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Land Degradation Mapping Using Integration of Remote Sensing and Geographic Information Systems in Maricá, Rio de Janeiro, Brazil

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Abstract

The purpose of this paper is to study the growing problem of soil erosion in the municipality of Maricá, Rio de Janeiro, Brazil. The study area has an excellent agricultural condition. However, due to human and natural factors, water erosion is becoming a major problem. Therefore, new approaches are needed to determine soil degradation not only for the identification of hotspots, but also to identify areas prone to degradation to develop appropriate land management policies. Mapping of water erosion was assessed according to methodology of the United Nations Environment Program/Priority Action program using different images from Landsat8, Airbus on Google Earth Pro, and ESRI Land Cover 2023 to identify the dominant erosion process, stable areas types, and producing land degradation and conservation priority maps. Results showed that stable areas spread over 200.22 km^2, while about 21.23 km^2 is considered as unstable areas. Additionally, a prioritization procedure was identified to determine hot spot areas for remedial measures, results showed the unstable areas which should have priority in conservation form about 22.14 km^2. Besides, a land use/land cover change detection procedure was done to investigate those changes using Landsat 1985 and 2022 images, showed a significant increase (14.49%) in urban area at the expense of decrease in wetland (–1.70%), pasture (–3.44%), and mosaic of uses (–9.70%). The results lead us to a conclusion that the increase in areas of urbanization and pasturelands were in forestlands, where large areas of the rolling hills and gentle mountain slops have been deforested. This finding suggests a set of remedial measures for soil conservation and for recovery of degraded areas to be applied to those hot spots.

Keywords: Land degradation, soil erosion, change detection, remote sensing, geographic information system (GIS), Maricá

INTRODUCTION

The municipality of Maricá is situated in the state of Brazilian state of Rio de Janeiro, to the east of Guanabara Bay, at 22º 55' 10" south latitude and 42º 49' 07" west longitude (Figure 1). Maricá is known for its rural properties – small farms and large ranches and has an area of 361,572 km^2 with population of 197,277 inhabitants and is considered among the highest growth rate in the state of Rio de Janeiro [1]. Since the 1970s, with the construction of the Rio-Niterói bridge and the Via-Lagos highway in 1996, all municipalities in the Região dos Lagos have experienced significant population growth. According to the classification proposed by Muehe and Valentini [2], Maricá belongs to the so-called Região dos Lagos in the southern coast, characterized by extensive beach arcs associated with transgressive coastal barriers. Its east-west

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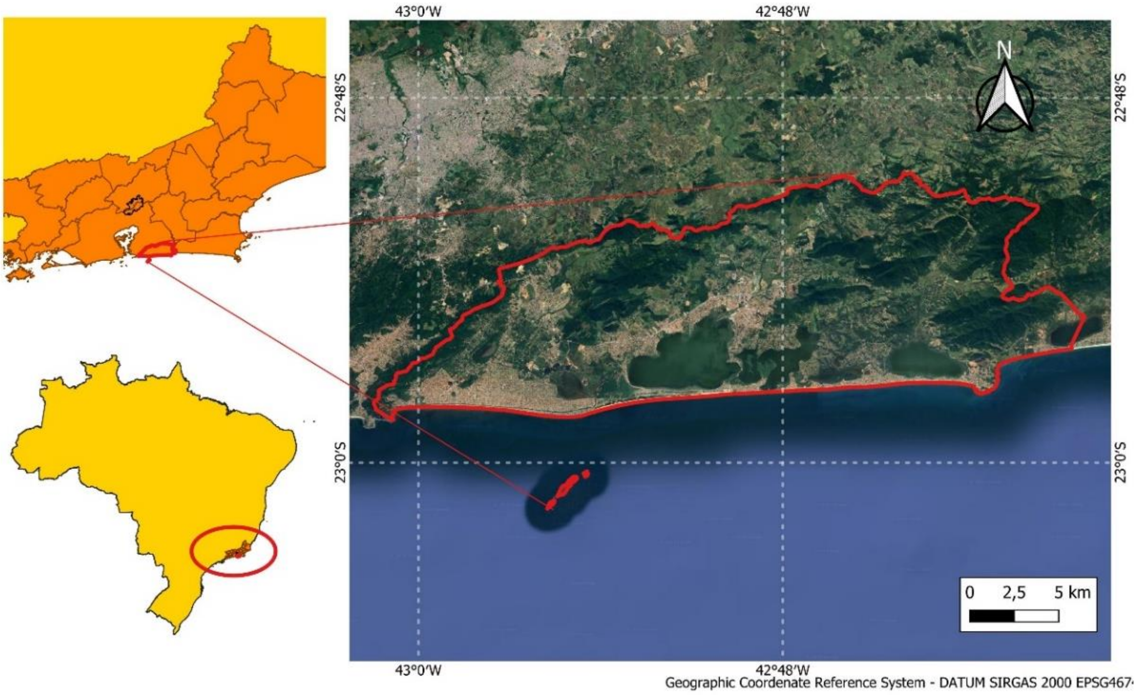
orientation and the near absence of natural protections make this coastline highly exposed to strong storms originating from the southern quadrant. The municipality is surrounded by coastal massifs, which form an arc, with a series of mountain ranges where the highest point up to 890 m, covered by the Atlantic Forest ecosystem. Another important formation is the vast coastal plain, between the bases of the massifs and the coastline. The municipality has one of the largest lagoon complexes in the state, called Maricá-Guarapina, with rivers, lagoons, streams, marches, and artificial channels that connect the lagoon complex to the sea, such as the Ponta Negra and Itaipuaçu channels.

The climate of municipality is classified as tropical, indicates a significant amount of annual rainfall, with a short dry season and a predominantly wet season during the summer. Maricá experiences hot, humid summers (annual average temperature is 23.4°C) and mild winters, with January being the warmest month and July the coolest. The region receives substantial rainfall (annual average rainfall of 1034 mm), primarily concentrated in the summer months. According to data from the National Institute of Meteorology (INMET), the highest accumulated precipitation in 24 hours was 141.6 mm on April 6, 2010, while the lowest was 104.7 mm on February 12, 1998 [3]. The municipal territory corresponds to the hydrographic basin of the large lagoon system, a very rare fact. In this way, practically all rivers are born and flow within the municipality. Its main river is the Ubatiba/Mombuca, which is no more than 20 m wide, but which supplies the city center and some neighborhoods. According to the digital soil map of the world, Maricá soils belong to two main classes Orthic Acrisols (Ao6-3b), and Dystric Gleysols (Gd3-3a) [4].

Soil erosion is becoming a major environmental problem in several areas of Maricá municipality due to many factors as inappropriate agricultural practices, urban expansion, deforestation, and heavy rainfall. Moreover, a lot of rolling hills and gentle mountain slops have been turned into areas with spares vegetation cover unable to protect soil from water erosion and run off. Consequently, if soils are not properly protected and managed, water erosion leads to a decrease in soil productivity in the short term and to complete soil degradation in the long term, as well as may produce catastrophic damages resulting from the runoff and landslides caused by the heavy rain. A lot of the Brazilian studies concluded that soil degradation is triggered by the removal of natural vegetation [5–8].



Marica Municipality Location Map

Figure 1. Location map of Maricá Municipality, Rio de Janeiro.

Besides, areas where the vegetation has been converted to pastures or cultivated crops and those with steep slopes and heavy rainfall are more susceptible to soil erosion and degradation [9, 10]. In addition, deforestation is associated with forest fragmentation, which increases forest vulnerability to soil erosion. Many parts of the world have witnessed severe deterioration of land and soils in the last century which is globally ongoing due to unsustainable land use, deforestations and climate change. Soil degradation has been a key factor in the collapse of various civilizations throughout history [11–13]. About 23% of the globe's terrestrial area is already degraded and the estimated current rate of arable land loss due to land degradation is 30 to 35 times the historical rate [14]. It is estimated that land degradation costs the global economy between 18 and 20 trillion USD annually [15]. Despite advances in scientific knowledge and extensive local knowledge regarding soil conservation, soil degradation continues and soil conservation programs do often not reach expectations [16].

Therefore, new approaches based on satellite data and geographic information system (GIS) are needed to determine soil degradation not only for the identification of hotspots, but also to identify areas prone to degradation to develop appropriate land management policies [17–21]. These techniques can integrate data from different sources; satellite images, aerial images, topographic maps, thematic maps, reports, and field works in erosion mapping. Erosion mapping is a very essential tool for the assessment of the distribution and geographic extent of the phenomena, as well as for its qualitative characterization, and combating land degradation. Huge number of scientific articles is published annually on soil erosion using remote sensing and GIS techniques [22–27]. The current research uses the methodology of the United Nations Environment Programme (UNEP), Priority Actions Program Regional Activity Centre [28, 29] to investigate the problem of land degradation in the study area. Many water erosion publications have demonstrated their reliability by using this consolidated UNEP/PAP/RAC approach for the assessment of land degradation [1, 18, 30–36]. This approach is conducted for the first time in the municipality of Maricá. The primary objectives are to evaluate the water erosion process by defining its type, distribution, grade of extent, and the expansion trend, as well as applying prioritization procedure to define the main hot spots in the study area in order to apply successful land degradation control measures.

MATERIAL AND METHODS

The investigations of soil erosion in Maricá municipality were carried out using modem remote sensing techniques and modern methods of mapping of erosion processes with the aid of GIS. The study activities, which have been completed in about 3 months, consist of image interpretation, land surveys and field work, as well as office work. The current study applied Landsat 8 images taken in 1985 and 2023, images of Airbus 2024 on Google Earth Pro, as well as images form ESRI land cover 2023. Mapping of water erosion in the study area was assessed according to the methodology of Mapping of Rainfall-Induced Erosion processes [28, 29], this descriptive soil erosion approach consists of two procedures; images interpretation and field observation, and divide any areas into stable areas (non-erosion affected areas) or unstable areas (erosion affected areas). For the stable areas we defined the grade of erosion risks and causative erosive agents; and for the unstable areas we defined the type of dominant erosion process, its relative intensity and evolutive trend, as follows [37].

Defining the Stable/Stabilized Environments

For the stable/stabilized environments, we defined the type, grade of instability risk, and causative agent of this risk. The classifying process was applied to the four dominant types of stable areas in Maricá as follows:

- 001 stable, unmanaged areas with potential for forestry use only
- 02 stable, unmanaged areas with agricultural potential (crops and pasture)
- 03 stable, managed areas with forestry use only
- 04 stable, managed areas with agricultural use (crops and pasture)

Grade of Instability Risk

Assessment of instability risk for all stable areas was expressed by a complementary digit (0 to 3) to the original stable unit's code as follow: 0: No risk (highest grade of stability), 1: Low to moderate risk, 2: High risk, 3: Areas in hazardous/critical state (highest grade of instability risk).

Dentification of Main Causative Causes

Instability risk assessment may be reinforced by the identification of its most probable/prevailing causative agents inherent in the landscapes, main basic components, namely: t: topography, g: geology, v: vegetation, h: human activities, and a: animal activities (trampling)

Defining the Unstable Environments

For the unstable environments we defined the type, grade of extent, and expansion trend. The classification process was applied to the dominant types of unstable areas in the study area which are sheet erosion (L), and rill erosion (D), followed by these two procedures:

- *Define the grade of extent:* Assessment of the extent rate for the sheet and rill areas was expressed by a complementary digit (1 to 3) to the original unstable unit's code as follow:1: Localized (<30% of the area is affected), 2: Dominant (30%–60%), 3: Generalized (>60%).
- *Define the erosion expansion trend (rate):* Assessment of erosion rate/trend for all unstable erosion-affected areas was expressed by a complementary digit (0 to 3) to the code: 0: Trend to stabilization, recession or limitation of spatial expansion, 1: Trend to local expansion or intensification, 2: Trend to widespread expansion or intensification, 3: Trend to increase generalized degradation towards an irreversible state.

Prioritization of Future Intervention Areas (Hot Spots)

The prioritization procedures play a significant role in applying the remedial measures where necessary. After defining the stable and unstable areas inside Maricá, a prioritization procedure on the descriptive erosion map was developed to apply successful land degradation control program. The prioritization procedure used 14 parameters based on the results of the descriptive mapping with the aggravating socioeconomic conditions (such as overexploitation, rural exodus, land tenure) and further considering actual and potential land use values according to different views, notably the perception of the local population, established national policies and assessment of potential for forestry, agricultural use and other land use forms. For the different criteria, a rating grid from 1 (lowest possible score) to 3 (highest possible score was applied for those 14 parameters as follow [18, 38]:

1. Physical instability risk (for stable areas, in compliance with the descriptive mapping code): 1: no or low to moderate instability risk; 2: high instability risk; 3: critical instability risk.
2. Extent of area affected by a specific degradation process (for unstable areas, in compliance with the descriptive mapping code): 1: localized extent, i.e., less than 30% of the area affected; 2: dominant extent, i.e., 30% to 60% of the area affected; 3: generalized extent, i.e., more than 60% of the area affected.
3. Expansion trend of a specific degradation process (for unstable areas, in compliance with the descriptive mapping code): 1: no expansion or only trend to local expansion; 2: trend to widespread expansion; 3: trend to generalized degradation towards an irreversible state.
4. Multiplicator for increased importance of unfavorable combination of causative agents (for stable areas) or for increased importance of a specific degradation process (for unstable areas): 1: no increased importance; 2: increased importance; 3: highly increased importance.
5. Influence on adjacent areas: 1: no or low negative influence on adjacent areas; 2: highly negative influence on adjacent areas; 3: critical negative influence on adjacent areas.
6. Overexploitation as aggravating socioeconomic factors: 1: no or insignificant influence; 2: significant influence; 3: crucial influence.
7. Rural exodus as aggravating socioeconomic factors: 1: no or insignificant influence; 2: significant influence; 3: crucial influence.

8. Land tenure as aggravating socioeconomic factors: 1: no or insignificant influence; 2: significant influence; 3: crucial influence.
9. Other aggravating socioeconomic factors: 1: no or insignificant influence; 2: significant influence; 3: crucial influence.
10. Value of current land use according to the point of view of the local population: 1: low value; 2: increased value; 3: high or crucial value.
11. Value of current land use according to the national policies: 1: low value; 2: increased value; 3: high or crucial value.
12. Potential for forestry: 1: low potential; 2: increased potential; 3 high or crucial potential.
13. Potential for agricultural use: 1: low potential; 2: increased potential; 3 high or crucial potential.
14. Other land use potentials such as recreational use, construction sites, industrial activities: 1: low potential; 2: increased potential; 3 high or crucial potential.

After giving a score for each criterion to the identified areas, the final prioritization scores were calculated by applying these two equations:

- Priority for stable areas =[(A * D + E) * F * G * H * I] + [(J + K) * L * M *N]
- Priority for unstable areas = [(B * C * D + E) * F * G * H * I] + [(J + K) * L * M *N]

In a final step, the final scores were grouped into priority classes:

- High priority for application of measures (priority class 3): 60 points and more as final score
- Medium priority for application of measures (priority class 2): 21 to 59 points as final score
- Low priority for application of measures (priority class 1): 20 points and less as final score

RESULTS AND DISCUSSION

In total, about 149 sites have been described using images of ESRI Landcover 2023, and Airbus 2024 on Google Earth pro. For each site we identified the type, grade of risk and causative agents for the stable area, as well as the type, grade of extent and expansion trend for unstable areas. Based on this description and investigation, the descriptive erosion map for Maricá was finalized, as shown in Figure 2. According to the Maricá descriptive land degradation map most of the areas are stable environments which are not affected by active erosion, as shown in Table 1, where the stable areas spread over 200.22 km^2 which form 55.38% of the study area with the main causative agents of risk instability belong to human activity.

It is remarkable that the “Managed Areas with Forest Use (03)” class is the predominant form of stable areas spread over 85.13 km^2 and form about 23.54% of the total area. This category is mainly dominant to the western and northern parts of Espraiado and east of Manoel Ribeiro city, where the relief is characterized by a dense presence of forest as well as a mountainous structure climb up to about 720 m.

While the category of “Unmanaged Areas with Forest Potential (01)” come second and spread over 71.03 km^2 and form about 19.65% of the total area, and mainly dominant to the southern parts of Maricá city, where the relief is less complex with fragments of original forest are structurally isolated from each other by a matrix of human settlements, pastures, plantations, and roads. However, a few large remnants of Atlantic Forest still exist and persisted in the landscape mainly because of its steep terrain, or because of mandatory legal reserves.

Table 1 also show that about 21 km^2 equal to 5.9% of the total area is covered by unstable zones in which sheet and rill erosion are active. The “Generalized Sheet Erosion (L32)" category is the predominant form of unstable area; it covers about 12.03 km^2 and this form about 3.4% of the total area, while the "Dominant Sheet Erosion Category (L22)" spread over 5.9 km^2 and form about 1.6% of the total area.

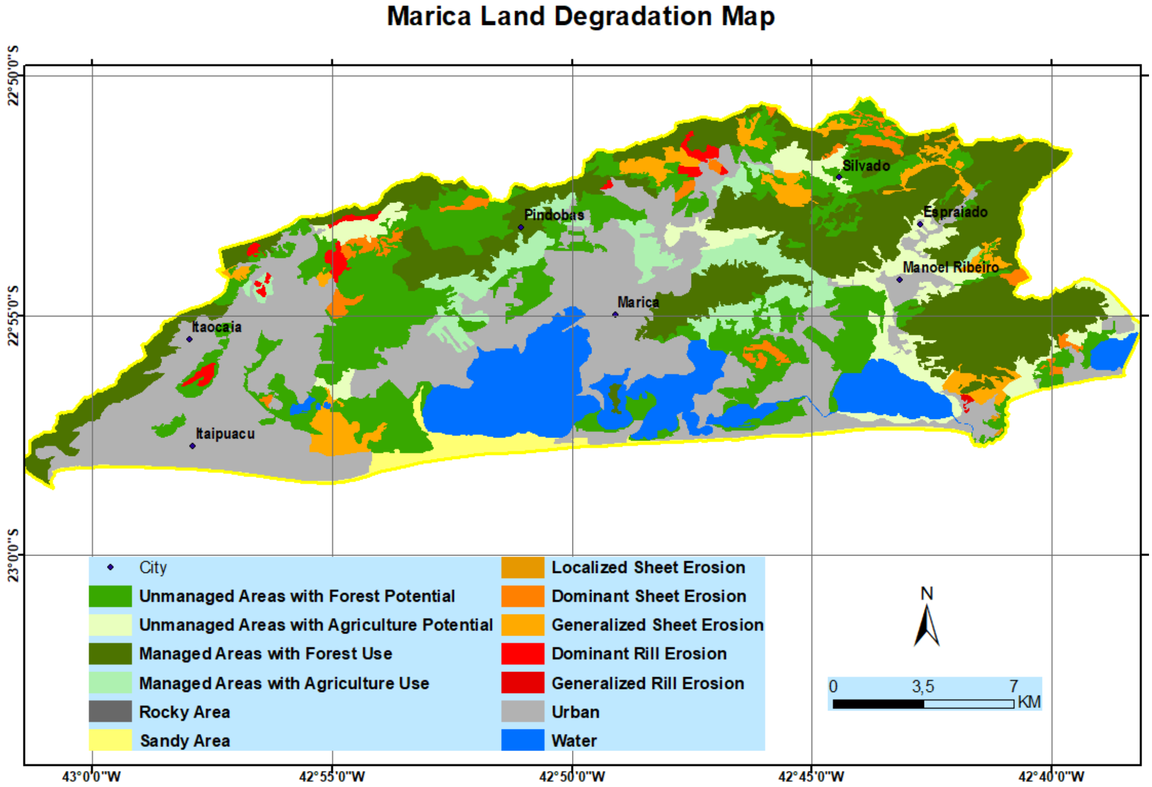


Figure 2. The stable and unstable areas of Maricá map.

Table 1. Land degradation state with area measures of Maricá.

	Code	**Type**	**Area (km^2)**	**Area (%)**	**Area (hec)**
Stable Areas	0R	Rocky Area	0.055	0.015	5.492068
	0S	Sandy Area	7.040	1.947	704.0144
	01	Unmanaged Areas with Forest Potential	71.033	19.646	7103.303
	02	Unmanaged Areas with Agriculture Potential	18.951	5.241	1895.107
	03	Managed Areas with Forest Use	85.130	23.545	8513.048
	04	Managed Areas with Agriculture Use	18.014	4.982	1801.398
			200.22	**55.38**	20022.36
	U	Urban	102.50	28.35	10250.26
	W	Water	37.29	10.32	3729.46
Unstable Areas	L1	Localized Sheet Erosion	0.312	0.086	31.23614
	L2	Dominant Sheet Erosion	5.842	1.616	584.2187
	L3	Generalized Sheet Erosion	12.031	3.327	1203.106
	D2	Dominant Rill Erosion	2.904	0.803	290.3931
	D3	Generalized Rill Erosion	0.144	0.040	14.41668
			21.23	**5.88**	**2123.37**
		Total	361.254	99.912	36125.45

In general, the generalized sheet erosion areas mainly surrounding Silvado city in the northeastern parts of the study area. While the dominant sheet erosion areas spread to the north of Itaocaia. These unstable areas are dominant by a relief of hills with sparse vegetation cover increased local instability and led to different degrees of water erosion. The replacement of forest by pasture, and anthropic activities such as inadequate road planning, are the main factor that trigger degradation processes in this Brazilian region [39].

Besides contributing to accelerating climate change, the removal of native vegetation is associated with increased soil degradation. According to the Global Forest Watch (GFW) [40] in 2010, Maricá had 17.4 kha of tree cover, extending over 48% of its land area. In 2023, it lost 37 ha of tree cover, equivalent to 21.8 kt of CO_2 emissions. In Maricá, the peak fire season typically begins in mid-February and lasts around 11 weeks, from 2001 to 2023, Maricá lost 271 ha of tree cover from fires and 782 ha from all other drivers of loss. The year with the most tree cover loss due to fires during this period was 2017 with 157 ha lost to fires — 53% of all tree cover loss for that year. Fires were responsible for 26% of tree cover loss in Maricá between 2001 and 2023. Furthermore, in 2000, Maricá had an aboveground live woody biomass density of 152 t/ha, and a total aboveground biomass of 2.77 Mt [40].

Additionally, the assessment of the prioritization procedure presented in Maricá land conservation priority map (Figure 3), showed the distribution of hot spots and where conservation priority classes should be applied over the study area. In addition, the priority classes with their areas were calculated in Table 2. The result of the procedure showed that about 37.55 km^2 consider as stable medium priority, 48.34 km^2 stable low priority, and 8.40 km^2 stable high priority. Those areas suffer from instability risk due to human activities as deforestation and transforming forestlands to other uses. The categories of stable medium priority and low priority (light greens) in Figure 3, spread mainly over those unmanaged areas with potential for forest and agricultural use to the south and north of Maricá city. While the stable high priority (dark green in Figure 3), spread mainly to the south of Itaocaia, surrounding Pindobas, and east of Manoel Ribeiro. Besides, the prioritization procedure showed that the area of unstable environments in the study area which need priority in conservation form about 22.14 km^2; where 12.54 km^2 fall into the high priority class, 9.46 km^2 classified as unstable medium priority class, and 0.13 km^2 as unstable low priority class. For these unstable areas, the unstable high, medium, and low priority areas in Maricá were identified as unstable areas showing active erosion processes mainly due to generalized sheet erosion (L32), dominant sheet erosion (L22), localized sheet erosion (L11), dominant rill erosion (D22), and generalized rill erosion (D31).

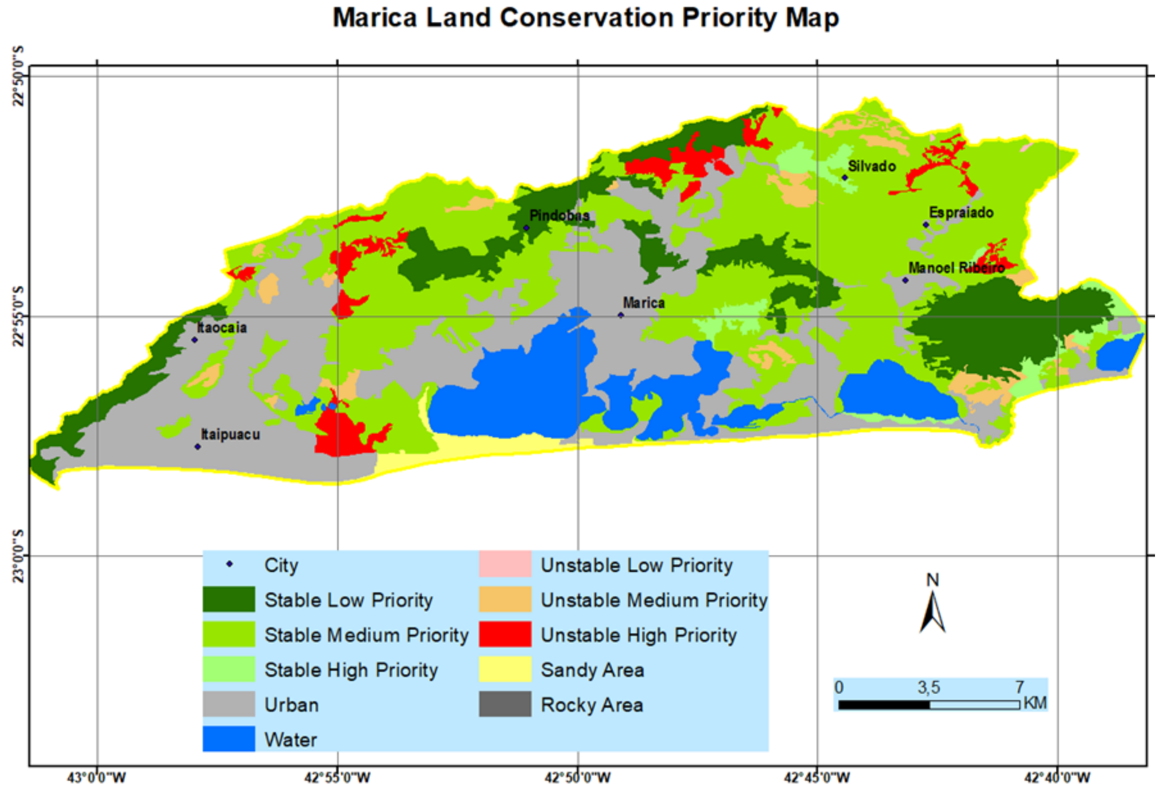


Figure 3. Maricá land conservation priority map.

Table 2. Conservation priority classes with areas in Maricá.

Area Type	**Conservation Priority**	**Area (km^2)**	**Area (%)**	**Area (hec)**
Stable Areas	Stable Low Priority	48.337	13.369	4833.706
	Stable Medium Priority	135.788	37.555	13578.79
	Stable High Priority	8.406	2.325	840.6296
	Rocky Area	0.055	0.015	5.492068
	Sandy Area	7.040	1.947	704.0144
Unstable Areas	Unstable Low Priority	0.134	0.037	13.38692
	Unstable Medium Priority	9.460	2.616	946.0087
	Unstable High Priority	12.546	3.470	1254.594
Urban		102.485	28.344	10248.54
Water		37.003	10.234	3700.281
Total		**361.254**	**99.912**	**36125.45**

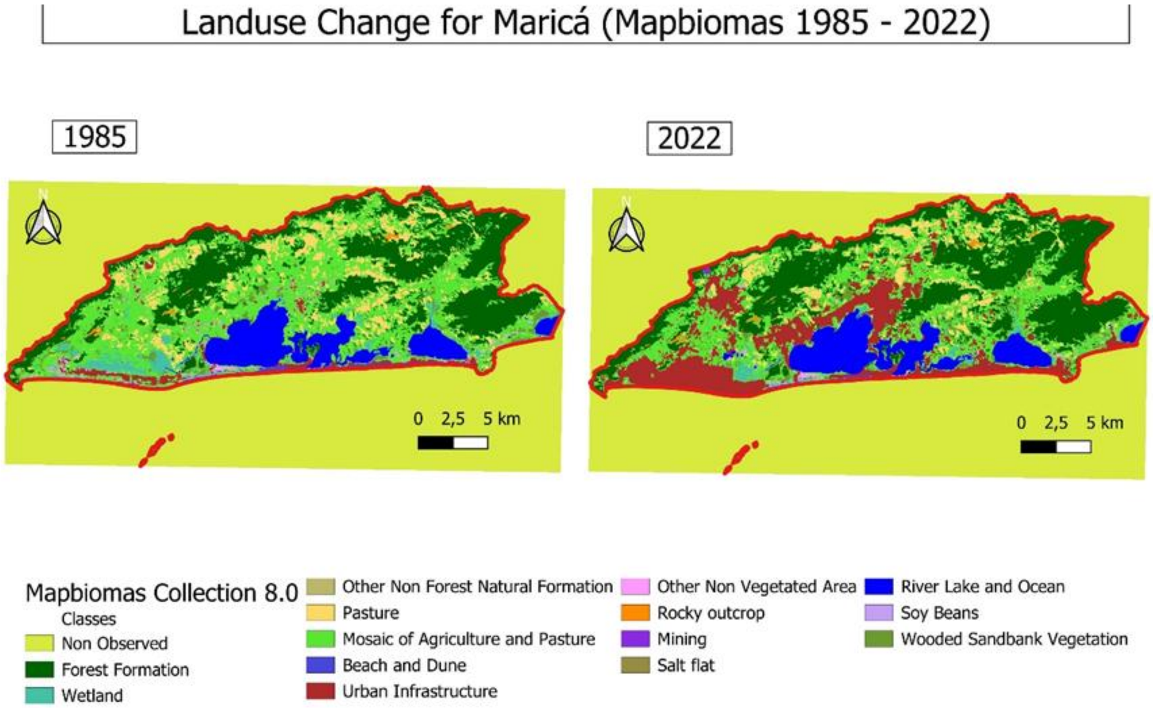


Figure 4. Maricá land use/land cover changes (MapBiomas [41]).

In general, the main high hot spots, which appear in red on Figure 3, mainly occur to the northwest of Itaipuacu and Pindobas cities, these areas suffer from sheet and rill erosion due to deforestation activities on the hills and undulating mountains. Thus, these spots need the highest priority for remedial measures. For the main medium hot spots, which appear in orange on Figure 3, they spread mainly around Silvado, and in some separated spots around Itacaia.

IMPACT OF LAND USE AND LAND COVER CHANGES ON SOIL EROSION

The resulted descriptive land degradation map and the conservation priority map showed the great influence of human activities on the spread of soil erosion. Therefore, a landuse/landcover change detection process was done based on the Brazilian MapBiomas methodology [41] to investigate those changes using Landsat images dated in 1985 and 2022 (Figure 4). The methodology utilizes Landsat images with up to 30m of spatial resolution. The MapBiomas databases was extracted using the script for Google Earth Engine, made available on the initiative website. Two Shapefile databases were then acquired for 1985 and 2022. Subsequently, for the percentage extraction of land use and land cover classes, the databases were clipped to the perimeter of Maricá, excluding classes outside this perimeter. The Plugin "r.report," provided by the native QGIS 3.34.1 add-on, GRASS 8.3.1, was then applied on the class occupancy per pixel, which was then converted to square meter areas. Finally, the data were processed in an Excel table to conduct a comparison of class changes within the study area (Table 3).

The result of land use/land cover change detection (Table 3) showed a significant increase (14.49%) in urban area, where its total area in 1985 was equivalent to 8.95 km^2, but increased to 61.36 km^2 in 2022, at the expense of decrease in wetland (–1.70%), pasture (–3.44%), and mosaic of uses (–9.70%). These results illustrate a significant loss and change of vegetative cover, primarily transforming into urban areas, which implies higher chances of erosion occurrence [42]. When monitoring areas with land degradation, lack of vegetation over a long period and forest cover loss are considered proxies for land degradation [7].

MANAGEMENT RECOMMENDATIONS FOR THE HOT SPOT AREAS

In general, the identification of the hot spots and the grade of priority is flowed by selection of remedial measures to be applied in those areas. These steps are very necessary for any effective land degradation control program [18]. Consequently, after identification of the high priority areas, a recommended set of remedial measures have been selected to be applied to those areas as follows:

- Recommended measures for unstable areas, the curative measures to be applied should be directed to construction of water outlets, provide financial aids and training to rural population, and applying reforestation programs and forest management activities. While the protective measures needed for the unstable intervention areas may also emphasis on education of the local people to the importance of forestlands, land management, as well as execution of reclaiming projects.
- Recommended measures for stable areas, the preventive measures needed should emphasis on forest management and forest treatment, construction of terraces, applying contour tillage, installation of anti-erosive structures mainly check dams, and applying drainage control and land consolidation measures on active erosion processes to minimize disturbance of highly susceptible areas. While the curative measures to be applied for the stable intervention areas should emphasis on the education of the rural community to the importance of forestland and land management, and execution of reforestation projects.

Table 3. Maricá difference in land use/land cover changes between 1985 and 2023.

ID	CLASS	1985 (km^2)	2022 (km^2)	Difference (km^2)	Difference (%)
3	Forest Formation	110.15	117.31	–7.16	+1.98
11	Wetland	11.32	5.17	6.15	–1.70
15	Pasture	37.21	24.75	12.45	–3.44
21	Mosaic of Uses	133.72	98.62	35.10	–9.70
23	Beach, Dune, and Sand Spot	5.41	3.37	2.04	–0.56
24	Urban Area	8.95	61.36	–52.40	+14.49
25	Other Non-Vegetated Areas	5.26	2.81	2.44	–0.67
29	Rocky Outcrop	1.36	1.40	–0.43	–0.01
30	Mining	16.50	193.92	–0.17	–0.04
32	Hypersaline tidal flat	41.22	0	0.00	–0.00
33	River, Lake, and Ocean	37.45	36.52	0.90	–0.25
49	Wooded Sandbank Vegetation	10.35	9.66	0.68	–0.18
0	Null	454.65	454.66	0.01	0.00

CONCLUSION

The study showed that Maricá soils suffer from sheet and rill erosion, and some soils need high priority in applying remedial measures to combat land degradation. Although the percentage of degraded areas is relatively small, the mapping indicated that most degradation patches are concentrated near the dense forest cover, making them vulnerable to erosion expansion trend.

Effective design and implementation of land degradation prevention, mitigation and restoration programs to protect Maricá soils requires collaboration between scientists, society, and policy makers. If soil is not properly protected and managed in Maricá, soil erosion leads to a decrease in soil productivity in short term and may cause totally soil loss and catastrophic damages in life and property resulting from the runoff in the long term.

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