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Space-time variation in water quality of the Aburrá-Medellín river using electrical conductivity in the period 2010-2020. Part 2

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Abstract

The deterioration of the environment and especially the crisis due to the availability of water, has led developing countries to advance in protection, avoiding the dumping of wastewater and monitoring quality. In the city of Medellín, the use of electrical conductivity as an indicator of water quality in the Aburrá-Medellín river was proposed as an alternative to explain and keep the community informed about how the river monitoring stations are doing through of colors and thus continue to raise awareness of the importance of caring for water. In order to study the spatial and temporal variations of the water quality in the river from the electrical conductivity indicator, and considering the categorical data obtained with the indicator, a number from 1 to 5 was assigned (very bad, bad , regular, acceptable and good quality, respectively). In these paper We used statistical methods as crosstabulation to describe relationships between the categorical variables through counts and multiple correspondence analysis for representing the associations between the factors affecting the wáter quality using the correspondence maps. It was found that low flows correspond to the most critical quality conditions, and although a deterioration is observed as the river flows downstream (between the monitoring stations) the influence of the water levels is greater. The statistical analysis showed a relatively high association of the quality indicator and the flows also, that the water quality deteriorates in the afternoon and in the final years of monitoring in low flows.

Keywords: Electric conductivity, Urban river, Quality indicator, Aburrá-Medellín river, Multiple correspondence analysis, Cross tabulation.

Variación espacio-temporal de la calidad del agua del río Aburrá-Medellín utilizando la conductividad eléctrica en el periodo 2010-2020. Parte 2

Resumen

El deterioro del ambiente y en especial la crisis por la disponibilidad de agua, ha llevado a que los países en vía de desarrollo avancen en la protección, evitando el vertimiento de aguas residuales y en el seguimiento a la calidad. En la ciudad de Medellín, se propuso el uso de la conductividad eléctrica como un indicador de calidad de agua en el río Aburrá-Medellín como una alternativa para explicar y mantener informada a la comunidad acerca de cómo están las estaciones de monitoreo del río a través de colores y así continuar sensibilizando en la importancia del cuidado del agua. Con el fin de estudiar las variaciones espaciales y temporales de la calidad del agua en el río a partir del indicador conductividad eléctrica, y considerando los datos categóricos que se obtienen con el indicador, se asignó un número de 1 a 5 (muy mala, mala, regular, aceptable y buena calidad, respectivamente). En este artículo utilizamos métodos estadísticos como la tabulación cruzada para describir las relaciones entre las variables categóricas a través de conteos y análisis de correspondencia múltiple para representar las asociaciones entre los factores que afectan la calidad del agua usando los mapas de correspondencia. Se encontró que los caudales bajos corresponden a las condiciones de calidad más críticas, y aunque se observa un deterioro a medida que el río fluye aguas abajo (entre las estaciones de monitoreo) la influencia de los niveles de agua es mayor. El análisis estadístico mostró una asociación relativamente alta del indicador de calidad y los caudales, además, que la calidad del agua se deteriora en la tarde y en los años finales de monitoreo en caudales bajos.

Palabras clave: Conductividad eléctrica, Río urbano, Indicador de calidad, Río Aburrá-Medellín, Análisis de correspondencia múltiple, Tabulación cruzada

1. Introduction

Throughout the world, environmental deterioration, particularly the water availability crisis, has led civic authorities in large cities of developed countries to re-consider and change their use of water resources, particularly at surface level. This has, in turn, led to a search for alternatives to recover and restore these water systems. Meanwhile, in developing countries, there has been increased research into wastewater treatment, while regulations have been developed to prevent the discharge of this, with the result that water quality is increasing or, at least, is not decreasing as the population grows.

Particularly in Colombia, there are major cities with rivers passing through them that act as hubs for development. However, these rivers are exposed to various discharges that upset the balance of the system, causing a loss in physicochemical and biological quality (Dourojeanni and Jouravlev, 1999; Rodríguez Valero, E., 2016). Regulatory development in Colombia over the past ten years has provided tools to reduce polluting actions that in the past were frequent and had a negative impact, limiting the use of the water resource, and making it a risk to public health that damaged the quality of life of the population.

Within the Colombian legal framework, Resolution 0631 of 2015 is of particular importance. This regulation establishes limits on water quality parameters and discharges. Also, Decree 2930 of 2010 sets out the Regulatory Plan for Water Resources (RPWR). Both these laws are compiled in Decree 1076 of 2015 (Ministerio Ambiente y Desarrollo Sostenible, 2015).

In the Aburrá-Medellín river basin, the RPWR is the planning instrument used to administer this water resource efficiently and monitor its quality and quantity, thereby contributing to its recovery and sustainability. Its overall aim is to “improve the availability of the water resource of the Aburrá-Medellín river and of its priority contributory streams, through improving their sanitation and the efficient distribution of water for the various uses set out in the law” (Área Metropolitana del Valle de Aburrá y Universidad de Antioquia, 2018).

An important aspect of the RPWR is the monitoring and follow-up programme of the quality and quantity of surface water resources. This programme seeks to periodically measure the quality of the water, to monitor the state of the river and evaluate progress in the implementation of the RPWR. It is carried out in the river basin through the regional water monitoring network "RedRío", which was established in 2003.

Over time, the network has evolved based on the needs of the Área Metropolitana, the results found in the river and its contributory streams, technological progress and the available financial resources (Giraldo L., 2022; Área Metropolitana del Valle de Aburrá, et al., 2014; Área Metropolitana del Valle de Aburrá y Universidad de Antioquia, 2016; Área Metropolitana del Valle de Aburrá y Universidad de Antioquia, 2019; Área Metropolitana del Valle de Aburrá y Universidad de Antioquia, 2020). The overall objective of evaluating the water resource remains the same, and the RWPR and "Plan for Environmental Management for the Aquifer" continue to be implemented.

The monitoring network carries out periodical campaigns in the Aburrá-Medellín river, its contributory steams and in some significant discharge outlets, measuring more than 20 variables. Moreover, it has three automatic stations known as San Miguel, Ancón Sur and Aula Ambiental, located in the municipalities of Caldas, La Estrella and Medellín respectively (the first 37 kilometres of the river), that carry out continuous monitoring of the electrical conductivity, pH, dissolved oxygen, turbidity redox potential and temperature.

In addition to the provision of technical findings on water quality by the monitoring network, it is necessary to provide information to the community on the state of the river, to make the local population aware of damage to the river water quality or of the improvements being made to it. In other words, the public should be made aware of the level of commitment to the stated aims of the RPWR, specifically, the restoration of water quality, so that the river can utilised effectively and cared for by everyone through small actions that, collectively, have a big impact.

The article "Aburrá- Medellín River Water Quality Space-Time Variation from the Electrical Conductivity and Its Use as an Indicator of Quality." (Giraldo L., 2022) and the research leading to its publication was based on the above-mentioned aim of providing information to the community. This work proposed the use of electrical conductivity as an indicator of water quality in in the Aburrá-Medellín river, considering the results obtained in the historic monitoring carried out on this parameter by the regional water resource network RedRío, similar proposal was made by Yap, c. k. (2013) in the river Langat, Malaysia to indicate the deterioration of water quality. This article determined that, in order to create parameters, it is necessary to establish a variation range of the indicator for each monitoring station. This is because, when considering the overall range for the river, it would be impossible to show a deterioration in the water quality in the stations at locations with lower anthropic impact and hence better water quality, such as those in the south of the region.

The use of electrical conductivity as a quality indicator is particularly valuable when evaluating the change in the water quality of the Aburrá-Medellín river over time, in response to intermittent discharges as well as to actions by municipal authorities such as the implementation of the RPWR and of the Medellin public utility companies' Sanitation and Discharge Management Plan (SDMP). Additionally, this indicator allows a rapid interpretation of water quality by the population. Specifically, the use of a colour-coding system of water quality is used to educate and inform the community as well as to raise awareness of the importance of caring for water and using it sparingly and efficiently (Área Metropolitana del Valle de Aburrá y Universidad de Antioquia, 2020; Giraldo L., 2013).

For the purpose of studying space and time variations in the water quality of the river through the electrical conductivity indicator, methods were considered to estimate indices for the measurement of water quality. These include multivariate methods such as principal component analysis (PCA), factorial analysis and cluster analysis, the aim of which is to build indices based on lineal relationships between indicators. Other methods exist, such as those based on artificial intelligence, including the fuzzy logic and genetic algorithm methods, the second of which consists of training an algorithm through pattern recognition, which requires large quantities of data. Another way of calculating the indices are deterministic techniques, where each indicator is assigned a weighting based on technical consideration. More information can be found in Abbasi, T. & Abbasi, S. A. (2012).

PCA has been widely used for the above-mentioned purpose (Sun et al., 2016; Garizi et al., 2015; Garizi et al., 2011), but it requires that the indicators are quantitative in nature. However, these is a technique called multiple correspondence analysis (MCA), equivalent to PCA for categorical or counting data, which allows indices to be constructed through categorical data and its graphical results simultaneously. This allows information related to the multivariate distances between the different observation units and the measured variables to be obtained. In the literature, various examples are found of the application of MCA to analyse pollution in environmental matrices. For example, Lavoie et al. (2006) developed an index based on diatoms to evaluate the effects of pollution on various water bodies. Faradiba & Azzahra (2021), estimated air, water, and ground pollution indices in rural regions of Indonesia. Carrasco et al. (2011), used MCA combined with multiple regression to analyse mercury and methylmercury bioaccumulation patterns in fish species in the Ebro River in Spain.

For this article, the following research questions were posed: (1) How does the water quality indicator respond to variations in flow? (2) How does the water quality indicator respond to spatial variations? (3) How does the water quality indicator respond to hourly and annual variation (4) Which of the three factors – flow, space and time - has the biggest influence on water quality?

In order to facilitate interpretation of the results, categorical data were used, for which a number from 1 to 5 was assigned as an indicator of quality (very bad, bad, poor, acceptable and good quality, respectively). Subsequently, cross tabulation was used considering the colour-code assigned to the quality indicator, and the results were represented in a “mosaic chart” where the width and height of each bar were scaled to represent the frequencies or were, in other words, proportional to the frequency. Additionally, the chi-squared test was used to determine whether the water quality indicator was independent of the factors, and the Cramer's V statistic was used to measure the degree of association between the indicator and the factors. Finally, MCA was used to study the space and time variations of the water quality of the river.

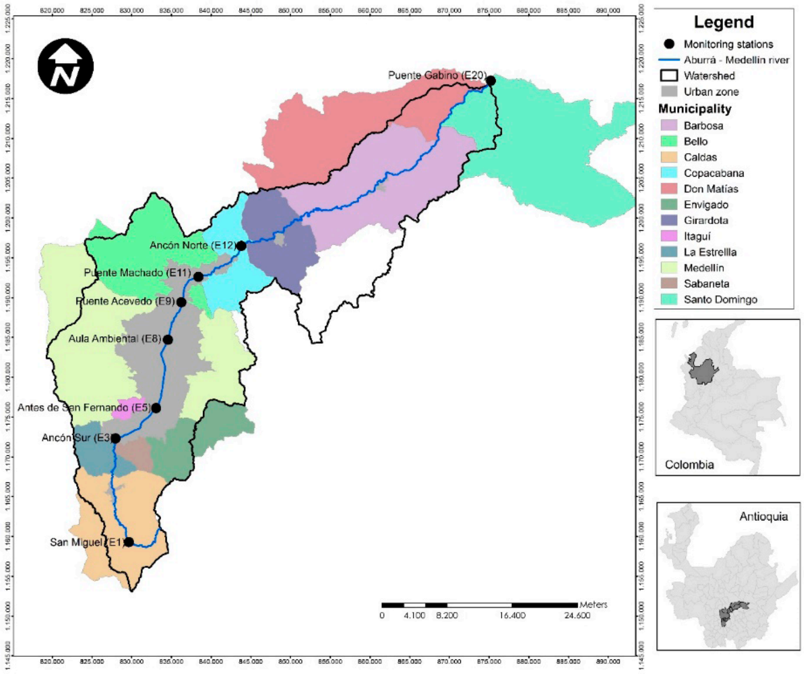
2. Study zone

The Aburrá valley is located in the department of Antioquia Colombia, in the middle of the Central Andres mountain range. The city of Medellín, the second biggest in the country in terms of population and importance, is located in this valley, along with nine other municipalities (Barbosa, Girardota, Copacabana, Bello, Itagüí, Sabaneta, Caldas, La Estrella and Envigado), which collectively have 3,726,219 inhabitants. The Aburrá-Medellín river is the main waterway, passing through the ten municipalities from south to north, and is a historical development hub for the region (Área Metropolitana del Valle de Aburrá et al., 2011).

The river, which is recognised as the articulator axis of the various municipalities of the valley, has around 250 tributaries of various sizes over its 100-kilometre length, from its spring in El Alto de San Miguel (Caldas) to its convergence with the River Grande. Some of these tributaries are polluted due to direct discharge of wastewaters, which reduce oxygen levels and increase the levels of organic load and inorganic and toxic substances, damaging the quality of the water resource in the region (Giraldo et al., 2010; Área Metropolitana del Valle de Aburrá et al., 2011).

The changes in the hydrodynamic characteristics presented by the river, together with the discharge of wastewaters (raw and treated) as well as solid wastes, have caused modifications to physicochemical processes, with a damaging impact on the ecosystem (Área Metropolitana del Valle de Aburrá y Universidad de Antioquia, 2016). Electrical conductivity has been established as an indicator to evaluate the space and time variation in water quality. This is measured in eight of the fourteen monitoring stations that make up the "RedRío" monitoring network, in order to provide an overall perspective over the study period (2010-2020). Figure 1 shows a map of the study location, created based on maps provided in the Aburrá River Basin Management and Development plan (ARBMDP).

Figure 1. *Geographical location of the study site.*



Source: Giraldo (2022).

3. Materials and methods

To respond to the previously posed research questions, the information recorded in the monitoring campaigns carry out in 2010-2010 by RedRío were taken. Based on this, a matrix of hourly measurement data of electrical conductivity was made. These data were classified based on the system described in Giraldo (2022), for which the following were considered as factors: monitoring station (8), flow level (3), time of day of measurement (12) and year of measurement (9).

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3.1 Quality classification regime

To classify the quality of each of the readings, the quality indicator (electrical conductivity) classification table proposed in article (Giraldo, 2022) was used.[1]

To better enable processing of the data, a value was assigned to each classification as shown in Table 1.

Table 1. *Classification of the quality indicator*

Station	**Good**	**Acceptable**	**Regular**	**Bad**	**Very bad**
Score	**5**	**4**	**3**	**2**	**1**
1	<30.1	30.1 – 31.7	31.8 – 33.7	33.8 – 36.7	>36.7
3	<79.7	79.7 – 119.1	119.2 – 154.4	154.5 – 194.2	>194.2
5	<121.9	121.9-146.9	145.0 – 181.0	181.2 – 238.3	>238.3
8	<204.6	204.6 – 383.4	383.5 – 470.2	470.3 – 531.0	>531.0
9	<274.1	274.1 – 358.0	358.0 – 503.8	503.9 – 586.2	>586.2
11	<288.1	288.1 – 393.31	393.4 – 480.0	480.1 – 551.2	>551.2
12	<255.4	255.1 – 396.0	396.0 – 473.0	473.1 – 565.1	>565.1
20	<146.3	146.4 – 187.0	187.1 – 210.0	210.1 – 239.33	>239.3

Source: Giraldo (2022).

3.2 Flow classification regime

Classification was carried out considering historic flow records in the river from 2004 to 2040 from RedRío, the water resource monitoring network in the region. The quartiles Q1 and Q3 allowed limits to be

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[1] Each station has its own classification, given that the use of the water resource and the surrounding area are different in each. Therefore, the indicator is very important when evaluating the changes found at the stations arising from population growth or actions carried out as part of the implementation of the Regulation Plan of the Aburrá-Medellín river.

defined for low (Q<Q1), medium (Q1<Q<Q3) and high (Q>Q3) flows in each monitoring station. In this way, the number 1 was assigned for low flows, 2 for medium flows and 3 for high flows, as shown in Table 2 (Área Metropolitana del Valle de Aburrá y Universidad de Antioquia, 2019).

Table 2. *Quartiles for flow classification (m3/s)*

Station	Inferior Quartile	Superior Quartile
	Q25	**Q75**
San Miguel	0.39	0.89
Ancón Sur	3.28	7.05
Antes de San Fernando	4.77	10.83
Aula Ambiental	11.12	21.55
Puente Acevedo	14.94	30.54
Puente Machado	17.5	39.22
Ancón Norte	20.84	43.79
Puente Gabino	72.7	132.0

3.3 Statistical analyses

3.3.1 Cross Tabulation

The cross-tabulation process is a statistical technique to describe relationships between two categorical variables through counts. It is organised in such a way that the counts of one variable appear in the rows and the counts of the other variable appear in the columns. This allows the correlations between the pairs of variables to be analysed. This information is represented in a “mosaic chart” where the width and height of each bar are scaled to represent the frequencies (counts) of each combination of categories.

3.3.2 Multiple correspondence analysis (MCA)

Correspondence analysis is a graphical procedure for representing associations in a table of frequencies or counts called a contingency table (Johnson & Wichern, 2014). Using the MCA method, we obtain a two-dimensional graphical display of the information in the multiway contingency table (Rencher & Schimek, 2001). MCA is similar to principal components analysis (PCA), in that they share the objective of describing and interpreting the data, with the difference that PCA is based on the matrix of correlations between the variables and MCA is based on the matrix of similarities (or distances) between the individuals (Peña, 2002). The usual output from MCA includes the best two-dimensional representation of the data, along with the coordinates of the plotted points, and a measure (called the *inertia*) of the amount of information retained in each dimension (Johnson & Wichern, 2014).

To test for significance of association of the two categorical variables in a contingency table, we use a chi-squared test. The null hypothesis is that the variables (column classifications and quality) are independent of each other. Small p-values (less than 0,05 for a confidence level of 95%) indicate a significant dependence between quality and factors under study (monitoring stations, flow level, time of measurement and year). If the null hypothesis is accepted, Cramer's V statistic is used to measure the degree of association. This varies between 0 and 1, and is calculated from the chi-squared test. The strongest association between rows and columns will result in the statistic closest to 1.

According to Johnson, R. A.; Wichern, D. W. (2014) the MCA formulation is explained as follows. Let X with elements x_{ij}, be an $I \times J$ two-way table of unscaled frequencies or counts (I for the rows and J for the columns), we take $I > J$. The rows and columns of the contingency table X correspond to different categories of different characteristics. If n is the total of the frequencies in the data matrix X, then in the equation (1) P is called the correspondence matrix.

$$P = \{p_{ij}\} = \frac{x_{ij}}{n} \qquad i = 1,2,\ldots,I \qquad j = 1,2,\ldots,J \tag{1}$$

Then, the vectors of rows and columns in equations (2) and (3) are used to calculate the square root matrices in (4) and (5).

$$r_i = \sum_{j=1}^{J} p_{ij} = \sum_{j=1}^{J} \frac{x_{ij}}{n} \tag{2}$$

$$c_j = \sum_{i=1}^{I} p_{ij} = \sum_{i=1}^{I} \frac{x_{ij}}{n} \tag{3}$$

$$D_r^{1/2} = diag(\sqrt{r_1}, \sqrt{r_2}, \ldots, \sqrt{r_I}) \tag{4}$$

$$D_c^{1/2} = diag(\sqrt{c_1}, \sqrt{c_2}, \ldots, \sqrt{c_J}) \tag{5}$$

Correspondence analysis can be formulated as the weighted least squares problem to select $\hat{P} = \{\hat{p}_{ij}\}$, a matrix of specified reduced rank to minimize equation (6).

$$\sum_{i=1}^{I} \sum_{j=1}^{J} \frac{(p_{ij} - \hat{p}_{ij})^2}{r_i c_j} = tr[(D_r^{-\frac{1}{2}}(P - \hat{P})D_c^{-\frac{1}{2}})(D_r^{-\frac{1}{2}}(P - \hat{P})D_c^{-\frac{1}{2}})^T] \tag{6}$$

All the mathematical and statistical calculations were carried out using Microsoft Office Excel 2010, RStudio Desktop 1.4.1717 and Statgraphics XIX.

4. Results

4.1 Flow regime classification in the monitoring campaign

Based on Table 2, flow classification was carried out for each of the stations and, in turn, for each of the campaigns, taking into account the predominant categorisation. In order to obtain equal representation of all the campaigns based on the flow, it was decided to take 12 (12) campaigns of each classification, selecting the campaigns presented in Table 3.

Table 3. *Classification of campaigns*

Year	Date	Flow	Year	Date	Flow	Year	Date	Flow
2010	17/03/2010	1	2013	27/02/2013	2	2016	06/07/2016	2
2010	23/03/2010	1	2013	17/04/2013	1	2017	22/02/2017	1
2010	25/08/2010	3	2013	22/05/2013	3	2017	26/04/2017	3
2010	08/09/2010	3	2013	19/06/2013	2	2017	10/07/2017	2
2010	15/09/2010	3	2013	25/09/2013	1	2017	02/08/2017	1
2010	22/09/2010	3	2014	26/02/2014	2	2017	27/09/2017	2
2010	29/09/2010	3	2014	22/10/2014	2	2018	25/04/2018	2
2011	23/03/2011	3	2014	12/11/2014	3	2018	13/06/2018	2
2011	06/04/2011	3	2015	11/03/2015	1	2018	10/10/2018	3
2011	03/08/2011	2	2015	05/08/2015	1	2019	14/08/2019	1
2012	24/10/2012	2	2015	23/09/2015	1	2019	18/09/2019	3
2012	14/11/2012	2	2016	25/02/2016	1	2020	19/02/2020	1

4.2 Behaviour of electrical conductivity as a quality indicator

4.2.1 Descriptive Analysis

In Table 4 the p-values of the independence test and Cramer's V statistic for the quality-factors ratio are presented.

Table 4. *Descriptive analysis of test results*

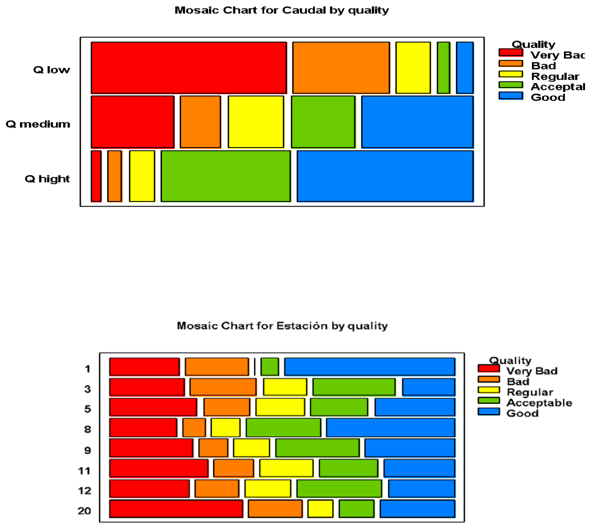
Factors	Chi-squared test p-value	Cramer's V statistic
Flows	<0.05	0.4825
Stations	<0.05	0.1766
The three flows at each station	Low <0.05 Medium <0.05 High <0.05	Low: 0.3430 Medium: 0.3688 High: 0.2617
Hours	<0.05	0.101
The three flows at each time of monitoring	Low <0.05 Medium > 0.05 High <0.05	Low: 0.1836 High: 0.1657
Year	<0,05	0,201

Cross-tabulation was carried out, establishing the colour-code shown in Table 3, which was applied to analyse the following:

- Variation of the quality indicator with respect to the flow
- Variation of the quality indicator with respect to the monitoring station
- Variation of the quality indicator with respect to the monitoring station for each flow level
- Time variation of the quality indicator

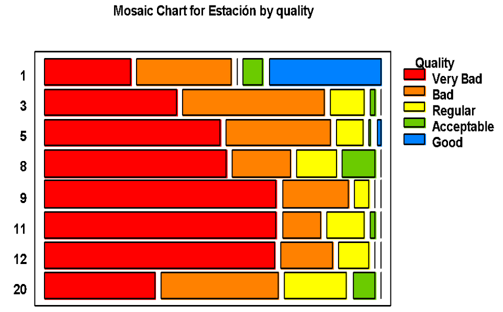
In Figure 2, the results obtained are presented. Here, it can be observed that, as the flow level rises, higher water quality is presented, while in low flows poor quality water according to the indicator predominates. On the other hand, when reviewing the quality indicator with respect to the spatial variation (station), the relationship is not so clear. This is supported by the values obtained with the Cramer’s V statistic, which show a greater association with flow.

Figure 2. *Mosaic chart for flow and station by quality*

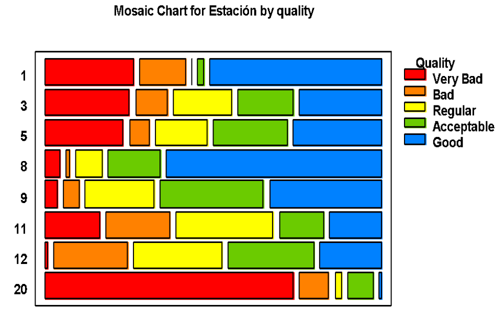


Despite the dependence shown by the Chi-squared test, the values obtained from the Cramer’s V statistic vary for each flow level (0,3430; 0,3688 and 0,2617, respectively), indicating a lower degree of association at high flows. In Figure 2, the charts are shown as a group to facilitate their interpretation.

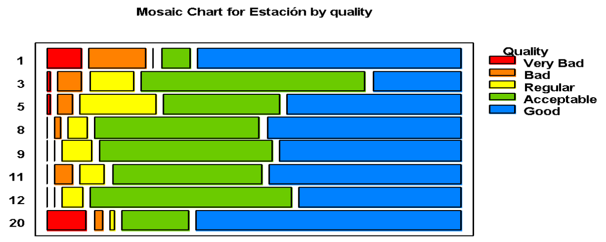
Figure 3. *Mosaic chart for station for each flow level*



Q low



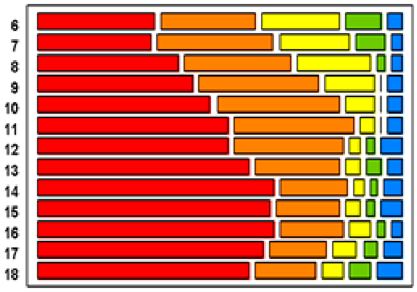
Q medium



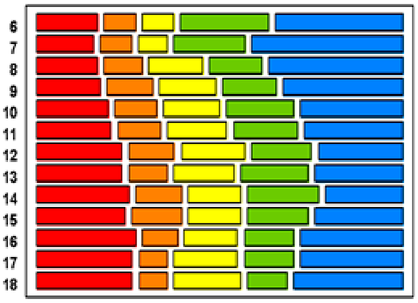
Q high

When analysing the temporal variation in hours for each of the flows (Figure 4), it was found with the chi-squared test that, at low flows, the most critical quality conditions were presented. Additionally, it was found that an association exists between the time of sampling and the quality according to the indicator. However, the Cramer's V statistic is low for this relationship compared with the flow classification. Meanwhile, in medium flows no relationship was observed between time and quality (p-value superior to 0,05), while in high flows the test shows a relationship between these variables, although the Cramer’s V statistic is slightly lower (0,1657).

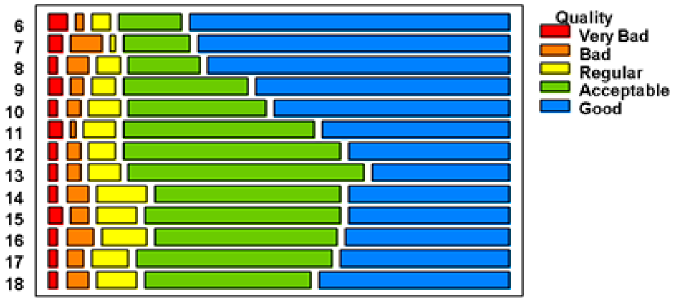
Figure 4. *Mosaic chart for hours for each flow level*



Q low



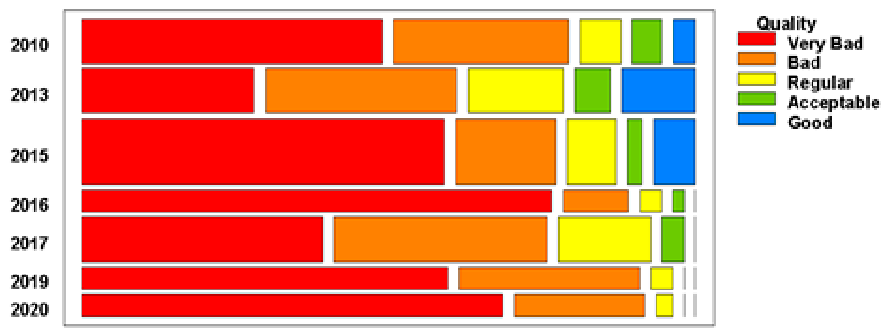
Q medium



Q high

The temporal variation (years) of the water quality was analysed for low flows, given that these have greater representativity in the study period. According to the results obtained (p-value<0,05), the hypothesis that quality and annual variation are independent can be rejected. Moreover, the value obtained from the Cramer's V statistic shows a degree of association that, although lower than that found for flow, is greater than that found for spatial variation. In Figure 5, the changes in the quality indicator in time are shown.

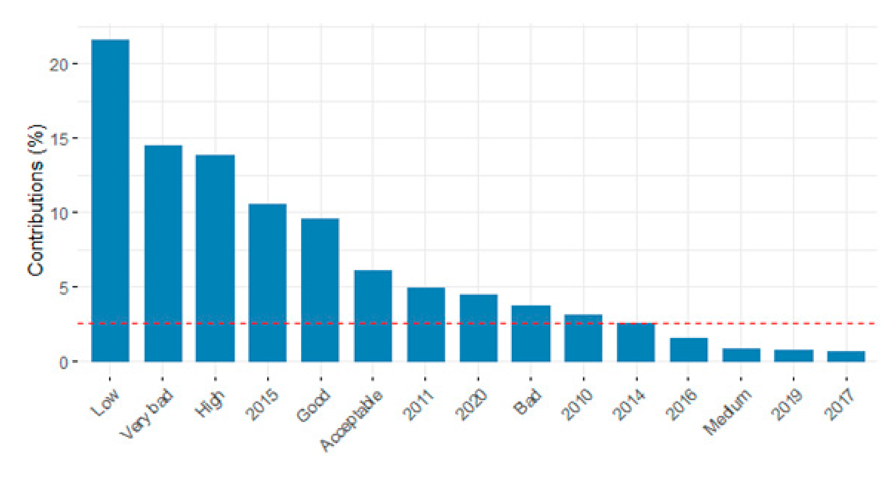
Figure 5. *Temporal variation of the water quality indicator in the river*



4.2.2 Multiple correspondence analysis (MCA)

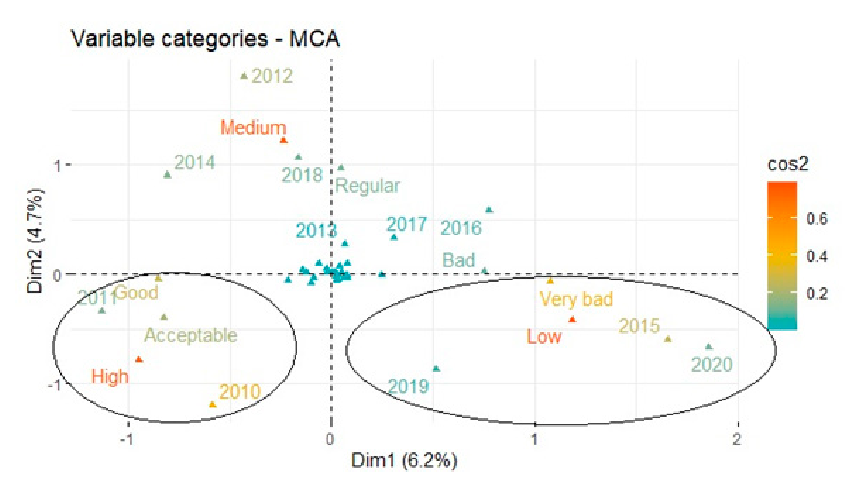
MCA was carried out to identify the data category with the greatest influence on variability of the data matrix. The results of this are shown in Figure 6, where it can be seen that the flows make the largest contributions, with the largest of these being made by the lowest flow, followed by the data obtained in the year 2015, and the qualities obtained with the indicator. It should be noted that the years with representative contributions were 2015, 2011, 2020 and 2010, and that the average quality and the other years do not contribute significantly to the variability of the data matrix.

Figure 6. *Contribution of data categories in the variability of the data group*



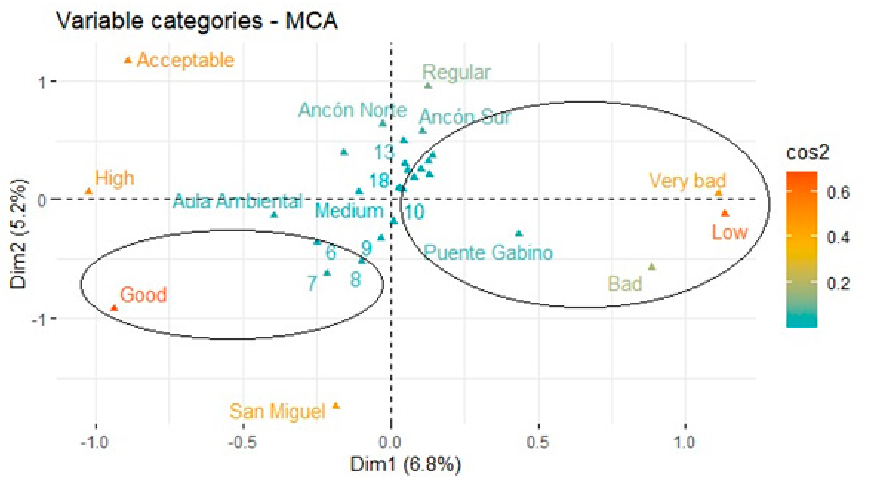
Below, the results obtained in the biplot are shown, considering quality, flow and temporal variation (years). It should be noted that the lowest quality is associated with low flows, and with the years 2015, 2019 and 2022 (lower right quadrant), while high flows are associated with good and acceptable quality, as are the years 2010 and 2011 (lower left quadrant).

Figure 7. *Correspondence map considering temporal variation (years)*



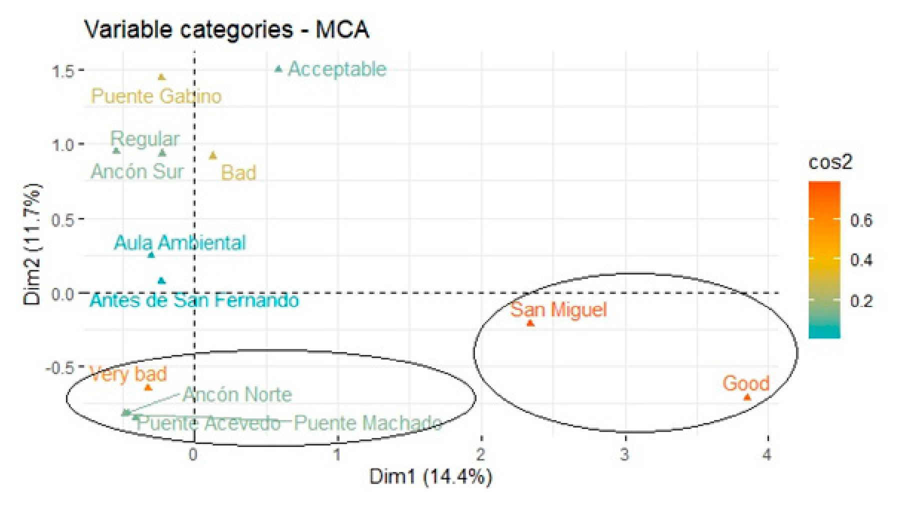
On the other hand, when considering quality, stations, and sampling time, the results once again show an association between good and acceptable quality and medium and high flow, with the San Miguel and Aula Ambiental stations located in the quadrant of good quality and early hours of the morning. Meanwhile, in the Puente Gabino and Ancón Sur quadrant, which is associated with the measurements where low and regular qualities were found, respectively, it should be noted that the quality ranges are different in each station (Figure 8).

Figure 8. *Correspondence map considering spatial variation (stations)*



To better understand the associations between space and time variation in low flows, which correspond to the most critical water quality conditions in the river, another biplot graph was made (Figure 9). This shows that the San Miguel station is associated with good quality, while the Ancón Norte, Puente Acevedo and Puente Machado stations are associated with very bad quality.

Figure 9. *Correspondence map considering time and space variation at low flows*



5. Discussion

According to the results obtained from the matrix of data measured in the period 2010-2020, the quality indicator is influenced by the flow (the chi-squared test shows dependency) (Carrera et al., 2016). This provides evidence that the improvement in the river water quality in high flows is due to dilution of the pollutants when higher-quality rainwater and runoff enters. For this reason, in Figure 2, the most critical conditions are observed at low flows, i.e., when the river has a very low base flow, and so a large percentage of the water in the river is composed of raw and treated wastewater generated by the population of the basin. It is noteworthy that much of these wastewaters, although they enter the river from the basin, originated from other areas and were brought in to provide for the needs of the local population (Giraldo *et al*., 2019).

On another note, when evaluating the variation in the quality indicator between stations, although each station has different ranges to describe the state, it was found that there was a dependency, although the Cramer's V statistic (0,1766) indicates a degree of association lower than that of the flow. However, Figure 2 shows a deterioration in the water quality as the river makes its way downstream, although there is a notable inconsistency at the Aula

Ambiental station (E8), where there are some measurements with good quality and others with very bad quality. This could be because the Horacio Toro bridge acts as an energy dissipator in the water above the station. This promotes the mixing of substances and increases oxygen levels, thereby facilitating oxidation reactions and reducing the quantity of ions, whose presence in the water was increased by the effluent of the San Fernando treatment plant.

Additionally, it is important to clarify that the indicator has different classification ranges in each station. This means that the classification is specific to each station; however, when evaluating the space variation, a deterioration in the water quality as the river progresses can be noted. When analysing the variation of the quality indicator between the different stations for each flow level, the chi-squared test shows dependency. Also, this illustrates graphically how the water quality at each station varies as the flow increases, reinforcing what is proposed in the paragraph above.

The above reaffirms the relationship between the flow and the water quality, i.e. the dilution effect of the pollutants caused by rainwater in the Aburrá-Medellín river. Particularly noteworthy is the water quality found in the Puente Gabino station (E20) in medium flows, where although a few measurements show good quality, the number of measurements resulting in bad quality increase. This is linked to many factors, including the agricultural and livestock uses of land in this area of the basin, which results in a large number of ions entering the river, thereby increasing its electrical conductivity.

When reviewing the variation of the quality indicator with respect to the time that the measurement is taken for each flow level, a deterioration is observed at low flows and later times of day. The evening is the most critical period (red) at low and medium flows, while measurements showing good quality predominate in the early hours of the morning. This behaviour is expected in an urban basin where the river, as a recipient of raw and treated wastewater, reflects the rhythm of a working day (the monitoring days included in this study are all working days, where there is a greater demand for water by certain sectors of industry).

It was also found that the Puente Acevedo(E9), Puente Machado(E11) and Ancón Norte (E12) stations present a greater number of measurements showing bad quality (red) at low flows. This is associated with the continuous discharge of raw wastewater from the eastern and western interceptor systems that transport raw wastewater from the south and central areas of the region and that, for many years, were discharging into the river near the Puente Acevedo station (E9). In 2019 the interceptors were connected to the Aguas Claras treatment plant in the municipality of Bello, which reduced the impact of raw wastewaters in the river at the river next to the Moravia neighbourhood (Área Metropolitana del Valle de Aburrá y Universidad de Antioquia, 2020).

On another note, attempts were made to analyse the variation in time of the quality indicator. However, this was only possible for low flow periods, which had better representation of information in time. In Figure 5, a reduction can be observed in measurements showing good quality, which predominate until 2015, after which most measurements show bad or very bad quality. This shows that the river conditions, as well as being critical at low flows, have deteriorated over time, which is associated with population growth and wastewater collection coverage and treatment.

It is notable that that population growth in the region has been affected by forced migration, which has caused a constant flow of migrants towards the big cities, as stated in Claghorn et al. (2015). These new arrivals normally settle in the hills at the urban periphery, where there is little collection or treatment of wastewater, which therefore tends to be discharged into nearby water bodies, causing a deterioration in water quality that subsequently affects the river.

With MCA, considering the quality indicator, flow and year, a relatively high association was found of measurements showing low quality with the years 2015, 2019 and 2020, and with low flows. In 2015, the El Niño phenomenon was particularly intense, while it was weak in 2019 and moderate in 2020, according to the ENSO (El Niño and La Niña Years and Intensities) (Golden Gate Weather Services, 2021), which demonstrates that water quality decreased despite the entry of rainwater, which favours dilution of the pollutants.

Meanwhile, good and acceptable classifications were found in the years 2010 and 2011 and at high flows. In these two years, the El Niño phenomenon was of strong intensity, which favours dilution. This analysis allows a relationship to be elucidated between the water quality and the different climatic phenomena of the region, showing that although there was a slight recovery in the water quality of the river, dilution or concentration of pollutants has occured, and the quality has not improved in recent years.

The correspondence maps results confirm what was found with the chi-squared test and the results of the Cramer's V statistic. These show a relatively high association of the quality indicator and the flows, as does the cross-tabulation chart, which shows that the water quality deteriorates in the afternoon and in the final years of monitoring in low flows.

6. Conclusions

Using electrical conductivity as a quality indicator in the water of the Aburrá-Medellín river, it was found that low flows correspond to the most critical quality conditions, and although a deterioration is observed as the river flows downstream (between the monitoring stations) the influence of the water levels is greater. This is because, in these conditions, there is a greater proportion of raw and treated wastewater compared to the base flow.

Meanwhile, when evaluating the variation in time, deterioration in quality was found over the passage of time (year), which is a result of population growth and hence an increase in the quantity of wastewater that enters the river. This is a sign that public service companies must increase wastewater treatment coverage, especially in the periphery of the city.

Finally, although there was not a significant relationship between the quality indicator and the sampling time, a deterioration can be observed graphically over the course of the day, with the most critical conditions presented in the evening.

As a complement to water treatment, it is clear that greater commitment is required by the population to reduce their generation of wastewater, which means that more efficient use of this resource is needed.

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