Comparative Analysis of Water Quality Indices and Their Relationship with Anthropogenic Activities. Case Study: Bogotá River

Wilfredo Marimon (✉ wmarimon@ucatolica.edu.co)

Universidad Católica de Colombia: Universidad Catolica de Colombia

Nathalie Toussaint Jimenez

Universidad Católica de Colombia: Universidad Catolica de Colombia

Carlos Jiménez

Universidad Católica de Colombia: Universidad Catolica de Colombia

John Chavarro

Pontificia Universidad Javeriana

Efraín Domínguez

Pontificia Universidad Javeriana

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COMPARATIVE ANALYSIS OF WATER QUALITY INDICES AND THEIR RELATIONSHIP WITH ANTHROPOGENIC ACTIVITIES. CASE STUDY: BOGOTÁ RIVER

Wilfredo Marimón-Bolívar^{1,2}, Nathalie Toussaint Jimenez², Carlos Jiménez², John Chavarro³, Efraín Domínguez¹.

1. Pontificia Universidad Javeriana, Faculty of Environmental and Rural Studies, Department of Ecology and Territory. Bogotá, Colombia.
2. Research Group in Engineering for Sustainability - GRIIS, Faculty of Engineering, Universidad Católica de Colombia
3. Research Group on Dynamics of GeoAgroAmbiental Systems - DSGAA, Center for Research in GeoAgroAgroAmbiental Sciences and Resources - CENIGAA.

ABSTRACT

The Water Quality Index is the numerical value that qualifies in categories, the water quality of a surface stream, based on the measurements obtained for a set of physicochemical and microbiological parameters registered in a water quality monitoring network. This indicator allows knowing the physical-chemical and microbiological quality conditions of a body of water and identifies contamination problems at a certain point. In the present study, the water quality was studied in 43 stations located in the Bogota river, considering different methodologies for calculating quality indices such as NSF, Oregon, IDEAM, Prati, and diffuse logic to establish the differences, advantages, and disadvantages of each method. Similarly, a correlation analysis was carried out between the parameters, and the land uses in the basin. The results indicated that all the indices showed regular or poor water quality for more than 80% of the stations for the temporal window studied. However, the methodology used in Colombia (ICA water quality index, in Spanish) has eclipsing problems in most of the evaluation points since where the water quality

qualifies as good, other indices such as the fuzzy logic show a degree of contamination by any of the parameters mainly manganese or total suspended solids.

Keywords: Bogotá River, Water quality index, water pollution, spatial and temporal evaluation.

1. INTRODUCTION

Water is a development engine for communities, so knowledge about this resource, distribution, and pressure on quantity and quality constitutes the support for territorial planning and decision-making (Fu et al., 2020). Likewise, social dynamics and population growth lead to increased use, alterations to natural conditions, and effects on water quality that must be evaluated to define comprehensive strategies for the conservation of water systems and disaster prevention (Mester et al., 2020; Walsh and Milon, 2016).

One way to assess these pressures on water quality is to apply water quality indices. Water Quality Index (WQI) is a simple tool or method to evaluate and categorize the water resource quality and compare the state of different water bodies in different places and at other times (Gradilla-Hernández et al., 2020; Kothari et al., 2021). This tool makes it possible to qualify the water quality as "good" or "bad", as well as give indications on the environmental effects from the measured parameters and establish which sections of rivers where the quality has changed significantly and that, if necessary, can be investigated in greater detail.

Despite their benefits, some water quality indices have complications in their uses or interpretations due to overshadowing problems where crucial information on water quality could be destroyed during the process of implementing the aggregation function, or problems of uncertainty where the variation in the selection of weights can affect the uncertainty of the evaluation and the decision making on the water body of interest (Uddin et al., 2021).

48 The Bogotá River, which is in the Cundiboyacense highlands, from northeast to southeast of
49 Cundinamarca, is one of the water bodies of great interest in Colombia. Although it is not a
50 navigable or fast-flowing river, the Bogotá River is significant for Colombia because, in its round
51 and the surrounding areas, economic activities are developed, representing 26% of the total
52 national level (CAR, 2018). Among them, agricultural, livestock, and industrial production stand
53 out. One of the activities that generate the most significant pollution in the river is the tannery
54 sector. The basin receives wastewater from more than 100 tannery companies between the
55 municipalities of Villapizon and Chocontá. These discharges are characterized by having a high
56 load of organic chemical components and heavy metals (Suarez Escobar et al., 2012). Additionally,
57 it receives high pollutant loads from the domestic discharges of Bogotá D.C., Soacha, and other
58 municipalities that contribute about 32% of the national Gross Domestic Product (GDP), but that
59 each second discharges more than 20,000 liters per second of wastewater per second (CAR, 2006).

60 Although studies have been carried out on the determination of water quality indices of the Bogotá
61 river, these have left aside studying the problems mentioned above. Various authors have
62 formulated quality indices according to the permissible limits in the environmental standard, the
63 criteria for the specific use of water and its potential, and a reduced number of parameters with
64 significance that generate information on the change in water quality and its impact (Lozada et al.,
65 2009). Díaz et al. (Díaz-Casallas et al., 2019) used the information from 29 monitoring stations for
66 the period 2008-2017 with records for five parameters (Dissolved oxygen, total suspended solids,
67 chemical oxygen demand, Electrical conductivity, and pH). In the Castro et al. report (Castro
68 Fernández et al., 2015), information for 2008 - 2015 was collected for the same five parameters
69 listed above. However, when they were calculating the WQI, importance weights were given
70 equally to the five parameters, which goes against the recommendations for most approaches to

calculating water quality indices where the weight of dissolved oxygen must be greater than the total suspended solids or pH due to its importance in the degradation of organic matter and other processes. Additionally, the existing correlations between the parameters found, the relationship of the calculated indices with the land uses were not studied, nor did they discuss in profound the possible implications of the calculation methodologies on the index, such as the aggregation function.

For this reason, the present study aims to evaluate the water quality index on 43 stations on the Bogotá River, considering different approaches, using 12 physicochemical parameters, assessing the effect of the aggregation function used, the correlations between the physicochemical parameters/land use, and a comparative analysis between different models of water quality index for its application as a water resource management tool.

2. MATERIALS AND METHODS

2.1. Study area

The study area is covered of the Bogotá river basin, located in the department of Cundinamarca, where its natural system is made up of various bodies of water (rivers, streams, lagoons, reservoirs, among others) represented in nineteen (19) sub-basins that reach a total area of 6000 km². The course of the river Bogotá is born at an altitude of 3300 meters above sea level in the municipality of Villapinzón. The upper part of the basin goes from this source to the urban area of the capital with a length of the river of 165 km; the middle part goes up to the following 90 km to the Salto del Tequendama and the lower part that includes 55km of the river to flow into the Magdalena river at 280 meters above sea level in the municipality of Girardot (Figure 1). As the main characteristics of this basin, the maximum water contribution is provided by precipitation through

a bimodal behavior per year with values of 2200 mm per year and at least 400mm per year and a range temperature between 6 and 30°C. The demand for this stream is given for agricultural, livestock, and industrial services, so that along its route, it receives water from rivers that cross large, populated centers, such as Bogotá, which leads to an increase in the polluting loads to the current principal.

Figure 1. Study Area, Bogotá river basin.

2.2. Data collection

Thirty-six (36) water quality parameters were analyzed during the monitoring campaigns carried out from 2013 to 2019 in two seasons (dry and wet season). The physicochemical parameters studied include pH, electric conductivity (EC), dissolved oxygen (DO), biochemical oxygen

demand (BOD₅), chemical oxygen demand (COD), turbidity, solids content (total suspended solids (TSS) and total solids (ST), alkalinity, total hardness, chlorides (Cl), sulfates (SO₄), total phosphorus (TP), total nitrogen (TN), ammonium (NH₄), nitrates (NO₃), nitrites (NO₂), total Coliforms, *Escherichia Coli*, Al, B, Cd, Ca, Co, Cr, Fe, Mg, Mn, Hg, Ni, Ag, Pb, Se, Na, and temperature. From these 36 parameters, twenty-nine (29) were selected (Supplementary material 1)0020that had a place within the equations for calculating the quality indices to be determined, the data collected were reported in the supplementary material.

Also, a collection of information was realized on the databases used for the development of the watershed management plans (POMCA in Spanish), which highlights crucial data on the use and exploitation of the natural resources in the area included in the basin, each of these data was analyzed and processed using ArcGis and summarized in detailed maps in the supplementary material. In this information, those layers were identified where the conflict over water resources use is the connection point with the possible causes of contamination in the riverbed. Similarly, the catchment points, discharges, and the main population centers were taken into account to identify the critical points of pollutant loads and their behavior along the river.

2.3. Correlation study

Pearson, Spearman, and Kendall's correlation coefficients were used to calculate the degree of association between the water quality variables, where there will be a force of proportion that is measured in a degree from 0 to 1 and a direction already be it positive or negative.

2.4. Calculation of quality indices.

Water quality indices were proposed to evaluate the degree of contamination and the main riverbed's general quality in the basin. The indexes provide a simple, objective, and rapid method that allows the integration of the essential parameters to quantify the degree of alteration of the water resource's natural qualities. The analysis was performed by calculating quality indices that differ in the aggregation function and evaluating the parameters.

2.4.1. Prati implicit contamination index. (IPI)

Prati, in 1971, established an index in which the parameters were transformed into pollution levels through mathematical expressions, considering the polluting capacity of the indicators (Prati et al., 1971), (Abbasi and Abbasi, 2012). The index is defined as a weighted average between 13 parameters or subscripts:

$$IPI = \frac{1}{13} \sum_{i=1}^{13} I_i$$

Where I_i , corresponds to the sub-index of each parameter.

2.4.2. Sanitation Foundation Water Quality Index (NSF-WQI)

This index was developed in 1970 by the National Health Foundation of the United States by selecting parameters utilizing the Delphi technique, where qualification of nine variables of importance that a source of the catchment for human consumption was made. It also had two toxic parameters (pesticides and toxic compounds) (Uddin et al., 2021). We applied an aggregation function based on a weighted arithmetic average to calculate the NSF-WQI index.

$$NSF - WQI = \sum_{i=1}^n SI_i W_i$$

Where SI_i corresponds to the sub-index of the parameter that arises from the parameter curves and W_i is the weighting factor for the sub-index.

2.4.3. Dinuis second index (IWQ).

This index is made up of nine chemical and two microbiological variables (coliforms toles and *E-coli*), which, unlike the previous indices, the added value is obtained through a weighted geometric average and whose use is oriented for management as a source of the capture of water for consumption, agriculture, fishing, and aquatic life, industry, and recreation (Castro et al., 2014). The following formula defines the second index of Dinius:

$$IWQ = \prod_{i=1}^n I_i^{W_i}$$

Where IQW , is the water quality index, I_i corresponds to the sub-index of the parameter that arises from the parameter curves and W_i is the weighting factor for the sub-index.

2.4.4. Aquatic toxicity index (ATI)

This index includes an additive aggregation of a modified unweighted average, which also transforms the parameters that affect the aquatic ecosystem. Among the parameters, the presence of heavy metals such as copper, chromium, lead, and nickel stands out. It is developed by:

$$ATI = \frac{1}{100} \left(\frac{1}{n} \sum_{i=1}^n q_i \right)^2$$

Where n is the number of parameters and q_i is the characteristic function of the indicator

2.4.5. Modified Oregon Water Quality Index (OWQI)

This index analyzes a group of defined water quality variables. It produces a general value through an aggregate by the square root of the unweighted harmonic average, where they involve a transformation of the parameter through a non-linear regression visualized in the curves, describing the water quality for rivers and streams (Castro et al., 2014). The calculation of the index is given by:

$$OWQI = \sqrt{\frac{n}{\sum_{i=1}^n \frac{1}{SI^2}}}$$

2.4.6. Water Quality Index (ICA)

During the National Water Study of Colombia (IDEAM, 2010) and in search of establishing a simple method for determining the global quality of a water source mainly for human consumption, IDEAM developed a simplified index based on the UWQI (Universal Water Quality) methodology which is formulated with parameters that reflect the various sources of organic pollution and the environmental response that the body of water may have:

$$ICA = \sum_{i=1}^n I_i W_i$$

2.4.7. ICAGA'S FUZZY WQ

Six fuzzy sets were used to define the membership functions in terms of input indicators for each parameter. The elements of the universe of discourse (X) were linked to the interval [0, 1] by this membership function. The fuzzy set $A \subset X$ is denoted by:

$$A = \{x \in X\}, 0 \leq \mu_A(X) = 1$$

Donde $\mu_A(X)$ is a degree of membership between 0 and 1.

For the parameters, the trapezoidal shape was used for the membership functions. A linguistic term introduced each set in X. The terms used for fuzzy sets were very low (VL), low (L), moderate (M), high (H), very high (VH), and extremely high (EH). The fuzzy sets were created using the trapezoidal approach. The rules cover different possible modes in the SWQ applying the parameters. For this research, more than 300 rules were created based on expert knowledge. The following are examples of the rules that met the expert knowledge obtained from (Camara et al., 2020; Srinivas and Singh, 2018; Zou et al., 2006):

- if the DO is "low" and the BOD is "very low", then the water quality is "moderate."
- if the pH is "low" and the temperature is "moderate", then the water is "moderate."
- if the fecal coliform is "very low" and the total coliform is "very low", then the water quality is "excellent."

The evaluation of the rules was performed where the composition of the result of a fuzzy *if-then* rule. In this process, the lowest class of any selected parameters becomes the fuzzy index class for that rule. The lowest class and corresponding value of the membership function for any selected parameters become the class of the rule's fuzzy index. In this step, the applicable fuzzy rules for the given data are identified. Next, an aggregation of rule outputs where the maximum value of the fuzzy index has the same class is considered among the available applicable rules. Finally, the results of all applicable rules are grouped into a single fuzzy distribution by fuzzy joining the applicable rules to convert the fuzzified output to the sharp value. All the rules and calculations were made using the Fuzzy Logic Toolbox in Python 3.8.

3. RESULTS AND DISCUSSION

3.1. Water quality

From the water quality data obtained from the information collection, the respective organization, tabulation, and graphing was carried out employing boxes and whiskers of each of the twenty-nine (29) key parameters for the development of the indices to determine the behavior along the riverbed, the average value obtained in recent years and the display of maximums, minimums, and outliers in the samples (Supplementary Material 1).

Figure 2. The behavior of water quality along the river.

When comparing the concentrations with the respective quality objective required for that section, it is observed that a large part of the points does not meet these quality objectives (Figure 2). The only variable that remains within the range required by the environmental authority is the pH. However, it fluctuates between 6 to 8 pH units, where the maximum value is in the stations near the river mouth.

A significant increase in the values in some parameters such as Electrical Conductivity (EC) and Chlorides was identified along the river, while a dissolved oxygen reduction was evidenced. These results are due to the anthropogenic activity in the area, which includes the tannery industry (mainly in the upper and middle part of the basin) that carries out dumping of soluble substances in its production process and susceptible to oxidation processes. Also, the agricultural activity has adverse effects on river quality, particularly the potato crops in the area and agrochemicals, fertilizers, and pesticides that reach the water body through secondary tributaries (Bautista, 2004).

The water body improves its quality with the discharge of water from the Sisga reservoir, causing a positive effect on the self-purification capacity of the Bogotá River, but as it descends and discharges from municipal treatment plants and industrial discharges are incorporated, that present a high concentration of suspended solids, the calculated indices showed a deterioration in water quality.

For dissolved oxygen, a constant decrease is shown when the municipalities' sewage discharges begin. As the river slope decreases, the BOD and COD indicators increase, generating anoxic conditions that significantly affect the self-purifying processes of the source. However, when reaching sections where the slope's value increases (stations after the Muña reservoir), the oxygen concentration gradually increases.

232 Relate to the concentrations of phosphorus and nitrogen compounds, eutrophication problems are
233 detected mainly in the middle basin, associated with increased organic matter generated by effluent
234 discharges from the capital and agricultural runoff promoting the algae and bacteria growth.

235 Regarding the causes of bacteriological contamination in water, high concentrations of
236 cauliflowers are due to livestock activities and domestic sewage. Additionally, the presence of
237 metals such as chromium was detected due to the micro-industries of tanneries; lead, mercury, and
238 nickel from agrochemicals but with low concentration values (< 0.01 mg/L). However, it was
239 possible to observe some atypical values, mainly in the parameter of total mercury, in the
240 monitoring carried out in 2017. Other of the metals detected were iron, sodium, magnesium,
241 calcium, and manganese, the latter found in high concentrations in water.

242 Finally, in the Magdalena River's vicinity, the Bogotá River has a higher concentration of
243 suspended solids and total solids, which indicates a significant increase in turbidity in the last
244 monitored stations. It is also important to emphasize that in addition to the pressure that the upper
245 and middle basin generates on the lower one, the slopes decrease, which affects the transport of
246 sediments and even the production of nutrients such as phosphorus and nitrogen, whose value is
247 higher. In this area, a large part of the lower basin pollution is caused by tourism development,
248 reaching the highest levels of pollution.

249 *3.2. Correlation*

250 The correlation matrix of the water physicochemical parameters in the study area shows the
251 correlation between different variables and the degree of correlation as a function of the Pearson,
252 Spearman, and Pearson correlation coefficient. The magnitudes of the coefficient of 0.7 - 1, 0.5 -
253 0.7, and less than 0.5 have been classified as strong, moderate, and weak correlations, respectively.

A positive correlation means that when one parameter increases, another parameter also increases along with that parameter. A negative correlation means that when the value of one parameter increases, the value of another parameter decreases, and its source, the characteristics are not homogeneous. The analysis showed a strong positive correlation between EC and Alkalinity (0.840). This strong relationship is due to metal ions like calcium carbonates in the water that increase the electrical conductivity. Hardness as a parameter presents a similar relationship with calcium ions and, in turn, with iron ions (Supplementary material 2).

Likewise, a positive correlation was found between nitrates, iron, and manganese, which supports a component of inorganic contamination associated with agricultural activities in the basin. Additionally, the positive correlation between biochemical oxygen demand and ammoniacal nitrogen supports the fact that anoxic conditions occur in some river parts.

3.3. Water quality indices

The quality indices were calculated by year and by season to carry out the respective comparison and identification of the behavior and evolution both temporally and spatially. The results were reported on location maps developed in ArcGIS (Supplemental Material 3 and 4).

It is remarkable to observe the indices' behavior in Figure 3, where the quality of the water deteriorates as the channel is traversed. A similar trend is shown between the ICA, Oregon, and aquatic indices, where there is a considerable reduction in the stations located in the upper basin, mainly in Villapinzón, due to the presence of tanneries in the area, extensive livestock, and the presence of rotating crops. After downstream of the Villapinzón, a recovery is appreciated due to incorporating good quality tributary channels that support pollutants' degradation. However, the

passage through the populated center's prints a gradual deterioration in water quality due to discharges of domestic origin, agricultural and industrial activities (Swamee and Tyagi, 2007).

Figure 3. Comparison of water quality indices in the Bogotá River.

When comparing the results of the water quality and the calculated water quality indices, it can be established that there is a concordance since, in the discharges reported by the environmental authority, there are records of 547 domestic and 150 non-domestic discharges, which corresponds to 78.5% and 21.5% respectively (Supplementary Material 5).

Within the characterization of these non-domestic discharges, it is found that there are conductivity values greater than 10,000 ($\mu\text{S}/\text{cm}$), COD greater than 4000 mg/L, and organic nitrogen above 70 mg/L, coming from cultivation activities that do not have water treatment plants or are of very low effectiveness. Additionally, there are records of several domestic discharges with a concentration of total suspended solids with values higher than 200 mg / L, total nitrogen above 40 mg/L, and total coliforms above 100,000 CFU/100 ml, which goes in deterioration of the surface water resource.

Wastewater management plans of the basin show how treatment plant works are being prioritized in the middle and/or lower part (for example, CANOAS wastewater treatment plant), which is unfortunate since it is much easier to carry out treatments due to the amount of water to be treated and according to the quality indices calculated, the impacts will be more significant for the ecological benefit of the basin.

Since the source of the river in the Guacheneque moor (water quality stations 5 to 10), the quality has been affected by the wastewater discharges associated with potato crops and Villapinzon wastewater (Domestic and industrial). These discharges are characterized by high phosphorus concentrations that tend to deteriorate the river water quality when released at a small flow of the river. Although all the quality indices decrease, ICA classifies it as water with good quality, which does not allow adequate management and planning of water resources.

On the other hand, when comparing the evaluation of each water quality index, when the Prati method is implemented (which uses a weighted average), it was observed that having a parameter in which there is a high value in the Manganese concentrations is you get a highly polluted water quality result that. However, when making the comparison with other indices such as the NSF-WQI, another classification of the quality of the water resource is obtained since they overshadow this potential contamination due to its aggregating function, that is, the index does not accurately reflect the real situation of the quality of the water.

The water quality index designed in Oregon has a greater sensitivity to changes in individual variables, so in specific critical parameters such as total solids, it shows a greater weight on the final assessment of water quality. This methodology confronts overshadowing problems leading to poor decision-making by the environmental authority (Torres Vega, 2009).

The opposite case is presented in the methodology proposed by IDEAM, of a weighted sum type formula, it is clear to notice a significant increase in the assessment of water quality since the index presents a lower sensitivity and eclipsing problems since values that do not, they have as much variability as the pH they have the same weight as parameters that can become more critical such as BOD or coliforms.

Unlike the other indices, the index calculated using fuzzy logic presents quality values within the range of highly contaminated since it is very susceptible to obtaining adverse or low results if any parameter is not within the range of good quality, being more demanding in the results. This methodology showed that it is necessary to meet all the parameters quality objectives, which avoids overshooting or inferior weighting in the implementation of water quality indices.

It can be seen how in the middle part of the basin (stations 40 to 50), where the river receives high pollutant loads of domestic origin added to point and diffuse pollution associated with agricultural activities, the NSF and ICA indices qualify the water quality as regular (approximately 60). This is totally contrary to the classification given when applying indices with more rigorous aggregating functions or that evaluate more critical parameters such as the aquatic toxicity index or the fuzzy logic index.

Comparing our results with previous studies (Nayak et al., 2020; Oladipo et al., 2021), we observe that the fuzzy logic approach reveals with greater accuracy the actual situation of the water resource in the study area regardless of the rate or intensity of surface water contamination. The use of indices that use a weighted average such as the NSF-WQI becomes deficient in the scenario with high pollutant loads (for example, the Bogotá River basin), since its curves for calculating subscripts have limitations for BOD and total solids.

In this sense, the classification of water quality in the upper part of the basin shows that for the indices such as NSF and ICA, it is fair or reasonable, while the quality index obtained through the fuzzy logic methodology the quality is terrible given finding high concentrations of coliforms (> 20,000 CFU/100ml), manganese (> 15 mg/L) or lead (> 5 mg/L) in measurements.

Finally, the results are essential for decision-making since, from the water quality classifications, development policies are created or implemented for the care or use of natural resources. Similarly, environmental authorities can further analyze water quality monitoring plans in order to increase the frequency of measurement of the parameters that had a more significant influence on the classification of water quality and thus have more tools in the issuance or evaluation of discharge licenses.

CONCLUSIONS

Water quality is directly affected by anthropogenic activities, where the constant discharges of residues produced by extensive livestock farming, the chemicals applied to crops and domestic waters lead the polluting loads in the Bogotá River, which due to its low self-purifying capacity in its journey and few treatment processes negatively affects the environment and surrounding ecosystems.

Water quality indices show global results, which manage to be another alternative for the various environmental control agencies, such as autonomous corporations, whose purpose seeks the efficiency in decision-making concerning the protection of the water source, such as granting any discharge permit or environmental evaluation and monitoring of the resource.

As the indices are a numerical value based on a subjective construction, they present problems mainly in the definition of the functions where the transformation of each of the concentrations of

the measured parameters is carried out. This happens since these functions depend to a large extent on the ecosystem contexts where they were developed and based on the opinion of groups of experts who analyzed the behavior of the water and the use that is to be made, causing the functions to vary in the indices and not there is a universal index applicable to all the water resources present on the planet. However, opting for the use of indices as a global measure is an efficient and simple way that must be promoted in order to optimize the results and make them consistent with reality.

Each one of the characteristics of the indices proposed by various authors was identified in accordance with the calculation criteria specified in each index in which they found deficiencies, problems of sensitivity, rigidity, overshadowing, behavior in similar results, and subjective descriptions of the quality of the Water. In accordance with the above, it is concluded that when implementing an index, each of the criteria must be considered, as well as the greatest number of parameters measured and applied in the mathematical expression, the uses of water and the effectiveness in currents.

Similarly, for time-scale studies, it is better to apply indices that use unweighted harmonic average or fuzzy logic in their calculation form, such as the modified Oregon index, since they are more susceptible to changes and negative values in individual parameters, and thus better assess the quality of the water resource in relation to the surrounding anthropogenic activities.

Data availability

The datasets supporting the conclusions of this article are included within the article and its additional file.

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382 **Ethics declarations**

383 Competing interests

384 The authors declare that they have no competing interests.

385 Ethics approval and consent to participate

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387 Consent for publication

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389 **Contributions**

390 All authors contributed to the study conception and design. Method implementation and optimization,
391 analysis, and data evaluation were performed by NT, JC and CJ. The first draft of the manuscript was
392 written by WM and ED and all authors commented on previous versions of the manuscript. All authors read
393 and approved the final submitted manuscript.

394 **Corresponding author**

395 Correspondence to Wilfredo Marimón-Bolivar.

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461

Figures

Figure 1

Study Area, Bogotá river basin. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

The behavior of water quality along the river.

Figure 3

Comparison of water quality indices in the Bogotá River.

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