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Aburrá- Medellín River Water Quality Space-Time Variation from the Electrical Conductivity and Its Use as an Indicator of Quality

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Abstract

This article aims to perform a space-time analysis of the electrical conductivity readings measured in the Aburrá - Medellín river, in the period 2006-2020, through the monitoring network of water resources in the region - RedRío, to evaluate the feasibility of using it as an indicator of water quality in the three automatic monitoring stations that are part of this network.

The classification of the flow regime was carried out considering the historical record of flows measured between 2004 and 2020 in the region's water resources monitoring network - RedRío. Then, to evaluate if there were statistically significant differences between the electrical conductivity measured in the stations and for the measurements in the three flow ranges, the non-parametric Kruskal Wallis test was performed, since the assumptions required for an analysis of variance were not met. Finally, to make the state of the river more visible from the electrical conductivity measurements, a categorization by ranges (quartiles) and color assignment is proposed, as established in the ICA water quality indices.

As a result of this study, two classifications of electrical conductivity expressed in five color ranges are proposed, as well as the quality index for surface water – ICA-. Finally, the readings obtained in the automatic stations from August 2019 to March 2020 are reviewed and classification ranges for these stations are adjusted.

This research highlights the proposal to introduce the use of this variable as an indicator of water quality, to illustrate and continuously inform the community about the state of the Aburrá- Medellín river through a color code, to sensitize the inhabitants of the basin on its protection, care, and the importance of efficiently use and save water.

Key Words: electric conductivity, water quality, urban river, quality indicator, Aburrá-Medellín river, lotico system, monitoring network, pollution, water resources, spatio-temporal analysis.

Variación espacio-temporal de la calidad del agua del río Aburrá-Medellín a partir de la conductividad eléctrica y su uso como indicador de calidad

Resumen

Este artículo tiene como objetivo realizar un análisis espacio-temporal de las lecturas de conductividad eléctrica medidas en el río Aburrá - Medellín, en el período 2006-2020, a través de la red de monitoreo de los recursos hídricos de la región - RedRío, para evaluar la factibilidad de su uso como indicador de la calidad del agua en las tres estaciones de monitoreo automático que forman parte de esta red.

La clasificación del régimen de caudales se realizó considerando el registro histórico de caudales medidos entre 2004 y 2020 en la red de monitoreo de recursos hídricos de la región - RedRío. Luego, para evaluar si existían diferencias estadísticamente significativas entre la conductividad eléctrica medida en las estaciones y para las medidas en los tres rangos de flujo, se realizó la prueba no paramétrica de Kruskal Wallis, ya que no se cumplieron los supuestos requeridos para un análisis de varianza. Finalmente, para hacer más visible el estado del río a partir de las medidas de conductividad eléctrica, se propone una categorización por rangos (cuartiles) y asignación de colores, según lo establecido en los índices de calidad del agua – ICA.

Como resultado de este estudio, se proponen dos clasificaciones de conductividad eléctrica expresadas en cinco gamas de colores, así como el índice de calidad del agua superficial – ICA-. Finalmente, se revisan las lecturas obtenidas en las estaciones automáticas de agosto de 2019 a marzo de 2020 y se ajustan los rangos de clasificación de estas estaciones.

Esta investigación destaca la propuesta de introducir el uso de esta variable como indicador de la calidad del agua, para ilustrar e informar continuamente a la comunidad sobre el estado del río Aburrá-Medellín a través de un código de colores, para sensibilizar a los habitantes de la cuenca sobre su protección, cuidado y la importancia de usar y ahorrar agua de manera eficiente.

Palabras clave: conductividad eléctrica, calidad del agua, río urbano, indicador de calidad, río Aburrá-Medellín, sistema lotico, red de monitoreo, contaminación, recurso hídrico, análisis espacio-temporal.

1. Introduction

Rivers have been a fundamental axis in the construction of cities; however, they have been exposed to different types of discharges that alter the balance of the system, which generates a loss of physicochemical and biological quality, which finally results in the limitation of water uses and its wastefulness, affectation to public health and obviously to life quality of population settled surrounding the basin, a context which becomes more noticeable with the growth of the population in urban areas, since, when there is no complete sanitation structure, negative effects are generated on the water resource and its infrastructure. This situation generates the need for a change of approach to the image of the "river" to integrate it as an element of life within a society [Dourojeanni and Jouravlev (1999); Rodríguez (2016)], which requires actions of monitoring, control, education, landscaping, and engineering, among others, to achieve this integration. Within the monitoring actions, it is important to make a periodic evaluation of water quality, as a tool to control the state of the water body and take the necessary actions to improve its quality [AMVA et al. (2018)].

In the Aburrá-Medellín river basin, with the support of the municipalities and environmental authorities, a series of actions have been undertaken to change the image of the river and improve the quality of surface waters, including increasing the coverage of wastewater collection, commissioning, and optimization of treatment plants, educational campaigns, and construction of “Parques del Río,” water resource management plan, following-up to sanitation plans and management of discharges and monitoring networks, among others. In the specific case of the urban zone, the Aburrá Valley Metropolitan Area, as an environmental authority, has a water resource monitoring network for the RedRío region, whose design began in 2004 and has been implemented since 2006 [AMVA and UdeA (2020); AMVA et al. (2018)].

This network has evolved according to the needs of the Metropolitan Area, the findings found in the river and its tributary streams, technological advances, and the availability of resources for its financing. Its design and operation have also undergone changes, initially with the participation of four well- known universities in the region, Universidad de Antioquia, Universidad Nacional, Universidad Pontificia Bolivariana, and Universidad de Medellín, then Universidad de Antioquia and the Early Warning System SIATA were in charge of the operation and improvement of its structuring and operation, the latter in terms of water measurement and gauging in the last two agreements. Once the Network was implemented, there have been three important moments that have generated adjustments in the operation, one of them was the incorporation of the communicational component to make the Network known to society and generate awareness of river care, another that took place this same year was the incorporation of the groundwater component in the network, and finally the construction and implementation of automatic monitoring stations, with which it can be said that RedRío has been a dynamic network that has been consolidating and adjusting to the conditions and needs [AMVA et al. (2014); AMVA and UdeA (2016); AMVA and UdeA (2019); AMVA and UdeA (2020)].

The monitoring network carries out periodic campaigns on the Aburrá - Medellín river and its streams and significant discharges, measuring more than 20 variables, which have allowed the evaluation of the quality with indexes recognized in Colombia and the structuring of an index for the river and another for the streams. The network also has three automatic stations, San Miguel, Ancón Sur, and Aula Ambiental, located in the first 37 kilometers of the river, and they are currently continuously monitoring electrical conductivity, pH, dissolved oxygen, turbidity, redox potential, and temperature. The review of the dynamics of the network, its experience, historical information and its analysis, makes it possible to propose a water quality indicator for the river that is quick and easy to determine and that allows describing the state of the resource, and at the same time can be used to present the state of the river to the community on a permanent basis and to continue raising awareness of the importance of efficiently caring, savings, and using water [AMVA and UdeA (2020); Giraldo (2013)].

Initially, the dissolved oxygen variable was considered, which, although it is very important, it does not adjust to an ideal response variable in the Aburrá - Medellín river, given that its interpretation in this body of water requires greater care, due to the amount of interventions in the river and its mountainous conditions, which cause average levels in places where the quality measured in terms of Chemical Oxygen Demand – COD, Biochemical oxygen demand – BOD, nutrients, and electrical conductivity show not so favorable quality conditions, i.e., these levels of oxygen gained by the physical conditions are quickly lost [AMVA et al. (2007); AMVA et al. (2011); AMVA et al. (2014); AMVA and UdeA (2016); AMVA and UdeA (2019); AMVA and UdeA (2020); Giraldo, Agudelo and Palacio (2010)].

Now we consider the electrical conductivity, which, although expresses the ability to conduct current and depends on the content of dissolved elements in the water [CENMA (2015)], it has been found relationship with primary production, degree of decomposition of organic matter, and geochemistry of the surrounding basin [CAR (2012); Ramírez and Viña (1998); Montoya and Aguirre (2009)]. Its variation can contribute to contamination sources detection and to the evaluation of water attitude for irrigation [Cortolima (2020)]. In addition, some studies have shown that electrical conductivity has eco-physiological effects on osmoregulation, survival, abundance, and presence of families of organisms such as macroinvertebrates in water bodies [Camacho and Camacho (2010); Mosquera, Bejarano and Asprilla (2006); Hahn-vonHessberg et al. (2009); Meneses, Castro and Jaramillo (2019)]. Therefore, it is considered as a determining physicochemical factor in the distribution of aquatic macroinvertebrates, in which organisms are more sensitive [Morelli and Verdi (2014)] cited by [Olarte and González (2018); Giraldo et al. (2015)].

In this sense, the objective of this article is to perform a space-temporal analysis of electrical conductivity, from 48 manual monitoring campaigns carried out in the Aburrá - Medellín river, in the period 2006-2020, through - RedRío - the water resource monitoring network in the region to evaluate the feasibility of using it as an indicator of water quality in the three automatic monitoring stations that are part of this network. Two classifications of electrical conductivity expressed in five color ranges are proposed, as well as the quality index for surface water – ICA-; finally, the readings obtained in the automatic stations between August 2019 and March 2020 are reviewed and the classification ranges are adjusted.

2. Study area

Aburrá Valley is in the south-central state of Antioquia-Colombia, through the middle of The Central Range of Los Andes. It is important because over it, Medellin, the third city in population and second largest in the country is located as well as nine other municipalities, which together have about three million seven hundred twenty-seven thousand inhabitants. This valley is crossed by a river that runs through its ten municipalities and has become a hub for the development of the region [AMVA et al. (2011); DANE (2019)].

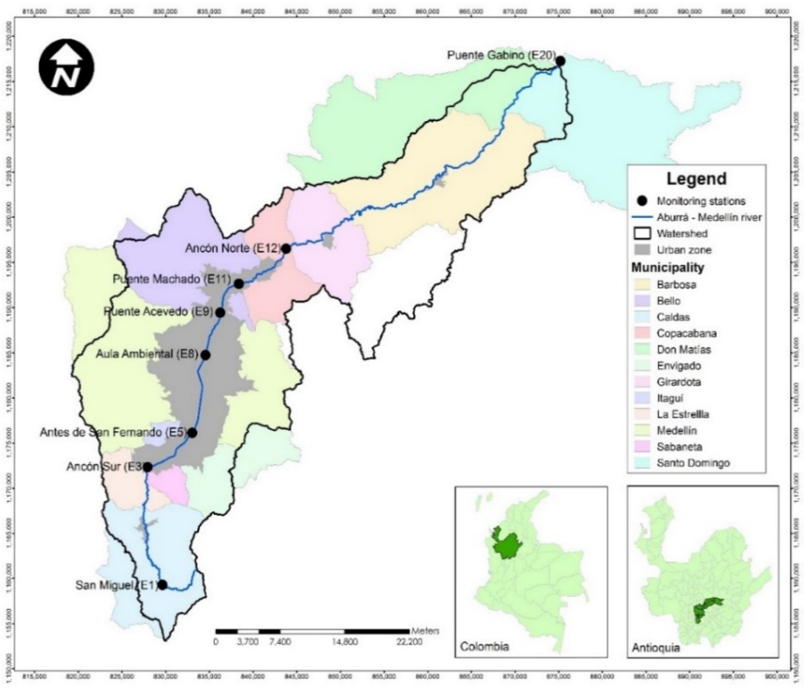
The hydrographic basin of Aburrá-Medellin river consists of the Central and Eastern branch that belong to the Central Range of Los Andes [EPM (1981)]. The altitude of the mountains around the valley can reach up from 2,500 to 3,000 meters above sea level and are divided by the river that runs in south-north direction. This valley extends from 1,795 m of elevation (Caldas) to 1,048 m (to the mouth of Rio Grande) [AMVA al. (2011)].

The Aburrá-Medellín river, recognized as the articulating axis of different municipalities that make up this valley (Caldas, La Estrella, Sabaneta, Envigado, Itagüí, Medellín, Bello, Copacabana, Girardota, and Barbosa), receives approximately 254 tributaries of different magnitude, in approximately 100 km of course (study section), from its source in the Alto de San Miguel (Caldas) to its confluence with Río Grande [AMVA et al. (2007)].

The river is characterized by being continuously exposed to contamination due to the pressure of anthropic activity. The following were identified as surface resource problems in the basin: poor land use, exploitation of materials in the riverbeds and slopes of the river and streams, soil degradation due to erosive processes, sedimentation processes, disposal of solid waste in the beds of the streams and the river, human settlements in high-risk areas, deforestation of stream sources, and discharges of domestic and industrial wastewater without prior treatment [AMVA and UdeA (2018)].

For the development of this research, eight of the fourteen monitoring stations that are part of the "Red se Monitoring-RedRío" were considered to ensure a general view of the river during the study period (2006-2020). Figure 1 shows a map with the location of the study site, made from drawings provided in Management and Development Plan of the Aburrá river basin – POMCA [AMVA et al. (2018)].

Figure 1. Geographical location of the study site (Modified AMVA et al. (2018)).



3. Materials and methods

3.1. Flow regime classification

The classification was carried out considering the historical record of flows measured between 2004 and 2020 in the water resource monitoring network of the region – RedRío, where the quartiles Q1 and Q3 allowed defining the limits for low (Q<Q1), medium (Q1<Q<Q3) and high (Q>Q3) flows at each monitoring station.

3.2. Recycled aggregate

Since the assumptions required for an analysis of variance were not met, the non-parametric Kruskal Wallis test, which is a homogeneity test for quantitative variables without normal distribution [Guisande et al. (2006)] was performed; however, to apply it, it was necessary to transform the data with power -0.2 for electrical conductivity and squared for ICA, all in the statistical package Statgraphics Centurion XVI.

3.3. Time variation of electrical conductivity and ICA

An analysis was made by station and in the river profile, of the variation of the electrical conductivity and the ICA in the three flow levels from graphs elaborated in Excel, additionally and seeking to evaluate the variation in time, the campaigns classified in low levels were selected for having greater representativeness of years during the study period and graphs were elaborated to evaluate the temporal changes that have occurred in each station and in turn in the river profile, considering low flows.

3.4. Calculation of the surface water quality index ICA (IDEAM)

The surface water quality index “ICA” is widely used in Colombia and seeks to make a general evaluation of the state of surface waters in the country. This index uses the variables: water pH, dissolved oxygen, electrical conductivity, total suspended solids, chemical oxygen demand, total nitrogen, and total phosphorus. The methodology established by the IDEAM [IDEAM (2015)] was followed for its calculation.

3.5. Electrical conductivity in automatic monitoring

The three automatic stations collect data constantly; however, to facilitate their interpretation without losing information, their analysis was done by taking the averages of 15-minute intervals, that is, the average of the readings taken in this time interval, to capture an image that is closer to the readings of that period; this also reduces the complexity of the preparation of files for analysis. It should be noted that a day has 1440 minutes and, therefore, 96 groupings of 15 minutes.

The measurements of the electrical conductivity of water in the stations between the months of August 2019 and March 2020 were reviewed; although the range of the study period depends on the start-up and operation of each station, in the case of San Miguel station, the period was the widest from August 1, 2019 to March 31, 2020, to compare results of manual monitoring classification ranges.

Additionally, to use electrical conductivity as an easily interpreted indicator of water quality in the automatic stations, a classification of water resource quality is proposed for each station based on electrical conductivity, according to the numerical value obtained and a color code, consistent with indexes used in the river is assigned, for this the percentiles 20%, 40% 60% and 80% were estimated.

4. Results

4.1. Classification of flow regime in monitoring campaigns

Based on quartiles, the classification was defined as follows: low flow (1) values below Q25, medium flow (2) values between Q25 and Q75 and high flow (3) values above Q75. Once the characteristic flow of the stations was defined and considering the predominant categorization, the classification of each campaign was made. To obtain equal representativeness of all the campaigns to perform an analysis of variance based on the flow rate, it was decided to take fourteen (14) campaigns from each classification, and the campaigns presented in Table 1 were selected.

Table 1. Classification of campaigns

Year	Date	Flow	Year	Date	Flow	Year	Date	Flow
2006	08/05/2006	3	2011	31/08/2011	2	2015	23/09/2015	1
2006	30/05/2006	3	2012	24/10/2012	2	2016	25/02/2016	1
2006	28/08/2006	2	2012	14/11/2012	2	2016	06/07/2016	2
2010	17/03/2010	1	2013	27/02/2013	2	2017	22/02/2017	1
2010	23/03/2010	1	2013	17/04/2013	1	2017	26/04/2017	3
2010	21/04/2010	1	2013	22/05/2013	3	2017	10/07/2017	2
2010	25/08/2010	3	2013	19/06/2013	2	2017	02/08/2017	1
2010	08/09/2010	3	2013	25/09/2013	1	2017	27/09/2017	2
2010	15/09/2010	3	2014	26/02/2014	2	2018	25/04/2018	2
2010	22/09/2010	3	2014	22/10/2014	2	2018	13/06/2018	2
2010	29/09/2010	3	2014	12/11/2014	3	2018	10/10/2018	3
2011	23/03/2011	3	2015	11/03/2015	1	2019	14/08/2019	1
2011	06/04/2011	3	2015	06/05/2015	1	2019	18/09/2019	3
2011	10/08/2011	2	2015	05/08/2015	1	2020	19/02/2020	1

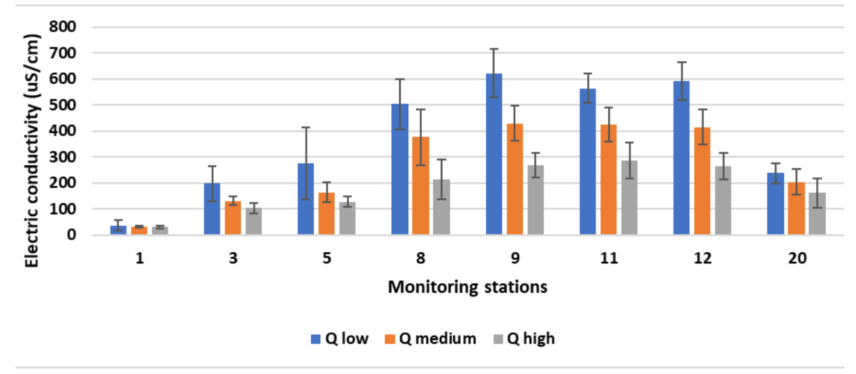
4.2. Behavior of electrical conductivity

According to the Kruskal Wallis test, there is a statistically significant difference between the electrical conductivity measured at the stations and for the measurements in the three flow ranges, with a 95.0% confidence level.

Based on this result, the evaluation of the electrical conductivity for different flow scenarios was carried out, from the matrix obtained with the data from the campaigns selected in Table 1. Figure 2 shows the variation of the electrical conductivity for the three flow scenarios in the river profile, showing that the most critical conditions of the river, i.e. high electrical conductivities, correspond to low levels, and that as water enters as a result of rainfall, a dilution of the pollutants is generated and, therefore, the river conditions improve.

It is also observed that, for all flows, the most critical conditions spatially occur between stations Aula Ambiental (E8) and Ancón Norte (E12).

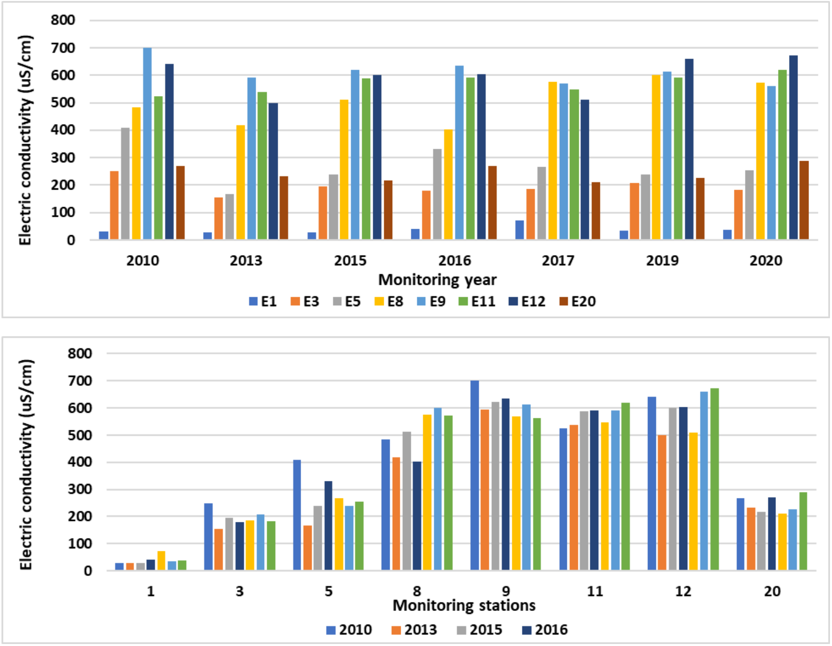
Figure 2. Variation of electrical conductivity in the river profile with respect to flow levels.



4.3. Behavior of the electrical conductivity during the study period.

Figure 3 presents the time variation of the electrical conductivity for the low flow scenario in the river profile, since this scenario has the largest amount of annual data. It shows that San Miguel station (E1) has the lowest and little variable values over time (29,1 uS/cm in 2015 - 71, 3 uS/cm in 2017), compared to the other monitoring stations, from this site, in general, the temporal variation of electrical conductivity changes depending on the station.

Figure 3. Temporal variation of electrical conductivity in the river profile at low flows.



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4.4. Electrical conductivity as an indicator by classification ranges.

To make the state of the river more visible from the electrical conductivity measurements, a categorization by ranges (quartiles) and assignment of colors, like that established in the ICA water quality indexes is proposed. Table 3 presents a classification by global ranges for the entire river and Table 4 considers the variation of each station, which makes this qualification a little stricter.

Table 3. Global ranking of the entire river

Classification of quality with respect to electrical conductivity	Numerical range of values	Color
Good	<121,6	Blue
Acceptable	121,7 – 198,4	Green
Regular	198,5 – 288,7	Yellow
Bad	288,8 – 449,0	Orange
Very bad	>449,0	Red

Table 4. Station-specific rankings for each station

Station	Good	Acceptable	Regular	Bad	Very bad
Percentil	<20	20-40	40-60	60-80	>80
1	27,0	27,1 - 28,9	29,0 - 33,6	33,7 - 36,8	>36,8
3	101,4	101,5 - 122,1	122,2 - 142,2	142,3 - 182,0	>182,'
5	121,8	121,9-146,9	145,0 - 181,0	181,2 - 238,3	>238,3
8	206,4	206,5 - 301, 0	301,1 - 409,0	409,1 - 500,4	>500,4
9	274,0	274,1 - 358,0	358,0 - 503,8	503,9 - 586,2	>586,2
11	288,0	288,1 - 393,31	393,4 - 480,0	480,1 - 551,2	>551,2
12	255,0	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

Figure 4 and Figure 5 show the results obtained with the color classification by station and global, respectively, for the flow scenarios, showing differences between flow levels, although "very bad" quality prevails in both classifications in the Aula Ambiental (E8} - Ancón Norte (E12) section for low flows. It should be noted that when the global ranges of the entire river are used, i.e., considering the historical measurements taken at all stations, the result is less strict in the initial part of the river and somewhat like the ICA.

Figure 4. Results of the state of the Aburrá Medellín river with respect to flow scenarios, considering the classification made at each station (Modified Giraldo (2013)).

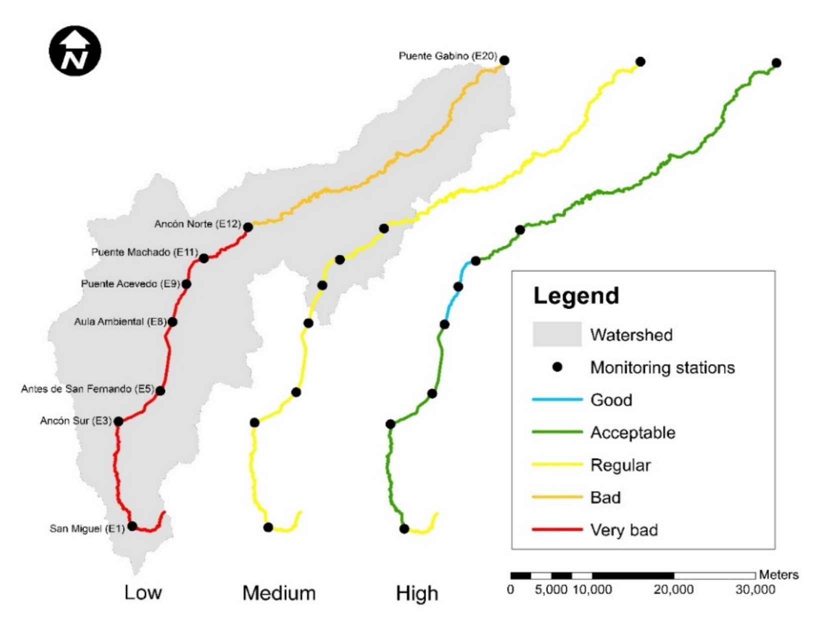
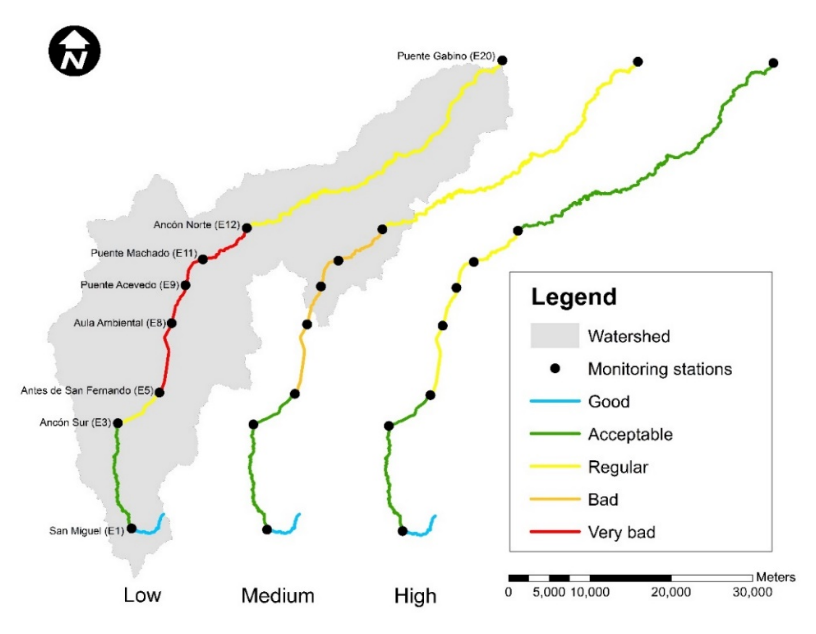


Figure 5. Results of the state of the Aburrá Medellín river with respect to flow scenarios, considering the global classification of the river (Modified Giraldo (2013)).



It is striking that the quality at the San Miguel station (E1) during the study period at low flows and considering the classification by station, which is why we zoomed in on what was obtained in each low flow campaign (Table 6), in which we can see a trend towards deterioration of water quality over time, a situation that is not perceived with the overall rating of electrical conductivity.

Table 5. Classification of each low flow campaign assigned to the San Miguel station (E1) considering the global range.

Date	Classification Electrical conductivity (uS/cm)	Date	Classification Electrical conductivity (uS/cm)
17/03/2010	Good	05/08/2015	Regular
23/03/2010	Bad	23/09/2015	Bad
21/04/2010	Regular	25/02/2016	Very bad
17/04/2013	Acceptable	22/02/2017	Very bad
25/09/2013	Acceptable	02/08/2017	Very bad
11/03/2015	Regular	14/08/2019	Bad
06/05/2015	Good	19/02/2020	Bad

4.5. Behavior of the ICA

Since the ICA is a guide indicator at the national level, as it is the one suggested by the National Water Resource Policy in Colombia, its behavior in the river was analyzed. According to the Kruskal Wallis non-parametric test, there is a statistically significant difference in the ICA estimated at the stations, but not for the three flow ranges, with a confidence level of 95.0%.

Nevertheless, the results of the campaigns for the different flow scenarios were evaluated to compare their difference with the electrical conductivity, obtaining the results presented in Table 5.

Table 6. ICA averages for different flow scenarios

Stations	Average ICA in low Q	Average ICA in medium Q	Average ICA in high Q
San Miguel (E1)	0,81	0,82	0,81
Ancón Sur (E3)	0,58	0,65	0,60
Antes de San Fernando (E5)	0,52	0,60	0,54
Aula Ambiental (E8)	0,38	0,42	0,47
Puente Acevedo (E9)	0,34	0,38	0,39
Puente Machado (E11)	0,29	0,31	0,36
Ancón Norte (E12)	0,27	0,32	0,36
Puente Gabino (E20)	0,52	0,52	0,49

The ICA presented a decreasing behavior in the stretch between E0 and E12, indicating a deterioration of water quality, subsequently, at station E20 an increase in the index was observed with respect to E12.

Figure 5 shows the space variation of the ICA indicator for the flow scenarios. Unlike the electrical conductivity, similarities were found between flow scenarios; however, the low flow prevails as the most critical in the river (low values of ICA), although this difference is not so marked. When observing the river profile for the three flow scenarios, the same behavior is found, i.e., deterioration up to Ancon Norte (E12) and recovery from Ancon Norte to Puente Gabino (E20).

Figure 6. Variation of the ICA in the river profile with respect to flow levels.

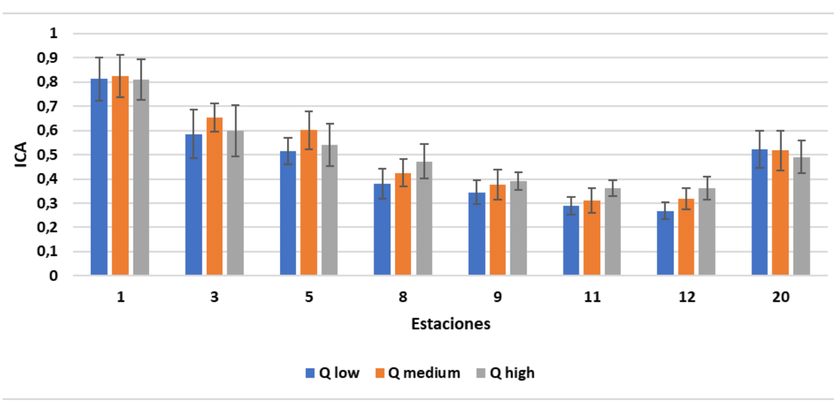
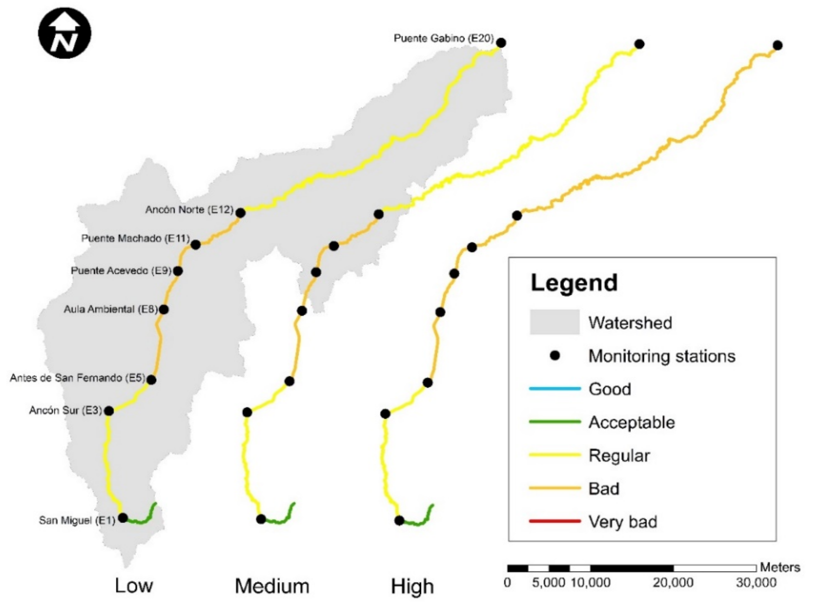


Figure 7 shows the results of the evaluation of the ICA indicator for the flow scenarios, through the color classification ranges. There are no sections of very poor quality in the river. However, the most unfavorable quality conditions for the three flow levels are between the stations Antes de San Fernando (E5) and Ancon Norte (E12), for the three flow scenarios.

Figure 7. Results of the water quality indicator ICA for the Aburrá Medellín river with respect to flow scenarios. (Modified Giraldo (2013)).



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4.6. Electrical conductivity in automatic monitoring

The classification ranges were obtained according to the 20%, 40%, 60% and 80% percentiles of the electrical conductivity readings, during the period of operation of each station August 2019 - March 2020, the classification is presented below.

4.7. San Miguel E1

San Miguel station has the lowest levels of electrical conductivity, given that, at the height of this station, anthropic intervention is low, these ranges of variation are similar to those obtained with manual monitoring (Table 7).

Table 7. Classification to the San Miguel station (E1)

Classification of water resource quality	Numerical range of values	Color
Good	<=30	Blue
Acceptable	30.1 – 31.7	Green
Regular	31.8– 33.7	Yellow
Bad	33.8– 36.7	Orange
Very bad	>36.7	Red

4.8. Ancón Sur E3.

For Ancon Sur, the classification of water quality based on electrical conductivity varies in its numerical range, given that the values obtained are higher than those of San Miguel station. In the following table the classification is shown. When comparing this classification with the one obtained in manual monitoring, a small difference can be seen since, with the automatic monitoring, a greater variation in water quality was observed, so the range of this parameter was greater (Table 8).

Table 8. Classification to the Ancón Sur station (E3)

Classification of water resource quality	Numerical range of values	Color
Good	<=79.6	Blue
Acceptable	79.7– 119.1	Green
Regular	119.2– 154.4	Yellow
Bad	154.5– 194.2	Orange
Very bad	>194.2	Red

4.9. Aula Ambiental E8.

In Aula Ambiental station, the classification of water quality based on this indicator varies again in its numerical range, given that the values obtained for electrical conductivity are the highest of the three automatic stations; the following table shows the classification. As in Ancon Sur, there was a greater variation of the electrical conductivity and, therefore, the numerical range of the classification changes when compared to manual monitoring (Table 9).

Table 9. Classification to the Aula Ambiental station (E8)

Classification of water resource quality	Numerical range of values	Color
Good	<=204.5	Blue
Acceptable	204.6– 383.4	Green
Regular	383.5– 470,2	Yellow
Bad	470,3– 531.0	Orange
Very bad	>531.0	Red

For obtaining a quick and economical estimate of the river's water quality, the measurement of this variable is proposed, given that by itself, it generates a good approximation to reflect the state of the current, and also use the classification by station, adjusted with what was obtained in the automatic stations. In this way, this classification can be used for both automatic and manual monitoring stations.

Table 10. Classification by specific ranges at each station unified with results from the automatic stations.

Station	Good	Acceptable	Regular	Bad	Very bad
1	<30,0	30,1 – 31,7	31,8 - 33,7	33,8 - 36,7	>36,7
3	<79,6	79,7 - 119,1	119,2 - 154,4	154,5 - 194,2	>194,2
5	<121,8	121,9-146,9	145,0 - 181,0	181,2 - 238,3	>238,3
8	<204,5	204,6 – 383,4	383,5 - 470,2	470,3 - 531,0	>531,0
9	<274,0	274,1 - 358,0	358,0 - 503,8	503,9 - 586,2	>586,2
11	<288,0	288,1 - 393,31	393,4 - 480,0	480,1 - 551,2	>551,2
12	<255,0	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

5. Discussion

In the Aburrá - Medellín river, the highest measurements, and largest deviations of electrical conductivity in the eight stations occurred at low flows, like the study conducted in the lower basin of the Cesar river [De la Parra and García (2019)], which is due to the fact that in these conditions the flow (low level) of the river is mainly made up of raw and treated wastewater from the region [AMVA (2020); Giraldo (2013)]. Additionally, a deterioration of the river can be noticed as it advances along its course towards the big city, highlighting the Aula Ambiental (E8) - Ancón Norte (E12) stretch as the most critical station, in which the river has already received about 90% of the region wastewater. This trend in the river profile is associated with land and water use, wastewater generation, and the population's habits, which, in turn, is related to the river's passage through the most densely populated urban areas of the region, such as Medellín, where there have been changes in the territory due to the increase in population density and the consequent need to meet their needs, and there are even authors who relate this increase to climate change [AMVA et al. (2011); Giraldo, Agudelo and Palacio (2010); Restrepo, Peña and Martínez (2019)].

Between stations E12 and E20, an improvement in quality for the three flow scenarios is observed, which is related to the reduction of wastewater inflow and the entry of a better-quality water from streams in the north of the region, where the pressure on the resource generated by population density and changes in land use decreases [AMVA and UdeA (2019); AMVA and UdeA (2020); Giraldo, Agudelo and Palacio (2010)]. It is also observed that as water enters because of rainfall, that is, in high flows, a dilution of pollutants is generated and, therefore, the river conditions improve in terms of electrical conductivity. This effect of rainfall on the Aburrá - Medellín river was recorded by [AMVA and UdeA (2019); AMVA and UdeA (2020)], a dilution process was also observed in the Tota river during the rainy season [Meneses, Castro and Jaramilllo (2019)] and has even been identified in lentic ecosystems [Camacho and Camacho (2010)].

In the time variation of the electrical conductivity for the low flow scenario, it is observed that San Miguel station (E1) has the lowest and little variable values in the study period, compared to the other monitoring stations. Between Ancón Sur (E3) and Ancón Norte (E12), the levels of electrical conductivity increase, because of greater settlement and the consequent generation of wastewater, which reaches the river raw and treated, and finally in Puente Gabino (E20), it decreases, as mentioned above. This trend does not change for all monitoring years; however, high levels of electrical conductivity are highlighted for the year 2010, which is associated with the climatic conditions of the first months of the year (monitoring period), where dry weather predominated, giving continuity to El Niño phenomenon presented in 2009, which began to weaken in April 2010, i.e., the time preceding the monitoring and even the monitoring occurred in dry weather [IDEAM (2010)]. In general, for each station there is no improvement in water quality over time, except at Puente Acevedo station (E9) where a slightly decreasing trend is observed, with improvement by 2020, which may be related to connection of the eastern and western interceptors of raw sewage that discharged directly into the river before this station, to the northern interceptor. Therefore, since 2019, this wastewater has been transported directly to the Aguas Claras Treatment Plant, which began operating this year [AMVA and UdeA (2016); AMVA and UdeA (2019); AMVA and UdeA (2020); EPM (2017)].

It is noteworthy that there is no improvement at Puente Machado station (E11), which is the next station after Puente Acevedo (E9), despite the fact that wastewater from the interceptors is reaching the plant, which could indicate, as in Aula Ambiental (E8), that part of the wastewater generated in the central and northern areas of the municipality of Medellín is still reaching the river through the streams that run through these communities, which were identified as streams with high and very high contamination [Giraldo and Agudelo (2017)]. This indicates the need to expand the coverage of wastewater collection even in hillside areas, where it will be necessary to make non-conventional designs for the collection of such waters, given the disorderly process of land occupation. The opposite situation is presented in the article Water quality modeling of Medellin river in the Aburrá valley conurbation, where a scenario was run in the river quality model, which considered the connection of interceptors to the treatment plant and improvements in the quality of tributary streams, which showed a significant recovery in terms of electrical conductivity from the Aula Ambiental station (E8) to Puente Machado (E11), located prior to the Aguas Claras treatment plant [Giraldo et al. (2015)].

In the article Evaluation of the Condition of Affluents of Aburra-Medellin River through Indices, the problems associated with water quality in the streams of the Aburrá Valley were identified and one of the main ones is water pollution by direct discharge, where despite the progress in the implementation of the Sanitation and Wastewater Discharge Management Plan, direct discharges into water bodies were still detected, so it is possible that this situation still continues in some sectors of the Aburrá valley, and another important problem is the inadequate disposal of solid and special waste that significantly affects water quality [IDEAM (2010)].

The use of electrical conductivity, a variable measured in the field, as a quick indicator of the state of the Aburrá - Medellín river is possible. This variable, with the two proposed classifications, describes the changes in water quality and trends similar to those presented by [AMVA et al. (2011); Giraldo, Agudelo and Palacio (2010); Giraldo et al. (2015); Giraldo (2013)]; however, the average of readings in low flows of the San Miguel station (E1) with a "very critical" classification according to the ranges defined by station stands out, which is due to unusual conditions found in the monitoring performed on August 2, 2017, date that had the highest reading measured in the operation of the network in the study period, which according to the records of the Network was due to a punctual discharge in La mina stream at 11 am, stream located upstream of this station [AMVA and UdeA (2020)]; when this date is not considered, the average classification obtained is "regular." However, when zooming in during the study period at low flows and considering the classification by station, at San Miguel station (E1), there is a tendency for water quality to deteriorate over time (Table 6), a situation that is not perceived with the overall rating of electrical conductivity, which takes into account all the readings obtained along the river during the study period, This would indicate that no matter how much the station deteriorates, it will always be classified as "good," given that the conditions and use of water in this sector is very different from the rest of the river, therefore, it would not show alarms, so it is suggested to use the classification by station, if what you want is to evaluate in a particular way the state of a station and how its quality evolution has been over time. Additionally, it is striking that as these classification ranges were obtained from the readings made 2006-2020, this classification will serve to evaluate the implementation of the Water Resource Management Plan (2020-2030), and therefore can generate alarms so that the quality of the river water does not deteriorate over [AMVA (2019)].

In general, when the global classification ranges of the entire river are used, i.e., considering the measurements at all stations, the result is less strict and somewhat like the ICA; however, when the classification is made by station, i.e., the electrical conductivity reading of a station is compared with historical measurements obtained only at this station, the results are stricter in the stations of better quality and, therefore, with small ranges of variation because the best medium values of the station since 2006 have been taken as a reference of good quality. However, the classification is also less strict at high flows for the stations with greater anthropic intervention, given that during the study period, their quality changes permanently and, therefore, the range of variation of electrical conductivity is wider, which makes their classification ranges also large.

The space variation of the ICA indicator for the flow scenarios shows similarities among flow scenario; however, the high flow prevails as the least critical in the river. This difference not being so marked, which is due to the subindex calculation model [IDEAM (2015); Giraldo (2013)].

In the specific case of Ancón Norte (E12), the increase in electrical conductivity in recent years may be due to the discharge of treated wastewater from the Aguas Claras Treatment Plant; this similar effect was presented in the article Epiphyton colonization on artificial substrates in the Aburrá-Medellin river, Colombia, where the increase in electrical conductivity in the river as a result of the discharge of treated wastewater from the San Fernando plant had an impact on the physiognomic group of erect algae [Giraldo, Palacio and Aguirre (2015)], so that in the future, in order to increase the biological diversity in the river, it is important to control this variable. With this premise, the quality objectives of the river were defined by the Área Metropolitana del Valle de Aburrá, Corantioquia and Cornare, as Environmental Authorities of this stream, in the Water Resource Management Plan. This plan was accepted by Metropolitan Resolution No. D 00-002994, and the quality objectives considered electrical conductivity as a long-term objective in the river [AMVA (2019)].

Additionally, there is a statistically significant difference between the electrical conductivity measured at the stations and also for the measurements at the three flow levels, with a 95.0% confidence level, indicating that the water quality expressed in terms of this variable is different as one moves along the river, which as previously mentioned is due to the use of soil and water [AMVA and UdeA (2019); AMVA and UdeA (2020); Giraldo (2013)], while in terms of flow, it shows a process of dilution of pollutants that affects the electrical conductivity reading, being the most critical conditions those of low flows, where the river is transporting a low base flow and a permanent flow of raw and treated wastewater from the region. These results have been similar to those obtained when evaluating parameters such as BOD, COD and nutrients in the river in the operation of the network [AMVA et al. (2014); AMVA and UdeA (2016); AMVA and UdeA (2019); AMVA and UdeA (2020)].

Figure 2 shows differences between stations for electrical conductivity as demonstrated by the Kruskal Wallis test. However, although the stations Aula Ambiental (E8), Puente Machado (E11) and Ancón Norte (E12) show similarities, their location in the river corresponds to a stretch that historically has been considered the most critical of the river [Giraldo (2013); AMVA et al. (2011); AMVA et al. (2014); AMVA and UdeA (2016); AMVA and UdeA (2019); AMVA and UdeA (2020)]. It should be noted that the three stations are very important in the monitoring network, with Aula Ambiental and Puente Machado the recovery of the river can be evaluated due to the connection of interceptors to the Aguas Claras treatment plant, and between Puente Machado and Ancón Norte the effect of discharge from the treatment plant can be evaluated; therefore, with keys in the operation of the network, these critical conditions again show that raw sewage is still arriving in this section, so it is necessary to evaluate alternatives for its collection. This situation had already been evidenced in the River Management Plan - PORH and therefore contemplated Strategic Line 1: Conservation, protection, and/or recovery of the water resource and Program 3: Water quality management, to contribute to the improvement of the ecosystems associated with the areas that favor the availability of the Aburrá-Medellín River water resource, in terms of water quantity [Restrepo, Peña and Martínez (2019); AMVA and UdeA (2018)].

A quick and frequent way of verifying the progress in the implementation of the Management Plan could be with a reading of the electrical conductivity, since the indexes usually used involve the measurement of several variables generating a greater effort both in time and money, so it cannot be done more frequently. Nevertheless, it is necessary to clarify that to make a complete evaluation of the quality and sanitary conditions of water, it is necessary to complement the study with physicochemical, biological, and hydraulic measurements [IDEAM and INVEMAR (2017)].

Finally, it is worth mentioning the opportunity to inform, in a simple and easy way, so that the community can understand Aburrá - Medellín river water quality status by means of electrical conductivity, in the three automatic stations. To make this possible, it is proposed to use the classification presented in this article in such a way that through the Aburrá Valley Metropolitan Area Web page the status of the river in its 37 kilometers may be informed using colors code. This action contributes to Strategic line 2 of the Ordering plan: Culture of efficient water consumption and to Strategic Line 3: Territorial management [Giraldo, Palacio and Aguirre (2015)].

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