



Evaluation of Remote Sensing Data for the Identification of Lake-Stream Behavior during Normal and Cyclonic Seasons: The Case of Lake Alaotra, Madagascar

Rabotovao Sebas David¹, Ratsimbazafy Aro Pascal², Andriazafinahazo Fridolin³, Rajaonah Rabevala⁴, Razafindrazanakolona Andrianjafimanjato Daniel⁵, Robijaona Rahelivololoniaina Baholy^{6,7}

¹Renewable Energy and Environment Thematic Doctoral School, University of Antsiranana, Madagascar

²Higher Normal School, Applied Physics Laboratory, University of Fianarantsoa, Fianarantsoa, Madagascar

³Faculties of Science, Applied Physics Laboratory, University of Fianarantsoa, Fianarantsoa, Madagascar

⁴Higher Polytechnic School, Applied Mechanics Laboratory, University of Antsiranana, Antsiranana Madagascar

⁵Higher Institute of Technology and Environment, University of Fianarantsoa, Fianarantsoa, Madagascar

⁶Industrial, Agricultural and Food Process and Systems Engineering, University of Antananarivo, Antananarivo, Madagascar

⁷Antananarivo Polytechnic School, University of Antananarivo, Antananarivo, Madagascar

Email: sebasdavid4226@gmail.com, ratsimbazafy.aro@gmail.com, fridolinlahinirina@yahoo.fr, rabevala.rajaonah@yahoo.fr, andrianjafimanjato@gmail.com, robijob111@gmail.com, baholy.robijaona@univ-antananarivo.mg

Abstract:

Employing a synergistic approach integrating remote sensing and environmental science, this investigation rigorously examined the spatio-temporal dynamics of Lake Alaotra, Madagascar, under baseline seasonal conditions. The study elucidates the significant potential of satellite-derived data, coupled with advanced geospatial analytics, for precise mapping and comprehensive monitoring of intricate hydrological systems within diverse environmental contexts. Multi-temporal satellite imagery facilitated the accurate delineation of the lake's spatial extent, the quantification of seasonal fluctuations in its surface area, and the detection of inter-annual changes. Multivariate analysis of environmental covariates, including climatic oscillations, anthropogenic pressures, and inherent topographical attributes, enabled the identification and hierarchical prioritization of factors influencing the lake's hydrological regime. These findings yield critical evidence-based insights for informed decision-making in water resource management and environmental conservation strategies within Madagascar. Furthermore, scenario-driven predictive modeling of future hydrographic network modifications provides a crucial anticipatory framework for addressing potential challenges related to water availability across the nation, thereby enabling proactive planning and the implementation of targeted adaptation measures to mitigate adverse impacts. This research underscores the indispensable and evolving role of remote sensing technologies in the continuous monitoring of vital water resources and environmental integrity, demonstrating the efficacy of combining satellite data streams, sophisticated analytical methodologies, and remote sensing expertise to address salient environmental challenges in ecologically sensitive regions such as Madagascar.

Keywords:

Lake Alaotra, seasons, remote sensing, cyclonic, hydrological Systems

I. Introduction

Currently, satellite imagery is rapidly developing, allowing for the study of images of the entire Earth. It has become easier to obtain clear images thanks to modern satellites that can capture real images. Numerous changes are affecting activities and elements present on Earth, and it is interesting to track these transformations. The use of Sentinel-2 images facilitates the processing of this information. This technology has revolutionized the

description of the Earth and is an essential part of its aquatic landscape. In this advanced technological context, our study focuses on Lake Alaotra, the largest lake in Madagascar, located in the Alaotra Mangoro region, particularly in the districts of Ambatondrazaka and Amparafaravola. This lake is important for regional biodiversity and the local economy, affecting agriculture, fishing, and providing essential habitat for endemic species. (Ourrai et al., 2024)

This study examines the processing of Sentinel-2 satellite imagery to assess the behavior of Lake Alaotra in Madagascar during normal seasons. Throughout this research, we focus on the effectiveness of this method for understanding changes in the lake. The objective was to determine the surface area of water bodies, to understand the behavior of this particular lake during normal seasons. To achieve these objectives, we will use remote sensing and satellite image processing via Google Earth Engine (GEE), utilizing Sentinel-2 imagery and the JavaScript API. Additionally, we will implement artificial intelligence through a Random Forest algorithm for automatic processing and classification. Finally, QGIS software will be employed to generate the final mapping. (Youssef & Hegab, 2019)

The goal is to monitor and evaluate changes in Lake Alaotra during normal seasons in order to analyze its behavior, particularly in relation to potential lake phenomena. The objectives are to determine the surface area of water bodies, detect changes in land use, and understand the behavior of this particular lake during normal seasons for decision-making purposes.

Mapping and analyzing water surfaces are now essential tools for understanding how territories evolve. Through the analysis of satellite images, we can measure changes in the amount of water over time. Furthermore, the high frequency of these current data and their high spatial resolution are particularly interesting for deepening our understanding of these developments. Our study aims to identify and compare water bodies in the districts of Ambatondrazaka and Amparafaravola from 2018 to 2022 using remote sensing. We also seek to determine water surfaces and detect changes in land use. (Masia et al., 2021)

The objective is to create a digital map that will be used in various fields such as agriculture and livestock, with the aim of promoting rapid development and tracking changes in land use with each occurrence. In our study, we present a methodology for processing this data that allows for the classification of land use in the districts of Ambatondrazaka and Amparafaravola. We then define the extents of Lake Alaotra in these districts and finally, we map the evolution of changes in water use.

II. Research Method

2.1 Study Site Characterization: Lake Alaotra, Madagascar

Lake Alaotra, the largest freshwater lacustrine system in Madagascar, is situated within the Alaotra-Mangoro Region (formerly Tamatave province), geographically delimited between the districts of Amparafaravola and Ambatondrazaka (17° 28' South latitude, 48° 30' East longitude) (Ferry et al., 2009). This significant hydrological feature encompasses approximately 8% of Madagascar's total surface area, with a total extent of around 63,000 hectares, of which approximately 43,000 hectares constitute palustrine wetlands (UNEP, 2018 ; Rabarimanana et al., 2011).

Lake Alaotra was strategically selected as the focal study area due to its prominence as one of Madagascar's largest lentic ecosystems. Its ecological and socio-economic significance

necessitates a proactive, remote sensing-driven approach to anticipate climate-induced risks, ensure the sustainable management of its water resources, and inform land-use planning to mitigate potential anthropogenic pressures such as uncontrolled wildfires and peri-lacustrine urban expansion (UNEP, 2018). Furthermore, Lake Alaotra functions as a critical agricultural hub, serving as a major rice granary for Madagascar with an annual production of approximately 200,000 tons of *Oryza sativa*, thereby underpinning national food security, stimulating the regional economy, and providing essential livelihoods for local communities. Beyond its agricultural importance, the lake contributes substantially to regional water resource regulation and the conservation of endemic biodiversity, despite facing ongoing environmental challenges including water-induced erosion and pedological degradation (Rabarimanana et al., 2011).

2.2 Establishment of Sampling Units

Lake Alaotra, the largest freshwater lacustrine ecosystem in Madagascar, is geographically situated within the Alaotra-Mangoro Region (formerly Tamatave province), spanning the districts of Amparafaravola and Ambatondrazaka (17° 28' South latitude, 48° 30' East longitude). This significant hydrological feature encompasses approximately 8% of Madagascar's total surface area, exhibiting a dynamic spatial extent of approximately 63,000 hectares, of which an estimated 43,000 hectares constitute palustrine wetland environments. This wetland area demonstrates significant seasonal variability and is characterized by a diverse mosaic of adjacent ecosystems. Given its pronounced ecological and socio-economic significance, Lake Alaotra presents an optimal study site for the implementation of remote sensing-based monitoring and analytical investigations. Figure 1 (adapted from Ferry et al., 2009) illustrates the geographical localization of the study area in relation to the broader spatial context of Lake Alaotra within Madagascar. (Ferry et al., 2009)

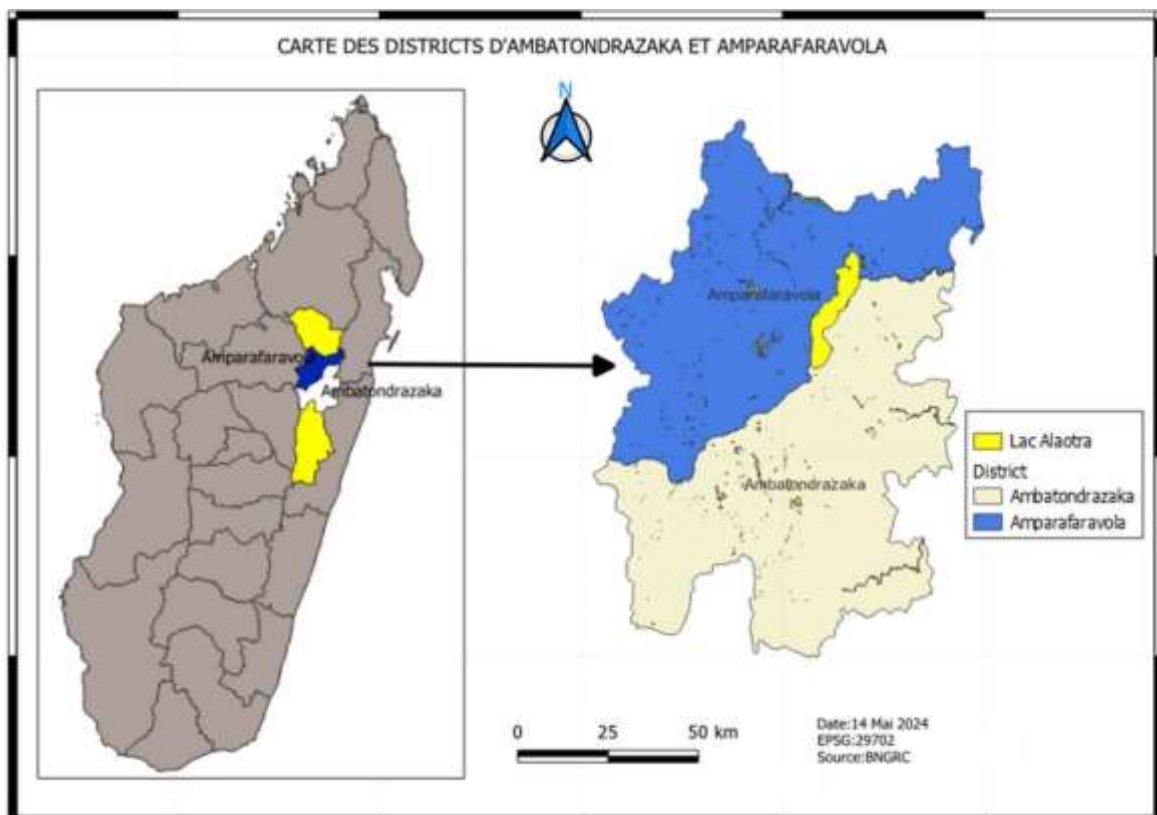


Figure 1. Location of Lac Alaotra in Madagascar

Figure 1 illustrates the geographical location of Lake Alaotra (17°28'S, 48°30'E) within Madagascar, emphasizing its regional hydrological and ecological significance for remote sensing studies.

2.3 Behavioral characterization of Lake Alaotra: A remote sensing approach

The ecological integrity of Lake Alaotra has been demonstrably altered by a confluence of environmental stressors, including accelerated sedimentation rates, the impacts of climate change, anthropogenic pollution, and deforestation within its catchment area (Rabarimanana *et al.*, 2011). Continuous and spatially explicit monitoring is therefore paramount for effective risk mitigation, sustainable water resource management, and the preservation of its unique biodiversity (UNEP, 2018). The application of satellite remote sensing offers a particularly efficacious methodology for the synoptic and repetitive identification and assessment of water bodies (Jensen, 2015).

In this investigation, we implemented supervised classification algorithms and spectral index calculations as primary analytical techniques to characterize the behavioral dynamics of Lake Alaotra within the Ambatondrazaka and Amparafaravola districts. Consequently, remote sensing is strategically employed as a critical tool for informed environmental decision-making (Lillesand *et al.*, 2015). Within these districts, a heterogeneous landscape comprising water bodies, bare soil, marshlands, other vegetation types (predominantly savanna), agricultural lands, and forested areas exists. However, the precise spatial distribution and temporal evolution of these land cover classes are challenging to ascertain without systematic and longitudinal monitoring.

To address this limitation and gain a more granular understanding of these land surface components and their diachronic trajectories, the generation of a land use/land cover (LULC) map is essential. This study adopts a robust methodological framework specifically adapted for the analysis of high-resolution Sentinel-2 multispectral imagery (Torgbor *et al.*, 2022), thereby directly addressing the identified information requirements.

Lake Alaotra experiences a semi-humid tropical climate regime characterized by two distinct seasonal phases: a wet season extending from November to April, marked by significant precipitation events and elevated temperatures, and a cooler, drier season from May to October. The region exhibits a mean annual temperature range of 25°C to 28°C, with an average annual precipitation of 1154 mm (Ferry *et al.*, 2009).

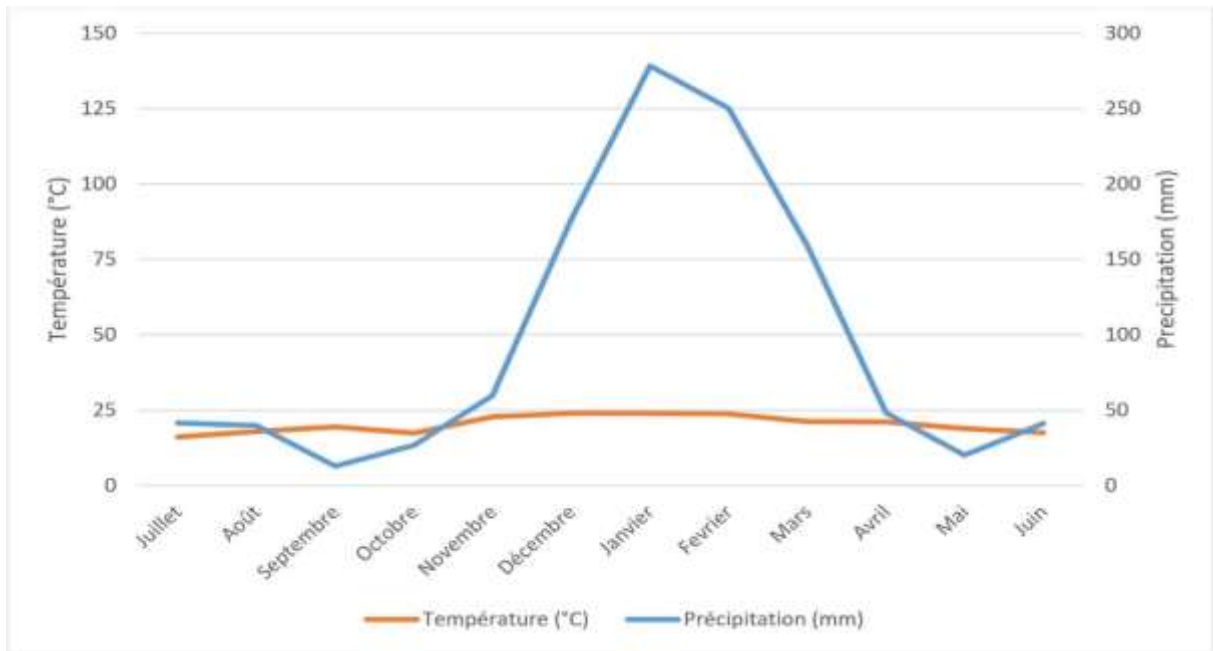


Figure 2. Ombrothermic curve of the study area between 2018 and 2022
 Note: (During cyclonic seasons)

The ombrothermic curve (Figure 2, 2018-2022) for the Lake Alaotra region (25-28°C mean annual temperature, 1154 mm average precipitation; **Ferry et al., 2009**) indicates a semi-humid tropical climate punctuated by a critical 20-30 day post-October rainfall dry spell, stressing agriculture and lacustrine resources, particularly exacerbated during the November-April cyclonic season (peak: January-March). Radiometric calibration ensures accurate sensor data for subsequent analysis.

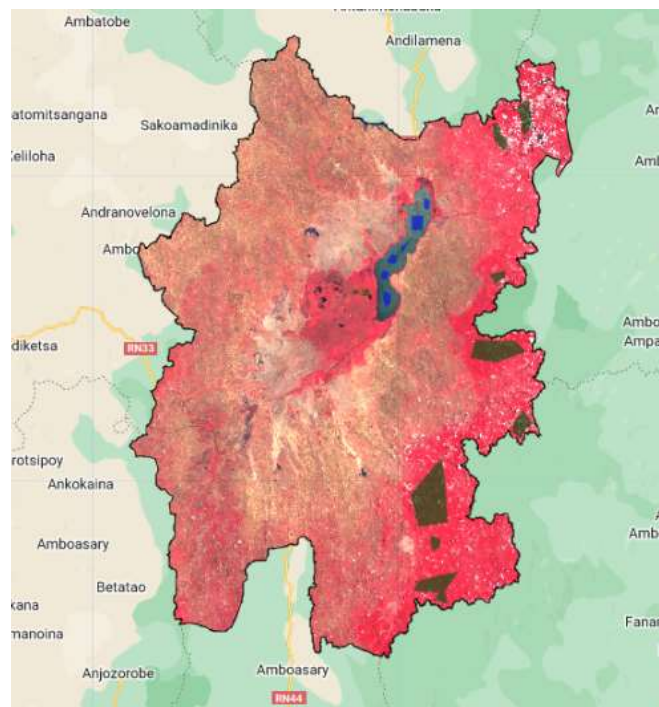


Figure 3. Radiometric Calibration
 Source: (Numerical simulation on GIS)
 Note: (During cyclonic seasons)

Figure 3 presents the radiometric calibration methodology (numerical GIS simulation) applied to satellite imagery, specifically during cyclonic seasons, for quantitative environmental analysis.

2.4 Specimen identification and classification methodologies

This study employs a rigorous remote sensing workflow, commencing with the acquisition of Level-2A Sentinel-2 multispectral imagery and the delineation of the Lake Alaotra study area. Pre-processing stages involve temporal filtering of imagery to encompass baseline seasonal conditions, application of cloud masking algorithms to ensure data quality, and subsequent mosaicking and spatial subsetting to the defined area of interest. Spectral bands with a spatial resolution of 10 meters (Blue, Green, Red, and Near-Infrared) were selected for subsequent analysis, and representative spectral signatures were collected through supervised sampling techniques (Richards & Jia, 2006).

For the accurate discrimination of land cover classes, including water bodies, bare soil, marshlands, and various vegetation types (e.g., savanna, crops, forests), a supervised classification approach was implemented utilizing the Random Forest (RF) algorithm (Breiman, 2001). The RF classifier, known for its robustness and efficacy in handling high-dimensional remote sensing data, was trained on the collected spectral samples. Classification accuracy was assessed using standard metrics derived from a statistically independent validation dataset (Congalton & Green, 2019).

Specifically, for water body detection and surface water extent quantification, the Normalized Difference Water Index (NDWI) was calculated using the Green and Near-Infrared bands of the Sentinel-2 imagery (Smith & Georgiou, 2021; McFeeters, 1996). This spectral index leverages the strong reflectance of water in the green portion of the electromagnetic spectrum and its strong absorption in the near-infrared.

The entire image processing and analysis workflow was implemented within the Google Earth Engine (GEE) cloud computing platform, utilizing its extensive Sentinel-2 archive and JavaScript API for efficient data management and algorithmic execution (Gorelick et al., 2017). The final cartographic outputs, including the classified land use/land cover map and water body extents, were generated using QGIS software for visualization and spatial analysis. This methodological framework aims to provide a robust and replicable approach for assessing the behavioral characteristics of Lake Alaotra during normal seasonal cycles.

2.5 Data Analysis: Seasonal Lake Area Dynamics

Emporal analysis of seasonal lake surface area revealed a unimodal pattern, peaking in July and reaching its nadir in January (Figure 4). This cyclical variability, precisely quantified via remote sensing, is crucial for elucidating regional hydrological regimes and their environmental sensitivity (Kumar & Reshmidevi, 2013). Interannual water area exhibited significant fluctuations with a slight overall decreasing trend. Spatially, seasonal lakes displayed connectivity with the main lacustrine system during the wet season and isolation during the dry period. Among natural covariates, temperature, evaporation, and precipitation exerted successively diminishing influences on seasonal lake area, with significant impact from Yangtze River inflow. Anthropogenically, traditional autumnal sub-lake enclosure for fishing exerted the most pronounced localized impact during specific temporal windows (Wei et al., 2018).

III. Result and Discussion

The subsequent results and discussion will present a comprehensive analysis of Lake Alaotra's spatio-temporal dynamics, leveraging the described remote sensing methodologies applied to Sentinel-2 imagery. Findings will detail the seasonal variations in lake surface area, quantified using the NDWI, and the spatial distribution of land cover classes derived from the Random Forest classification. Furthermore, the influence of key environmental covariates, including climatic oscillations and anthropogenic pressures, on the lake's hydrological behavior will be elucidated, providing critical insights into its ecological functioning and informing sustainable management strategies

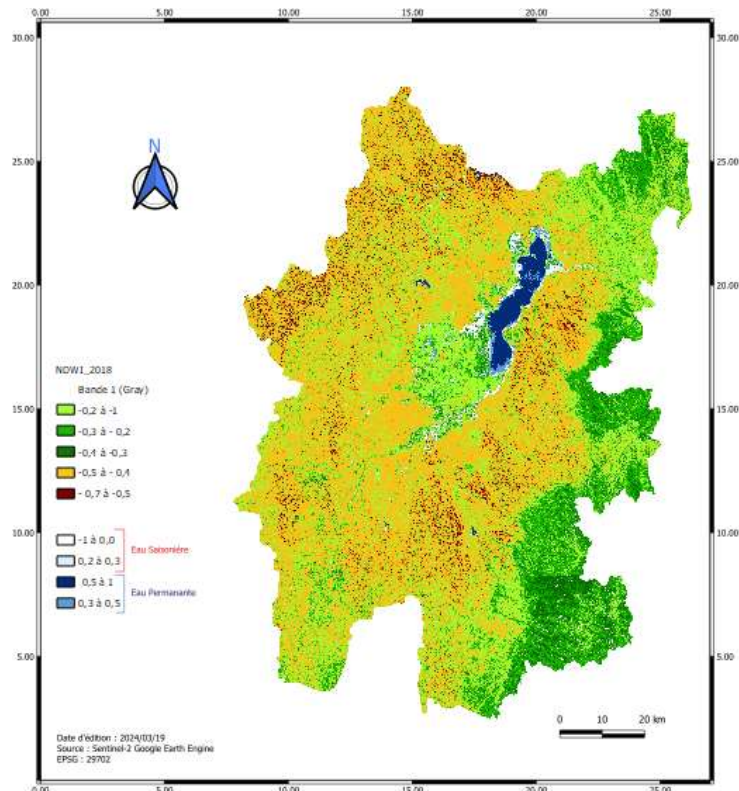


Figure 4. Water NDWI index to 2018 Lake Alaotra

After calculating the water index, we evaluated the changes between two dates:
Water loss: The purple area indicates a decrease in water surface compared to the reference date.
Water gain: The light blue area indicates an increase in water surface.
Water body: The dark blue area represents the water surface on a given date.
2018-05-01: The image on the left shows the extent of the water body on this date.
2022-05-01: The image on the right shows the extent of the water body on this date.

Following the computation of the Normalized Difference Water Index (NDWI) (McFeeters, 1996; Smith & Georgiou, 2021), Figure 6 visually depicts the diachronic changes in surface water extent within the study area.

Figure 5 presents the Land Use/Land Cover (LULC) maps for the Ambatondrazaka and Amparafaravola districts, comparing the spatial distribution of various land cover classes between 2018 and 2021. Analysis of these classifications, derived from supervised algorithms applied to Sentinel-2 imagery (Torgbor *et al.*, 2022), indicates a notable increase in the overall land area, primarily at the expense of forested areas, palustrine wetlands, and savanna

ecosystems. Conversely, the spatial extent of rice cultivation exhibited relative stability during the study period.

Further disaggregation of LULC change reveals a statistically significant decrease in the area occupied by water bodies, forests, marshlands, rice paddies, and other vegetation types across both districts. Concurrently, a substantial increase in the spatial extent classified as "bare soil" was observed, suggesting potential land degradation processes or altered agricultural practices (Lillesand *et al.*, 2015).

During classification, the Kappa coefficient is a quality estimator that takes into account errors and varies from 0 to 1. Here is the Kappa interpretation table.

Table 1. Kappa coefficient is a quality estimator

Years	2018	2019	2020	2021	2022
KAPPA	0,93	0,91	0,86	0,92	0,93
CONFUSION	0,94	0,92	0,91	0,93	0,94

Table 1 presents the Kappa coefficient, a robust measure of inter-rater agreement for the land cover classifications derived from satellite imagery (Congalton & Green, 2019). The consistently high Kappa values (0.86-0.93) across the 2018-2022 period indicate a strong level of agreement between the classified data and the reference data, signifying high accuracy and reliability in the derived land use/land cover maps for subsequent environmental analysis of the Lake Alaotra region.

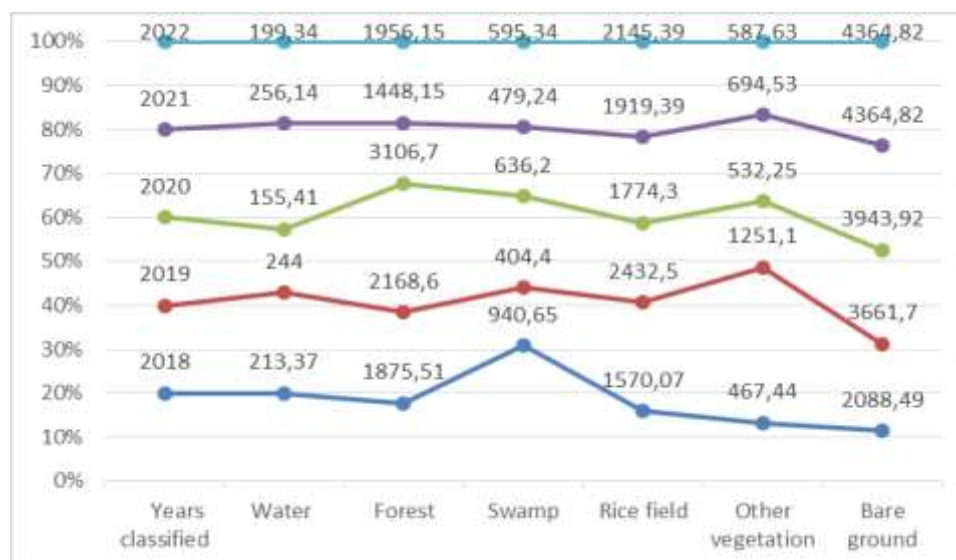


Figure 5. Comparison of land use 2018-2022

Figure 5 presents a comparative analysis of land use/land cover (LULC) in the Lake Alaotra region between 2018 and 2022, derived from classified satellite imagery (Torgbor *et al.*, 2022). Quantitative change detection analysis would provide precise areal statistics for each LULC (Land Use and Land Cover) class transition, crucial for understanding landscape dynamics.

Table 2. Comparison of land use area (km²)

Years classified	2018	2019	2020	2021	2022
Water	213,37	244,00	155,41	256,14	199,34
Forest	1875,51	2168,60	3106,70	1448,15	1956,15

Swamp	940,65	404,40	636,20	479,24	595,34
Rice field	1570,07	2432,50	1774,30	1919,39	2145,39
Other vegetation	467,44	1251,10	532,25	694,53	587,63
Bare ground	2088,49	3661,70	3943,92	4364,82	4364,82

Table 2 quantifies land use/land cover (LULC) area (km²) in the Lake Alaotra region (2018-2022), derived from classified satellite imagery (Jakovljević *et al.*, 2018; Torgbor *et al.*, 2022). Notable interannual variability is observed, with water area fluctuating significantly (155.41-256.14 km²). Bare ground shows a consistent increase, reaching 4364.82 km² in 2021-2022, potentially indicating land degradation or altered agricultural practices impacting other LULC (Land Use and Land Cover) classes.

The map shows that the Ambatondrazaka and Amparafaravola region experienced significant land use changes between 2018 and 2021. Deforestation is the main trend observed, with a substantial conversion of forest into bare soil and non-aquatic areas. It is important to note that this analysis is based on a single map, and further studies are needed to understand the causes and implications of these changes.

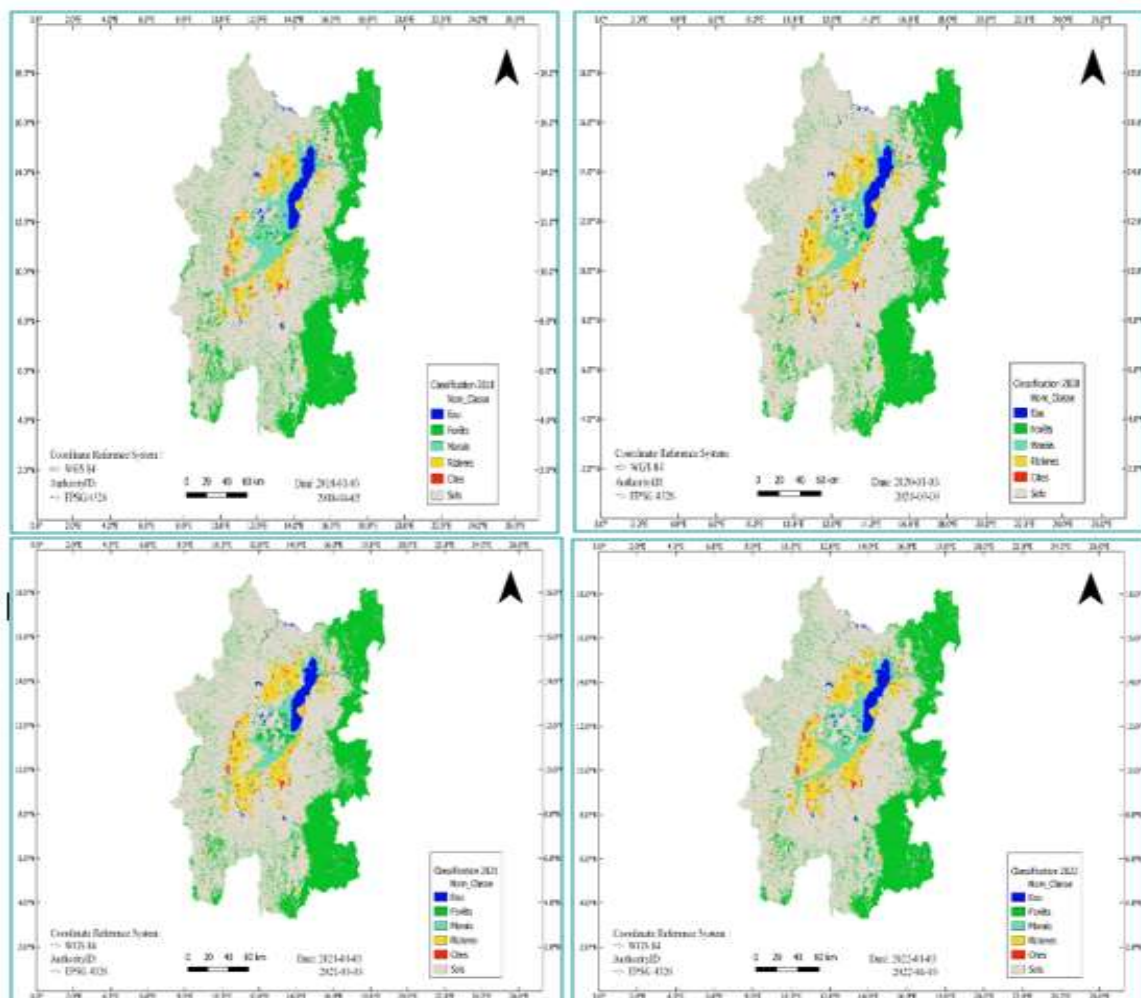


Figure 6. Land image 2018 to 2022 cyclone period
(Source: Digital simulation on SIG)

After the classification, an annual change in land use is observed. Regarding agriculture around Lake Alaotra, it is noteworthy that it is entirely dependent on the water level, as it is observed that the lower the water level, the more land can be used for rice cultivation.

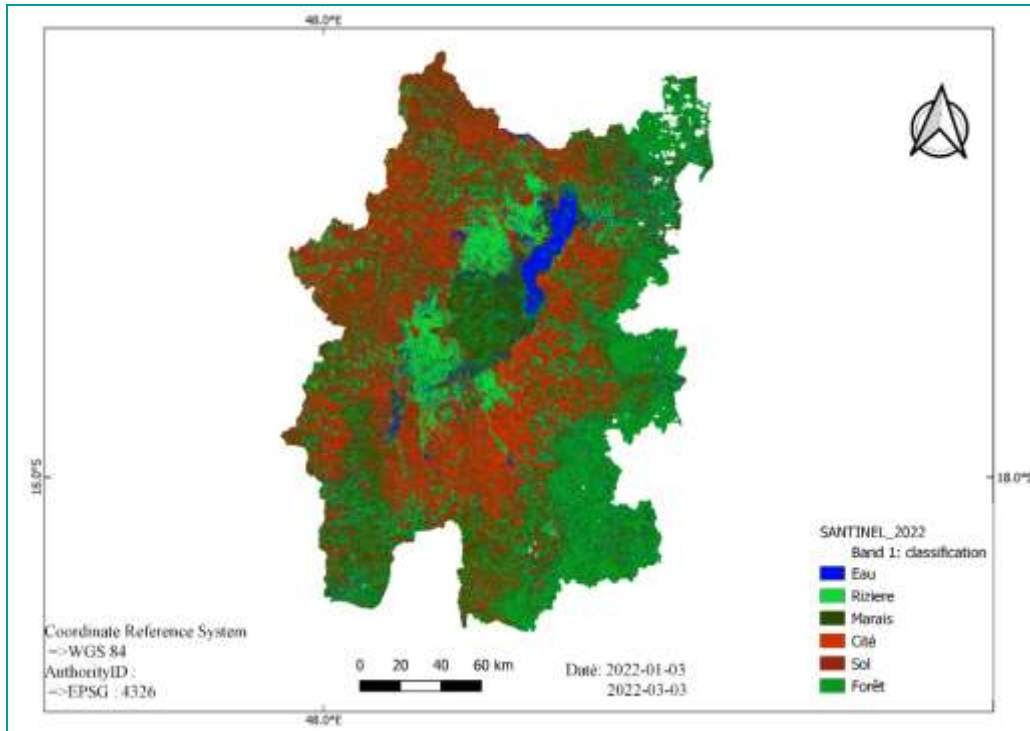


Figure 7. Satellite image processing in Sentinel-2 on Google Earth Engine (Source: numerical simulation on GIS)

During classification, the Kappa coefficient is a quality estimator that takes errors into account and varies from 0 to 1. Here is the interpretation table for Kappa.

Table 3. Comparison of land use area (in km²) between Ambatondrazaka and Amparafaravola from 2018 to 2022.

Years	2018	2019	2020	2021	2022
KAPPA	0,93	0,91	0,86	0,92	0,93
CONFUSION	0,94	0,92	0,91	0,93	0,94

Table 3 presents the Kappa coefficient and overall classification accuracy (Confusion) for land use/land cover (LULC) maps of Ambatondrazaka and Amparafaravola districts (2018-2022), derived from satellite imagery classification (Congalton & Green, 2019). Consistently high Kappa values (0.86-0.93) and accuracy (0.91-0.94) indicate robust and reliable LULC classifications for subsequent comparative environmental analysis between these regions within the Lake Alaotra ecosystem.

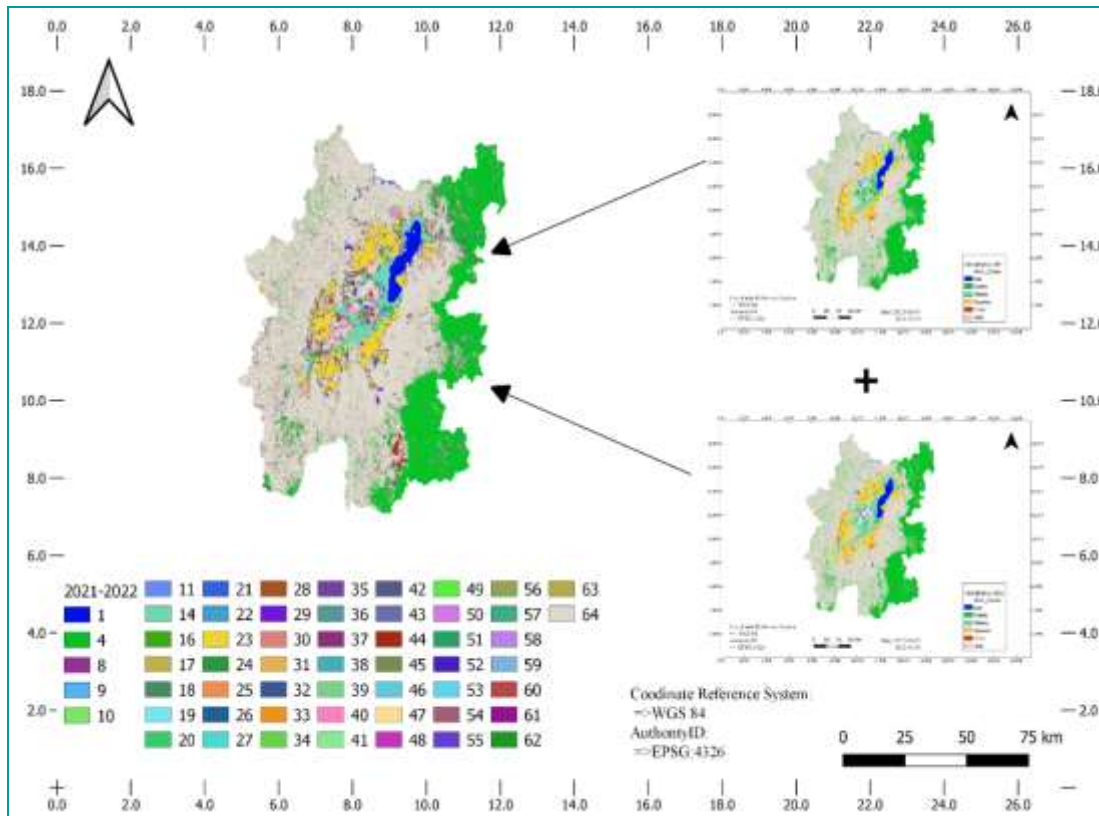


Figure 8. Potential changes detected between 2021 and 2022
(Source: numerical simulation on GIS)

Figure 8, derived from numerical GIS simulation of satellite imagery, depicts potential land use/land cover (LULC) changes between 2021 and 2022 within the Lake Alaotra region. Areas highlighted indicate modeled transitions, potentially reflecting alterations in agricultural practices, wetland dynamics, or deforestation patterns requiring field validation and further investigation using change detection algorithms (Jakovljević *et al.*, 2018).

Here are some recommendations for ensuring the sustainability of the wetland:

- Strengthening lake monitoring.
- Implementing protective measures for the wetland and forest.
- Combating soil erosion.
- Constructing dikes to protect riparian areas.
- Promoting the sustainable use of water resources.

3.1 Validation

The validation is based on the classification results after correction by polygon to achieve high accuracy; the validation method consists of two parts: the first is the accuracy validation of the classification and the Kappa index; the second is done via Google Earth imagery and classified images on GEE.

The accuracy validation of the classification depended on the percentage standard and Kappa, meaning that according to the Kappa concept (Table 3 Interpretation of Kappa), it is observed that obtaining a value between 81 and 1 is almost perfect; a decision can be made to ensure that the result is acceptable. Of all the classifications that were made, Kappa proved to be between 86% and 93%. Therefore, in my personal opinion, I decided that the classification was appropriate and proceeded with the mapping (Scorsino & Debolini, 2020).

Conventional methods for assessing the thematic accuracy of a map were employed. These include the confusion matrix and the Kappa index. The confusion matrix provides an evaluation of the overall accuracy of the mapping and classification results for each thematic class. The Kappa index evaluates the agreement between the obtained results and the ground truth within the confusion matrix. It ranges from 0 to 1 and is divided into five categories: very weak agreement from 0 to 0.20; weak agreement from 0.21 to 0.40; moderate agreement from 0.41 to 0.60; substantial agreement from 0.61 to 0.80; and almost perfect agreement from 0.81 to 1 (Landis & Koch, 1977).

The confusion matrix, also known as the error matrix, is a table that presents various predictions and test results by comparing them with actual values. These matrices are used in statistics, data mining, machine learning models, and other applications of artificial intelligence.

The confusion matrix: it is a Machine Learning technique that involves feeding an algorithm with data to teach the computer to perform specific tasks. In classification problems, this model predicts outcomes to be compared with reality in order to measure its performance level. For this, we use the confusion matrix, which highlights the correct and incorrect predictions for comparison with defined values (Yang et al., 2023).

The Kappa coefficient is a quality estimator that takes into account errors in rows and columns. It ranges from 0 to 1.

To obtain the Kappa index in classification, we have the following formula:

$$K = \frac{N \sum_{i=1}^n m_{i,i} - \sum_{i=1}^n (G_i C_i)}{N^2 - \sum_{i=1}^n (G_i C_i)}$$

Here is the translation of your text into English:

i: is the number of classes

N: is the total number of evaluated pixels

m_{i, i}, **i**: is the number of values belonging to class i that have been correctly classified in class i (i.e., the values located on the diagonal of the confusion matrix)

C_i: is the total number of pixels assigned to class i

G_i: is the total number of pixels that truly belong to class i

The following method is based on the results of land cover classification, in which a comparison is made with the actual image from Google Earth, meaning that a small part of a location or area is compared to the results obtained on the same date.

Here are some examples: in the municipality of Andreba, as shown in the following figures 12:

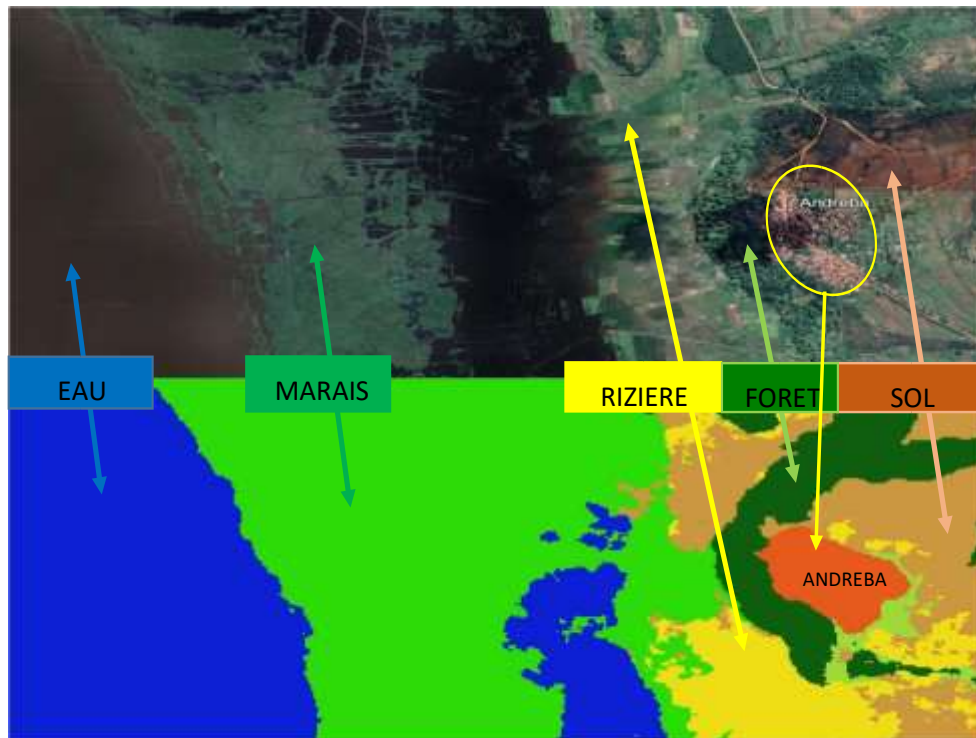


Figure 9. Validation of classification in the commune of Andreba

Based on Figure 9, it has been decided that the result of the land use classification can be validated because it is evident from the image on Google Earth that there is water, forest, soil, etc. This is also reflected in the image on GEE, allowing for progress in the creation of the cartographic map (Zhang *et al.*, 2023).

IV. Conclusion

In this study, we examined the behavior of Lake Alaotra in Madagascar during normal seasons, thereby demonstrating the potential of remote sensing to monitor and understand complex hydrological systems in varied environments. Satellite data, combined with advanced analytical techniques, enabled us to accurately map this lake, track seasonal variations, and detect changes over the years.

We identified various factors of change, such as climate variations, human activities, and topographical features, and prioritized them based on their impact on the lake. These results provide important information for decision-making regarding water management and environmental protection in Madagascar.

Furthermore, our predictions concerning future changes in the hydrographic network, based on specific scenarios, help anticipate potential challenges related to water availability in the country. This paves the way for proactive planning and appropriate adaptation measures to mitigate negative impacts.

This study underscores the ongoing importance of remote sensing in monitoring water resources and the environment. It also demonstrates how a combination of satellite data, advanced analyses, and remote sensing expertise can be utilized to address significant environmental issues in sensitive regions like Madagascar.

Thus, this study shows that remote sensing is very useful for monitoring lakes and the environment. It also indicates that by using satellite images and advanced techniques, we can help solve important problems for places like Madagascar. Therefore, it is crucial to take care of Lake Alaotra during normal seasons so that future generations can have a bright future.

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