNT site, it is thought that the local geology combined with the high slope terrains, the lack of maintenance of the road structures, and the orographic rains are the determining factors for triggering landslides on Redentor Road. Besides that, it was necessary the development a methodology based on the adjustments of previous methodologies to identify hazards in roads that are situated in protected areas within urban environments.

Usually, road hazard mapping is performed on a smaller scale to cover a bigger area in minor time. Previous road hazard mapping methodologies do not deliver the PNT technical crew requirements: ultra-detailed scale mapping at low cost (time and resources). Also, the Redentor Road is only 8km long, very small if compared to regular roads. Previous road hazard mapping methodologies do not consider small structures, such as manholes. For Redentor Road, this kind of structure plays a major role in hazard mapping. With this context in mind, it can be noted that the aim of this paper is to develop a methodology for detailed hazard mapping in roads that are situated within urban environmentally protected areas and then evaluate the results of the methodological application.

Methodology

The Detailed Hazard Mapping in Urban Environment Protected Areas is an adjustment of some methodologies, such as CPRM (2018) and GEORIO (2022). It has the main objective to identify hazardous processes that are going on roads that are situated within protected areas inside the urban context. The methodology application is straightforward, being necessary three main parts: data collection, field work and data processing. During the data collection, it is fundamental to look for old landslides, scars or others evidences by satellite imagery or orthophotos and also old geological survey reports; in the field work, with the aid of GPS, cellphone camera and a booklet, all features from the road that are not in good condition should be mapped and described. Then, the processing part, all information collected will be classified according to the degree of hazardousness and the impact area. Finally, the output is the map that indicates where the areas are with the highest levels of hazard. It helps protected areas' board members to identify where the main focus of mitigation and conservation should be focused, in a very cost-effective manner.

Throughout the development of this research, it was necessary to consult a series of spatial data provided by government entities at various levels, from municipal to federal. These public, open and free data, present in Table 1, formed the fundamental basis for the analyses carried out within the Tijuca National Park.

Table 1 – List of used datasets

Data	Source
Aerophotogrametry	Instituto Pereira Passos (IPP)
Digital Elevation Model (DEM)	Instituto Pereira Passos (IPP)
PNT Cartography Basis	ICMBio/PNT
Rio de Janeiro Geologic Map 1:25.000	CPRM

Data and data source for everyone used to develop this research. Source: Authors (2022).

(1) Study Area

Parque Nacional da Tijuca is within the Guanabara Graben, and it has a variety of rocks dating from the Mesoproterozoic to the Neoproterozoic, with units that were influenced by different Brasiliano cycles (CPRM, 2001).

The lithologies that we can find within PNT are Rio Negro Complex, Favela Granite, Pedra Branca Leucogranite, Cordeiro Suite, Rio de Janeiro Suite and São Fidélis Gneiss (Figure 1).

Rio Negro Complex presents two units, the most representative of the Tijuca National Park is the one with syenitic gneisses with nepheline and sodalite, besides enclaves of basic rocks. It has a white matrix and migmatized texture (Valeriano and de Morisson, 2012).

Favela Granite occurs in the form thin dikes, intercalated with the surrounding gneissic rocks. They present a grayish color and are very homogeneous, since their texture varies from equigranular to porphyritic (Valeriano and de Morisson., 2012).

Pedra Branca Leucogranite is a porphyritic granite, rich in pertitic microcline in the form of megacrystals, which stand out from the monzogranite matrix (Valeriano and de Morisson, 2012).

Cordeiro Suite has a series of orthogneisses, however, in the PNT region, more specifically the Carioca Hills, the "Leptinitic Gneiss"/"Leptinite" predominates (Lamego, 1945; Eirado et al., 1991). These are quartz-feldspathic gneisses with white or light gray coloration, with isolated garnet crystals (Valeriano and de Morisson, 2012).

Rio de Janeiro Suite is characterized by a well foliated orthogneiss, popularly called facoidal gneiss because of the almond-shaped microcline megacrystals in the midst of a granitic and biotite-rich matrix (Valeriano et al., 2012).

São Fidélis Gneiss are quartz-feldspathic sillimanite-granada biotite gneisses. They have banding defined by the concentration of mafic (biotite) and felsic (quartz+feldspar) minerals (Valeriano and de Morisson, 2012).

The Tijuca Massif is considered the southern edge of the Guanabara Graben, which was formed during the Paleogene period in a distensional regime movement that culminated in an alkaline magmatism event - thus forming other important massifs throughout Rio de Janeiro state - and also in the formation of normal faults (Ferrari, 1990).

These local structures, according to several authors, are part of a rifting system which extends from Paraná to Rio de Janeiro, thus receiving several names: Serra do Mar Rift Systems (Almeida, 1976), Taphrogenic Basin Systems of Southeast Basin Systems of Southeast Brazil (Melo et al. 1985), Continental Rift Continental Rift of Southeast Brazil (Riccomini, 1989) and Cenozoic Rift Systems of Southeast Brazil (Zálan, 2005).

The faults mapped in the Guanabara graben show two main directions: ENE and WNW. The predominant ones in the Carioca Hills, within PNT area, are ENE-directed faults, with filling of silicified breccias (Valeriano and de Morisson, 2012).

(2) Spatial Data and Management

To find the highest landslides occurrence areas on PNT's Carioca Hills sector, 9 aerophotogrammetry imageries provided by Instituto Pereira Passos (IPP) with 1m resolution were analyzed, collected in a 16-year time range, from 1999 to 2015. All aerophotos were georreferenced in the SIRGAS 2000 UTM 23S datum with the aid of QGIS software. Having this amount of information, it was obtainable a landslide inventory map (Figure 2), as proposed in Spieker and Gori (2000,2003A, 2003B).

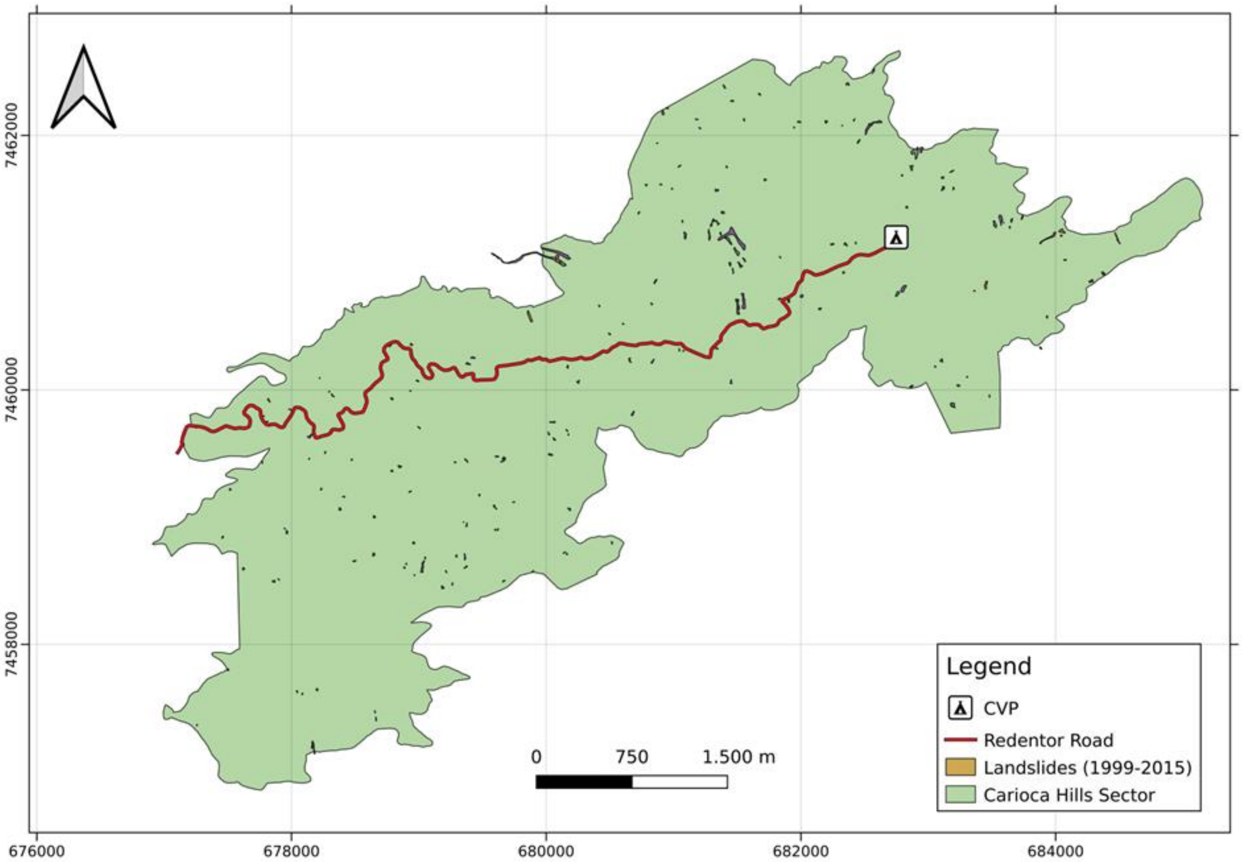

Figure 2 – The small dots and polygons within the green area show all landslides events that occurred within Carioca Hills sector from 1999 to 2015 mapped through aero photogrammetry images provided by IPP. Source: Authors (2022).

Also, a few local studies were consulted to have an idea of the main landslide triggers (Coelho Netto, 1979; Coelho Netto, 1996, Fernandes et al., 2004; Valeriano & Morrison, 2012), and in which geomofologic-geologic and structural settings these events were located in. Another consulting source was the PNT's occurrence records, besides the people who maintain the trails' knowledge. Thus, all information collected through all these sources was imputed in a data base, which facilitates future consultations, both for researchers and for the managers.

(3) Investigation and Hazard Mapping

To map the Redentor Road, it was necessary to take into consideration not only natural considerations such as geology, structural, relief, and landslides but also road and infrastructure-related features. In total, 9 structures that have some degree of hazardness were surveyed, besides showing a direct or indirect relationship with landslides and increasing erosion rate. These categories are landslide scars, road cracks, clogged manholes, containment structures, fractures rocks outcrops, falling blocks, pluvial and fluvial erosion, intermittent drainage, and road cuts.

According to Varnes (1984), hazard landslide is defined by the probability of occurrence within a certain time period and in a certain area for a potentially damaging phenomenon. The definition of hazard map includes zones that indicate the probability of a landslide occurring in an area (Spieker & Gori, 2000, 2003A, 2003B).

At all the points surveyed, data was collected such as coordinates, photos, and a description of the site, to get more detailed records of the current situation. All this information was cataloged and will be part of the PNT database for monitoring landslides.

Different from what was proposed Francisco (1996), that also mapped the risk for landslides within PNT, the approach here presented is more focused on investigating on site, instead of just using GIS tools. Then, having control of what is going on the roads makes it possible to analyze the process more closely, improving time for response.

(4) Data Processing and Data Modeling

Finally, an analysis and modeling of all the data were performed. A database was created using the previously assessed components to carry out the processing and generate the Landslide Hazard Map. During the data processing, it was noticed that each variable's radius area and each visited point were different, some impacting more locally, such as a clogged manhole, and others impacting over longer distances, such as a large landslide. Due to this interpretation, a new variable (Table 2) was assigned to weight each class and each surveyed point. Points with local impact – low influence, receive a value of up to 50m. Medium influence are those that impact up to 100m, and high influence are the ones that impact up to 150m.

After each point already had a hazard classification and radius of influence, the Heatmap algorithm of the QGIS software was used to perform the interpolation, placing the radius of influence as a weight factor. Then, assigning the color palette from cold to hot, as pointed out in Table 2.

For the terrain analyses, a Digital Elevation Model (DEM) was used, provided by the Instituto Pereira Passos (IPP), with a spatial resolution of 1m. Using the QGIS software tools, it was possible to obtain synthetic shading (hillshade), which allowed the highlighting of regional structures. In addition, the slope algorithm was also used, which, from the processing of the DEM data, had as output the terrain's inclination angle in relation to the horizontal. Such information is very important for understanding the scenarios in which landslides occurred.

In order to facilitate the interpretation of the slope of the terrain, three classification classes were created, as shown in Table 2. These classifications were developed by the authors empirically, based on discussions and assessments of local terrain characteristics. In case there is no experienced technical staff to determine the parameters during replication of the methodology, it is recommended to adapt the slope scale of the De Biase (1970).

Table 2 – Classification Table

Variable	Class	Grade
Slope (degrees)	0° - 15°	**1**
	15° - 45°	**6**
	> 45°	**10**
Distance (meters)	0 - 50	**2**
	50 - 100	**5**
	100 – 150	**7**
	> 150	**10**
Features	Intermittent drainage	**4**
	Containment structures	**5**
	Pluvial and Fluvial Erosion	**6**
	Blocked Manholes	**6**
	Road Cracks	**6**
	Road Cuts	**7**
	Falling blocks	**7**
	Fractures rocks outcrops	**7**
	Landslides scars	**10**

The table shows all three variables that have influence on landslides, with their classification, from 1 to 10, and their respective class. Source: Authors (2022).

According to the review made on Fernandes et al. (2001), the main conditioning factors for landslides are tectonic, lithostructural, geomorphological, climatic and anthropic features. Considering these main features, the elements were chosen to perform the mapping. Before selecting the Redentor Road features, there was a preliminary visit to the road to verify whether they match Fernandes et al (2001) or not.

From the sum of the classification points of the variables presented in Table 4, it is necessary to divide by 3, as shown in the formula below:

$$Hazard = \frac{slope + distance + feature}{3}$$

And then it will be possible to determine the hazard level. Such classification is an adaptation from CPRM (2018) risk level classification. If a surveyed point receives a sum between 0 and 2, it receives blue color, that means very low hazard. Between 2 and 5, it's classified as low hazard, green color. Scoring more than 5 and less than 6, it has the yellow color and medium hazard classification. More than 8, it means the point has a high hazard level and red color (Table 3).

Table 3 – Hazard Classification Index

Color	Hazard Level	Points
	Very Low (1)	H <= 2
	Low (2)	2 < H <= 5
	Medium (3)	6 < H <=8
	High (4)	H > 8

Hazard classification index after performing the calculation. Source: Authors (2022), adapted from CPRM (2018).

The rainfall intensity classification comes from Alerta Rio - GEORIO, which is a weather risk and disaster alert system managed by Rio de Janeiro's City Hall. In total, there are four categories of rainfall intensity, which take into consideration not only the amount of rainfall but also the duration, as shown in Table 4.

Table 4 – Rain intensity classification

Rain classification	Rain Intensity
Weak	R < 5 mm/h
Moderate	5 mm/h >= R < = 25 mm/h
Strong	25.1 mm/h >= R <= 50 mm/h
Very Strong	R > 50 mm/h

Rain intensity classification according to Rio's weather & risk alert system. Source: GEORIO (2022).

Results

On the Redentor Road, which is almost 8km long, 134 points were mapped, broken down in quantity of occurrence in Figure 3. The classes that were mapped the most along the roads were Road Cuts (36), cracks in the pavement (27) and manholes (22).

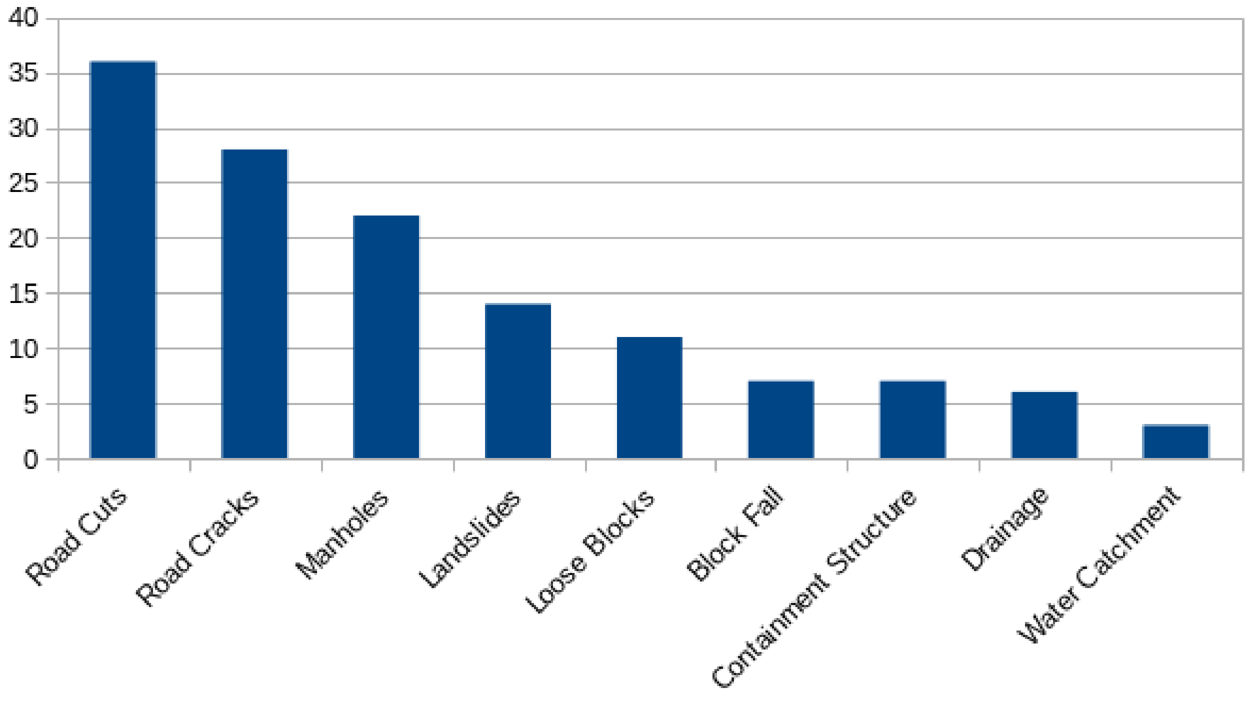

Figure 3 – Classes that were mapped the most during the research's investigation phase. Source: Authors (2022).

There are two types of road cuts: rock and soil. In most cases, the rock cuts have a high density of fracture families, which favors the fall of blocks (Figure 4).

Figure 4 – Biotite-Gnaisse outcrop in an advanced stage of weathering with its high angle bedding leaning towards the road. Source: Authors (2022).

On the other hand, soil cuts often present a high erodibility rate, and record small mass movements, resulting in destabilization of the cut, exposure of roots (Figure 5). All these consequences result in increasing even more the erodibility rate, especially in periods of high rainfall, since the rain has the ability of causing erosion due its kinetic energy of the raindrops summed to the area slope and soil characteristics (Roose,1978).

Figure 5 – Road cut in soil with a small mass movement and roots exposure, culminating in the increase of erodibility rate and hazard level. Source: Authors (2022).

Gravitational mass movement and erosive processes are related but different processes. According to the World Landslide Inventory (1990), the landslide definition is 'the movement of a mass of rock, earth, or debris down a slope.' On the other hand, McCool & Williams (2008), states that soil erosion happens because of the force of the wind and water, dislodging the soil particles, further being transported and then sedimented in another place.

Despite being different processes, both of them happen within the park boundaries. In many points visited you could see one or another happening. In many cases, products of erodibility process can lead to some infrastructure interference. For example, several manholes, responsible for directing water to the natural drainage of the PNT, were blocked by sediments (Figure 6), and generally, in the vicinity, there were a series of cracks with decimetric extensions and 5cm of road gap on average, thus indicating an accommodation and/or subsidence of the terrain (Figure 7).

Figure 6 – Manhole completely clogged by sediments coming from a drainage in Central sector. Source: Authors (2022).

Figure 7 – Road cracks with significant displacement nearby a clogged manhole, indicating subsidence towards downstream. Source: Authors (2022).

Another class with significant impact, but in smaller quantity than the three above mentioned, are the GMM. In total, there were 14 landslides, with predominance in areas with medium to high slope, represented in Figure 8 by light blue and dark blue color, respectively. These points are located mainly in the central and east sector of Redentor Road.

All data analyzed resulted in the Hazard Map for the Redentor Road, with locations where there is danger, divided into three sectors (West, Middle and East), in order to facilitate data interpretation. The East and Middle sectors have longer zoned in which the danger level is medium or high, in relation to the West sector (Figure 8).

In the eastern and central sectors, there is a greater occurrence of landslides, road cuts in rock without alteration, and a greater presence of water. In the western sector, no landslides were registered, and the events with the highest erodibility rate are linked to road cuts, which are mostly cuts in soil. Talking about water presence, it is notable that the sector is drier when compared to the ones, with a smaller amount of intermittent drainage and no water appearance in the rocks.

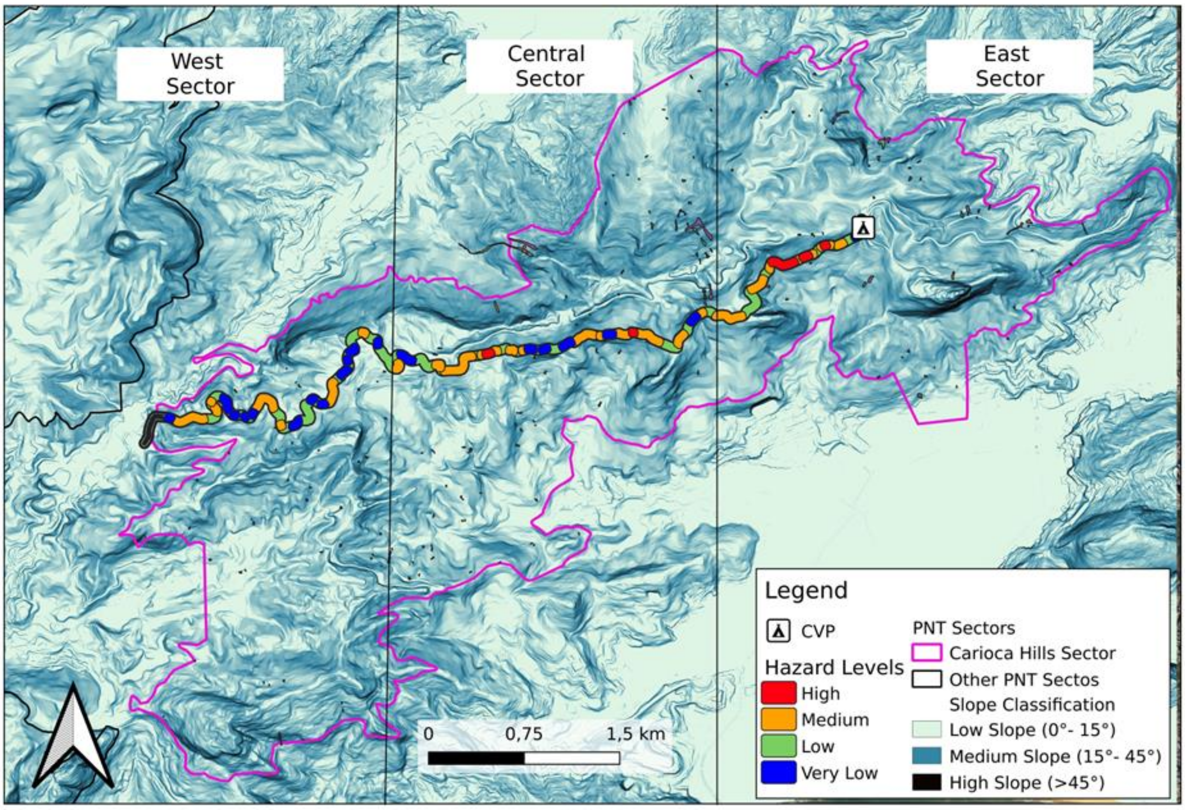

Figure 8 – Slope and Hazar Maps around Redentor Road. The slope classified as low is represented by a light blue color; medium slope is in blue and high slope in black. The classification for slopes is presented in Table 2. The colors and hazard classifications are described in Table 2. The road was segmented in three sectors in order to facilitate the interpretation. Source: Authors (2022).

In Redentor Road, there are 3784.3m of low hazard zones (47.46%), it is the longest length classification. Then, the second longest is the medium hazard zone, with 2743.7 meters (34.42%). The least common hazard classes in length are very low with 1091m (13.66%) and high with 353.2 meters (4.46%).

Discussion

Overall, the methodology is not complex, and it has a low cost. Due to this, it is not necessary to collect samples and make laboratory analyses, nor does it require expensive equipment or software licenses. Simple tools like GPS, mobile, a geology compass, and a hammer are already enough to map and map the hazard areas in the interested area.

The concentration of points and the level of hazard in each sector of Redentor Road is directly related to the different characteristics found along the road. For example, the greater presence of intermittent drainage in the eastern and central sectors is since these sectors have their mountain face facing the sea, with a higher concentration of humidity and cloud retention. Besides this, there is also the fact that it is an area with greater slope and altitude.

Naturally, during the construction of the road, several road cuts had to be made, a very common procedure. If we take into consideration that it is an 18th century engineering work, it is reasonable to say that its condition is so poor, since mitigation surveys are rare. Many of these road cuts have block falls due to the ENE and WNW fracturing pattern in the outcrops, and cuts in soil with a high erosion rate due to high degree of saturation, causing a high rate of runoff and surface sediment carriage.

This fracturing pattern, which reflects the regional geology, can also be seen in the banding of the biotite-gnaisse, presenting a sagging to the road. The landslides might happen because of consolidated material characterized by a high degree of fracturing and friability. Ideally, the cuts in banded rocks should always be done perpendicularly, thus avoiding cutting the layers, resulting in a lower probability of debonding. If this is not possible, as was the case at some points on Redentor Road, the correct thing to do is to apply some kind of containment structure, avoiding greater damage. In addition, these exposed rocks are highly susceptible to weathering (Toledo, 2014). This, added to the ease of weathering, increases the hazard in the area. According to Highland & Bobrowsky (2008), oriented structural discontinuity is one of the triggering mechanisms of landslides.

Most clogged manholes are in sectors with higher water presence. The reason for clogging is the presence of several drainage channels, which may be intermittent or not, and end up carrying many sediments of the most varied types, from silty fraction to rolled blocks. Therefore, the water is not properly drained by the drainage system, thus flowing through the road and its cracks. These cracks, as shown in Figure 6, sometimes present long extensions, reaching up to 30m in length.

These asphalt displacements, in most cases, had a vertical variation of up to 5 cm, which indicates a creep, and eventually may culminate in a landslide. Most likely, the relationship between these two features, clogged manholes and cracks in the asphalt, are because water infiltrates into the soil layer below the asphalt, and also because of the intense flow. These two processes cause the carrying of these supporting sediments, thus causing the asphalt layer to settle.

Due to the correlation of these two classes, it can be said that there are two landslide triggering mechanisms: runoff or rapid filling of structures (natural physical cause), in addition to water leakage from infrastructure (human cause), as classified in Highland & Bobrowsky (2008). This brings an increased degree of hazard on the road, especially in times of higher rainfall intensity that can lead to a landslide.

The landslides, which have a higher concentration in areas with medium to high slope, are found in a region with very strong topographic control, as pointed out by Fernandes et al (2004). According to PNT's employees, the Sumaré Road, located above Redentor Road in the East and Central Sector, also has infrastructure problems, such as lack of rainwater channeling, which causes an inappropriate discharge, and consequently, increasing erodibility rates. This, added to the high slopes and altitudes of this part of the Carioca Hills, brings even more strength to the landslide trigger factors, thus justifying why the 14 landslides were concentrated in these two sectors.

Another relevant point in the high incidence of landslides, besides geological, geomorphological and structural issues, are frontal and convective rains. Unlike what was hypothesized, orographic rains in the summer hardly have a significant impact on the issue of water volume, but convective rains caused by heat islands and sea breeze circulation do (Freitas et al 2007, Dereczynski et al 2013, Silva Dias et al 2013), large frontal systems, in addition to the South Atlantic Convergence System (ZCAS) that produces a significant volume of precipitation in the southeast region of Brazil during the summer (Cavalcanti et al 2015). In the Fluminense Mountain Region, the ZCAS was responsible for two extreme rainfall events in 2011 and 2022 – the last one more concentrated in Petrópolis downtown. With rainfall volume of one month in a couple of hours, these events triggered a large amount of landslides, leading to the death of hundreds of people, damage of infrastructure.

Although the landslides within the PNT areas are not on the same scale as those in the events, it can still be said that there is a possible correlation between the events and these types of rainfall.

Conclusion

The methodology proposed for Hazard Mapping in Urban Environmental Protected Areas proved to be easy, replicable, and adaptable to the protected areas in urban zone specificities. Also, it delivers a level of detail that helps to understand where the most important problems are and where to apply mitigation efforts. While the high level of detail is one of the principal advantages, it can also be a restriction depending on the road size. Long roads on ultra-detailed surveys will desire long work time.

These characteristics made the methodology responsive in relation to the data collected and evaluated, bringing satisfactory results. However, validation in other protected areas is necessary in order to make further improvements in the methodology, guaranteeing the best performance of its application, and then the creation of a common basis for hazard scale in protected areas.

When mapping the road to develop a Hazard Map, it was found that there are several road cuts, which occur both in rock and soil. The rock road cuts have a higher concentration in the eastern and central sectors of Redentor Road, while the soil road cuts prevail in the western portion. Other classes with predominance are clogged manholes and road cracks, also concentrated in the East and Central sectors. In the vast majority of times, they present one next to the other, indicating that there is a correlation of cause and consequence between the manholes and the cracks.

The Parque Nacional da Tijuca, which is the smallest park in Brazil and also the most visited, is responsible for much of Rio de Janeiro's beauty. However, it is also a place that concentrates many erosive processes and mass movements due to its geological, geomorphological, structural and climatic conditions. Redentor Road, an important road connecting the Paineiras Visitors Center to the headquarters of Parque Nacional da Tijuca, in Alto da Boa Vista.

Another highlight point is the landslides, which are also prevalent in the East and Central sectors. These sectors of the road have a higher rainfall load because they are more exposed to the rainfall mass compared to the West sector. Besides that, they also have greater slopes and Sumaré Road in the upper part without the necessary infrastructure for water dispersion. All these attributes culminate in the increase of water runoff, carrying sediments and increasing the rate of erosion and/or landslides.

Therefore, it can be concluded that the problems involving landslides and erosion on Redentor Road are the sum of several factors, ranging from natural issues to human action. The most critical zones are those present in the East and Central sectors, reflected by the Hazard Map in red, much in function of the greater presence of water, greater slope, and litho-structural constraints, such as rocks high degree of fracturing, friability and regional faulting.

One issue that went against initial thoughts is the fact that orographic rainfall does not have a large influencing factor on landslides, since it has less volume and lower intensity than convective and frontal system rainfall, which happens especially in summer (Freitas et al 2007, Dereczynski et al 2013, Silva Dias et al 2013, Cavalcanti et al 2015).

In view of all these problems raised along the Redentor Road, it is recommended the following topics:

(a) Periodic surveys along the Road to evaluate the conditions.
b) Development of a study and application of this methodology on Sumaré Road.
c) Evaluation of the danger in the highlighted areas and start mitigation plans.
d) Cleaning of the manholes during rainy periods.
e) Maintenance of the existing containment structures.

To conclude, this methodology is simple and offers potential improvement in the user's (visitors) safety of protected areas within the urban context. It was observed that it does not need a big personnel team; brings more detail about the situation on the roads when compared to previous methodologies, and with a positive cost-effective. However, it needs to be improved in terms of standardization of road features and validate the rain classification for other regions that don't have similar rainfall data patterns as in the present area of study. New studies adjusting these factors can be performed in the future.

Data availability statement

The dataset that supports the results of this paper is available at SciELO Data and can be accessed via https://doi.org/10.48331/scielodata.VCGIKW.

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