Impact of land cover variations on the Morroa aquifer (Colombia) static and dynamic levels through remote sensing analysis.

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ABSTRACT

The Morroa aquifer plays a crucial role supplying drinking water to around one million residents across Sucre, Córdoba, and Bolívar departments in Colombia. However, it faces severe water stress, ranking as the second most overexploited aquifer globally according to recent research using the Groundwater Footprint (GF) indicator. This situation threatens the sustainability of the aquifer and the well-being of the region's inhabitants who rely on it. To tackle this challenge, CARSUCRE, the entity responsible for aquifer management, has implemented various strategies. These include establishing a monitoring network with piezometers to track static and dynamic aquifer levels and conducting civil works to redirect rainfall runoff towards artificial recharge projects. Yet, the impact of vegetation variations in the recharge areas of the aquifer levels remains uncertain due to many different factors like drought, heavy rainfall, and economic changes. This research introduces a methodology that leverages remote sensing data, particularly high-resolution images from the Planet platform (3m), combined with land cover analysis in piezometer influence areas. The primary aim is to assess how changes in vegetation affect both static and dynamic levels of the Morroa Aquifer and then identify strategies to enhance land cover and improve water capture. The results obtained show a significant correlation between NDVI, EVI, and LULC for the aquifer recharge zone, with an average of 0.858 for all applied tools. These findings provide valuable information for the management and preservation of this vital water resource in the region.

Keywords: Static Level, Aquifer, Planet, Remote Sensing, land cover.

1. INTRODUCTION

Colombia, blessed with a strategic geographic location, stands out globally as a privileged Country in terms of water resources. It is the only South American nation with coastlines on two oceans, the Atlantic and the Pacific, and ranks among the top ten countries with the largest freshwater reserves in the World[1]. Despite these natural advantages, the effective management of these resources has been a constant challenge for governments both at the central and regional levels[2,3]. A significant portion of the national territory faces worrying water scarcity, affecting both rural and urban areas across the Country. From the arid lands of La Guajira to bustling coastal cities like Santa Marta, the lack of this vital resource becomes evident during numerous months of the year, posing urgent challenges in terms of environmental sustainability, food security, and human well-being, in line with the Sustainable Development Goals[4].

The department of Sucre, located on the Colombian Caribbean coast, reflects this complexity in the Country's water management. The Mojana region, to the South, stands out as an important water and food reserve at the national level, although recurrent floods pose a constant challenge to its inhabitants[5]. The central zone of the department, the focus of this research, is the most densely populated and hosts key cities like Sincelejo and Corozal, along with other municipalities such as Sampués, Los Palmitos, Ovejas, and Morroa. These communities heavily rely on groundwater sources, with the Morroa aquifer being the main supply source for the Sabana Sucreña, home to approximately one million inhabitants. However, this confined aquifer faces significant challenges due to pollution and overexploitation. The water quality risk index for human consumption (IRCA) has increased to a medium level since 2005 in Sucre[6], raising concerns about the future potability of water in the region[7]. Additionally, according to recent research, the Morroa aquifer is among the most overexploited in the World, based on the Groundwater Footprint (HAG) indicator[8].

All the above highlights the vital importance of the aquifer, which has become indispensable for thousands of families. However, it currently faces two critical issues: contamination and overexploitation. Various studies have employed advanced technologies such as satellite imagery, artificial intelligence tools, data science, and sensorization to monitor and contribute to the management of these underground reservoirs. Their fundamental role in society and global

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development is increasingly recognized. For example, Adeyeri[9] investigated the impact of various factors on temperature distribution in West Africa using machine learning models, including downscaling models. Arrechea-Castillo[10] proposed a methodology based on convolutional neural networks to classify land use in Sentinel-2 images, achieving a high accuracy of 96%. Additionally, Xie[11] used Google Earth Engine (GEE) to map changes in vegetation cover in Queensland, Australia, using Landsat satellite data and field observations. A 20% decrease in vegetation cover was observed in the study area, with some parts recovering and the rest remaining stable.

Regarding the work of such tools with aquifers, Yang[12] propose a deep learning model, the CNN-LSTM-ML, which accurately predicts groundwater levels even with limited data. This approach combines convolutional neural networks (CNN) and a long short-term memory (LSTM) network and is noted for its effectiveness both in the short term (1 month) and long term (12 months). Additionally, Ahmadi[13] conducted a systematic review of groundwater prediction models, highlighting the capability of machine learning models to monitor and predict various hydrological features.

On the other hand, Jeong[14] developed a cost function for training recurrent neural network models, specifically designed for groundwater level data with outliers and noise. This approach proved effective in rejecting the influence of outliers during model training. Regarding data science and artificial intelligence tools, Manrique[15] presented the application of these tools to predict variables related to water levels and flow rates in confined aquifers, using data from the Morroa aquifer in Colombia. The results suggest that these tools are viable for broader use in groundwater resource management.

2. METHODOLOGY

Figure 1 outlines the methodology employed in this research. First, the problem was defined, and the data source was delimited, using the PlanetScope platform due to its high resolution of 3 meters/pixel and surface reflectance correction. The delineation of the Morroa aquifer defined by ENA 2014 was used as a mask[16]. For Land Use and Land Cover (LULC) classification, six classes were established: surface water, built-up area, cultivated area, bare soil or small vegetation, medium vegetation or medium herbs, and areas of tall vegetation.

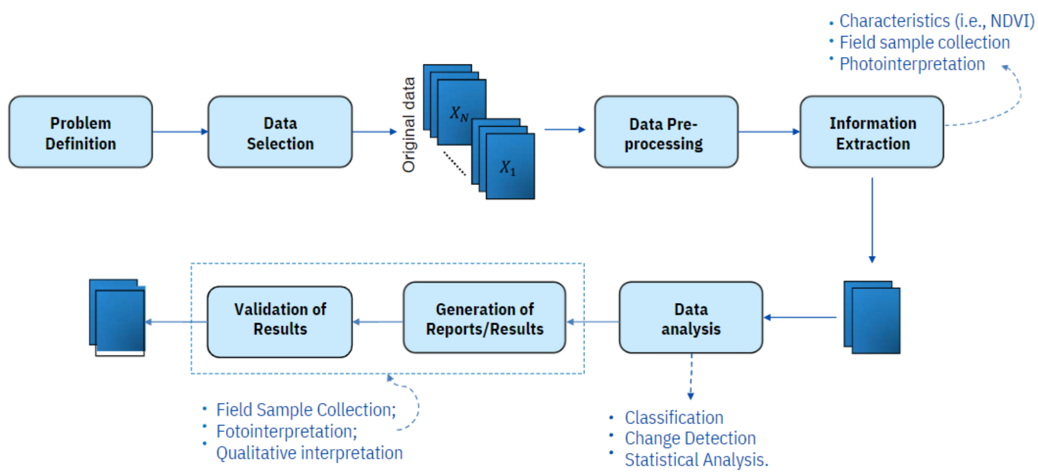

Figure 1. Methodological scheme carried out in the present research.

On the stage of extracting and analyzing the data, a classifier based on the Random Forest algorithm, configured with 250 classification trees and 50 training points for the Built, Water, and Crops classes was used. Specific indices were employed to identify vegetated areas, water bodies, urban areas, and bare soils, thus enhancing the accuracy and efficiency of the models. For instance, the Enhanced Vegetation Index (EVI) enabled the detection of differences in forest density, the NDVI assessed the health of vegetation cover, and the NDWI identified small water bodies such as ponds. Additionally, the number of training samples for the Forest, Grass, and Bare Ground classes was increased to between 65 and 100 samples to enhance the results.

Finally, the training samples for the proposed model were selected through photointerpretation. To improve this selection, a feature set was employed, including preprocessed bands from PlanetScope and Sentinel-2, six radiometric indices, and the Digital Elevation Model (DEM). However, the training samples exhibit imbalance due to the naturally unequal distribution of coverages in the study area. Therefore, additional balancing of the original samples was required to correct this bias in the learning process.

3. STUDY AREA AND DATA

The study area of this research is in the department of Sucre, Colombia. Figure 2 depicts, on the left, its geographical location in red, while on the right is visualized the specific location of the Morroa aquifer, situated in the central region of Sucre department. With an approximate extension of 900 km^2, of which 645 km^2 are surface area, this aquifer is the largest and most important in the region, as indicated by Manrique[15]. However, the focus of the project is on the so-called Recharge Zone (RZ), strategically designated as such by the governmental entity responsible for water management, Carsucre. Figure 2 (right) clearly shows this RZ (DEM_Recharg) within the framework of the projected aquifer image. In this zone, several recharge works were implemented in 2006, strategically located to capture rainwater through runoff, infiltration through the soil, or through streams of small tributaries that feed the aquifer. This strategic area is located within the property known as El Tesoro, in the municipality of Sabanas de Cali. The purpose of this construction is to conduct a comprehensive analysis to determine the feasibility of artificial aquifer recharge as a method to counteract the overexploitation of the Morroa aquifer. Figure 3 illustrates the general scheme of these water collection structures to improve water capture for the aquifer. The civil infrastructure for rainwater and runoff harvesting is located in the Recharge Zone (ZR), as illustrated in Figure 3. This area is surrounded by major populations that depend on the aquifer, such as Sincelejo, Corozal, and Morroa. It is a strategic point due to its high population density and the rapid decrease in water levels in this specific zone.

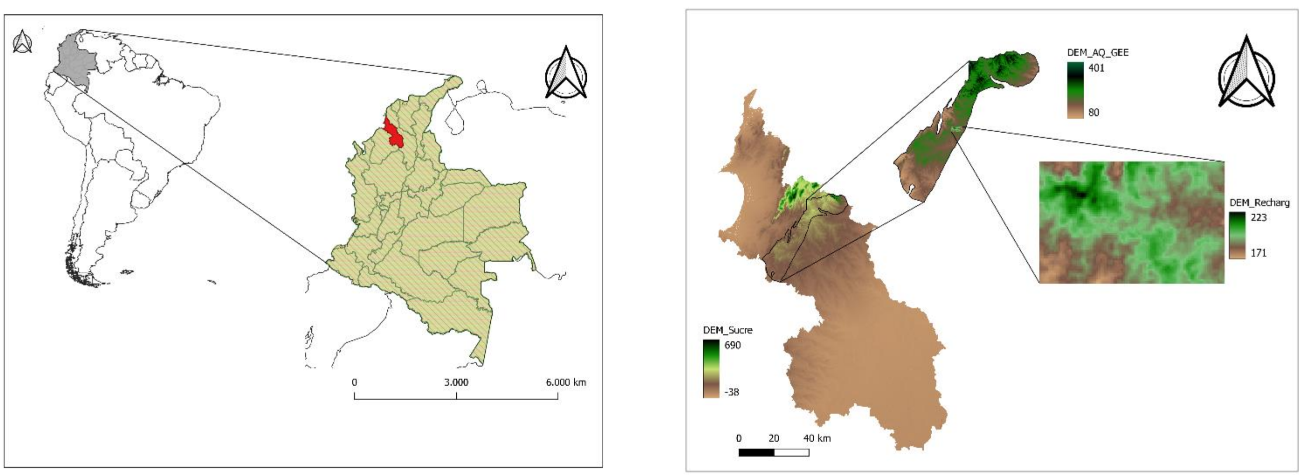

Figure 2. Study area location.

The artificial recharge works operate as follows: rainwater (point I in Figure 3) is diverted by a containment wall towards the system of works. Firstly, it enters a sedimentation pond (D), comprised of three coils that reduce suspended sediments and the velocity of the water before entering the artificial recharge system (G)[17]. Once the amount of sediment from runoff is reduced, the water is channeled towards infiltration trench 1 (A), the large-diameter well (B), and the infiltration pond (C), where the water column is allowed to infiltrate. The water that does not infiltrate in the pond passes through filters designed to enhance its quality before reaching the pool (E), where it is treated before being injected into the injection well (H), which operates by gravity. There is also a trench 2 (F) that receives the excess water from the infiltration pond. The purpose of this structure is to direct a larger volume of rainwater towards the aquifer to improve its quality using natural sand, clay, and silt filters incorporated into the infrastructure. Additionally, it aims to mitigate erosion issues by reducing the velocity of runoff and improve the aquifer level by increasing its infiltration.

The RZ comprises two recharge structures located at coordinates 9°21'31"N - 75°17'35"W and 9°21'34"N - 75°17'20"W, corresponding to wells 44-IV-D-PZ-02 and 44-IV-D-PZ-04, identified as element (H) in Figure 3. These wells are used for measuring water level and quality through piezometers, conducted three or four times a year, to assess the static and dynamic levels of the aquifer. In this manner, historical data were obtained through Carsucre between the years 2002 and 2022 for both wells.

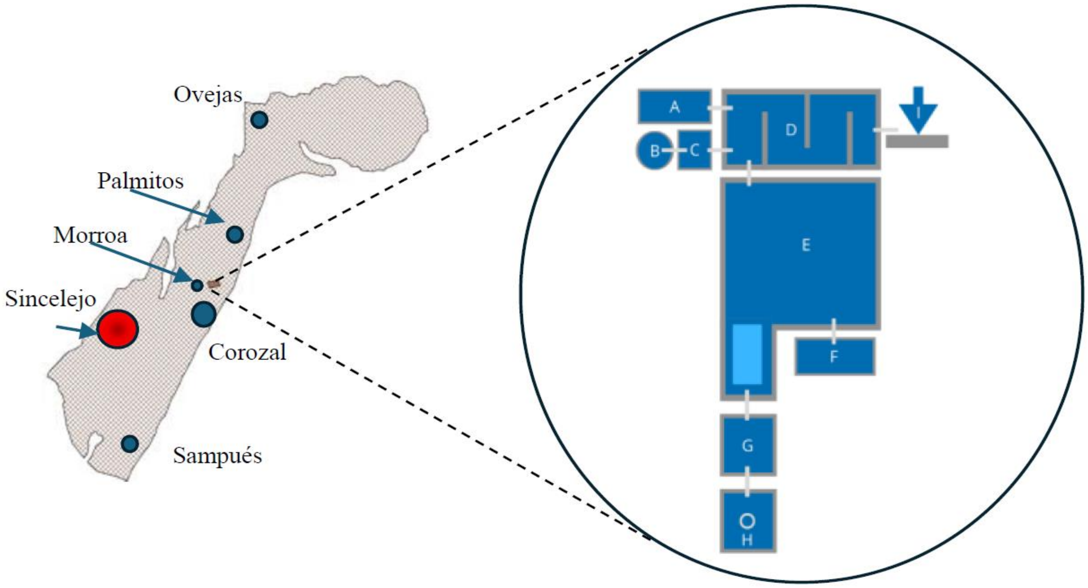

Figure 3. Location of the RZ in the aquifer area and general structure of recharge works (adapted from Navarro Mercado, J. L., 2020).

4. RESULTS

The data obtained for wells 44-IV-D-PZ-02 (well 02) and 44-IV-D-PZ-04 (well 04) regarding the static water level are shown in Figure 4.

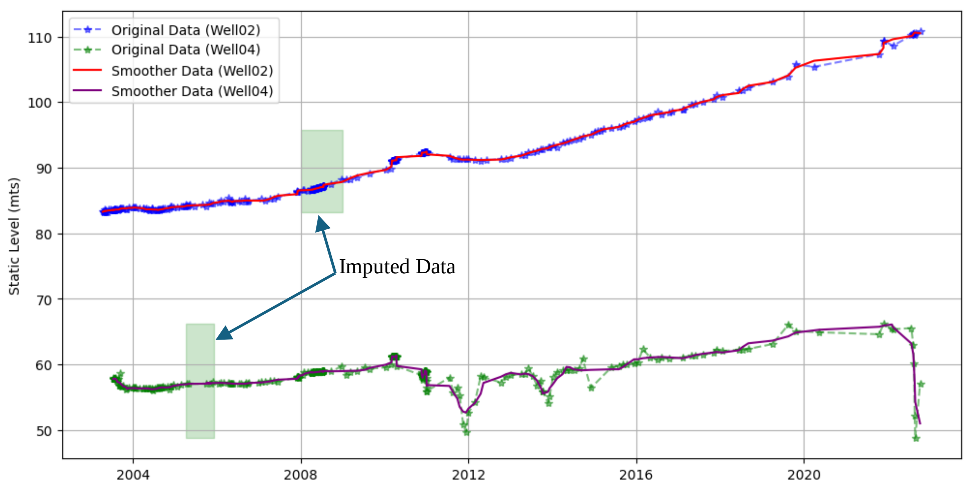

Figure 4. Static water level data of the aquifer obtained during the years 2002-2022 in wells 4-IV-D-PZ-02 (well 02) and 44-IV-D-PZ-04 (well 04).

During the analysis of static water level data in the wells, intervals with missing information were identified (represented by green bars in the data). To address this limitation, the data imputation tool proposed by Manrique[15] was applied, which is based on a multilayer artificial neural network (ANN)[18]. Additionally, a Whittaker smoother (WS) with a parameter lambda (λ=0.2) was implemented to reduce the noise present in the data, as shown in Figure 4. The choice of this value was based on previous studies[19,20] and trial and error methods. Both tools, the ANN and the WS, were developed in Python. Figure 4 illustrates the multi-year trend of the static water level in the aquifer for wells 02 and 04, showing a gradual increase, but with moderate impact. This phenomenon is mainly attributed to artificial recharge works. When applying the same tools (ANN and SW) to data from other wells located outside the ZR, different behaviors are observed, as shown in Figure 5. In this case, the slopes of static level growth are steeper, indicating a decrease in the liquid at concerning rates.

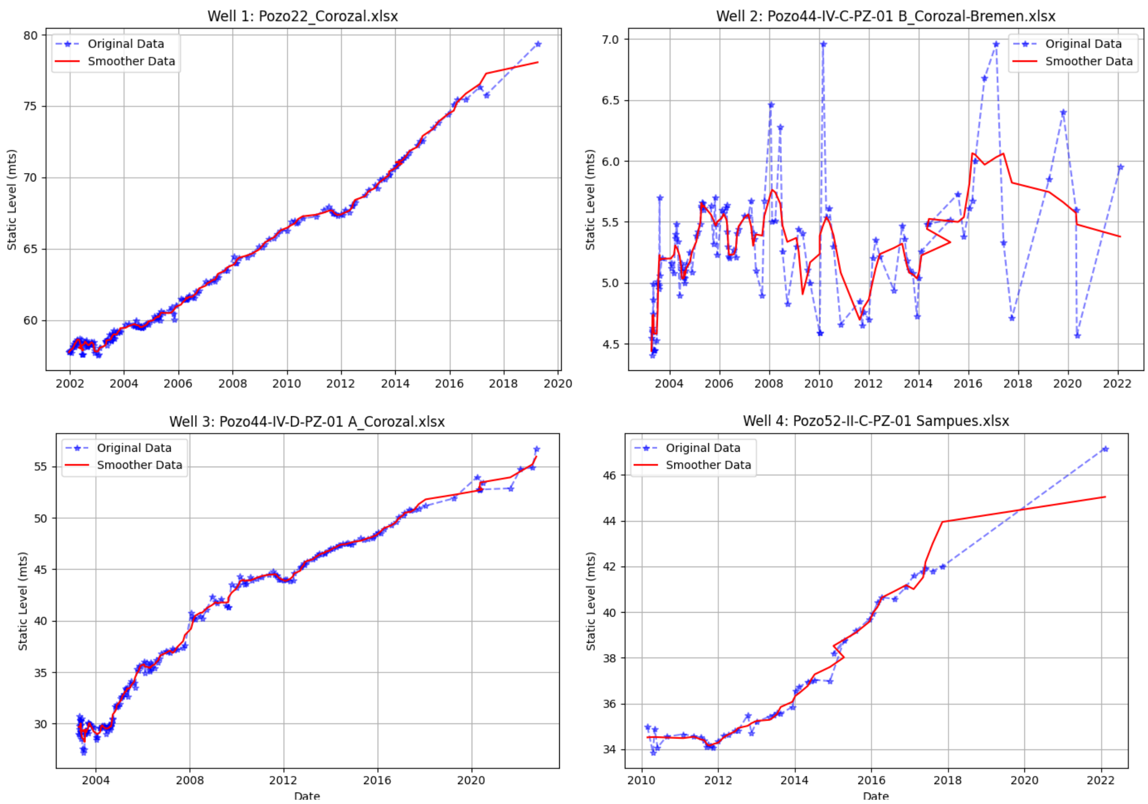

Figure 5. Static water level of wells 22, 01A, and 01 in Sampués (Sucre).

The static water level data from the wells belonging to the RZ, namely wells 02 and 04, were correlated with satellite data obtained from PlanetScope images and the GEE tool for NDVI indices and were related to the LULC data obtained in the Morroa aquifer coverage area. This was done to estimate the relationship between changes in vegetation and aquifer levels in recharge areas, to understand how these changes in coverage affect the static and dynamic levels of the aquifer. Figure 6 illustrates the behavior of the NDVI coefficient for the time series between 2000 and 2024 for well 02 (point 1) and well 04 (point 2), extracted from GEE using the MODIS sensor (MODIS/061/MOD13Q1- Terra Vegetation Indices 16-Day Global 250m resolution).

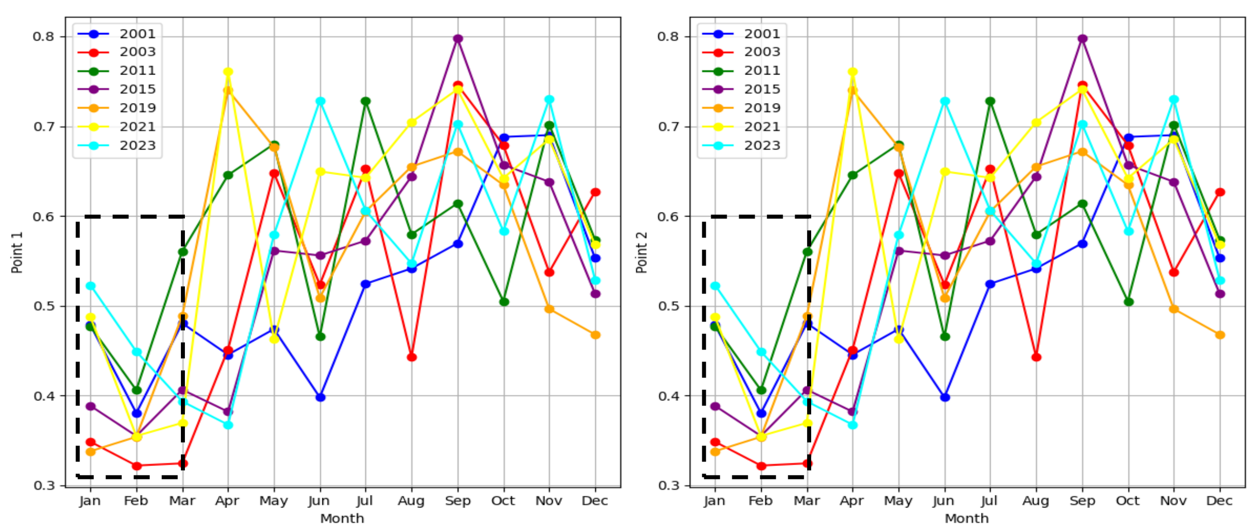

Figure 6. NDVI for a time window between 2000 and 2024.

Figure 6 shows that during the first months of the year, vegetation cover in the RZ is affected by the intense summer, which brings higher solar radiation and temperatures. This causes abrupt changes in the landscape between winter and summer seasons, not only in this area but throughout the aquifer in general. According to the soil condition classification proposed by Karfs[21], which evaluates the land's ability to respond to rainfall and produce useful forage, four classes are distinguished: A and B represent a stable condition of the land or vegetation cover, C indicates a potential decrease in condition that may require a change in land management, and D indicates a significant decrease that would require major management actions. In summer, the soil condition in the RZ is classified as class C, with moderate to low density of preferred grasses or low density of intermediate grasses, annual herbs, and weeds. However, in winter, the landscape changes considerably, becoming more herbaceous and denser, which could elevate the classification up to class B or even A, although this may be a considerable challenge[19]. The MODIS sensor was also employed to extract EVI and NDWI indices in the region of interest, within the same time window.

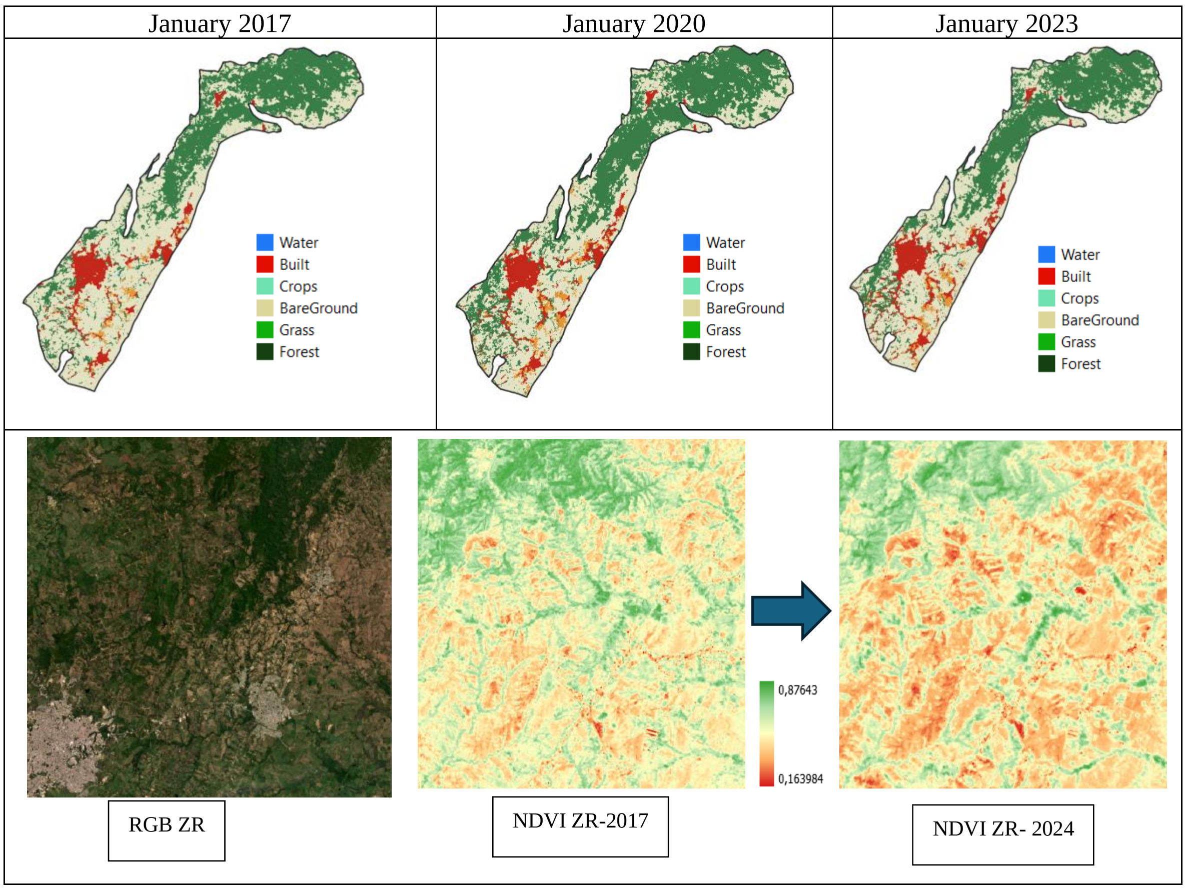

Figure 7. Classification maps 2017-2023 and NDVI maps for the months of January 2017 and 2024.

Regarding land use and land cover (LULC) classification, various algorithms were used through the GEE platform and high-resolution 3-meter images provided by PlanetScope. Validation of classification points was conducted by field experts, including professionals from Carsucre. Among the algorithms tested (CART, SVM), the Random Forest machine learning method proved to be the most effective (kappa coefficient of 0.8921 and an accuracy of 91.12%). This algorithm combines predictor trees, where each tree is based on values from a randomly sampled vector independently and with equal distribution for each[22]. Figure 7 presents three classification maps corresponding to the summer months across the entire aquifer area, showing a reduction in vegetation cover due to the dry climate. Additionally, at the bottom of the figure, the change in the aquifer RZ during the same summer months is evident. It is observed that, despite efforts made by relevant authorities, vegetation in the RZ is experiencing an increase in water stress, exacerbated by summer weather conditions. Table 1 provides a summary of the values corresponding to each assigned class in the aquifer area, using the Corine Land Cover methodology adopted by the IGAC (Agustín Codazzi Geographic Institute). It highlights the increase in built-up areas (11% since 2018), expansion of bare soil (37%), and the decrease in forested (-3%) and grassland (-11%) areas.

Table 1. Results of LULC analysis conducted from the year 2000 to 2023.

	Area (ha)						**2018-2023**
COVER	2000-2002	2005-2009	2010-2012	2018	2020	2023	% Growth
Built	2443,98	2684,73	2753,79	3619,19	3934,71	4063,72	11%
Water	0,00	0,00	0,00	59,68	85,40	120,10	50%
Crops	9132,68	5593,29	6718,84	14937,42	15609,83	17415,92	14%
Bare ground	334,51	496,96	351,10	254,87	325,70	405,30	37%
Grass	30508,01	37492,19	37227,20	24351,48	22189,18	21866,66	-11%
Forest	22084,25	18236,26	17452,49	21280,78	22358,61	20631,72	-3%

A correlation analysis was conducted between the static and dynamic variables of the aquifer water level, measured in situ (see Figure 5), as well as the NDVI, EVI, NDWI, and LULC indices. This analysis was based on PlanetScope images obtained between 2017 and 2023, using R Studio's Regressor software. The results are presented in Table 2, highlighting the high degree of correlation between the NDVI and EVI indices with the aquifer levels in wells near the RZ. Results such as those obtained with Random Forest, which showed an average correlation of 0.9605 for both indices, demonstrate the importance of maintaining a healthy vegetative cover in these strategic areas, especially a canopy cover, as it helps to better retain soil moisture[23].

Table 2. Correlation analysis between the static level of the aquifer and the calculated indices.

Static Level	**NDVI**		**EVI**	
ID	MSE	Correlation	MSE	Correlation
Random Forest	1.05	0.971	1.28	0.95
Classification and Regression Trees	2.98	0.887	1.84	0.92
Radial Suport Vector Regression	2.52	0.81	1.37	0.79
K-Nearest Neighbors	2.36	0.839	2.68	0.86
Penalized Regression - LASSO	4.57	0.785	3.02	0.77

5. CONCLUSIONS

Vegetative coverages play a crucial role in the long-term maintenance of both surface and underground water reserves globally. It is imperative that the Morroa aquifer, as the primary water source for a vast population in the department of Sucre, Colombia, receives constant attention from governmental entities, authorities, industry, and society at large. Increasing public awareness and concern are fundamental to drive improvements in current conditions, including vegetative land covers and reduction of pollution in aquifer recharge areas. Likewise, the results of this research indicate a pronounced depletion of groundwater levels in the study area and the surrounding zone of the Morroa aquifer. This phenomenon is largely attributed to significant changes in land use and vegetative cover, population growth in adjacent areas, and the notable reduction of vegetation during the prolonged periods of drought characteristic of the region. Furthermore, this research highlights the effectiveness of a methodology employing artificial intelligence tools and remote sensing data analysis to significantly contribute to the conservation of this vital resource.

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