Water Quality Assessment of Calderas Lagoon: Statistical Indicators for Sustainability and Volcanic Lake Monitoring

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ABSTRACT

An assessment was conducted to evaluate the physicochemical quality of water in Laguna de Calderas, prompted by the need to understand its environmental condition in the context of recreational and agricultural pressures. Key water quality parameters including pH, electrical conductivity, and total dissolved solids were measured through in situ sampling at 17 georeferenced points. The analysis incorporated descriptive statistics, box plots, histograms, and scatter plots to identify patterns, variability, and outliers. Results indicated a slightly alkaline environment, with an average pH of 8.28 and moderate conductivity levels averaging 0.3415 mS/cm, reflecting a balance between natural conditions and human influence. Variability in total dissolved solids highlighted the dynamic interaction between surrounding land use and water chemistry. Spatial trends and statistical descriptors such as skewness and kurtosis revealed localized anomalies likely linked to runoff, evaporation, or site-specific disturbances. The findings offer a technical foundation for continuous environmental monitoring and support the development of sustainable water resource management practices. Outcomes are relevant for environmental agencies, land use planners, local communities, and researchers working to safeguard the ecological integrity of the lagoon.

Keywords: Alkalinity, Conductivity, Environmental Management, Water Resources, Sustainability.

INTRODUCTION

Water quality is fundamental to both environmental health and human well-being. It plays a vital role in supporting key economic activities such as tourism and water supply. In the case of Laguna de Calderas, located between the municipalities of Amatitlán and San Vicente Pacaya, water quality holds particular importance due to the lagoon's volcanic origin and its role as a natural resource. This lagoon represents a fragile ecosystem that is increasingly threatened by urban development and agricultural activity, both of which place pressure on the integrity of its water.

Laguna de Calderas is considered mesotrophic [1], meaning it contains a moderate level of nutrients and supports an intermediate level of aquatic productivity. This classification is based on physicochemical indicators such as chlorophyll concentration, water depth, and dissolved oxygen levels. Studies assessing water quality commonly focus on key physical and chemical parameters such as pH, electrical conductivity, and total

dissolved solids. These indicators are essential for evaluating both the ecological health of the water body and its capacity to sustain biological productivity. Previous research[2,3] has shown that land use changes and management practices have a significant impact on water quality, highlighting the need for an integrated approach to its assessment.

Moreover, the lagoon currently lacks effective land-use regulations to control human activity in its surroundings. Unplanned urban expansion and intensive agricultural practices present serious challenges to water quality, as documented in earlier studies. Effective land management is crucial to mitigate these pressures by reducing soil erosion and limiting the discharge of pollutants into the ecosystem [4].

In recent years, the lagoon has experienced algal blooms, likely driven by a rise in nutrient levels following ashfall from the Pacaya Volcano. An assessment carried out on May 1, 2021, reported an increase in algae from the general Limnoraphis and Sphaerocystis, both considered indicators of eutrophication and ecological vulnerability in aquatic environments [5].

This study aims to evaluate the influence of human activities on the water quality of Laguna de Calderas, a volcanic crater lake, by analyzing key physicochemical parameters through in situ field measurements. Emphasizing the lagoon's geologically active setting, the research examines how both land use practices and the inherent geochemical characteristics of volcanic systems interact to shape the lagoon's environmental condition and potential ecological vulnerability.

LITERATURE REVIEW
Volcanic crater lakes such as Laguna de Calderas represent complex and sensitive hydrogeochemical systems where physicochemical properties are shaped by the interplay of geothermal activity, rainfall patterns, and anthropogenic influence. Several studies highlight that parameters like electrical conductivity (EC) and total dissolved solids (TDS) are key indicators for understanding ionic concentrations, pollution sources, and geochemical variability in lake environments [6,7]. The relationship between EC and TDS, although widely used in water quality assessment, is non-linear and dependent on site-specific ion composition. This necessitates localized studies, particularly in volcanic lakes, where groundwater recharges and mineral interactions introduce unique ionic profiles [8].

Moreover, volcanic lakes are known to be vulnerable to both geogenic hazards and anthropogenic pressures. There is a work which [9] documented the impacts of untreated runoff and eutrophication in Lake Barombi Mbo, a volcanic crater lake in Cameroon, reinforcing the risk of ecological disturbance even in seemingly isolated basins. Likewise, another study [7] employed multivariate statistical methods to assess water quality in crater lakes, demonstrating how integrated field measurements can reveal patterns of degradation and guide management decisions. Given that Laguna de Calderas lacks continuous monitoring and is increasingly exposed to human activity, this study provides a necessary baseline using in situ measurements and spatial sampling. By adopting a field-based statistical approach, it contributes new knowledge to the underexplored domain of volcanic freshwater quality in Central America.

Volcanic lakes are dynamic and geochemically active systems where water quality is shaped by complex interactions between hydrothermal inputs, groundwater exchange, and atmospheric conditions. These lakes often exhibit unique ionic compositions, making them especially sensitive to geochemical shifts and environmental pressures. Two studies [10, 11] have shown that volcanic crater lakes, such as Quilotoa and others in Central America, may accumulate dissolved gases and mineral solutes that affect surface chemistry, stratification, and ecological

functioning. Electrical conductivity (EC) and total dissolved solids (TDS) are particularly important indicators in these systems, reflecting both natural geochemical processes and anthropogenic influence. However, as another study which [2] point out, the EC–TDS relationship is highly variable depending on ion type and concentration, necessitating localized studies to properly interpret these metrics.

Despite their importance, volcanic lakes are rarely included in long-term water quality monitoring programs, particularly in tropical regions. Studies such as those worked in Lake Barombi Mbo [9,12] and in Laguna de Calderas [2] have emphasized the vulnerability [3] of these systems to nutrient enrichment, microbial contamination, and hydrological change, even in regions characterized by low levels of urbanization. The limited empirical data on such lakes not only hinders environmental risk assessments but also prevents effective conservation planning. In this context, the present study of Laguna de Calderas offers a timely and necessary evaluation of physicochemical conditions through EC and TDS, providing a baseline for future monitoring and contributing to the broader understanding of freshwater volcanic systems in Central America.

MATERIALS & METHODS

This study was conducted to assess the water quality of Laguna de Calderas; a volcanic crater lake located between the municipalities of Amatitlán and San Vicente Pacaya in Guatemala. The evaluation focused on three key physicochemical parameters: pH, electrical conductivity (EC), and total dissolved solids (TDS). A descriptive, field-based methodology was employed, emphasizing the direct collection of data through on-site measurements and geospatial mapping.

The methodological process was organized in multiple stages. It began with preliminary reconnaissance visits to verify access routes, evaluate logistical conditions, and determine the availability of transportation by boat.

These preparatory steps were essential to ensure full spatial coverage of the lagoon during sampling. Panoramic and aerial photographs were also taken using an unmanned aerial vehicle (UAV) to visually document the state of the lagoon and its surroundings (Figure 1).

Figure 1. *Aerial photograph of Laguna de Calderas (2022)*

Note. Prepared by the authors.

Seventeen georeferenced sampling points were strategically established across the water surface to ensure spatial representativeness. At each location, measurements of pH, EC, and TDS were obtained using a previously calibrated HORIBA multiparameter probe, which allowed for in situ recording of data at various depths (Figure 2). Measurements were conducted under stable weather conditions to minimize potential variability and environmental interference. The equipment was cleaned and recalibrated prior to each use to ensure measurement precision and reliability.

Figure 2. *Map of sampling points in Laguna de Calderas (2022)*
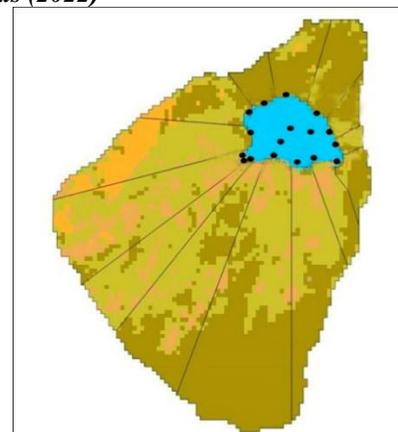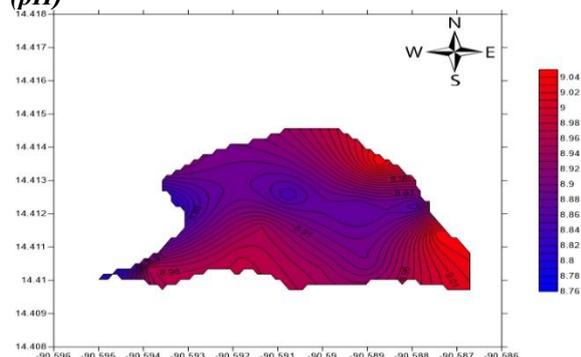

Note. Prepared by the authors.

The fieldwork utilized a range of tools and instruments, including a rowboat, life vests, the multiparameter probe, a Phantom drone for aerial imaging, and geospatial software such as Google Earth® and QGIS®. Data processing and analysis were performed on a computer equipped with an Intel Core i7 processor.

Following data collection, the values were tabulated and subjected to descriptive statistical analysis. Measures of central tendency, dispersion, and correlation were calculated to identify patterns, assess water quality conditions, and explore relationships among the measured variables. This methodological approach supports the development of a baseline assessment for environmental monitoring and potential management strategies in volcanic freshwater systems like Laguna de Calderas.

RESULT

This section presents the findings from the water quality analysis conducted in Laguna de Calderas, focusing on three key variables: pH, electrical conductivity, and total dissolved solids. These parameters were selected for their importance in assessing the ecological condition and overall health of the water body. Through a rigorous process of sampling and analysis, meaningful data were obtained that provide a deeper understanding of water quality in the lagoon and its potential connection to human activities and land use in the surrounding area. The following subsections detail the results for each of the studied variables.

Figure 3. *Isogram of surface hydrogen potential (pH)*

Note. Prepared by the authors.

The isogram in the figure 3 displays of surface pH in Laguna de Calderas illustrates a spatially heterogeneous distribution of alkalinity across the lagoon. Values range from approximately 8.76 to 9.04, indicating an overall alkaline environment. A clear gradient is visible, with lower pH values concentrated in the southwestern and central regions, while higher values are found toward the eastern and southeastern margins. This variation suggests that localized environmental factors such as water flow, sediment interaction, and external inputs are influencing pH levels across different zones of the lagoon.

The highest pH values, which exceed 9.00 (Table 1), may be linked to anthropogenic pressures such as agricultural runoff, the use of basic substances nearby, or recent volcanic activity that has altered the chemical composition of the water. Biotic processes, including photosynthetic activity from algal blooms, could also contribute to this elevated alkalinity. These findings are ecologically significant, as pH levels above 8.5 can begin to affect aquatic species' physiology and the solubility of nutrients and metals, potentially disrupting ecosystem balance. This underscores the importance of continuous water quality monitoring and the development of mitigation strategies to manage land use and protect the lagoon's aquatic health.

**Table 1.** *Descriptive statistics for pH results at various depths*

pH Parameter	Value
Average	8.27760
Standard Error	0.05263
Median	8.49000
Mode	8.71000
Standard Deviation	0.58839
Sample Variance	0.34620
Kurtosis	-1.20312
Skewness	-0.46952
Range	2.03000
Minimum	7.03000
Maximum	9.06000
Sum	1034.70000
Count	125.00000
Confidence Level (95.0%)	0.10416

Note. Prepared by the authors.

The statistical analysis of pH data from Laguna de Calderas reveals a moderately alkaline aquatic environment, with an average pH of 8.28. This level of alkalinity is considered suitable for many aquatic organisms but may pose risks under prolonged exposure, especially for species that require more neutral conditions. The median (8.49) and mode (8.71) are both higher than the average, confirming a clear central tendency toward higher pH values. These measures suggest that the lagoon consistently exhibits alkaline conditions. The standard deviation of 0.59 and variance of 0.35 reflect a moderate dispersion around the average, while the range of 2.03, spanning from 7.03 to 9.06, highlights the breadth of variation across sampling locations. Understanding this variability is essential for interpreting the lagoon's ecological dynamics, especially in relation to external disturbances and natural fluctuations.

Additionally, the negative kurtosis (-1.20) and negative skewness (-0.47) indicate that the data distribution is somewhat flattened and left-skewed, meaning that while most values are alkaline, there is a tail of lower pH values occurring with slightly greater frequency. This asymmetry could be linked to localized inflows or natural buffering processes. The standard error of 0.05 and a 95% confidence interval of ±0.10 demonstrate strong reliability in the average estimate, providing a robust statistical foundation for ongoing monitoring. These findings emphasize the importance of continued observation, as the lagoon's pH balance is sensitive to both anthropogenic inputs and geochemical influences that could shift its equilibrium over time.

Figure 4. *Isogram of surface electrical conductivity (mS/cm)*
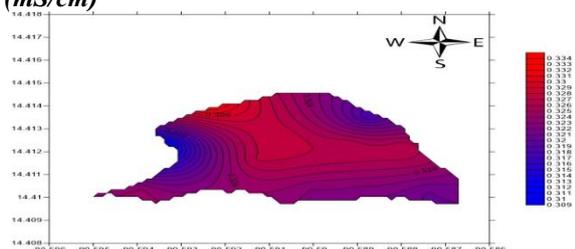
Note. Prepared by the authors.

The isogram of surface electrical conductivity (Figure 4) reveals a spatial gradient across Laguna de Calderas, with values ranging approximately from 0.309 to 0.334 mS/cm. Higher conductivity readings are concentrated in the northeastern and central-northern portions of the lagoon, indicated by red and dark pink tones. These zones suggest a localized increase in dissolved ionic content, which could result from runoff enriched with nutrients or salts, evaporation processes, or limited water circulation that concentrates solutes. In contrast, the northwestern and southeastern areas exhibit lower conductivity values, as seen in the blue to purple range. These regions may correspond to freshwater inflows or less-impacted zones, where dilution or lower anthropogenic pressure maintains a reduced concentration of dissolved solids.

Table 2. *Descriptive statistics for electrical conductivity results at various depths*

Electrical Conductivity (mS/cm)	Value
Average	0.3415
Standard Error	0.0020
Median	0.3280
Mode	0.3250
Standard Deviation	0.0224
Sample Variance	0.0005
Kurtosis	-1.2139
Skewness	0.6516
Range	0.0760
Minimum	0.3090
Maximum	0.3850
Sum	42.6900
Count	125.0000
Confidence Level (95.0%)	0.0040

Note. Prepared by the authors.

The evenly spaced contour lines across the lagoon surface reflect a gradual transition in conductivity rather than abrupt fluctuations, indicating relatively stable hydrodynamic conditions. While the measured values fall within a moderate conductivity range, their spatial variability is ecologically significant. Elevated conductivity can be an early indicator of nutrient loading, pollution, or organic matter decomposition, which, over time, may lead to water quality deterioration

or promote conditions for algal blooms. These findings reinforce the need for systematic water quality monitoring and the implementation of land-use practices that minimize runoff and protect the ecological integrity of the lagoon.

The measured electrical conductivity values in Calderas Lagoon fall within the moderate range for freshwater ecosystems, yet the interpretation of these readings requires caution (Table 2). The relationship between EC and TDS [13] is not always linear and may vary depending on ion composition, pH, and temperature. In similar studies, TDS was estimated to use empirical coefficients ranging from 0.5 to 0.9 depending on the ionic nature of the water[6]. Magnesium and sodium salts have a disproportionately strong effect on conductivity due to their ionic mobility, suggesting that even small changes in groundwater composition can shift this relationship significantly. These factors highlight the need for site-specific calibration when estimating TDS from EC in volcanic lake environments like Laguna de Calderas

The descriptive analysis of electrical conductivity measurements (in mS/cm) from Laguna de Calderas indicates a moderate level of conductivity, with an average of 0.3415 mS/cm. This average suggests a balanced concentration of dissolved ions in the water, consistent with moderately mineralized freshwater systems. The median value of 0.3280 mS/cm and the mode of 0.3250 mS/cm reflect a tendency for measurements to cluster slightly below the average, which aligns with a symmetrical distribution of values. The standard deviation of 0.0224 mS/cm and a variance of 0.0005 confirm low dispersion, indicating that the conductivity measurements are closely grouped around the average. The range of 0.0760 mS/cm, from a minimum of 0.3090 mS/cm to a maximum of 0.3850 mS/cm, demonstrates moderate variability, pointing to subtle but consistent differences across sampling points and depths.

Further interpretation of the distribution's shape reveals meaningful patterns. A negative kurtosis value of -1.2139 suggests a flatter-than-normal distribution, where the data are more spread out across the extremes rather than concentrated at the center. Meanwhile, the positive skewness coefficient of 0.6516 indicates a slight right skew, implying that higher conductivity values are more common than extremely low ones. These tendencies may reflect areas within the lagoon influenced by ion-rich runoff, localized evaporation, or biological processes. With a very small standard error of 0.0020 mS/cm and a 95% confidence interval of ±0.0040, the statistical precision of the average is high, making the findings robust and reliable. This level of accuracy is vital for assessing changes in water quality over time and detecting emerging environmental pressures that could affect aquatic life and ecosystem health.

The surface isogram of total dissolved solids (TDS) in Laguna de Calderas reveals a moderately variable distribution (Figure 5), with concentrations ranging from approximately 0.198 to 0.217 g/L. Higher TDS values are concentrated in the north-central and northwestern regions of the lagoon, suggesting localized accumulation of dissolved substances likely influenced by agricultural runoff, organic matter decomposition, or evaporative processes. Conversely, lower concentrations appear in the southwestern and southeastern areas, possibly indicating zones of freshwater input or reduced anthropogenic influence. The contour lines show a smooth gradient, reflecting stable water mixing dynamics without abrupt changes. While overall TDS levels remain within moderate freshwater thresholds, the spatial variability highlights the importance of targeted monitoring, as elevated concentrations can affect aquatic life, water clarity, and chemical balance over time.

Figure 5. *Isogram of total dissolved solids (g/L) at the surface level*
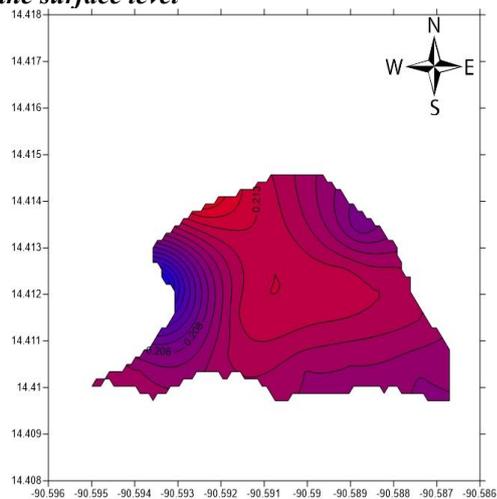
Note. Prepared by the authors.

**Figure 6.** *Histogram of Hydrogen Potential (pH)*
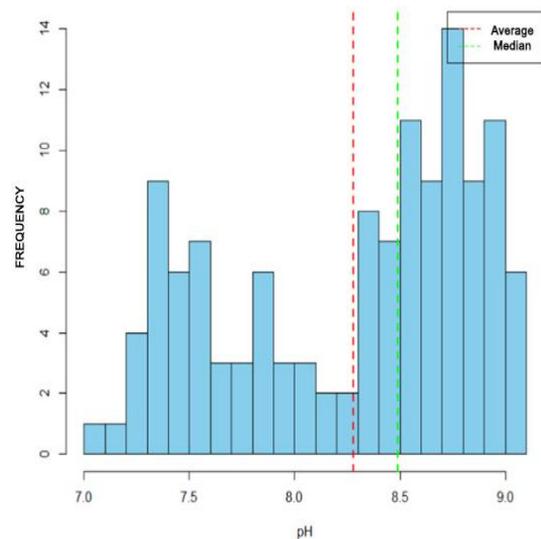
Note. Prepared by the authors.

DISCUSSION

This section analyzes the possible causes behind the variations observed in key water quality parameters (namely pH, electrical conductivity, and total dissolved solids) and evaluates their ecological implications. As illustrated in the histogram of pH measurements (Figure 6), values range primarily between 7.0 and 9.0, with a noticeable concentration toward the alkaline side. The average (red dashed line) is slightly lower than the median (green dashed line), suggesting a moderate skew in the distribution that may indicate localized influences or episodic events affecting water chemistry. Such shifts could stem from natural processes like mineral dissolution or algal activity but may also reflect anthropogenic pressures such as agricultural runoff or nearby urban discharges. These physicochemical dynamics are critical in assessing the lagoon's ecological health, as imbalances can disrupt aquatic life and compromise long-term sustainability. The analysis highlights the need to monitor human-induced changes and establish management strategies that preserve the lagoon's environmental integrity.

The boxplot in Figure 7 illustrates the distribution of pH measurements, offering a clear view of the data's central tendency and variability. The box itself represents the interquartile range (IQR), capturing the middle 50% of the data. The thick black line inside the box corresponds to the median value, calculated at approximately 8.49, which divides the dataset into two equal halves. This suggests that the typical pH level in the lagoon tends toward the alkaline side. The upper and lower edges of the box reflect the third (Q3) and first quartiles (Q1), respectively, while the "whiskers" extend to the minimum and maximum values within 1.5 times the IQR, indicating no extreme outliers in this case. Overall, the relatively widespread from about 7.0 to 9.0 suggests moderate variability in the lagoon's pH conditions. This distribution reinforces the histogram findings and supports the idea that while pH levels are generally stable and mildly alkaline, they remain sensitive to both natural and anthropogenic factors. Such stability is crucial for aquatic life, though deviations from the optimal range could signal disturbances that warrant further investigation.

**Figure 7.**
Boxplot of pH Measurements
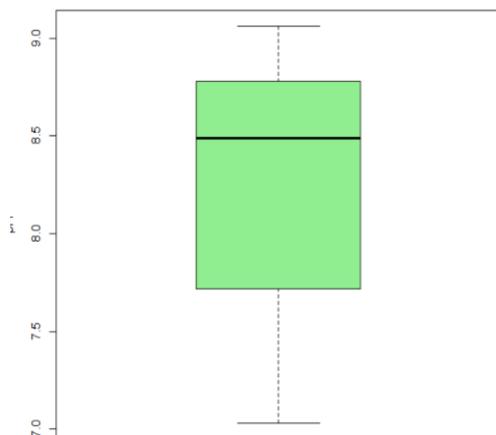
Note. Prepared by the authors.

Figure 8 presents a scatter plot of pH measurements taken from the Calderas lagoon, with each point corresponding to an individual observation indexed along the x-axis. This visualization effectively illustrates both the sequence and variability of the pH data over the sampled period. Most of the data points fall within a relatively alkaline range, between approximately 7.0 and 9.0, with a noticeable concentration above the median value previously discussed. The upper and lower dashed lines denote the observed maximum and minimum pH values, providing a visual reference for the overall spread. The relatively dense clustering of points around 8.5 confirms the tendency toward mildly alkaline conditions, as shown in both the histogram and boxplot analyses. However, the presence of wider fluctuations at various points suggests localized or temporal variability, potentially linked to environmental factors or anthropogenic inputs. This pattern of dispersion reinforces the importance of continuous monitoring, as even small shifts in pH levels can have significant ecological consequences for aquatic organisms sensitive to chemical imbalances.

pH is a fundamental indicator of water quality, as it reflects the acidity or alkalinity of the aquatic environment, directly influencing the health of ecosystems and the solubility of both nutrients and potential contaminants. In the case of the Calderas Lagoon, pH values range from 7.03 to 9.06, with an average of 8.28, indicating that the water is predominantly alkaline. Such a pH level suggests a relatively low concentration of hydrogen ions, a condition that can be favorable for many aquatic species, which often thrive in mildly alkaline environments. However, elevated pH values may also signal the presence of pollutants, such as alkaline compounds introduced through agricultural runoff or industrial activities.

Figure 8. *Scatter Plot of pH Measurements in the Calderas Lagoon*
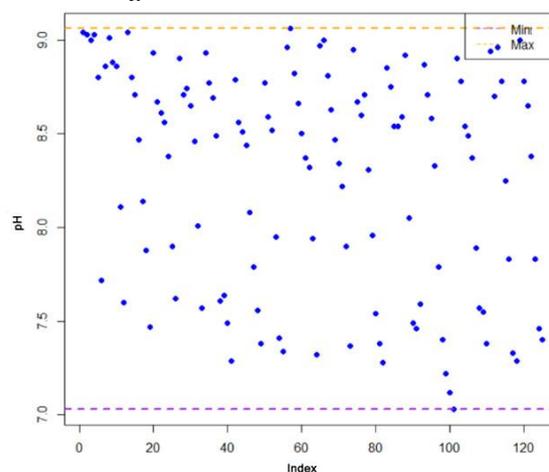
Note. Prepared by the authors.

The statistical indicators further support this characterization. A median value of 8.49 and a mode of 8.71 confirm a consistent trend toward alkalinity. Meanwhile, the standard deviation of 0.59 and a range of 2.03 reflect notable variability within the dataset. This variation may be associated with temporal fluctuations, spatial heterogeneity in sampling locations, or differences in biological activity and water inflow sources across the lagoon.

From a technical perspective, moderately alkaline pH does not inherently imply poor water quality. Nonetheless, continuous monitoring remains essential, especially when elevated pH levels may coincide with nutrient imbalances or contamination events. Complementary parameters—such as nutrient concentrations, total dissolved

solids, and electrical conductivity—should also be analyzed to fully assess the ecological status and detect any early signs of degradation.

The scatter plot reinforces this interpretation by illustrating the dispersion of pH values across observation indices, highlighting the heterogeneity of measurements over time or space. A high level of dispersion suggests dynamic environmental conditions or multiple influencing factors. The purple and orange dashed lines mark the minimum (7.03) and maximum (9.06) observed values, visually framing the full range of data and underscoring the need to interpret such fluctuations within a broader environmental context.

Figure 9 presents a histogram displaying the distribution of electrical conductivity (EC) measurements in the Calderas Lagoon, expressed in microsiemens per centimeter (µS/cm). Each bar represents the frequency of observations within specific conductivity intervals, providing insight into how the data is concentrated across the measured range. The histogram reveals a clear right-skewed distribution, with most values clustered around 0.32 µS/cm, as shown by the highest bar. This suggests that low conductivity levels are the most frequent occurring in the dataset.

Figure 9. *Histogram of Electrical Conductivity*
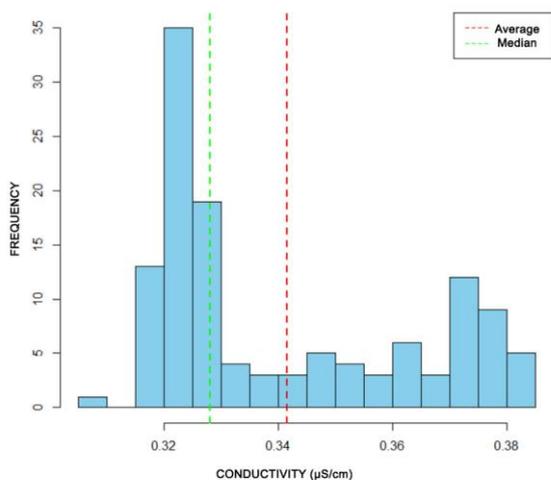
Note. Prepared by the authors.

The vertical dashed lines represent the average (0.3415 µS/cm, in red) and median (0.3280 µS/cm, in green), both indicators of central tendency. The fact that the average is noticeably higher than the average suggests is a skewed distribution, likely influenced by a subset of higher conductivity values that shift the average upward. This skewness may indicate localized zones of elevated ionic concentration, possibly linked to anthropogenic sources such as nutrient-rich runoff, or natural geochemical variability.

In environmental terms, electrical conductivity is a proxy for the total ion content in water and is influenced by dissolved salts, minerals, and other chemical compounds. A predominance of lower EC values, as shown here, typically indicates relatively low mineralization or dilution from freshwater inflows. However, the tail toward higher values may reflect episodic increases in solute concentration, requiring further investigation into potential sources and temporal patterns.

Comparing average and median values in future monitoring campaigns will be valuable to detect changes in data symmetry and potential shifts in water chemistry. This kind of statistical profiling supports the identification of trends and anomalies that may inform water quality management and conservation strategies.

Figure 10 displays a boxplot of electrical conductivity (EC) measurements in the Calderas Lagoon, highlighting the median and the interquartile range (IQR), which contains 50 percent of the data. The median value, close to 0.328 µS/cm, confirms a central tendency toward lower conductivity levels, consistent with the distribution observed in the histogram. The IQR shows moderate variability, suggesting differences in ionic concentration across the sampled locations or periods. This variation may result from changes in natural inputs or human activities, such as runoff or dissolved substances from nearby land uses.

**Figure 10.** *Boxplot of Electrical Conductivity Measurements*
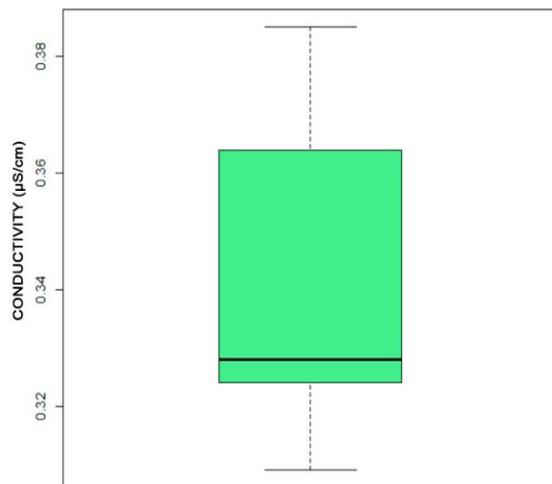
Note. Prepared by the authors.

There are no outliers beyond the whiskers, which represent the range of values within one and a half times the IQR. This indicates that the dataset is relatively stable without extreme deviations. However, the histogram revealed a skew toward higher values, with the average exceeding the average, suggesting occasional increases in conductivity that may reflect localized environmental impacts. These findings highlight the importance of continuous monitoring, as changes in ion concentration can significantly influence water quality and the ecological health of the lagoon.

Figure 11 displays the scatter plot of electrical conductivity (EC) measurements collected from the Calderas Lagoon, with each point representing a single observation across the sampling sequence. This visual format reveals the variability and potential distribution patterns within the dataset. The purple and orange dashed lines mark the minimum (0.3090 mS/cm) and maximum (0.3850 mS/cm) conductivity values, offering a visual reference for the total observed range. Most measurements appear concentrated between 0.315 and 0.345 mS/cm, although there are instances of higher variability dispersed throughout the series.

Figure 11. *Scatter Plot of Electrical Conductivity Measurements in the Calderas Lagoon*
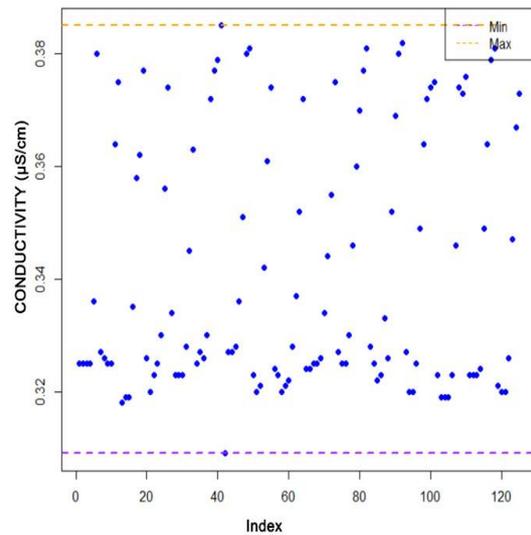
Note. Prepared by the authors.

The dispersion of points suggests that while many values cluster toward the lower end of the range, some localized increases are evident, possibly linked to environmental events, episodic inflows, or shifts in geochemical conditions. No consistent trend over time is immediately apparent, indicating a relatively stable system, though further temporal analysis could help clarify any seasonal or anthropogenic influences. As of a technical perspective, electrical conductivity is a key parameter for assessing water quality, as it reflects the concentration of dissolved ions, particularly salts and minerals.

The measured values in the Calderas Lagoon fall within a moderate range. With an average of 0.3415 mS/cm, the lagoon's water shows characteristics typical of low to moderately mineralized freshwater bodies. These conditions are not immediately concerned from a contamination standpoint. However, changes in conductivity, especially upward trends, could signal increased solute input due to runoff, wastewater discharge, or reduced dilution capacity.

Although the current conductivity values do not suggest alarming levels of contamination, it is crucial to interpret them

alongside other parameters such as pH, turbidity, and total dissolved solids. Together, these indicators provide a more comprehensive picture of the ecosystem's health. Continuous monitoring remains essential to identify emerging trends and ensure timely management of the lagoon's environmental quality.

Figure 12 presents a histogram of total dissolved solids (TDS), where the height of each bar reflects the frequency of measurements within specific concentration intervals, measured in grams per liter (g/L). The distribution is skewed to the right, with most values concentrated around 0.210 g/L, as shown by the tallest bars. The median, indicated by the green dashed line, lies slightly to the left of the red dashed line representing the average, suggesting a moderate positive skew in the dataset. This skewness implies that while most samples exhibit relatively low concentrations of dissolved solids, there are several higher values that elevate the average. Such a distribution may result from localized increases in mineral input, runoff, or evaporation effects that concentrate solutes. The comparison between average and average help identifies this asymmetry and suggests the presence of variability in water chemistry that should be considered when evaluating the lagoon's overall water quality.
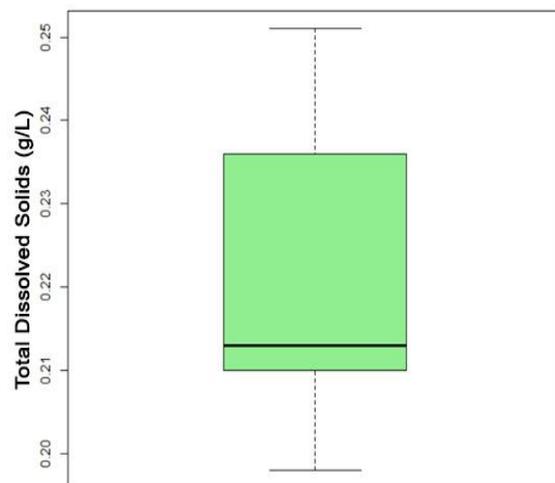
Figure 12. *Histogram of Total Dissolved Solids*
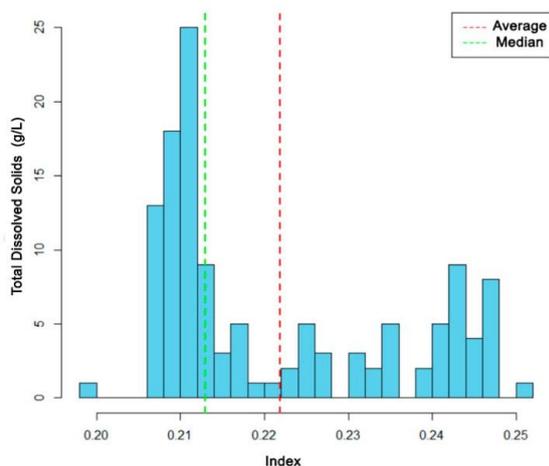
Note. Prepared by the authors.

Figure 13 presents a boxplot of total dissolved solids (TDS) measurements, offering a clear visualization of the central tendency and variability within the dataset. The black line inside the green box marks the median, representing the central value of the data, while the box itself encompasses the interquartile range (IQR), which contains the middle 50 percent of observations. The relatively wide span of the box, along with the extended whiskers, suggests moderate to high variability in TDS concentrations. This spread reflects fluctuations in the amount of dissolved inorganic and organic matter, possibly due to natural inputs, evaporation, or human-related factors. The absence of outliers beyond the whiskers indicates that the data is relatively consistent, with no extreme or anomalous value detected. Overall, the boxplot highlights a stable but variable distribution, reinforcing the importance of regular monitoring to understand the processes influencing the lagoon's solute content.

**Figure 13.** *Boxplot of Total Dissolved Solids Measurements*

Note. Prepared by the authors.

Figure 14 presents a scatter plot of total dissolved solids (TDS) measurements from the Calderas Lagoon, illustrating the variation in concentration across individual observations. Each blue dot corresponds to a specific sampling point, allowing for a detailed view of distribution and variability.

The purple and orange dashed lines represent the minimum and maximum recorded values, respectively, helping to frame the full range of TDS values, which span from approximately 0.200 to 0.250 g/L. The plot shows a concentration of points around 0.210 g/L, suggesting that this is the most common TDS level, while the spread of values above this range indicates moderate variability. The absence of visible clusters or periodic patterns suggests that fluctuations are somewhat random or influenced by a range of small-scale environmental factors, such as rainfall, evaporation, or local runoff. The visual distribution supports earlier findings from the histogram and boxplot, confirming that while the TDS levels are generally consistent and within a moderate range, ongoing monitoring is essential to detect any shifts that could affect water quality and ecosystem health.

Figure 14. *Scatter Plot of Total Dissolved Solids Measurements in the Calderas Lagoon*
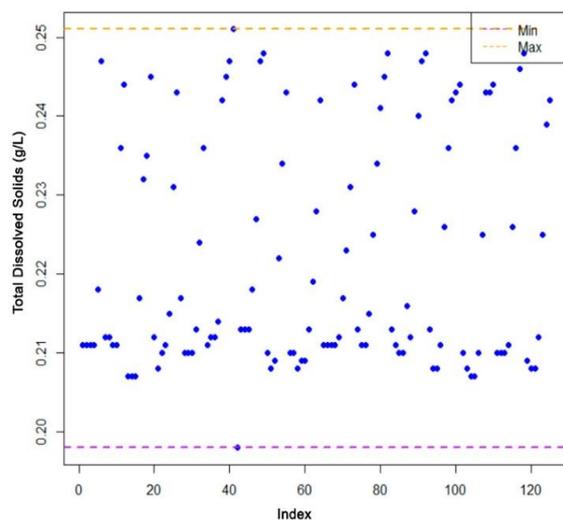
Note. Prepared by the authors.

The observed range of total dissolved solids, while moderate, showed enough spatial variation to warrant further exploration of the sources and composition of the solutes. This aligns with findings by a study where [1] was used both in situ and satellite-derived techniques to estimate TDS and TSS in Mosul Dam Lake and found seasonal and spatial patterns tied closely to runoff and evaporation. Their study supports the integration of spatially referenced TDS mapping to distinguish between natural geochemical processes and anthropogenic pressures

CONCLUSION

In addition to the specific findings on water quality, this research introduces a novel approach by integrating georeferenced in situ sampling with statistical and spatial analysis tools to assess the physicochemical conditions of a volcanic lagoon. The use of descriptive statistics, boxplots, histograms, scatter plots, and isograms allowed not only the detection of central trends and variability but also the identification of localized anomalies and spatial gradients in pH, electrical conductivity, and total dissolved solids. This combined methodological framework provides a replicable model for the assessment of small-scale aquatic ecosystems in volcanic or mesotrophic contexts and offers a technical basis for linking land use dynamics with water quality variations. As such, the study contributes new knowledge that strengthens both academic understanding and practical strategies for sustainable watershed management in Laguna de Calderas and similar environments.

The physicochemical analysis of water in Laguna de Calderas reveals several key findings with implications for both environmental monitoring and watershed management. The average pH of 8.28 indicates a slightly alkaline environment, likely influenced by underlying geological conditions such as volcanic mineral presence, yet also suggestive of potential anthropogenic factors including agricultural runoff or nearby human settlements. This alkalinity remains within tolerable limits for many aquatic species but may pose ecological stress if persistent or increasing.

Electrical conductivity, averaging 0.3415 mS/cm, reflects a moderate level of dissolved ionic compounds in the lagoon.

This concentration suggests relatively balanced mineralization typical of low to moderately impacted freshwater systems. However, variations in conductivity observed across spatial gradients point to localized influences (such as runoff or evaporation) emphasizing the role of surrounding land use in shaping water quality dynamics.

Measurements of total dissolved solids demonstrate notable variability, indicating a fluctuating solute load driven by changes in hydrology, soil erosion, or inputs from human activity within the basin. This variability underscores the importance of managing land use activities (particularly agriculture and informal development) to prevent further degradation of water quality. The findings from this study are consistent with regional assessments of small-scale volcanic lakes, such as the work previously written [2], but they also reveal gaps in how conductivity and TDS are interpreted under local geochemical conditions. Recent literature confirms that these parameters are highly dependent on the ionic makeup of water and that the EC–TDS relationship should be calibrated based on site-specific ionic concentrations and temperature profiles. Studies [6,13] underscore the complexity of EC–TDS dynamics and the potential for misinterpretation if default assumptions are applied universally. Therefore, strengthening the chemical profiling of Laguna de Calderas, possibly with seasonal sampling and ion-specific analysis, is recommended for future studies

Based on the variability and spatial patterns observed in pH, electrical conductivity, and total dissolved solids, it is recommended that future research prioritize the establishment of a long-term and seasonal monitoring program. Extending sampling over time will help identify fluctuations driven by climatic factors or anthropogenic pressures, providing a more dynamic understanding of water quality trends. In addition, the current study revealed areas with higher variability and the presence of statistical outliers, which suggests the need to increase the spatial resolution of sampling, particularly near potential inflow zones, agricultural areas, or sites of urban expansion. A denser and more strategically distributed sampling grid would improve the ability to detect localized changes and guide site-specific management actions.

To enhance the interpretation of water quality dynamics, future studies should also seek to integrate land use analysis with physicochemical data. Linking satellite imagery or GIS-based land cover classifications with observed water quality parameters would allow researchers to statistically assess the influence of deforestation, agriculture, or settlement expansion on lagoon conditions. Furthermore, given the slightly alkaline conditions and moderate solute concentrations found, it is essential to expand the set of monitored parameters to include nutrients (such as nitrogen and phosphorus), dissolved oxygen, and turbidity. These additions would strengthen the ecological assessment and help detect early signs of eutrophication or degradation, thus supporting more comprehensive conservation and management strategies.

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