Control estadístico de procesos aplicado a la evaluación de la calidad del agua: Un estudio de caso de la Laguna de Cabrero, Caribe Colombiano

Statistical process control applied to water quality assessment: A case study of the Cabrero Lagoon, Colombian Caribbean

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Resumen los cuerpos de agua en los países en vía de desarrollo a nivel mundial enfrentan crecientes presiones antropogénicas debido al crecimiento poblacional, la industrialización, entre otras. Estos estresores causan que los cuerpos de agua pierdan su biodiversidad y que la calidad del agua se deteriore cada día más. En la laguna del cabrero, Cartagena se lleva a cabo un plan de monitoreo desde el año 2000 con el fin de establecer la calidad del agua de este cuerpo de agua, en este trabajo se utilizaron herramientas del control estadístico de procesos para verificar el estado del cumplimiento de la normatividad de la calidad del agua desde un punto de vista del control de la calidad. Las variable estudiadas fueron oxígeno disuelto (OD), demanda bioquímica de oxígeno (DBO_5), demanda química de oxígeno (DQO), fosforo total (FT), coliformes totales (CT) y fecales (CF). Algunas de estas variables no están bajo control estadístico y la laguna no es capaz de mantener los estándares químicos y microbiológicos establecidos por la ley colombiana. Los resultados de esta investigación pueden dar luces a las agencias municipales encargadas del medio ambiente en el estado actual de la calidad del agua en la laguna del cabrero y tomar las medidas pertinentes para mejorar las condiciones ambientales del cuerpo de agua.

Palabras claves: calidad de agua, control estadístico de procesos, cartas de control, capacidad de procesos.

Abstract Water in developing countries worldwide faces growing anthropogenic pressures due to population growth, industrialization, among others. These stressors may cause that water bodies lose their biodiversity and quality every day. In the Cabrero lagoon, Cartagena, a water monitoring program has been carried out since 2000 in order to check the quality of water in this natural resource, and in this work statistical process control tools were used to verify the status of compliance with the regulation of water from a quality control view. The variables studied in this research were dissolved oxygen, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total phosphorus (TP), total coliforms (TC) and faecal coliforms (FC), several are not under statistical control and the lagoon is not capable of maintaining the chemical and microbiological standards established by Colombian law. The results of this investigation may give clarity on the current state of water quality in the Cabrero lagoon, for the municipal agencies in charge of the environment.

Keywords water quality, statistical process control, control charts, process capacity.

1 Introduction

Aquatic ecosystems and water management have become one of the main concerns for humanity, not only in areas where this resource has always been scarce but also in developed countries and in areas where water has until now been considered an unlimited resource. Coastal lagoons are particular ecosystems where many interests may conflict, from fisheries to tourism, and from aquaculture to harbor facilities or urban development. In developing countries water-related tourism is an increasing source of incomes. Clean water contributes to the recreation and tourism industry (Loehr et al., 2021), that is why quality water availability is often considered the main limiting factor for developing tourism (Pérez-Ruzafa et al., 2011)(Custodio et al., 2019). Population growth and industrial activities located along bays, rivers and coastal lagoon margins have led to the discharge of untreated waste effluents into water, a situation that has affected the biota, fisheries and man himself (Barakat et al., 2018)(Hou et al., 2016). Variation in water quality of Coastal lagoon is regularly attributed to anthropogenic activities, as well as natural processes such as hydrological features, precipitation, etc. (Koklu et al., 2010)(Pati et al., 2014). The input of freshwater and domestic sewage effluent into coastal lagoon waters may have several ecological consequences such as reduce in salinity, organic matter and nutrients increase; algal blooms, formation of hypoxia or anoxia in the bottom water and change in the phytoplankton community structure (Baldiris-navarro & Sanchez-aponte, 2018).

Cabrero lagoon is a water body that has been affected by anthropogenic issues due to the lack of control by authorities over the communities around the lagoon. Some communities are invasions of people that did not find other home opportunity but to invade the natural lagoon space. As a result of this, the quality of water, soil and mangrove swamps are under high stress in the lagoon. Artisanal fishing activities are also made in the lagoon by natives, but these economic activities may put in risk the health of consumers of these products depending on the water contamination levels.

Statistical Process Control establishes an observation system, permanent and intelligent, to detect early the emergence of special causes of variability and help identify their origin, with the ultimate goal of minimize them from the process and taking measures that prevent their reappearance in the future. Control charts are useful to observe and analyze with statistical tools, the variability and behavior of a process over time, for one or several quality characteristics or output variables. Therefore, these tools were used first to assess the behavior of the process (Díaz et al., 2009). By the other hand, the capability of a process is usually interpreted as its ability to produce results according to specifications. It is also commonly interpreted as the ability of the process to meet the limits of tolerance, in this case will be the capability of the lagoon to maintain the properties of water under the law values (Montgomery, 2020)(Gutiérrez Pulido & de la Vara Salazar, 2013). The aim of this study is to analyze and interpret a large data set obtained from 14 years (2008–2021) of monitoring programs in Cabrero lagoon. To do this, statistical process control techniques such as control charts and capability analysis were applied to determine the compliance of the Colombian environmental laws. The results will permit to evaluate the evolution of water quality in this important water body in the city and may lead to decision makers to design environmental programs that permit the lagoon to become a healthy source of products, tourism and natural scenarios for the people of Cartagena-Colombia.

2 Study area

Cabrero lagoon is located at coordinates 10° 25' 52.8"N 75° 32' 27" W, has an approximate length of 1.38 km, a water extension of about 26 hectares and an average depth of 2.3 m (see figure 1). The study area is characterized by exhibiting two climatic periods, one of rainfall between the months of April and

November and a dry period is and goes from December to April.

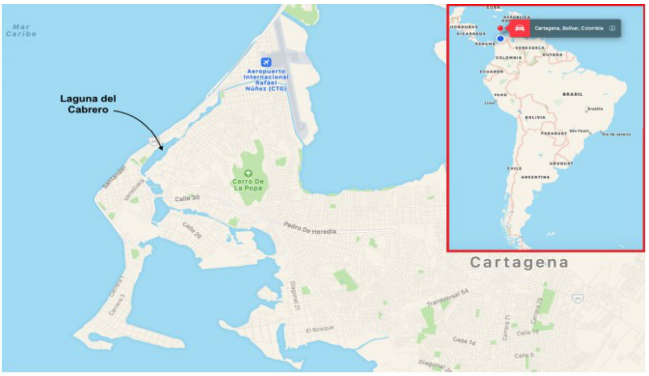

Figure 1. Map of Cabrero lagoon

Sampling and transportation to the laboratory as well as samples storage were done in accordance with methods described by APHA. Samples were taken six times for year in different seasons of the year (dry-rain) in a single point of the lagoon (10º25'50.4''N – 75º32'27.7''W). In situ studied parameter was dissolved oxygen (DO). Parameters, biological oxygen demand (BOD5), chemical oxygen demand (COD), total coliforms (TC) and fecal coliforms (FC) were analyzed in laboratory following the standard methods for water and wastewater analysis. Data were compared to the limit values of the Colombian water quality law (decree 1594-1984) adopted by the Ministry of Environment of Colombia.

2.1 Statistical analysis

To all variables except for dissolved oxygen (DO), natural logarithm was applied to approximate their distribution to a normal one. After this, process control charts were used and the capability indexes were calculated to show the real situation of the Cabrero lagoon. The data was analyzed using free software R and Microsoft office excel(Darzé et al., 2022).

2.2 Control charts

The control charts for variables are applied to continuous type variables (temperature, concentration, areas, etc.), being the most usual, according to the statistics that is plotted the $\underline{X}$ for means, $\underline{R}$ for ranges and X for individual means. For this study, only variable control charts are going to be used, specifically charts for individual means. Individual chart is a diagram for continuous variables, it is a particular case of the chart $\underline{X} - R$, when the size of the sample or subgroup is n = 1 and the limits are calculated directly from the individual measurement of the variable X (Montgomery, 2020). Therefore, the limits are obtained with the expression:

$$\mu_x \pm 3\sigma_x$$

where μ_x y σ_x are the mean and standard deviation of the process, respectively. That is, the control limits in this case coincide by definition with the actual limits, these parameters are estimated as follows:

$$\mu_x = \underline{x}$$

$$\sigma_x = \frac{\underline{R}}{d_2} = \frac{\underline{R}}{1.128}$$

where $\underline{X}$ is the mean of measurements and $\underline{R}$ is the average of the mobile ranges of order 2 (range between successive observations in the process); by dividing the average range between the constant d_2 an estimate of the standard deviation of the process σ is obtained. For this case the mobile range is of order 2, then, the value of n will be n = 2, according to the table factors for the construction of the control charts, they are given by:

$$UCL = \underline{X} + 3\left[\frac{\underline{R}}{1.128}\right]$$

$$Central\ line = \underline{X}$$

$$LCL = \underline{X} - 3\left[\frac{\underline{R}}{1.128}\right]$$

2.3 Process capability

It is the ability of a process to comply with the quality specifications of a product, it may be a nominal value or be within a certain higher or lower specification range, and it is quantified through the capability index(Silva et al., 2022). The potential capability index of a process (Cp) is defined as follows:

$$C_p = \frac{US - LS}{6\sigma}$$

where σ represents the standard deviation of the process, and US y LI are the upper and lower quality specifications. The Cp index compares the width of the specifications or tolerated variation for the process with the amplitude of the actual variation of the process:

$$C_p = \frac{tolerated\ variation}{Real\ valoration}$$

A process is considered potentially capable, if the real variation is always lower than the tolerated variation, so the ideal is that the Cp index be greater than 1, if it is less than 1 it is evidence that the process does not set with the specifications. Values of Cp index and its interpretation are based on three assumptions: a normal distribution of the quality characteristic; process is stable; and a known standard deviation of the process. The limitation of the Cp index is that it does not take into account the centering of the process, since in its definition does not intervene the process mean, therefore, the real capability index Cpk is used as a complement, it consist in calculating a capability index for the lower specification (Cpi) and another for the upper one(Cps), in both cases upper and lower capability are evaluated; the distance from the process mean to one of the specifications represents the tolerated variation for the process of only one side of the mean. That is why it is divided by 3σ, instead of 6σ (as in the case of the Cp index), so the Cpk index is determined by the smallest value between Cpi and Cps. The index interpretation is made under the same criteria of the Cp index. Mathematically

$$C_{pi} = \frac{\mu - LS}{3\sigma}$$

$$C_{ps} = \frac{US - \mu}{3\sigma}$$

$$C_{pk} = min\ (C_{ps}, C_{pi})$$

Cpk index always will be lower or equal to Cp index. If they are too close to each other, it indicates that the process mean is near the middle point of specifications. If Cpk is lower than Cp, it indicates that the process mean is far from the middle of specifications. The real process capability (Cpk) is delimited by: If Cpk is bigger than 1.33, it is considered an adequate capability, Cpk between 1 and 1.33, is considered a partially adequate process capability, and finally if the Cpk is lower than 1, the process is considered not capable.

3 Results and discussion

A summary of the threshold values for water quality for secondary contact in Colombia is provided in table 1. The control charts of individual means and moving ranges were used because the experimental data were obtained by individual observations.

Table 1. Threshold values for water quality

Variable	Threshold value
DO	> 4 mg/L
BOD_5	< 3 mg/L
COD	< 1000 mg/L
TP	< 0,032 mg/L
TC	< 5000 MPV/100 ml
FC	< 1000 MPV/100 ml

Values of the statistical parameters are summarized in Table 2. Total phosphorus (TP), total coliforms (TC) and faecal coliforms were transformed using natural logarithms in order to establish normality in data.

Table 2. Summary of the statistical parameters

	DO	BOD_5	COD	TP	TC	FC
Min	2,260	1,000	261	-3,219	0,693	0,588
1st Qu	5,560	3,530	826	-2,120	2,874	1,967
Median	6,950	5,045	1138	-1,802	4,013	3,111
Mean	6,593	5,276	1091	-1,880	3,708	3,187
3rd Qu	7,595	6,798	1254	-1,609	5,069	4,241
Max	9,040	10,620	2019	-0,083	6,194	5,438

3.1 Analysis of statistical control and capacity

Dissolved oxygen measures the quantity of dissolved gaseous oxygen in an aqueous solution, depending on the concentration of this parameter it can be a threat for aquatic life. Control chart for dissolved oxygen revealed a significant variation from 2.26 m /L to 9.04 mg/L in the study period, showing a mean concentration of 6.14 mg/L (see figure 3).

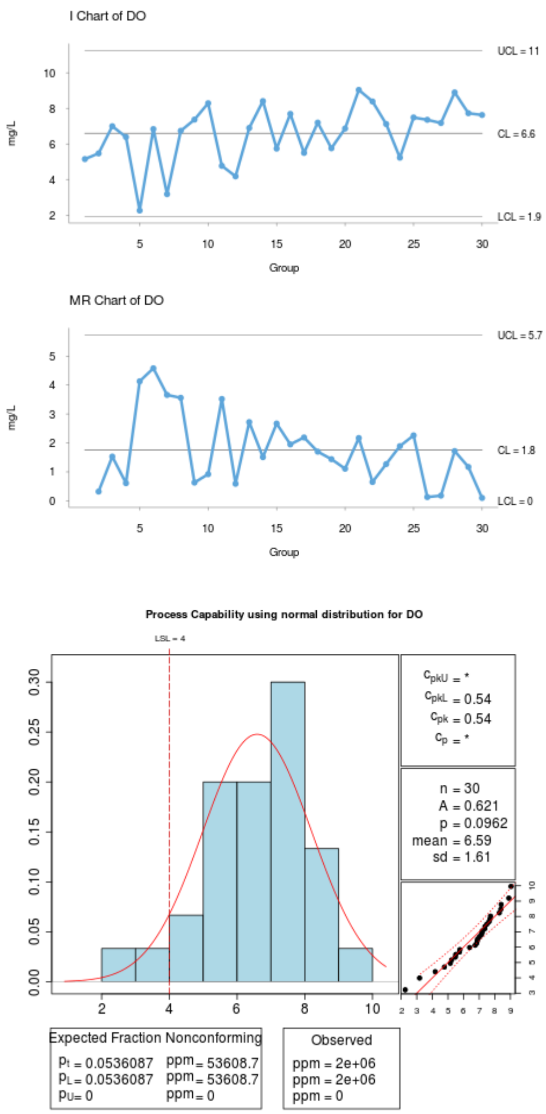

Figure 2. DO Behavior on Cabrero lagoon

This evidences an acceptable DO level by the contribution of different oxygen sources (O.D.> 4 mg/L) to the Cabrero lagoon that allow it to carry out oxidation processes of organic matter and may keep the equilibrium in the aquatic ecosystem. So, the hypothesis that the process is in a state of statistical control with a confidence level of 95% can Not be rejected. Since the short and long-term lower specification indices for DO are less than 1(see fig. 2), it is possible that dissolved oxygen concentrations might be below 4 mg / L at some moments. According to the capability plot the lagoon may maintain good levels of oxygen during day because of photosynthetic processes but at night this may change and low oxygen levels may be found.

BOD_5 denotes the pollution related to organic matter, high levels of it may be dangerous for living organism. Figure 3 shows the control chart for BOD_5, it indicates that the distribution fits reasonably good to normal and the central tendency is around 5.28 mg/L (should be <3 mg/L) with a standard deviation of 2.15 mg/L, in this study made with a sample of 30 observations contained within the control limits below 0 mg / L and above 12 mg / L. So, the hypothesis that the process is in a state of statistical control with a confidence level of 95% can Not be rejected.

Since lower and upper specifications indexes for BOD_5 are less than 1, it is possible that concentrations of this are above 3 mg/L in the sampling station. The percentage out of specification corresponds to 85.4%, which corresponds to 853164 ppm. This indicates that the organic load discharged into the lagoon is above the values that the lagoon may naturally transform, and lagoon is not capable of processes it. These may be caused by wastes generated by communities living around the lagoon, untreated wastewater coming from buildings or another anthropogenic activity (Tanahara et al., 2021)

COD is a parameter that measures the substances capable of being oxidized by chemical means that are dissolved or in suspension in a liquid sample. It is used to measure the chemical contamination levels.

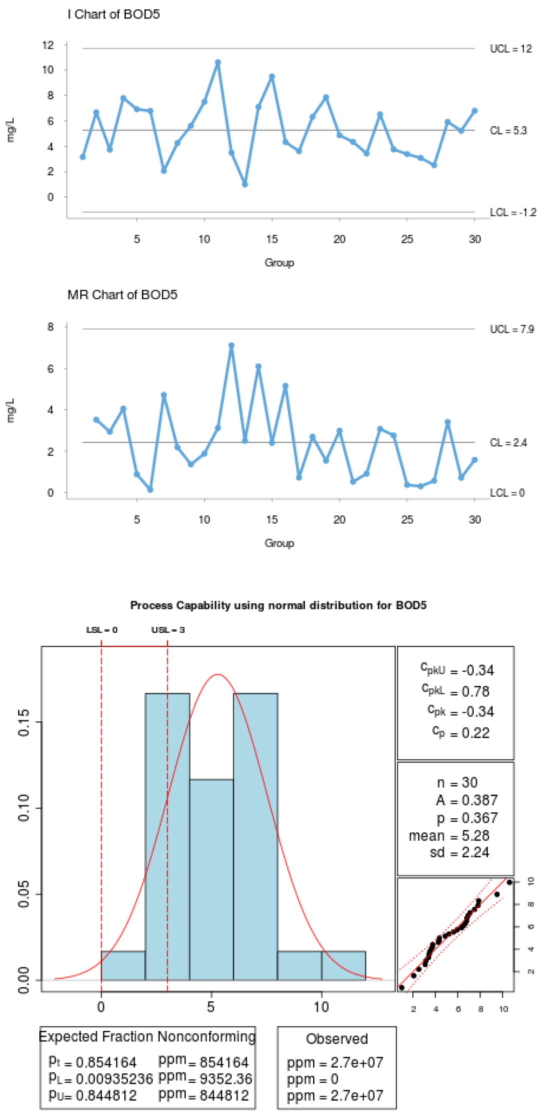

Figure 3. BOD_5 behavior on Cabrero lagoon

Figure 4 shows the COD control chart, it indicates that the distribution fits reasonably good to normal and the central tendency is around 1091.48 mg/L with a standard deviation of 367.37 mg / L, in this study the lower control limits was 92 mg / L and higher 2091 mg / L. One point is outside the control limits of the mobile range control chart, so it may be declared that the process is out of control with a confidence level of 95%.

Since the specifications indexes for COD are less than 1, it shows that the process is not capable, although it is possible that concentrations of this are above 1000 mg / L in the sampling point. The percentage out of specification corresponds to 59.3%, which corresponds to 592973 ppm. It means that the lagoon may not handle with the amount on non-biodegradable waste and chemicals coming from the human activities like automobile service station, which is one of the most common activities in the zone (Priya & Jeyanthi, 2019).

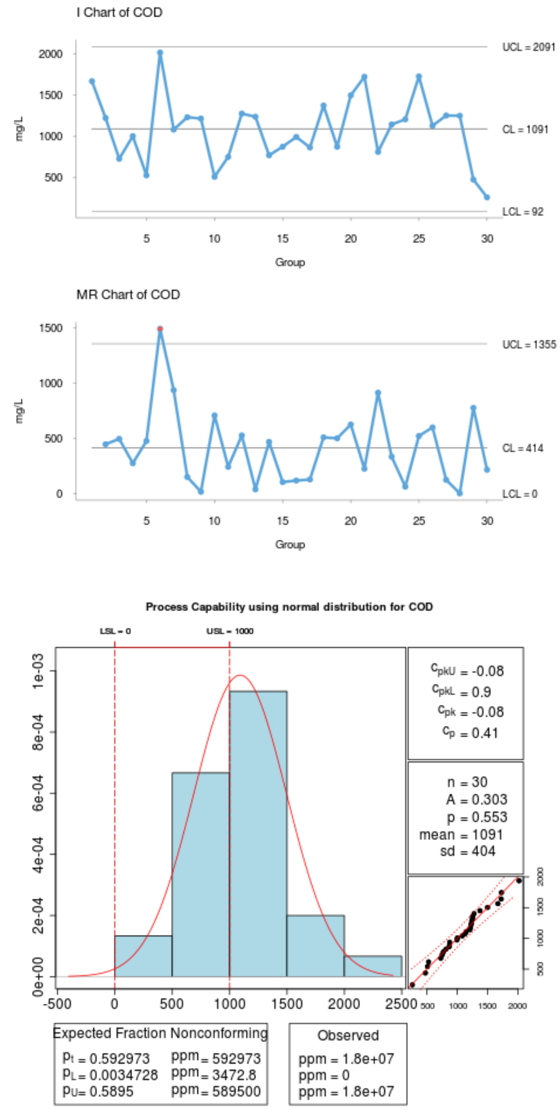

Figure 4. COD behavior on Cabrero lagoon

Total phosphorus (TP) is an essential component for life, it is one of the fundamental nutrients for plant and animal growth. Total phosphorus concentration measures the amount of phosphorus available in organic and inorganic form, dissolved and particulate in aquatic systems.

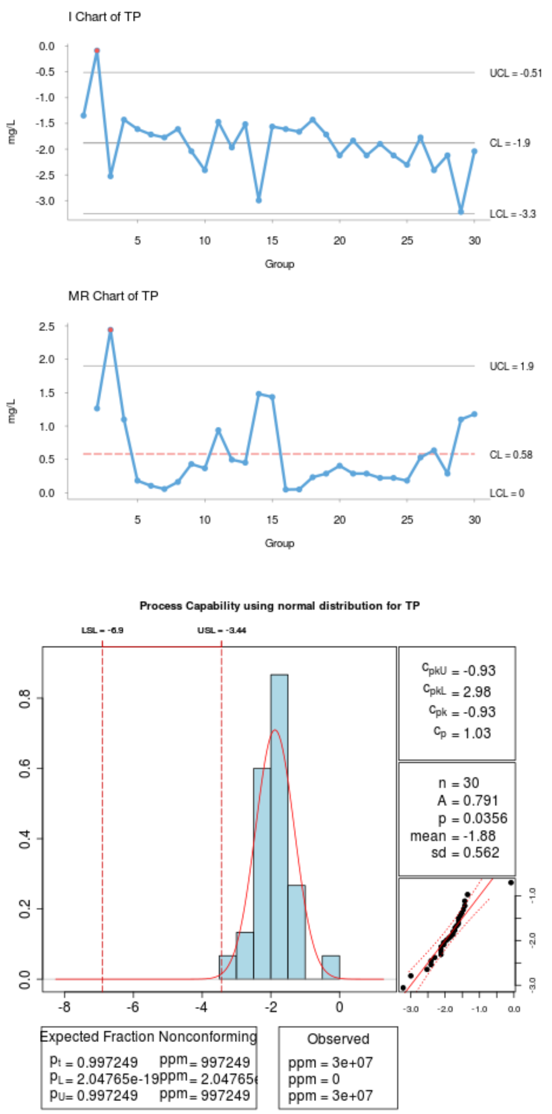

Figure 5. Total phosphorus

For TP process, 30 non-excluded observations were made and they are shown in figure 5, indicating that the distribution fits good to the normal and the central tendency is around 0.149 mg/L (should be <0.032 mg/L) with a standard deviation of 1.675 mg/L, which vary within the control limits below 0.036 mg/L and higher 0.600 mg /L. one point is out of the limits in the individuals chart and moving range chart. So, the process is out of statistical control with a confidence level of 95% (see figure 5).

Analysis showed that Cp and Cpk indices for TP are less than 1, it demonstrates that the process is not capable to handle these specifications, showing that 99% of the data is outside the limits. Wastewater from human activities cause elevated values for this nutrient, these high levels of TP may produce the eutrophication of water, which may lead to lower level of oxygen and death of animal in the lagoon (Xiong et al., 2022).

The presence of total coliforms indicates that water is contaminated with human or animal excrement or sewage waste and has the potential to cause different diseases. For example, E-coli is a subgroup of coliform fecal bacteria and is one of the most frequent causes of many common bacterial infections, including cholecystitis, bacteremia, cholangitis, urinary tract infection (UTI), and traveler's diarrhea, and other clinical infections such as neonatal meningitis and pneumonia.

According to Figure 6, it is expected that the Total Coliforms of the samples vary between 2 and 490 (MPV / 100ml), with a mean for Total Coliforms of 44.45, with a standard deviation of 4.039 (Figure 6). All the observations were contained within the control limits 0.613 and 2697.282(MPV / 100ml). The hypothesis that the process is not in a state of statistical control with a confidence level of 95% can Not be rejected. Figure 10 shows a central tendency to 108 for this parameter, the percentage expected for nonconforming fraction is 1.43%, the process is not capable, but if the total coliform in the lagoon is higher than the allowed (TC> 5000). It is clear that the lagoon is Not able to control them, because the values are well above the threshold values. Sewer discharge sites where the limits exceed the norm, especially in dry season (Whitehead et al., 2018).

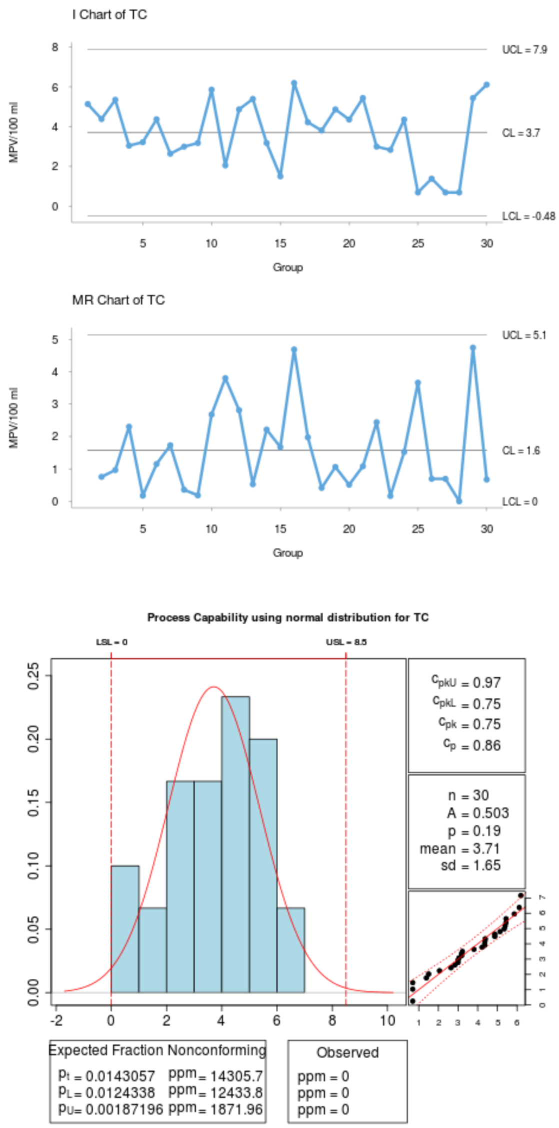

Figure 6. Total Coliform behavior on Cabrero lagoon

According to figure 7, Faecal Coliforms in samples varied between 1.80 and 230.44 (MPV/100 ml), with an average of 24,53.

There are no values outside the control limits and one outlier. The distribution of this parameter fits reasonably well to the normal. Therefore, the hypothesis that the process is in a state of statistical control with a confidence level of 95% can Not be rejected. The central tendency is around 24.53 MPV/100ml. the percentage expected fraction nonconforming of FC corresponds to 3,49%, the process is not capable. It is important to control this parameter, because outbreaks of diseases and epidemics have shown a relationship between the presence of fecal coliform bacteria and the presence of viruses and bacteria that cause different diseases, called pathogens (E. coli, hepatitis and Salmonella) (EL Bilali et al., 2021).

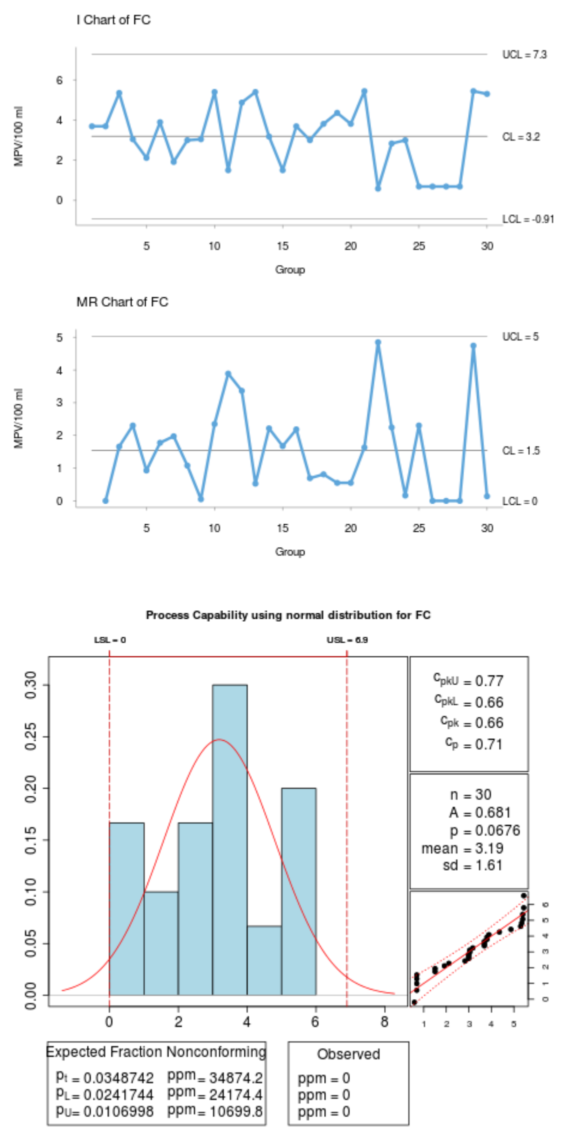

Figure 7. Faecal Coliform behavior on Cabrero lagoon

A summary of control and capabilities are deposited in table 3. As may be seen the lagoon in not capable to transform toxins into safe products, this is probably cause by excessive load of contaminants especially wastewater and solid waste coming from the community near the lagoon.

Table 3. Analysis of statistical control and capacity summary for Cabrero lagoon

Variable	Threshold value	Statistical control	Capable to meet the regulations
DO	> 4 mg/L	under control	is not capable
BOD_5	< 3 mg/L	under control	is not capable
COD	< 1000 mg/L	out of control	is not capable
TP	< 0,032 mg/L	out of control	is not capable
TC	< 5000 MPV/100 ml	under control	is not capable
FC	< 1000 MPV/100 ml	under control	is not capable

4 Conclusions

In the individual control charts analysis, the dissolved oxygen (DO) parameter showed that it was under statistical control, but it is not capable of complying with the regulations established in decree 1594 of 1984. High values of oxygen in the lagoon are possible due to the excess of phosphorus in the water which make than microalgae via photosynthesis increase the concentration of oxygen in water during daylight but probably during night OD values are lower.

In recent years, the Biochemical Oxygen Demand (BOD_5) has had a decreasing trend. However, its average is 5.28 mg / L, which implies that there are large amounts of organic matter in water which may become a threat for human health in the community. Total phosphorus (TP) has been above the eutrophication limits, which may become a danger to flora and fauna since algae abound and may affect the biological cycle due to excess nutrients. This may lead to dissolved oxygen depletion in the lagoon. The Chemical Oxygen Demand (COD) averaged 1091 mg / L, which implies a possible contamination of the water due to the effects of chemical products, such as detergents, chlorides, wastewater from car washes. The rising behavior of Total Coliforms (TC) and Faecal Coliforms (FC) are a warning for the public health of residents of the sector, since they increase the risk of acquiring gastrointestinal diseases such as diarrhea, cholera, among others. The results of this study may help local authorities to make decisions regarding the environmental management of this body of water using statistical process control tools.

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