Research Article

New Method to Identify Potential Illegal Water Use Location by Using Remote Sensing and Neural Networks in Laguna de Aculeo, Chile

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The Aculeo lagoon basin is facing a severe drought, resulting in a restriction of water usage solely for domestic purposes, and legal sanctions for those who use water for grass irrigation. To identify illegal use of water resources, this project evaluates the health of lawns during a dry season, using multi-spectral and multitemporal satellite data. Soil indices, including NDVI, EVI, GNDVI, SAVI, NDMI, MSI, and BSI, were derived between October 2021 and April 2022. Cluster analysis was performed to evaluate the statistical distribution of healthy vegetation cover, with results available on an ArcGIS web map. The study estimates the areas and corresponding water consumption of lawns in the basin, identifying properties that have used water illegally. The cluster analysis also indicates an unusual pattern of healthy vegetation cover, suggesting that these areas may be responsible for the illegal use of water resources. The study presents tools and protocols for identifying illegal water usage in areas facing water scarcity, providing crucial information for governmental authorities to enforce legal sanctions and undertake personal inspections. Overall, the study provides an effective approach to monitoring and enforcing water usage restrictions in water-scarce areas.

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1. Introduction

Chile has been facing a complex water scenario related to drought and water scarcity, understanding drought as a meteorological phenomenon and scarcity as a long-term imbalance between supply and demand [1]. The predictability of water availability is decreasing in numerous locations. Droughts in certain regions are worsening water scarcity, leading to adverse effects on both health and productivity of individuals [2]. Securing access for all to sustainable water and sanitation services emerges as a crucial strategy for mitigating climate change in the coming years [3][4].

In a similar context, increased temperatures and more extreme, unpredictable weather conditions are anticipated to impact the availability and distribution of rainfall, snowmelt, river flows, and groundwater. This is expected to exacerbate the deterioration of water quality [5][6]. Furthermore, the rise in temperatures will coincide with significant alterations in the Earth's water cycle. Regions that are already wet are expected to become even wetter, while areas that are already arid will be more susceptible to increased drought [7][8][9].

In Chile, the President can issue water scarcity decrees in regions affected by severe droughts, based on hydrometeorological criteria outlined in the Water Code [10]. However, there is a lack of monitoring tools for water usage and demand, hindering effective management of water scarcity. These decrees empower the Directorate General for Water (DGA) to set limits on water extraction and provide measures to mitigate drought damage [11][12]. They typically last for six months but can be extended up to one year in areas of significant water scarcity [11][12].

The Chilean Water Code, implemented since 1981, establishes a tradable water-use rights system, separate from land titles. These rights, known as DAAs, are allocated to users upon request and can be freely traded. However, individuals do not need water rights to build a well for domestic use on their property [13][14]. The WHO recommends a daily water consumption of 100 liters per person, but irrigating a 10x10 m^2 grass area requires 500 liters per day [15]. To combat illegal water use, it is crucial to report such activities to the Directorate General of Water (DGA) and local authorities. Unauthorized water extraction can result in fines ranging from approximately $35,000 to $77,000, with aggravating factors potentially increasing the penalties by up to 100% [12]. The DGA has the power to block unauthorized abstractions to prevent further illegal water extraction. Complaints about illegal water use can be initiated by citizens or scheduled DGA inspections. Complaints should include gathering information, such as personal testimonies and visual evidence like photos and videos [16][17]. However, there is currently no interactive platform available to capture reliable details regarding land surface conditions. Therefore, acquiring information and improving knowledge is essential for decision-making and problem-solving, enabling authorities to determine the most effective course of action to address illegal water use.

Significantly, remote sensing and geographic information systems (GIS) not only aid in gathering, analyzing, and visualizing information but also address spatially linked environmental and socio-economic challenges. This serves as a potent tool for integrating both spatial and non-spatial datasets with analytical and spatial models across various knowledge domains [18][19]. Recent progress in contemporary spatial tools, including remote sensing and GIS, coupled with advanced computational techniques, has heightened the efficiency and capabilities of policy development [20].

Remote sensing databases exhibit distinctive characteristics, encompassing methods for estimating climate-related variables, grid resolution, spatial coverage, sensor attributes, orbital aspects, and time range. Notably, Sentinel data products adhere to a free, full, and open data policy established for the Copernicus programme, ensuring accessibility for all users [21].

Sentinel-2 is a high-resolution, multi-spectral imaging mission with a wide swath. It plays a crucial role in supporting Copernicus Land Monitoring studies, facilitating the monitoring of vegetation, soil and water cover. Additionally, it is instrumental in observing inland waterways and coastal areas [22][23]. The Multispectral Instrument (MSI) on SENTINEL-2 captures data across 13 spectral bands. These include four bands at a 10-meter spatial resolution, six bands at a 20-meter spatial resolution, and three bands at a 60-meter spatial resolution. The global spatial coverage extends from 60S, 180W to 90N, 180E. Specifically, bands B2 (490 nm), B3 (560 nm), B4 (665 nm), and B8 (842 nm) possess a 10-meter spatial resolution, while bands B5 (705 nm), B6 (740 nm), B7 (783 nm), B8a (865 nm), B11 (1610 nm), and B12 (2190 nm) have a 20-meter spatial resolution [24].

The temporal resolution of a satellite in orbit refers to how frequently the satellite revisits a specific location. In the case of each individual Sentinel-2 satellite, the revisit frequency is 10 days, and when considering the combined constellation, the revisit frequency is reduced to 5 days [25]. Consequently, the data available is often not sufficient for compiling a continuous and evenly spaced time series. This limitation arises from the long revisiting intervals of satellites (i.e., extended orbits) and the presence of clouds [26]. Nonetheless, it remains a notable instrument for capturing the overall trend.

Over time, the scientific community has developed spectral indices by combining spectral reflectance from two or more wavelengths. A spectral index involves a scientific calculation applied to multiple spectral bands of an image per pixel, yielding significant insights. These indices play a crucial role in modeling, predicting, or inferring surface processes [27][28]. Diverse applications and uses of satellite indices have been explored in previous studies. These encompass agriculture, groundwater assessment, water resources management, urban development monitoring, forest ecology analysis, geological studies, soil characterization, vegetation monitoring, and various other applications [29][30][31][32]. To address the challenge of detecting illegal water intrusion, one study presented an improved algorithm based on YOLOv3. This algorithm combines residual and dense modules to enhance accuracy in detecting large targets. Our RD_YOLOv3 model achieves higher mean average precision (MAP) values on relevant datasets, indicating improved performance in identifying illegal wells and intrusions in water areas [33]. However, this method relies solely on image detection and requires a clear well representation. No study has yet inferred illicit wells based on land cover limitations for water usage in irrigation.

The primary aim of this study was to contribute to the advancement of techniques for monitoring land surfaces, promoting responsible water use, and reducing the efforts required for gathering information for water regulatory compliance. The study's specific objective was to assess the potential of utilizing free Remote Sensing Satellite Data, particularly the MSI Sentinel-2 multispectral sensor, to improve the effectiveness of inspections in regions where water is a scarce commodity. In this case, the study area is Laguna Aculeo, Chile. However, the system will be adopted and implemented to analyze water-scarce regions with similar legal regulations.

In the present study, the following indices were calculated: Normalized Difference Vegetation Index (NDVI), Enhanced Vegetation Index (EVI), Green Normalized Difference Vegetation Index (GNDVI), Soil Adjusted Vegetation Index (SAVI), Normalized Difference Moisture Index (NDMI), Moisture Stress Index (MSI), and Bare Soil Index (BSI) as illustrated in Figure 1.

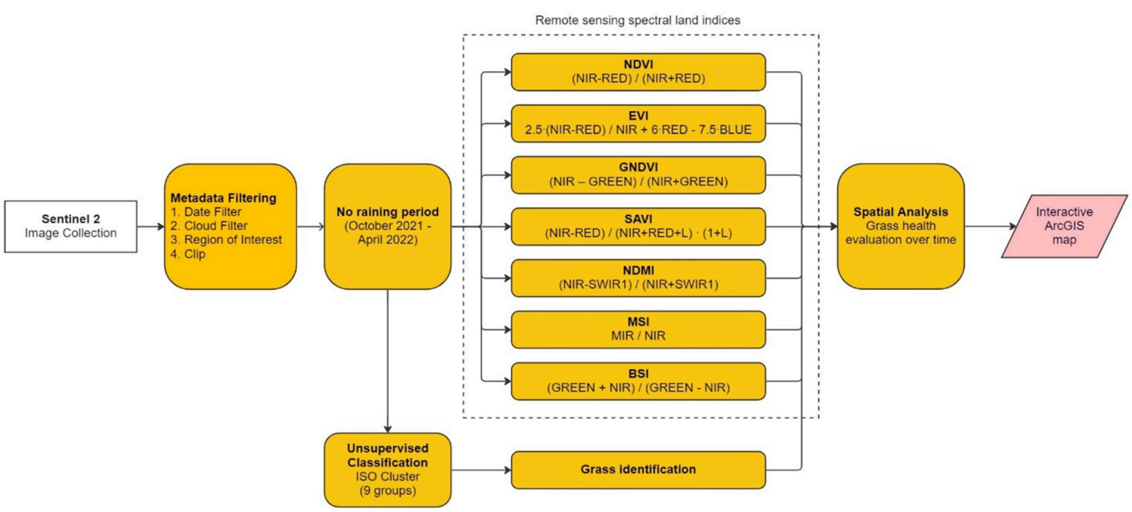

Figure 1. Diagram of research methodology.

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2. Materials and Methods

The enchanting Laguna de Aculeo, nestled in the Estero Angostura between Estero Paine (II) and the Río Maipo Sub-Basin, lies within the confines of Paine city, in the Maipo Province of Santiago's Metropolitan Region, Chile. Positioned at 33º 50’ 30’’ S latitude and 70º 54’ 24’’ W longitude, and perched at an altitude of 350 meters above sea level, this once idyllic summer retreat is now facing a dire reality of vanishing waters. The lake, which previously spanned 11.5 square kilometers, boasted an average depth of 3.4 meters, peaking at 7 meters, and held a substantial water volume of $53.6 \cdot 10^6$ cubic meters. It received an annual average precipitation of 611 millimeters. The climate, characterized as Mediterranean, is predominantly influenced by the shallow groundwater that replenishes the lake. The catchment area covered a vast expanse of 264 square kilometers, with a hydraulic conductivity of 15 cubic meters per day. Historical data spanning 27 years, from 1970 to 1997, indicates an annual evaporation rate of roughly 1200 millimeters. Amidst this climatic backdrop, January emerges as the warmest month, with temperatures averaging 20.3 ºC, while July offers a cooler respite at an average of 7.6 ºC. [34][35].

Local residents and government officials have convened to address the declining water levels of Laguna de Aculeo. The community suspects the desiccation is due to reduced yearly rainfall, rising average temperatures, population increase, and excessive water use from unauthorized wells, as well as livestock and farming practices. On August 16, 2018, the Chilean government enacted Exempt Resolution No. 12/2018, acknowledging the lake's significant water resource depletion, attributed to both natural and human-induced factors. The resolution reveals that the average annual water consumption for agriculture is 572 liters per second, with peaks reaching 1000 liters per second, leading to the conclusion that the water demand in the catchment exceeds the available supply. Furthermore, it has been noted that many land parcels are being over-irrigated to sustain a green appearance, resulting in the misuse of well water resources.

There is strong evidence that dry seasons are highlighted by rising average temperatures and increasing duration, frequency, and severity of drought events [36]. Furthermore, a zero-precipitation rate over long periods of time has a negative impact on soil moisture and vegetation cover by diminishing or degrading their inherent properties [37]. Thus, the study has a time frame-work from the non-registration of precipitation events (October 2021) to the first precipitation record (April 2022) at Lacuna de Aculeo, analysing seven consecutive months with zero rainwater. Hence, we can infer that vegetation covers and soil degradation is related to an external factor that should be inspected by local authorities.

Data Collection

From October 2021 to April 2022, we gathered all Level-2A remote sensing data from the Sentinel 2 satellite. This dataset includes spectral band information spanning 16 days, with a spatial resolution of either 10 meters or 20 meters. The research derived several indices, namely: NDVI (Normalized Difference Vegetation Index), EVI (Enhanced Vegetation Index), GNDVI (Green Normalized Difference Vegetation Index), SAVI (Soil Adjusted Vegetation Index), NDMI (Normalized Difference Moisture Index), MSI (Moisture Stress Index), and BSI (Bare Soil Index). Additionally, the Sentinel-2 Level-2A data is an enhanced version of the original imagery, having been subjected to advanced atmospheric correction and further image processing.

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NDVI is a prevalent index for assessing vegetation health, contrasting near-infrared (NIR) with red light (RED). Higher NDVI values denote healthier plants. The formula is: NDVI = (NIR-RED) / (NIR+RED) or NDVI = (B8-B4) / (B8+B4), with a value range from -1 to +1. NDVI is crucial for tracking vegetation and ecosystem changes, correlating positively with regular irrigation and grassland proliferation.

EVI, an enhanced version of NDVI, corrects NDVI's inaccuracies to better represent vegetation. EVI ranges from -1 to +1, with 0.2 to 0.8 indicating healthy vegetation. The EVI formula is: EVI = 2.5·(NIR-RED) / NIR + 6·RED - 7.5·BLUE + 1 or EVI = 2.5·(B8-B4) / B8 + 6·B4 - 7.5·B2 + 1.

GNDVI, akin to NDVI but using the green spectrum, is sensitive to chlorophyll in leaves, aiding in moisture and nitrogen assessment. GNDVI's formula is: GNVI = (NIR – GREEN) / (NIR+GREEN) or GNVI = (B8-B3) / (B8-B3), and it ranges from -1 to +1.

SAVI incorporates a soil-brightness correction to reduce soil's impact on NDVI, beneficial in low-vegetation areas. SAVI's equation is: SAVI = (NIR-RED) / (NIR+RED+L) · (1+L) or SAVI = (B8-B4) / (B8+B4+L) · (1+L), where L is typically 0.5 or 0.48.

NDMI utilizes NIR and SWIR to analyze soil moisture, with higher values in wetter soils. The NDMI formula is: NDMI = (NIR-SWIR1) / (NIR+SWIR1) or NDMI = (B8-B11) / (B8+B11).

MSI, an index sensitive to leaf water content, indicates water stress with higher values. MSI's range is 0 to over 3, with 0.4 to 2 typical for green vegetation. The MSI equation is: MSI = MIR / NIR or MSI = B11 / B8.

BSI measures bare soil reflectance, with higher values showing more bare soil, useful for detecting soil issues. BSI's formula is BSI = NIR / (NIR + Red) or BSI = (B11 / (B11 + B4).

Unsupervised Classification

This scientific article presents a classification methodology applied to a satellite image captured in October 2021. The objective of the study is to accurately categorize different features or objects present in the image. To achieve this, the researchers employed the Iso Cluster Unsupervised Classification approach, a technique commonly used in remote sensing and image analysis.

The Iso Cluster Unsupervised Classification approach is a data-driven method that aims to partition a given dataset into distinct groups or clusters based on their inherent similarities. In this study, the image was divided into 10-pixel groups using data from Sentinel bands 2, 3, 4, 5, 8, and 11. These bands were selected due to their relevance and ability to capture valuable spectral information necessary for accurate classification.

The smallest class size was determined to be 20 pixels, which implies that a group of pixels needed to have a minimum of 20 members to be considered a distinct class. This criterion helps to ensure that smaller and potentially less significant features or objects are not mistakenly classified as individual classes. Additionally, a sampling interval of 10 was applied, which implies that every 10th pixel was selected for the classification process. This approach helps to reduce computational complexity and improve the efficiency of the classification algorithm.

To facilitate the classification process, a cell size of 10 meters was utilized. The cell size represents the spatial resolution of the resulting classified image and determines the level of detail at which the classification is performed. In this case, a cell size of 10 meters was chosen, which indicates that each pixel in the classified image represents an area of 10 meters by 10 meters on the ground. This value was determined as the minimum among the input bands, ensuring that the finest level of detail present in the data is preserved during the classification.

3. Results

3.1. Precipitation

In order to enhance transparency and make institutional information accessible to the public, the General Directorate of Water (DGA) has established the National Water Information System (SNIA), which maintains historical records of hydrometeorological and water quality data obtained from the National Hydrometric Network. In this study, we utilized data collected by the Laguna Aculeo Meteorological Station (BNA ID: 05716005-5), which is situated near the Pintue estuary at coordinates Latitude: 33° 53' 09'' and Longitude: 70° 52' 39''. The station has been recording precipitation data since 1988, which we extracted from the SNIA portal. Our analysis reveals that there were no instances of rainfall between October 2021 and April 2022. These findings highlight the importance of continued monitoring and evaluation of meteorological patterns, particularly in water resource management (Figure 2).

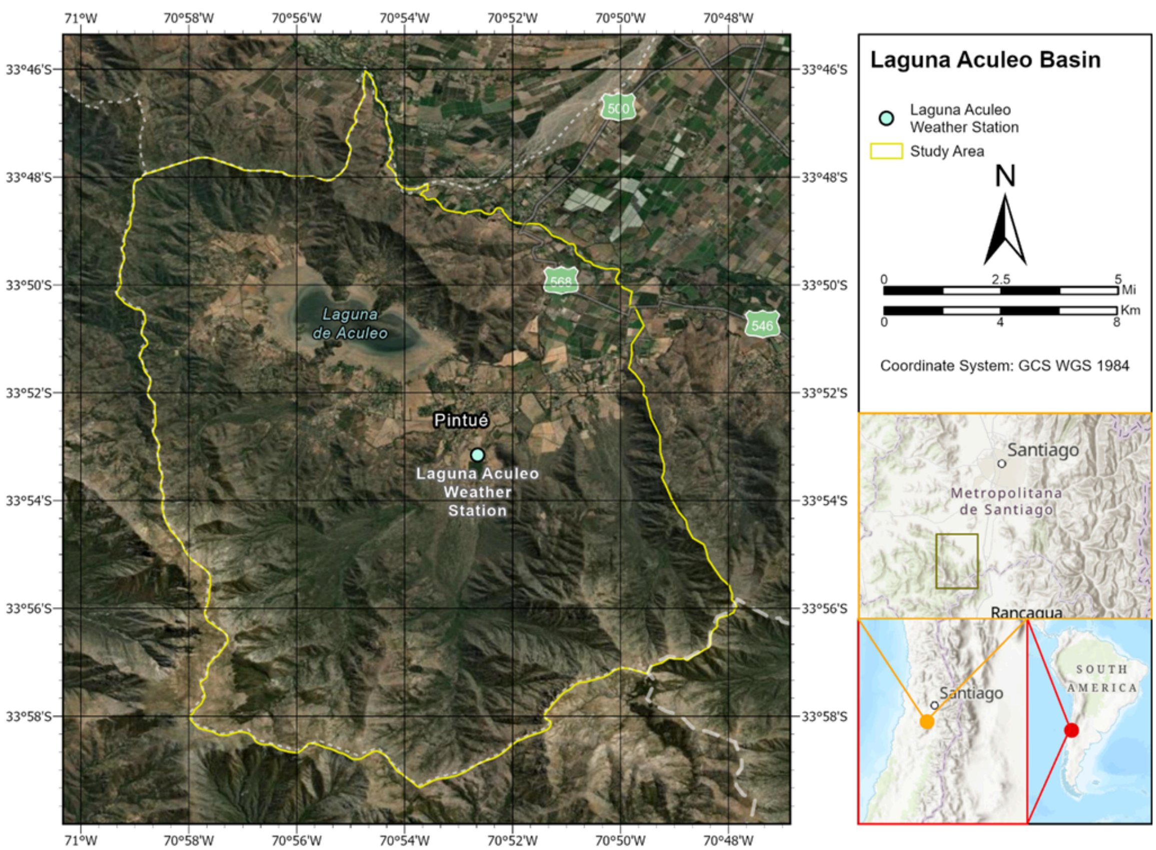

Figure 2. Study area, Laguna Aculeo at Chile

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3.2. Remote Sensing

This study utilized the Copernicus Sentinel-2 Level-2A collection with atmospheric correction (S2MSI2Ap) to collect optical images of the study area at intervals of approximately 15 days, between October 25, 2021, and April 13, 2022. A total of 16 high-resolution multispectral imagers at 10 m spatial resolution were analyzed and processed to evaluate the condition of vegetation over a period of 171 days (5 months and 20 days). The results of this investigation suggest that if a lawn area demonstrates consistent or improved health relative to different soil indices, it may be indicative of illegal water use for irrigation. However, the use of a free remote sensing database limited the spatial and temporal resolution of the images, which highlights the need for a commercial agreement with a private satellite company to obtain more frequent and higher resolution data. Additionally, we recommend the development of a GIS and remote data analysis division to unlock the full potential of remote analysis in various research areas, such as the estimation of climatic variables like precipitation and evaporation. By analyzing a water balance for each pixel, unusual evaporation levels in a particular area can be identified, which may be indicative of illegal water use and trigger real-time action. The findings suggest that the graphical representation of five indices' estimations for Aculeo on October 25, 2021, as depicted in Figure 3, offers significant information regarding the vegetation's vitality and status within the area under examination.

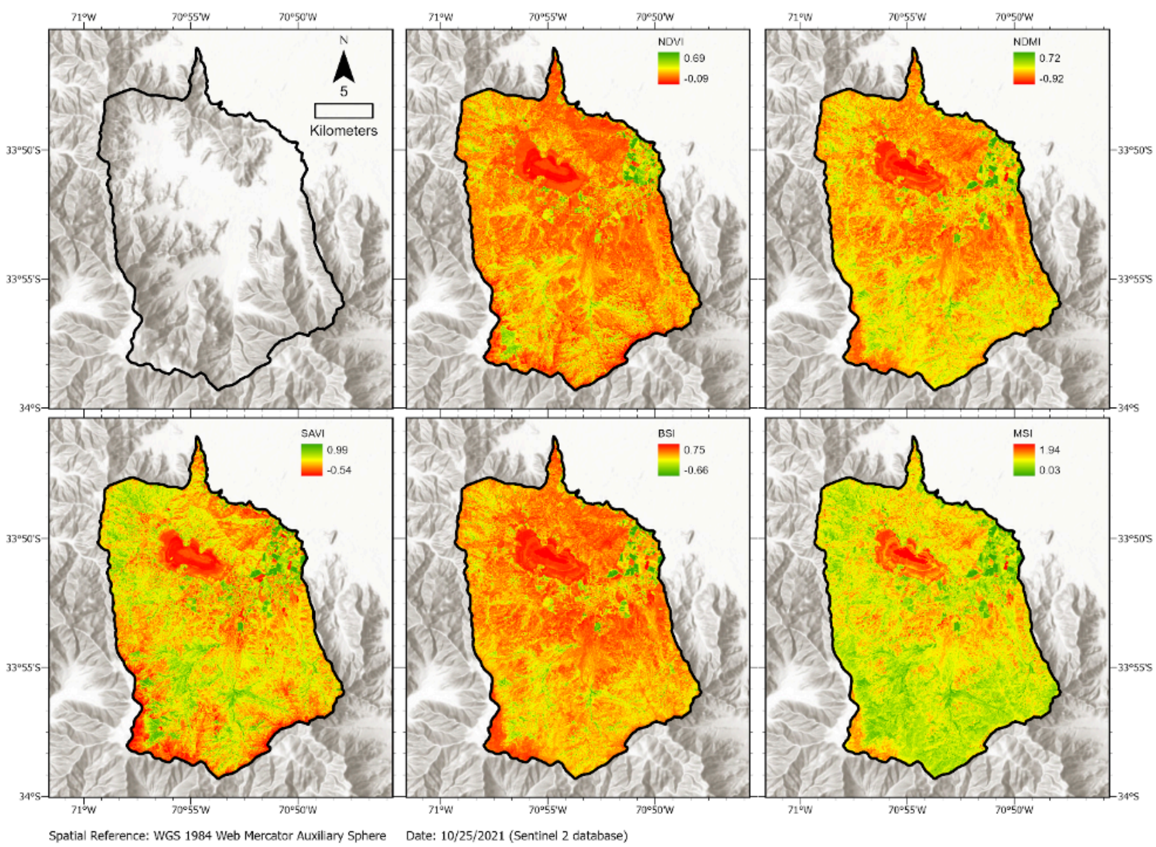

Figure 3. Land indexes estimation on November 25th, 2021, at Laguna Aculeo

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3.3. Trend analysis

Various soil indices such as NDVI, EVI, GNDVI, SAVI, NDMI, MSI, and BSI were estimated at a spatial resolution of 10 m2 to identify areas with high vegetation coverage over time. The entire study area was evaluated, and it was found that all soil indices decreased from October to April in 171 days, which had no rain events. The decline in vegetation health was observed globally in the basin, regardless of the mathematical calculation made on each pixel using GIS tools. This could be due to the high temperatures in summer and limited water access for the vegetation. An analysis of only NDVI values showed that certain areas within the watershed had abnormal values compared to the mean, with some areas having values as high as 0.99. The Moisture Stress Index values supported these results, indicating values above 2.5 in certain areas, which could be attributed to maintaining or improving the vegetation cover. Moreover, there are period of time where we can detect values higher than 50. In essence, higher MSI values indicate a greater amount of water content. However, it is worth noting that we are currently experiencing a period of no precipitation, and it is illegal to water lawns. Hence, it is peculiar to observe higher water content values in such circumstances. The Bare Soil Index showed that there was almost no growth of new vegetation cover in the study period, with an increase in bare areas from December to February due to adverse conditions affecting vegetation health (Table 1). By setting a threshold of NDVI equal to or higher than 0.5, we were able to identify pixels that represent areas of significant healthy vegetation, which may indicate the presence of sufficient water or nutrient supply to support healthy plant growth. Similarly, we applied the same approach of setting threshold values to all the land indices evaluated in the study to identify pixels that exhibited characteristics associated with healthy vegetation growth (Figure 4).

Date	Year	2021					2022										
	Month	10	11	12			01			02			03			04	
	Day	25	14	04	14	24	03	13	23	02	12	22	04	14	24	03	13
NDVI	Mean	0.44	0.42	0.40	0.39	0.38	0.37	0.36	0.38	0.21	0.20	0.19	0.19	0.20	0.20	0.20	0.44
	STD	0.15	0.15	0.15	0.15	0.15	0.15	0.16	0.15	0.08	0.08	0.07	0.07	0.07	0.07	0.07	0.15
	Maximum	0.96	0.95	0.94	0.94	0.94	0.95	0.98	0.99	0.70	0.69	0.68	0.70	0.71	0.72	0.72	0.96
	Minimum	−0.53	−0.55	−0.70	−0.61	−0.68	−0.73	−0.72	−0.71	−0.18	−0.13	−0.07	−0.09	−0.19	−0.12	−0.15	−0.53
SAVI	Mean	0.39	0.02	0.07	0.06	0.14	0.34	0.34	0.34	0.08	0.16	0.09	0.05	0.04	0.15	0.07	0.29
	STD	0.15	0.15	0.15	0.15	0.15	0.15	0.16	0.15	0.08	0.08	0.07	0.07	0.07	0.07	0.07	0.15
	Maximum	0.96	0.95	0.94	0.94	0.94	0.95	0.98	0.99	0.70	0.69	0.68	0.70	0.71	0.72	0.72	0.96
	Minimum	−0.53	−0.55	−0.70	−0.61	−0.68	−0.73	−0.72	−0.71	−0.18	−0.13	−0.07	−0.09	−0.19	−0.12	−0.15	−0.53
BSI	Mean	0.08	0.09	0.09	0.10	0.11	0.12	0.13	0.12	0.07	0.07	0.06	0.07	0.07	0.07	0.07	0.07
	STD	0.12	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
	Maximum	0.75	0.78	0.68	0.70	0.70	0.75	0.77	0.86	0.34	0.32	0.32	0.35	0.40	0.42	0.49	0.62
	Minimum	−0.66	−0.60	−0.59	−0.59	−0.61	−0.63	−0.56	−0.61	−0.37	−0.37	−0.34	−0.36	−0.38	−0.38	−0.34	−0.36
EVI	Mean	1.00	0.98	0.92	0.91	0.83	0.87	0.80	0.98	0.22	0.22	0.20	0.20	0.21	0.23	0.21	0.22
	STD	0.93	0.21	0.22	0.20	0.18	0.27	0.20	0.70	0.03	0.03	0.02	0.02	0.03	0.30	0.02	1.00
	Maximum	0.33	0.21	0.34	0.40	0.50	0.60	−0.40	0.54	0.00	0.00	0.00	0.00	0.00	0.48	0.00	1.00
	Minimum	−0.53	−0.83	−0.70	−0.69	−0.47	−0.86	−0.71	−1.00	−0.19	−0.17	−0.17	−0.17	−0.19	−0.21	−0.17	−0.20
GNDVI	Mean	0.44	0.42	0.40	0.39	0.38	0.37	0.36	0.38	0.21	0.20	0.19	0.19	0.20	0.20	0.20	0.44
	STD	0.15	0.15	0.15	0.15	0.15	0.15	0.16	0.15	0.08	0.08	0.07	0.07	0.07	0.07	0.07	0.15
	Maximum	0.96	0.95	0.94	0.94	0.94	0.95	0.98	0.99	0.70	0.69	0.68	0.70	0.71	0.72	0.72	0.96
	Minimum	−0.53	−0.55	−0.70	−0.61	−0.68	−0.73	−0.72	−0.71	−0.18	−0.13	−0.07	−0.09	−0.19	−0.12	−0.15	−0.53
NDMI	Mean	−0.04	−0.05	−0.05	−0.05	−0.07	−0.08	−0.09	−0.07	−0.05	−0.05	−0.03	−0.06	−0.05	−0.05	−0.06	−0.05
	STD	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.13	0.08	0.08	0.07	0.08	0.08	0.08	0.08	0.08
	Maximum	0.72	0.74	0.7	0.67	0.69	0.71	0.66	0.72	0.57	0.58	0.55	0.57	0.58	0.58	0.53	0.59
	Minimum	−0.92	−0.91	−0.87	−0.88	−0.88	−0.86	−0.93	−0.96	−0.45	−0.45	−0.42	−0.48	−0.55	−0.54	−0.62	−0.62
MSI	Mean	0.90	0.92	0.92	0.93	0.95	0.98	1.00	0.96	0.91	0.91	0.87	0.92	0.91	0.90	0.91	0.90
	STD	0.28	0.29	0.28	0.28	0.28	0.29	0.3	0.29	0.18	0.18	0.15	0.18	0.18	0.18	0.18	0.19
	Maximum	23.6	21.28	14.53	15.38	15.52	13.8	25.94	54.67	2.66	2.67	2.45	2.87	3.45	3.36	4.23	4.25
	Minimum	0.16	0.15	0.18	0.19	0.18	0.17	0.2	0.16	0.36	0.35	0.38	0.36	0.35	0.35	0.4	0.34

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Table 1. Land indexes values from October 2021 to April 2022 at Laguna Acuelo Basin

Figure 4. Threshold conditions for Laguna Aculeo

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3.4. Unsupervised classification

An unsupervised classification method was used to categorize satellite image data into nine groups based on their spectral characteristics, with the first optical image collected on November 25, 2021 used as the reference image due to its higher vegetation density compared to other satellite images. The grass cover was visually identified and validated to ensure no mixing of land covers, and an If statement was developed to identify pixels meeting certain conditions that potentially indicate well-maintained or abnormal grass cover. These pixels were shown on an interactive map as red areas, and were recommended for further investigation to assess whether illegal water use for lawn watering was a factor. The unsupervised method was chosen due to the unfeasibility of carrying out supervised field work to corroborate pixel samples, although future research may benefit from this approach. The classification method was found to have an efficiency of 85.33% when assessing grass cover using a manual analysis of 150 randomly selected pixels. Misclassifications may occur due to confusion with trees or bare ground, and incorporating additional spectral bands may improve the classification accuracy (Figure 5). Combining the results of machine learning with our identification of healthy pixels, we were able to pinpoint areas of the study region that corresponded to grass cover and exhibited consistent or improved health over the study period, despite the absence of rainfall events. This strongly suggests that these areas were likely treated with water or nutrient inputs, supporting the hypothesis of illegal water use for irrigation in residential areas of Aculeo.

Figure 5. Unsupervised Classification results at Laguna Aculeo

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3.5. Potential water consumption for grass irrigation

3.6. ArcGIS web application

Further refining our analysis, we identified the areas of the study region classified as grass vegetation that had surpassed the established threshold values at least once during the study period, indicating that these areas had received sufficient water or nutrient inputs to sustain healthy growth over time, further supporting the hypothesis of illegal water use in Aculeo. It was determined that 667,000 m2 of land cover was classified as grass and exhibited improved health from October to April. However, this grass was not uniformly distributed throughout the study area and showed a cluster distribution in residential areas, indicating that it could had been watered with a water source. On the other hand, the majority of grass and vegetative covers did not display increased health over the study period. Overall, it was observed that grass and other land covers, except crops, tended to experience a decrease in health during this time. The application of this methodology, whereby the government could recollect up to 133200 million of CLP by utilizing the maximum fine per lawbreaker, highlights the potential economic benefits of using remote sensing to identify illegal water use for irrigation in residential areas. Based on the assumption that the total area corresponds to 444 houses and the maximum fine per lawbreaker for illegal water use (5000 UTM) is applied, the potential revenue generated from fines could be significant and may act as a deterrent for future instances of illegal water use in residential areas.

The interactive map can be accessed by anyone through the provided link (*https://uagis.maps.arcgis.com/apps/webappviewer/index.html?id=06a35fa54f6541429a8b8216023e0f2b*) (Figure 6). The map allows users to generate time series data for a single pixel or obtain average, maximum, or minimum values for a specific area defined by the user. Additionally, it displays the ROL (ID) of each parcel and all the data is available for free download. This allows people or authorities to conduct their own analysis, and a link to report legal complaints and notify authorities of potential violations is also incorporated. However, it should be noted that using a private license application such as Esri generates a monetary and server dependency. Therefore, we suggest creating a similar application using an open-source program such as Open Street Map. However, it is essential that the authorities and the public become familiar with this innovative method first.

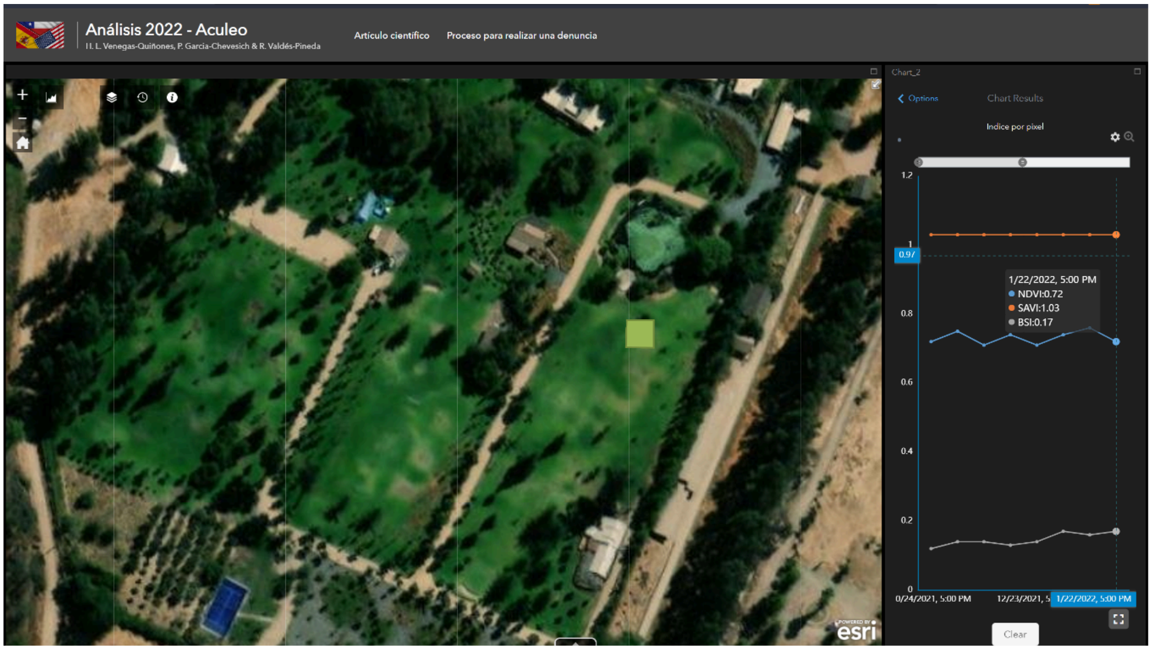

Figure 6. Interactive map - Web App Builder – ArcGIS screenshot

4. Discussion

Water conservation is a crucial issue, particularly in arid regions where water resources are scarce. Remote sensing technology has been increasingly used as a powerful tool to monitor and manage water resources. In this study, we used remote sensing data to classify land cover and analyze potential water consumption for grass irrigation in Laguna Aculeo Basin.

We utilized an unsupervised classification method based on the spectral characteristics of each pixel to segregate the data into nine groups. We visually defined the grass cover by comparing it with other land covers, field information, and satellite images. We assessed that the grass cover was well defined and not confused with other classifications, such as tree cover. However, we acknowledge that the unsupervised method has limitations, as it requires an arbitrary decision to define which classification corresponds to each group of pixels. Thus, future research should corroborate the results by conducting field expeditions.

Our study identified 667,000 m2 of land cover classified as grass, which increased in health from October to April, indicating potential water consumption for grass irrigation. We found that grass areas were not evenly distributed throughout the study area, with a cluster distribution in residential areas, suggesting that lawn had been watered since October using a water source. In contrast, most grass and vegetative covers did not increase in health over time, and tended to decrease in health in this period. These findings have implications for water management in the region, as they suggest that there may be illegal use of water for lawn irrigation.

To make our findings accessible to a wider audience, we developed an interactive map that anyone can access for free. The map allows users to generate values in reference to time series in relation to a single pixel, or average, maximum, or minimum value for a specific area that the user can define. It also shows the ROL (ID) of each parcel, and all the data can be downloaded for further analysis. In addition, we incorporated a link to fill out a legal complaint and notify the authorities of potential lawbreakers. However, we acknowledge that the application we used requires a private license and generates a monetary and server dependency. Thus, we recommend building a similar application in an open-source program, such as Open Street Map.

Overall, our study provides important insights into the potential water consumption for grass irrigation in Laguna Aculeo Basin, and highlights the importance of remote sensing technology and public access to information for water management in arid regions. Our findings can inform water conservation policies and practices, and help to ensure sustainable use of water resources in the region.

5. Conclusions

This study has demonstrated the potential of remote sensing information as a reliable database for investigating various areas with excellent spatial and temporal resolution. This innovation has created a new field of research that eliminates the need to go to the field to obtain information on any study area. In particular, this research has proved that it is possible to assess the health of vegetation cover in an entire watershed over time, and neural networks are a reliable tool for pixel classification and cluster analysis. The research also highlights that the Laguna de Aculeo region has no studies related to satellite information, and the government authorities lack a professional team to develop remote sensing analysis studies. The methodology developed in this study is a turning point in how to assess extensive study areas at high resolution and remotely.

The hybrid application developed in this study brings together classic methodologies for estimating soil indicators and modern applications. It has the potential to help people or inspectors easily identify potential areas where water is being used illegally. It is necessary to evaluate the efficacy of this new method and how successful it is in generating positive inspection results and collecting capital for the government.

This research is a cornerstone in establishing the potential use of remote satellite information in other areas of Chile. The implementation of neural networks to correlate input and output values can be applied in any field of research. The next step is to encourage people and authorities to use the interactive applications developed in this study. In September 2022, a meeting is scheduled to present the results and teach people how to use the application.

The use of satellite information and neural networks is a radical change in the way of solving current problems in society, making it an indispensable tool for creating crucial research. Therefore, this study's findings have the potential to have a significant impact on future research in similar areas and other fields.

Statements and Declarations

Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Author Contributions

- Héctor Leopoldo Venegas-Quiñones: Conceptualization, data processing, methodology, validation, writing - original draft, and visualization.
- Rodrigo Valdes-Pineda: Review & editing.
- Pablo García-Chevesich: Review & editing.

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