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Sedimentation Risk Assessment Using Satellite and Geospatial Data in Lagoa Feia, Brazil

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Abstract

Lagoa Feia is a lake located in Rio de Janeiro, Brazil, which historically experienced sedimentation impacts due to channel ditching which was enacted to manage water resources for agricultural practices and to avoid flooding. This study models the significance of erosion in the lake basin integrated with land-use, soil types, and climatic data using geographic information system (GIS) techniques. The erosion model was built using the above input variables by applying weighted overlay methods, and the vulnerable areas were mapped. Landsat 8 images were utilized for remote sensing analysis, such as image enhancement indices to detect depth, sedimentation and land-use changes over time. The results of the study are useful to implement Best Management Practices to overcome the issue in the lake.

1. Introduction

1.1 Lagoa Feia

Lagoa Feia is the second largest lake in Brazil and is localized in the State of Rio de Janeiro (Fig. 1). The lake has a great economic importance, as it is the main water supply for the urban region of Quissamã and to the surroundings rural areas. The water is used to irrigate sugar cane, pineapple and coconut plantations. Commercial fishing activity is present in the lake: fish, such as tilapia, acará, bagre and morobá are a source of profit for the population. A channel, namely Canal das Flechas was built connecting Lagoa Feia to the sea in 1948. The purpose of the channel was to drain the water from Lagoa Feia, to avoid floods the city of Campos dos Goytacazes.[1] The negative impact of the canal was sediment loading to Lagoa Feia due to poor management. Furthermore, the construction of Canal das Flechas and other anthropogenic interventions caused a loss of 2/3 of its area in its water surface of Lagoa Feia.[2]

1.2 Erosion and Sedimentation

Soil erosion is mainly caused by land-use, rainfall, slope and soil type.[3] After the soil is eroded, it can enter into the stream system by precipitation.[4] Land-use practices, such as agriculture and urban development, can threaten aquatic species by degrading the habitat via runoff and sediment loads.[5] Landscapes with inclined slopes maximize the runoff velocity, making the water carry sediments in higher quantity and size, while terrains with lower slope will have less sediment transport.[6] Each soil type has its own erodibility and water absorbance indices, clay based soils have lower erodibility and water absorbance rates since its particles are very small and does not allows water to go through easily. Precipitation is primarily responsible for the transportation of the sediments load into stream systems.[7]

Figure 1: Study area that comprehends the basin of Lagoa Feia - Rio de Janeiro, Brazil; Locator Map

The pollution of bodies of water by fine particulate terrestrial materials, such as silt or clay, is characterized as sedimentation. Sediment deposit in the stream's bed suffocates fish eggs, eliminates breeding areas, and can become embedded in the fish's gills causing respiratory problems. It blocks the sunlight, reducing the growth of organisms. The decreasing depth and flow of the stream from sediment accumulation affects the stream's navigation, and during heavy rains maximizes the chances of flood.[8]

1.3 Geographic Information Systems

Geographic Information Systems (GIS) is a computer system designed to store, manipulate, analyze, and display geographically referenced information.[9]

1.3.1 Weighted Overlay

Weighted overlay is a tool from the Spatial Analyst extension in ArcMap. It is one of the most wildly used approaches to solving multi-criteria problems. Different criteria layers can be combined into one analysis while weighting the important criteria more than the other criteria.[10]

Nick[11] used Weighted Overlay to combine the main four factors of erosion and build an erosion model. With this model, it is possible to predict sites that are more susceptible to suffer erosion according to the factors.

1.4 Remote Sensing

Remote Sensing is the acquisition of information about an object without making physical contact with it.[12] Commonly, satellites and aerial pictures are the sources of data for Remote Sensing. Environment for Visualizing Images (ENVI) is a conventional Remote Sensing software that groups several professional tools to process and analyze geospatial images.[13]

1.4.1 Change Detection Workflow

The change detection workflow in ENVI compares images from different time steps and outputs the differences between them. The differences can be related to specified Indices, such as NDVI and NDWI.[14]

1.4.1.1 Normalized Difference Vegetation Index (NDVI)

This index is a math equation using the Red part of the visible spectrum and Near Infrared (NIR) bands:

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

By applying this index to an image makes it possible to highlight photosynthetically active vegetation. Features that present a NDVI near to +1 have high photosynthetic activity, in other words the vegetation is healthier and denser. Features that present a NDVI near to 0 have low photosynthetic activity, a particularity found in unhealthy vegetation or features other than vegetation.

1.4.1.2 Normalized Difference Water Index (NDWI)

This index is a math equation using the Green part of the visible spectrum and Near Infrared bands:

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR}$$

Applying this index to an image is possible to highlight all the open water features. Water features have a positive NDWI while vegetation and soil have zero or negative values.[15] Is possible to conclude that water features with higher NDWI does not have interference of vegetation and soil, otherwise water features with lower NDWI have interference of vegetation and soil.[16]

1.4.2 Spear Relative Water Depth

The relative water depth in ENVI produces a relative depth analysis in water features using an albedo-independent Bathymetry algorithm.[17] It is important to have an image that is not corrected when performing this kind of analysis, since it can change the data and produce unsatisfactory products. This tool only measures the relative depth, not the absolute depth, so it comprehends a range from zero to one, where zero is the minimum depth and one is the maximum depth.

The objective of this study is to predict sites that are more likely cause sediment erosion and to assess the spatial and temporal changes in the lake and in its basin. The results of the land-use change model and the sedimentation model are useful for land managers to implement best management practices to overcome the impact of sedimentation in vulnerable areas.

2. Methods

The project is separated into two parts; the first part is the erosion model that was built using the geospatial software ArcMap, and the second part comprehends the Remote Sensing analysis using ENVI software and the data processed using ArcMap.

2.1 Erosion Modeling

For the geospatial modeling analysis proposed by this project, we used three shapefiles (Table 1). Each shapefile presents one factor of erosion. The data was reclassified into intervals; each interval has an index that shows its susceptibility to erosion.

Shapefile	Date	Author
Annual precipitation means	1977 to 2006	CPRM
Soils map of Brazil	2001	IBGE - EMBRAPA
Land-cover map	2002	SIVAM

Table 1: Information about the spatial data used

The annual precipitation intervals and its erosion indices are listed in Table 2.

Annual Precipitation mean (mm)	Erosion Index
800 to 1040	1
1040 to 1280	2
1280 to 1520	3
1520 to 1760	4
1760 to 2000	5

Table 2: Annual precipitation mean intervals and indices

The land-use types and its erosion indices are listed in Table 3.

Land-use type	**Erosion Index**
Forest	1
Sandbanks	3
Agriculture / Anthropogenic	5

Table 3: Land-use classes and erosion indices

The types of soils and its erosion indices are listed in Table 4.

Soil type	**Erosion Index**
Water body	1
Inceptisols	3
Molisols	4
Oxisols	4
Spodosols	5
Entisols	5
Gelisols	5

Table 4: Soil types and erosion indices

The Erosion Index Model was built with the tool “Weighted Overlay,” using the following equation:

$$\textit{Erosion Index Model} = \textit{Preciptation} * \frac{1}{3} + \textit{Soil type} * \frac{1}{3} + \textit{Land use} * \frac{1}{3}$$

Each erosion factor contributes equally to the model.

2.2 REMOTE SENSING ANALYSES

For the Remote Sensing analysis proposed by this project, we acquired two Landsat 8 images of the region of Lagoa Feia using Earth Explorer (Table 5)

Identity ID	Date acquired	Cloud Cover	Spatial resolution	Radiometric resolution
LC82160752013287LGN00	2013-10-14	1.2	30 meters	16 bits
LC82160752016040LGN00	2016-02-09	0.13	30 meters	16 bits

Table 5: Imagery used in the analyses

The Landsat data was processed using ENVI software according to the flowchart below (Fig. 2). To perform the map creation was used the software ArcMap.

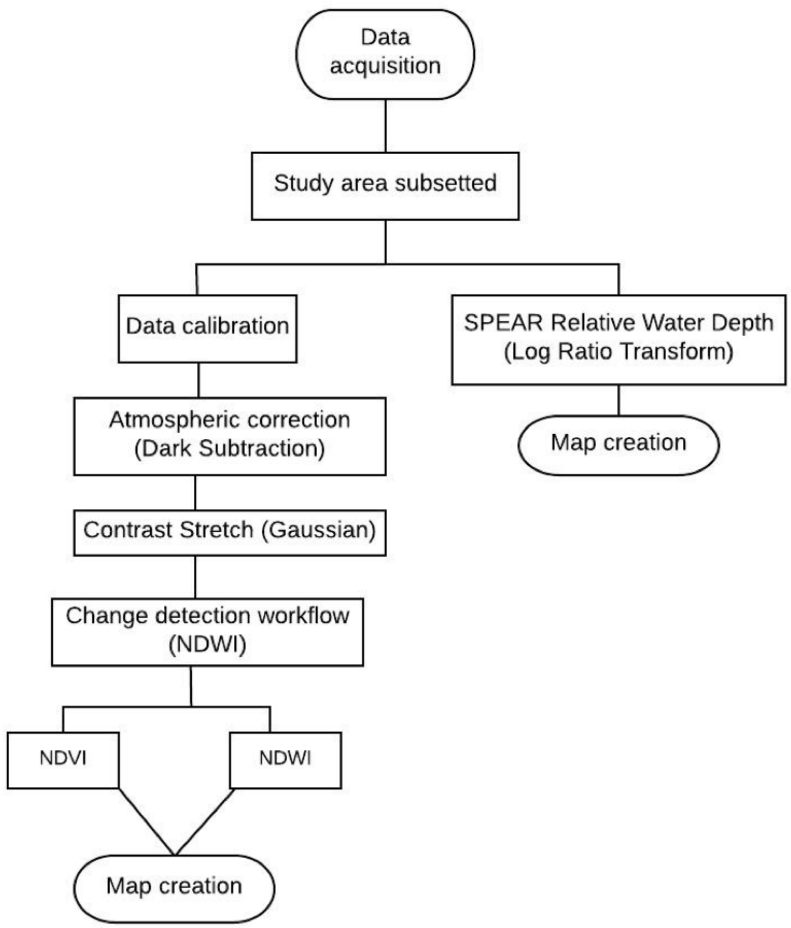

Figure 2: Flowchart showing the main steps for change detection Lagoa Feia basin

2.2.1 Change Detection Workflows

The change detection of the Lagoa Feia basin was analyzed using three different indices such as, NDVI, NDWI and SPEAR Relative Water Depth to map the vulnerable areas.

2.2.1.1 Normalized Difference Vegetation Index (NDVI)

The objective of this project was to analyze the differences in the NDVI using the lake images from 2013 to 2016.

2.2.1.2 Normalized Difference Water Index (NDWI)

The objective of this project was to analyze the differences in the NDWI using the lake images from 2013 to 2016.

2.2.1.3 Spear Relative Water Depth

For this project we performed two in-depth analyses using the Log Ratio Transform method; one from 2013 and another one from 2016. The following classes were adopted to classify each category of depth (Table 6):

Depth class	**Relative depth index**
Very shallow	0.01
Shallow	0.1
Moderate	0.3
Deep	0.6

Table 6: Classes of Relative Depth

3. RESULTS

3.1 Erosion Index Model

The Erosion Index Model indicates that areas with medium and high susceptibility to erosion primarily surround the lake. Sites with Very high susceptibility to erosion were only present in the south of the study area (Fig. 3).

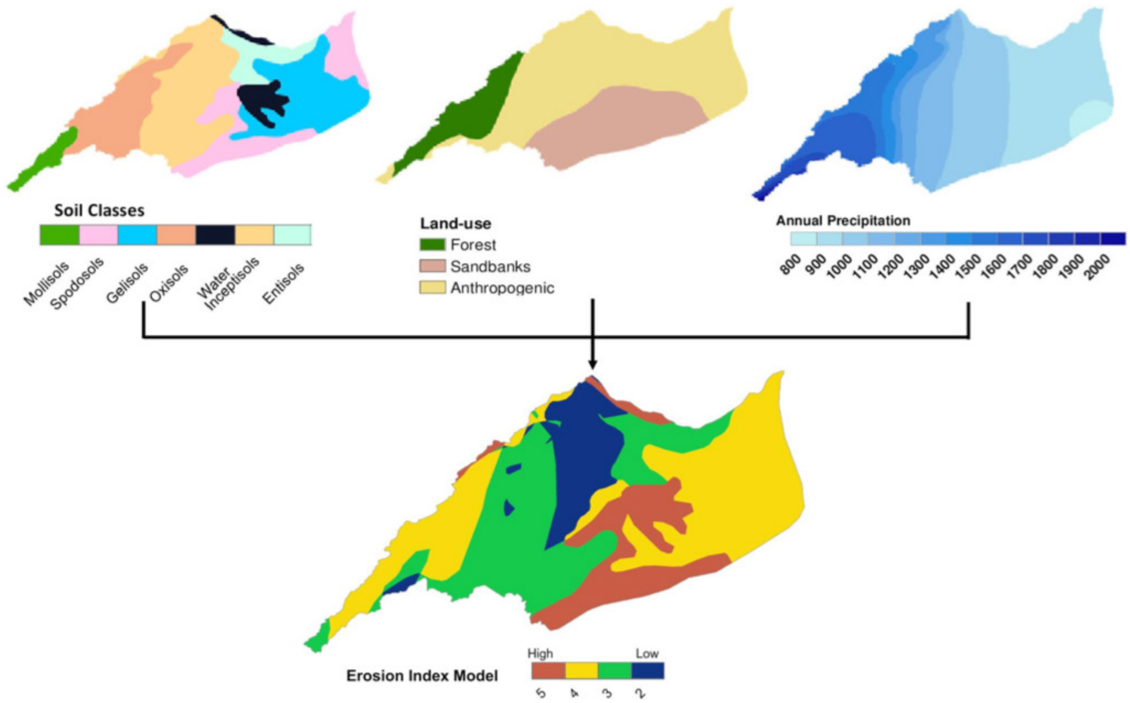

Figure 3: Erosion Index Model created using soil, land-use and the precipitation data in the Lagoa Feia basin

3.2 Remote Sensing Analysis

Relative depth variation was performed using remote sensing and geospatial analysis methods. The results are presented in Fig. 4.

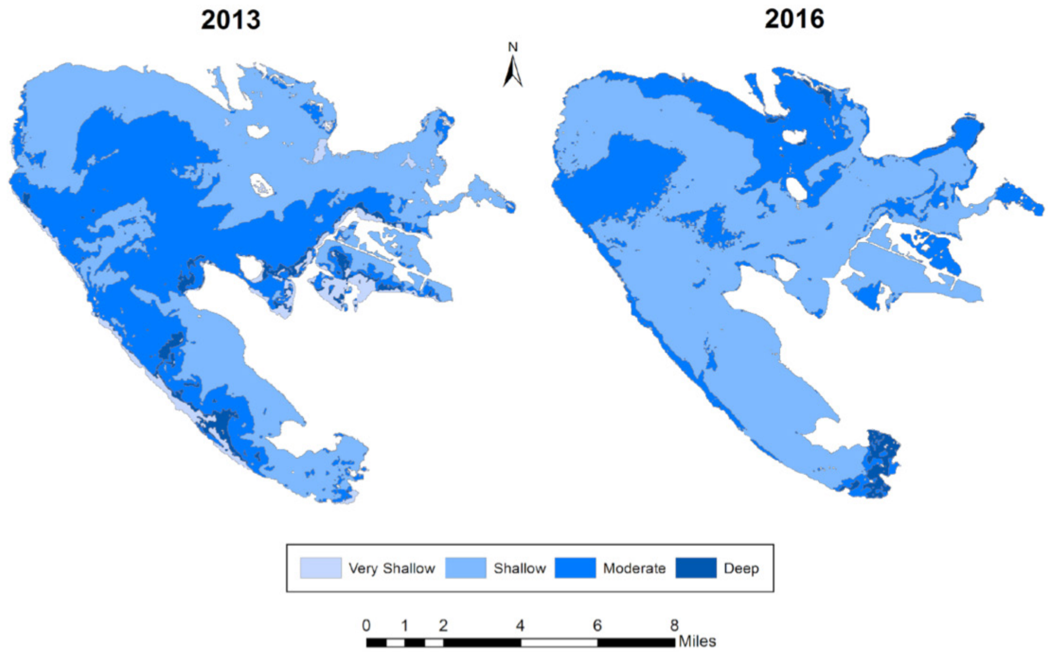

Figure 4: Relative depth variation of Lagoa Feia between 2013 and 2016

By analyzing the map, one can observe that many areas that had a Moderate depth in 2013 now have a Shallow depth in 2016. Measurements of the area were calculated for each of the depth classifications (Table 7).

Date	Very shallow (km^2)	Shallow (km^2)	Moderate (km^2)	Deep (km^2)
2013	9.558	89.8758	71.0721	5.3001
2016	1.3509	119.5155	52.7634	3.2175
Difference (%)	-4.672	16.459	-10.590	-1.195

Table 7: Superficial area of each classification of depth

The area of Shallow depth increased almost 16.5% between these 3 years. Note that Very Shallow, Moderate, and Deep depths decreased over this time frame.

Figure 5: NDWI difference of Lagoa Feia between 2013 and 2016

It is possible to observe that areas near the edges of the lake experienced a decrease of the NDWI (Table 8).

NDWI	Area (km^2)	Percent (%)
Large increase	0	0
Large decrease	11.835	2.962819

Table 8: Superficial area of NDWI changes

Almost 3% of the lake area experienced a decrease of the NDWI, while no other area of the lake experienced an increase (Table 8 & Fig. 6).

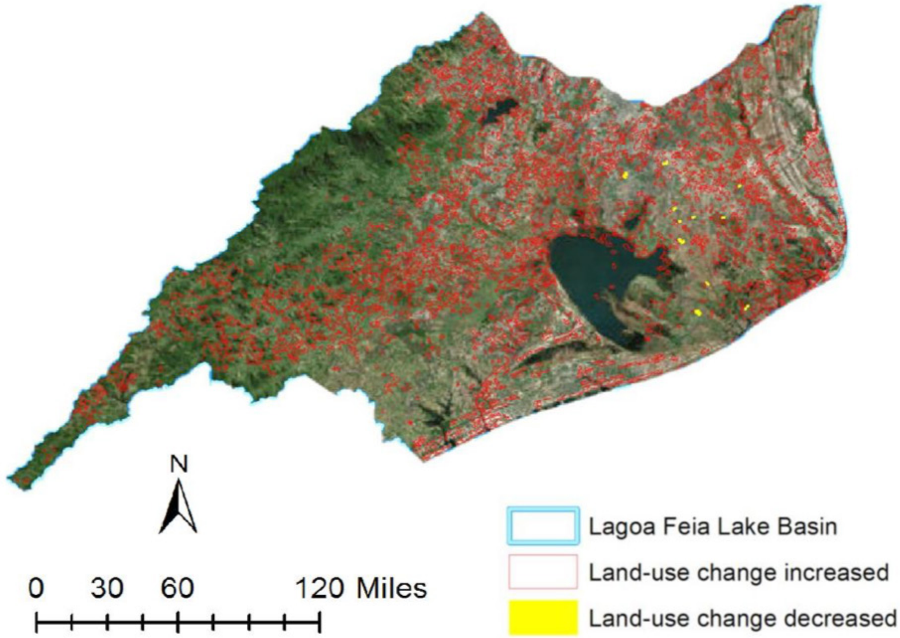

Figure 6: Map of NDVI difference in the basin of Lagoa Feia between2013 and 2016

Many sites in the basin experienced an increase of land-use change between 2013 to 2016. In other words, the NDVI of these sites has decreased. Small parcels show a decreased land-use because the NDVI was greater at 2016.

4. Discussion and Conclusion

The Erosion Index Model indicated that many areas that surround the lake are vulnerable to erosion. The soil erosion allied to sediment transport by precipitation or wind can reach to the lake, ultimately polluting the water.

By analyzing the Relative Depth Map it is possible to identify areas that had once been deep or moderated are now shallow. Over these three years, the shallow area of the lake increased 16.5%. It is most likely due to the sediment accumulation in the bottom of the lake.

By analyzing the NDWI difference map, it is possible to identify that experienced a significant decrease in the Normalized Difference Water Index. If the NDWI is lower, one can assume that the water has suffered interference of either vegetation or soil. Over these three years, the NDWI decreased at an area of 11.835 km^2, which is almost 3% of the total area of the lake.

The NDVI difference map shows that the land-use has increased in the last three years. Due to the fact that parcels are being deforested in order to make space for agriculture and urban areas.

The basin is going through land use changes. Since there is a medium to high risk of erosion, the land use changes can be strictly related to the sedimentation issues that are occurring at Lagoa Feia basin. The areas with large sedimentation are evidenced by the NDWI difference and the increase of shallow depth in the lake.

To avoid further sedimentation to the lake, it is highly recommended that the land managers should implement Best Management Practices such as, tree planting and establish riparian buffers for filtering the sediments to avoid more soil erosion. Artificial sediment barriers can be built to prevent more sediment load into the lake. Otherwise, natural sediment barriers as dense riparian vegetation can mitigate the water pollution.

About the Authors

Dr. Buddhika Madurapperuma is a Lecturer at the Departments of Environmental Science and Management, and Forestry and Wildland Resources at Humboldt State University (HSU). He conducts multidisciplinary research on land-use/cover change, forest silviculture, and predicting and mapping invasive species distribution using Geographic Information Systems (GIS) and remote sensing techniques. He is passionate about teaching diverse courses at HSU, including Introduction to GIS, Intro/Intermediate Remote Sensing and Mobile Mapping. Dr. Madurapperuma has mentored several students from the Brazil Scientific Mobility Program (BSMP) and his students have produced numerous research outputs through the internship program. For example, he and U.B. Rohrer, a BSMP scholar, produced this article through the 2016 BSMP summer internship program. *The authors would like to acknowledge Sara Hanna for the Remote Sensing technical support.* *Buddhika Madurapperuma can be contacted at bdm280@humboldt.edu.*

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