



Article Multitemporal Total Coliforms and *Escherichia coli* Analysis in the Middle Bogotá River Basin, 2007–2019

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Abstract: Currently, one of the main environmental problems that need to be addressed is the pollution inflicted upon different ecosystems by anthropic activities. One example of this problem can be seen in the Bogotá River, a major river in the Cundinamarca department of Columbia and the main water source supplying the Bogotá savannah, which reaches the Colombian capital city. The Bogotá River is highly affected by effluents and wastewater of domestic and industrial origin, among others. These pollutants are generated and accumulated throughout the entire basin, without ever receiving any type of treatment. The pollution levels to which the Bogotá River is subjected can be determined with the calculation of environmental indices, including microbiological contamination indicators such as total coliforms (TC) and fecal coliforms, which include Escherichia coli, Enterobacter, Klebsiella, Serratia, Edwardsiella, and Citrobacter bacteria, living as independent saprophytes. This paper assesses the quality of the water in the Bogotá River, using microbiological indicators and data provided by the Regional Autonomous Corporation (CAR) of Cundinamarca to assess water samples, extracted based on the climatic bimodality exhibited in the basin in dry and wet seasons. The scope of this study was limited to the 35 monitoring Regional Autonomous Corporation of Cundinamarca (CAR) stations located throughout the middle basin. For these purposes, a multitemporal analysis of the TC and Escherichia coli variables was conducted for the 2007–2019 period, which evidenced the contamination levels in this section of the water body. In broad terms, the current state of the middle section of the Bogotá River basin is unacceptable, due to the different activities occurring within its riparian buffer zone, such as uncontrolled domestic, industrial, and/or commercial wastewater discharges. To optimize water treatability, the continuous improvement of existing treatment plants is expected, as well as the implementation of new sustainable treatment alternatives aimed at improving water quality.

Keywords: total coliforms; fecal coliforms; *Escherichia coli*; Bogotá River; wastewater; water quality; microorganisms

1. Introduction

Over 2,000,000,000,000 people live in countries experiencing high water stress, and 4,000,000,000 people worldwide experience severe water scarcity for at least one month of the year. The environmental impact of this shortage will continue to increase, as water demand grows and the effects of climate change intensify [1]. Within this context, it is evident that some rivers exhibit high concentrations of organic matter and nutrients, high pollution levels caused by heavy metals, and high levels of contamination. Hence, continuous inspection and improvement are required to prevent major negative effects in



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Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). these rivers [2]. The 2030 Agenda for Sustainable Development is committed to "leaving no one behind", seeking universal and equitable access to drinking water, thus fostering socio-economic development and achieving the full realization of human rights across the globe [3].

Its vast hydrographic wealth ranks Colombia among the top 10 countries in the world in terms of water availability. Its water supply is 59 L/s/km², which equates to six times the world average and three times the Latin American average. In addition, the country reports an annual rainfall of 3000 mm, exceeding the global average by three times and approximately twice the South American average [4]. However, according to the World Health Organization (WHO), 1,500,000 young children (under the age of 5) die every year due to the lack of safe water and sanitation, which is a common issue in developing countries such as Colombia [5].

Moreover, if Colombia is to remain a water power, the national government must be committed to defending the country's water resources. It must also enforce the local regulations issued by Colombia's Ministry of Environment, Housing and Territorial Development [6]. It is important that for the proper management of domestic and industrial wastewater treatment plants (WWTPs), investments are made to ensure that they run at optimal operating conditions throughout the national territory [7].

Colombia reports significant progress in the management of conventional and hazardous solid waste against other Latin American countries. However, this is not completely feasible because there are still opportunities for improvement regarding the final disposal of solid waste in rural areas and municipalities, which still face issues due to the inappropriate disposal of solid waste, a situation fueled by poor landfill infrastructure and poor coverage of basic sanitation services [8]. Solid-waste mismanagement has caused cracks in landfills around the country, leading to landslides and leachate leakage, in addition to biogas accumulations that can generate atmospheric pollution [9]. This issue directly or indirectly affects the quality of water resources, since the subsoil and groundwater may become contaminated. Furthermore, poor garbage collection service coverage contributes to degrading not only the environment but also human health [8].

Total and fecal coliforms are Gram-negative bacteria, with aerobic and facultative growth capacity, that are commonly found in plants, soil and animals, as well as in humans [10]. The presence of coliforms in water bodies clearly indicates contamination by sewage discharges or decaying matter and especially by organic waste. Fecal contamination constitutes the main sanitary risk for water bodies since, given these conditions, this water will contain pathogenic microorganisms that can cause diseases threatening human health [11]. In fact, the presence of enteropathogenic microorganisms represents a high risk to public health [12].

Waterborne diseases are related to the presence of these fecal bacteria in both sewage and drinking water, which generate high morbidity and mortality rates, mainly in children [13]. Acute diarrheal disease is characterized by frequent discharges of feces with abnormal consistency. Approximately 85% of diarrhea-related deaths involve children under one year of age. The pathogens associated with diarrhea are: viruses, such as rotaviruses, which usually infect 10–50% of all humans; protozoa, such as *Cryptosporidium* sp., *Giardia lamblia*, and *Entamoeba histolytica*, which report a lower frequency of 1–8%; and bacteria, such as *Shigella* sp. (8–30%), enterotoxigenic *E. coli*, and enteropathogenic *E. coli*, which usually affects 5–40% of the population [14]. As mentioned above, *E. coli* is one of the direct causes of diarrheal diseases. Therefore, sanitary controls aimed at mitigating microbiological risks are extremely important and represent a critical measure for the population. Environmental management in watersheds should necessitate a social responsibility approach, with the participation and commitment of different stakeholders at the governmental and national levels [15].

The Magdalena river basin has an area of 257,400 km², occupying 22.5% of the Colombian territory, with a length of 1612 km [16]. This basin supplies water to 80% of the country's population and supports ~85% of the national GDP [17]. However, due to its

high level of contamination, the Magdalena River represents a health risk for a large part of the population in the center of the country who consume drinking water from this river [18]. The Magdalena riverbed experiences greater microbiological contamination by total coliforms (TC) and *Escherichia coli* during the dry season than during the rainy season because, during the rainy season, its flow increases due to rainfall, thus generating a dilution in the concentration of microorganisms [17]. Given that its major tributary is the Bogotá River, which flows directly into this body of water, serious social, economic, political, and environmental problems are observed [19].

In fact, one of the 17 goals proposed in the UN's Sustainable Development Goals for 2030 refers to adequate sanitation to ensure a clean watershed. In 2017, Colombia ranked 16th among 179 countries in the world, with a volume of 50,000 m³ of water per inhabitant per year. With respect to this total volume, the Bogotá River provides ~300 m³ of water per inhabitant per year [20]. The Bogotá river basin has been named as the most polluted water body in Colombia, as a result of sewage discharges from more than 7.4 million people residing in the area [21], and its waters flow into the Magdalena River, a major national river system [18].

The high concentrations of total and fecal coliforms in the middle reaches of the Bogotá River basin during the dry season are largely due to human and industrial settlements. There is also a relationship between the effects of climatic seasons and the pollution sources evaluated in this study [22]. In addition, discharges of untreated wastewater are the main source of contamination by these Enterobacteriaceae [23]. According to the 2014 Colombian Water Study, the Bogotá River reports an extremely high vulnerability index to water stress, which evidences the fragility of supply experienced by this water system during climatic phenomena, such as the El Niño event. Another critical variable to be evaluated is the water pressure reported by the different ecosystems and the amount of water that does not return to the basin. In fact, when analyzing the relationship between the green water footprint, which refers to the use and retention of surface- and groundwater (rivers, lagoons, and aquifers) by anthropogenic activities, it becomes evident that water availability is seriously threatened by the large number of agricultural and livestock activities that are concentrated in the river subzones [24].

Historically, the Bogotá river basin has experienced significant uncertainty due to its pollution and sanitation, as well as water imbalances in its channel caused by inadequate land use and overexploitation. The different variables that influence anthropogenic modifications must be evaluated in order to preserve these ecosystems [25]. A better understanding of tipping points in lotic ecosystems will help to identify long-term impacts caused by human–ecosystem interactions and to establish adaptive and transformative management plans for large rivers [26]. Pollution caused by industrial and domestic wastewater in the municipalities of the Capital District is also fostered by nefarious and underperforming treatment plants [27]. The increasing development of urbanization has exceeded the normal balance, thus stimulating an increase in environmental services and goods, which is coupled with increased waste generation [28].

According to the 2018 Progress Report of the Colombian Water Study, the capital city of Bogotá accounts for most of the domestic pollutant load on water sources [29]. For this reason, multiple prevention and correction activities aimed at reducing pollution are being carried out, which directly benefits the city's localities, since the middle section of the Bogotá river basin is located in the urban area of the Colombian capital [20]. However, although the "El Salitre" WWTP has been in operation since 1999 [30], it has not been able to remove the expected load volume, as it cannot keep up with processing the required wastewater levels. This plant has the capacity to treat 4 m³ of wastewater per second but receives 15 m³ per second, generated by the ~3 million people living in Bogotá alone. Therefore, most of the wastewater is not adequately treated. In addition, the Bogotá River also receives multiple discharges as it passes through the city [20].

This work focuses on determining the spatiotemporal patterns of microbiological conditions reported between 2007 and 2019 by the 35 stations located along the middle basin of the Bogotá River.

2. Materials and Methods

2.1. Study Area

The Bogotá River runs through the Cundinamarca and Boyacá highlands, crossing the department of Cundinamarca from northeast to southeast. Its headwaters are at 3300 m above sea level (masl) in the Páramo de Guacheneque forest reserve, in the municipality of Villapinzón, and flow into the Magdalena River, in the municipality of Girardot, at 280 masl, covering an area of influence of ~589,143 ha [31]. The Bogotá River is divided into three basins—the high, middle, and low basins—passing through 47 municipalities of the department of Cundinamarca, which route represents an influence on just over 10 million people, who are mainly from the city of Bogotá [32].

The middle basin of the Bogotá River corresponds to the section located between the monitoring stations, as shown in Figure A1: Quebrada La Tenería (No. 68) and downstream Quebrada Honda (No. 67). This river basin receives discharges (either directly or indirectly) from the municipalities of Chía, Cota, Tenjo, Subachoque, El Rosal, Funza, Madrid, Mosquera, Bojacá, Facatativá, Soacha, Tena, San Antonio del Tequendama, and part of the discharges from Cajicá, but especially the discharges from the Capital District of Bogotá. Its main tributaries in this section are the discharges from the Frio, Chicú, Balsillas, Salitre, Fucha, Tunjuelo, Soacha rivers, and the La Cuy and Honda streams. The data of the stations in this study were provided by the Corporación Autónoma Regional de Cundinamarca (CAR).

2.2. Station Sampling Design

For the last 12 years, the Environmental Laboratory of the CAR has studied the middle basin of the Bogotá River, performing microbiological analysis in 35 monitoring stations, taking as a reference the highest values, these being the most representative of the study. The sampling frequency was in the two seasons of the year, taken as the high-water and low-water seasons, which indicate the rainy and dry periods. For the development of microbiological analysis, two periods were identified. They were given the numbers 01, which includes the months from January to June, and 02, which includes the months from July to December. This designation is added after specifying the year of sampling, for example, 2014-02. The numbering of each station corresponds to the identification provided in the data by the CAR; these numbers do not have a sequential order. The monitoring stations are described below: Quebrada La Tenería (No. 68), upstream of Chía (No. 14), Chía Municipal Discharge (No. 29), downstream of Chía (No. 3), Limnigrafica (LG) bridge (Pte). La Balsa station (No. 42), River Frio (No. 75), downstream River Frio (No. 10), Cota Municipal Discharge (No. 30), LG Pte. La Virgen station (No. 43), River Chicú (No. 74), Limnimetric (LM) Vuelta Grande (No. 58), Juan Amarillo Bypass (No. 22), El Salitre WWTP (No. 59), El Cortijo (No. 39), Jaboque discharge (No. 28), Engativá discharge (No. 27), Engativá downstream (No. 4), La Ramada (No. 53), LG Pte. Cundinamarca (No. 56), LM Hacienda San Francisco (No. 57), River Fucha (No. 76), downstream River Fucha (No. 11), Gibraltar pump (No. 24), LG La Isla (No. 54), Rio Tunjuelo (No. 70), downstream River Tunjuelo (No. 13), Rio Balsillas (No. 72), River Soacha (No. 79), Soacha cannel (No. 23), LG Las Huertas (No. 55), Mondoñedo bridge (No. 60), upstream Salto Tequendama (No. 18), San Antonio. Tequendama municipal discharge, Quebrada La Cuy (No. 31), Quebrada Honda (No. 67), and downstream Quebrada Honda (No. 9). Of the abovementioned stations, the ones closest to the urban area can be seen in Figure 1.



Figure 1. Location of Middle Basin Monitoring stations located with the identification number described above, Bogotá River approach. Source: prepared by the authors, 2021.

At a methodological level, coliforms were reported as per the Colilert method, which detects TC and *E. coli* using the defined substrate and a fluorescence technique. Then, spatial-temporal graphs were plotted for the TC and *E. coli* variables. The values reported were compared with the reference value of 2.0×10^4 MPN/100 mL for TC and 2.0×10^3 MPN/100 mL for *E. coli*, established by Executive Order 1594 in 1984.

The data collected for the middle Bogotá River basin were analyzed using a quantitative study that compared the results reported by the Regional Autonomous Corporation (CAR) in the 12 years from 2007-01 to 2019-02 at the 35 wastewater quality monitoring stations located along the waters of the middle river basin, taking the values established by Executive Order 1594 in 1984 as a reference. The results from the 35 stations or sampling points were organized sequentially according to each location within the middle basin, based on the coordinates provided by the Regional Autonomous Corporation (CAR), with each location being pinpointed using a geographic information system (ArcGis). Subsequently, the sets of values collected were cleaned using Excel and Origin Lab. Data analysis was performed using a descriptive statistical method to understand and analyze a given set of data [33], comparing the microbiological results of total coliforms and *Escherichia coli* over the 12-year period, in relation to the two seasons of the year, taking into account the maximum values of each season along the middle basin of the Bogota River (multitemporal analysis).

3. Results

After assessing the microbiological water-quality data collected from 35 stations during the 2007–2019 period for the middle Bogotá River basin, the following results were obtained.

For Station (No. 68) Quebrada La Tenería, the highest TC and *E. coli* levels were evidenced in 2014-02, with TC exceeding 2.4×10^8 MPN/100 mL and *E. coli* reaching 9.3×10^7 MPN/100 mL. The most recent report, for 2019-02, records 1.00×10^8 MPN/100 mL and 7.50×10^6 MPN/100 mL for TC and *E. coli*, respectively.

In the section that covers the municipality of Chía, three monitoring stations provided behavioral data. First, the upstream Chía station (No. 14) reported peak values for the first period of 2007, with a TC concentration of 2.40×10^7 MPN/100 mL and an *E. coli*

concentration of 2.00×10^7 MPN/100 mL. A third maximum peak was reported in 2019-01, with 1.70×10^6 MPN/100 mL for TC and 8.20×10^5 MPN/100 mL for *E. coli*.

The Chía municipality discharge station (No. 29) reported a maximum concentration of 2.50×10^7 MPN/100 mL for TC and 1.70×10^6 MPN/100 mL for *E. coli* in the 2008-02 period. In addition, in 2014-02, these concentrations increased from the previous year to 1.60×10^7 MPN/100 mL for TC and 4.60×10^6 MPN/100 mL for *E. coli*. The third station is the downstream Chía station (No. 3), which reports concentrations of 6.50×10^7 MPN/100 mL for TC and 1.10×10^7 MPN/100 mL for *E. coli* in 2010-01, as may be observed in Figure 2, below.



Figure 2. Downstream Chía concentration chart. Source: prepared by the authors, 2021.

The LG Puente la Balsa Station (No. 42) reported a significant increase in 2014-01, with TC values exceeding 2.40×10^{6} MPN/100 mL and *E. coli* levels of 8.20×10^{5} MPN/100 mL; in 2019-02, this station reported TC concentrations of 2.40×10^{6} MPN/100 mL and *E. coli* concentrations of 2.90×10^{5} MPN/100 mL.

At the next station, Rio Frio (No. 75), TC concentrations for 2011-01 were 5.80×10^7 MPN/100 mL, with *E. coli* levels of 9.60×10^6 MPN/100 mL. However, in 2019-02, TC concentrations decreased to 9.90×10^3 MPN/100 mL, as well as for *E. coli* concentrations, which showed a value of 100 MPN/100 mL.

Subsequently, at the downstream Rio Frio station (No. 10), concentrations remained high, as evidenced in 2010-01, when the station reported TC concentrations of 4.60×10^7 MPN/100 mL and *E. coli* concentrations of 1.80×10^7 MPN/100 mL; in 2016-02, TC values were observed of 1.70×10^7 MPN/100 mL, while the concentration of *E. coli* decreased (2.70×10^5 MPN/100 mL) (Figure 3).



Figure 3. Downstream Rio Frio concentration chart. Source: prepared by the authors, 2021.

The Cota municipality station (No. 30) reported a large number of total coliforms and *E. coli*. Below, we list the main concentration peaks recorded throughout our 12-year assessment period: in 2010-01, concentrations were reported of 2.00×10^8 MPN/100 mL for TC and 5.30×10^7 MPN/100 mL for *E. coli* and, in 2019-02, TC concentrations were reported of 1.50×10^8 NMP/100 mL and *E. coli* concentrations of 3.40×10^7 MPN/100 mL.

The next monitoring point was the Puente La Virgen station (No. 43), where maximum concentrations were reported in 2007-01, with values of 9.80×10^6 MPN/100 mL for *E. coli* and 7.30×10^7 MPN/100 mL for TC. An overall decrease in coliforms was observed at this station for 2019-01; TC concentrations were 2.40×10^6 MPN/100 mL and *E. coli* concentrations were 5.00×10^5 MPN/100 mL (Figure 4).



Figure 4. LG Puente La Virgen station concentration chart. Source: prepared by the authors, 2021.

The Rio Chicú station (No. 74) reported a 2007-01 TC concentration of 2.40×10^6 MPN/100 mL, and an *E. coli* concentration of 4.30×10^5 MPN/100 mL; in 2019-02, this station reported TC concentrations of 2.40×10^3 MPN/100 mL and *E. coli* concentrations of 3.10×10^2 MPN/100 mL. Here, the maximum concentrations reported by these stations significantly decreased for total coliforms and *E. coli*.

Subsequently, the data recorded at this point reveals higher concentrations than the LM Vuelta Grande station (No. 58). In 2014-02, these concentrations increased even more, as TC concentrations were reported at >2.00 × 10⁷ MPN/100 mL and *E. coli* concentrations were 2.00×10^7 MPN/100 mL, which denotes a lack of interest from the corporations in charge of improving water quality. However, in 2019-01, the maximum TC values (>2.40 × 10⁶ MPN/100 mL) and *E. coli* values (5.80 × 10⁵ MPN/100 mL) decreased from the previous peak in 2014-02, but these values still exceeded the maximum permissible limits.

Subsequently, data from the Juan Amarillo Bypass station (No. 22) shows that for the season of 2008-02, the TC concentrations were 1.90×10^8 NMP/mL and *E. coli* was 1.20×10^7 NMP/mL; for 2014-02, these concentrations increased even more, since the TC concentrations were 2.00×10^8 NMP/mL and *E. coli* levels were 2.20×10^7 NMP/mL, which shows great disinterest on the part of the corporations in charge of improving the quality of the water.

Station No. 59, located at the discharge (channel) of the El Salitre Wastewater Treatment Plant reported high TC concentrations of 1.50×10^8 MPN/100 mL and *E. coli* concentrations of 1.30×10^7 MPN/100 mL for 2008-02. Although the plant has been in operation since 1999, high levels of contamination at 2.0×10^3 MPN/100 mL of TC were still being reported in 2008. In fact, 6 years later, in 2014-02, concentrations had increased significantly to 1.70×10^8 MPN/100 mL for TC and 2.20×10^7 MPN/100 mL for *E. coli*, as can be observed in Figure 5.



Salitre WWTP

Figure 5. El Salitre WWTP concentration chart. Source: prepared by the authors, 2021.

Next in line is the monitoring station of El Cortijo (No. 39), located 500 m downstream of the El Salitre WWTP discharge point. In 2009-01, this station reported a TC concentration of 2.20×10^8 MPN/100 mL and *E. coli* concentrations of 1.20×10^7 MPN/100 mL. However, in 2016-02, this station reported TC concentrations of 1.70×10^8 MPN/100 mL

and *E. coli* concentrations of 8.20×10^6 MPN/100 mL. These concentrations are extremely high compared to the concentrations reported by the Jaboque discharge station (No. 28), which are lower than the rest of the stations mentioned. For example, in 2011-01, TC concentrations only reached 4.70×10^3 MPN/100 mL and *E. coli* concentrations reached $<1 \times 10^2$ MPN/100 mL, as shown in Figure 6. However, a peak was reported in 2015-01 with the presence of TC concentrations of 2.40×10^7 MPN/100 mL and *E. coli* concentrations of 9.8×10^4 MPN/100 mL.



Jaboque discharge

Figure 6. Jaboque discharge concentration chart. Source: prepared by the authors, 2021.

Upon entering the Engativá community, the water body is further affected, as is seen in the data reported by the Engativá discharge station (No. 27) for the year 2019-02, which shows that concentrations increased even more, reaching 2.00×10^8 MPN/100 mL for TC and 4.10×10^7 MPN/100 mL for *E. coli*.

The La Ramada station (No. 53) registered a decrease in the values reported by the downstream Engativá discharge station, given that the station reported TC concentrations of 1.4×10^7 MPN/100 mL and *E. coli* concentrations of 6.7×10^6 MPN/100 mL in 2010-01; no data records are available for more recent years. However, even so, high concentrations of these coliforms, which are pathogenic to humans, are evident.

The downstream Engativá station (No. 4) reported concentrations in 2016-02 for TC of 1.1×10^8 MPN/100 mL and 2.0×10^6 MPN/100 mL for *E. coli*, reaching a significant increase; to date, these results far exceed the permissible limits provided for in Decree 1594 from 1984 (Figure 7).

At this point, the Rio Fucha station (No. 76) reported TC concentrations of 4.5×10^8 MPN/100 mL and *E. coli* concentrations of 2.0×10^7 MPN/100 mL for the first half of 2009. Likewise, in subsequent years, these concentrations reached higher values. For example, in 2019-01, the station reported TC concentrations at 1.0×10^8 MPN/100 mL and a significant increase in *E. coli* concentrations at 5.5×10^7 MPN/100 mL, representing the maximum values of fecal coliforms reported, due to domestic, commercial, and industrial wastewater discharges [34].



Figure 7. Downstream Engativá concentration chart. Source: prepared by the authors, 2021.

In 2009-01, the downstream Rio Fucha station (No. 11) reported TC concentrations of 1.5×10^8 MPN/100 mL and *E. coli* concentrations of 3.4×10^6 MPN/100 mL (Figure 8). The microbiological load was extremely high, showing that concentrations of TC and E. coli were maintained over the years.



Figure 8. Downstream Rio Fucha concentration chart. Source: prepared by the authors, 2021.

In 2008-01, the Rio Tunjuelo station (No. 70) reported TC concentrations of 2.4×10^8 MPN/100 mL and *E. coli* concentrations of 1.1×10^7 MPN/100 mL.

Downstream Engativá

The lower basin of the Tunjuelo River covers an area of 390 km² from the Cantarrana dam to the mouth of the Bogotá River [35]. In the downstream Rio Tunjuelo station (No. 13), in 2008-02, TC concentrations reached a maximum value of 1.7×10^8 MPN/100 mL and *E. coli* concentrations reached 1.2×10^7 MPN/100 mL, which indicates that there was a high contribution of wastewater and industrial waste throughout its course. In 2019-01, the same level of contamination was observed, with TC concentrations of 3.9×10^7 MPN/100 mL and *E. coli* concentrations of 8.6×10^6 MPN/100 mL. This station is affected by anthropic influences from the urban periphery (Figure 9).



Downstream río Tunjuelo

Figure 9. Downstream Rio Tunjuelo concentration chart. Source: prepared by the authors, 2021.

At the Rio Balsillas station (No. 72) in 2019-01, concentrations had decreased with respect to previous stations, yielding TC concentrations of 1.6×10^7 MPN/100 mL and *E. coli* values of 1.9×10^6 MPN/100 mL.

At the Rio Soacha station (No. 79), the 2009-01 microbiological results revealed that TC concentrations were at 1.6×10^8 MPN/100 mL and *E. coli* concentrations were at 1.1×10^7 MPN/100 mL. However, in 2019-02, TC concentrations had decreased to 9.2×10^7 MPN/100 mL but *E. coli* concentrations had increased to 2.6×10^7 MPN/100 mL.

At the Puente Variante Mondoñedo station (No. 60), the 2008-02 microbiological results revealed that TC concentrations were at 8.7×10^7 MPN/100 mL and *E. coli* concentrations were at 2.7×10^6 MPN/100 mL; for 2016-02, TC concentrations were 1.1×10^8 MPN/100 mL, and *E. coli* concentrations were 7.2×10^6 MPN/100 mL. At this point, the body of water had a very high level of biological oxygen demand (BOD), with a value of 320 mg BOD/L in 2012, which was directly related to the high TC and *E. coli* concentrations measured at this station.

At the station before reaching Tequendama Falls (the upstream Salto de Tequendama Station No. 18), a significant number of coliforms was recorded. In 2009-01, TC concentrations were at 2.4×10^8 MPN/100 mL and *E. coli* concentrations were at 1.5×10^5 MPN/100 mL (see Figure 10).



Figure 10. Upstream Salto de Tequendama concentration chart. Source: prepared by the authors, 2021.

At the Quebrada La Cuy station (No. 31), San Antonio Tequendama municipal discharge, an all-time-high percentage of coliforms was again recorded, In 2018-01, TC concentrations were at 1.6×10^8 MPN/100 mL and *E. coli* concentrations were at 2.0×10^7 MPN/100 mL (see Figure 11).



Figure 11. San Antonio Tequendama Quebrada, La Cuy Municipio. Discharge concentration chart. Source: prepared by the authors, 2021.

At the point when the Bogotá River reaches the Quebrada Honda station (No. 67) and these two water bodies merge, TC levels remain elevated and *E. coli* decreases. The concentrations recorded in 2019-02 of TC were 9.8×10^4 MPN/100 mL and those of *E. coli*

Upstream Salto de Tequendama

were 8.4×10^2 MPN/100 mL. However, during the 12 years of study, it is evident that the highest peak was in 2007-01, with a total coliform value of 6.5×10^6 MPN/100 mL and *E. coli* value of 1.4×10^6 MPN/100 mL. Station Nos. 9, 21, 23, 54, 55, 56 and 57 also present maximum values of TC and *E. coli* in the different periods of the last 12 years; these data are shown in Table 1.

Table 1. Description of the 35 stations in the middle basin of the Bogotá River during the years 2007–2019, with their main characteristics, such as maximum values for TC and *E. coli*, the most representative of the study. Source: prepared by the authors, 2021.

POINTS ID	STATION NAME -	COORDINATES				TC	E. coli
		Latitude	Length	- MUNICIPALITY	Year	MPN/100 mL	MPN/100 mL
3	Downstream of Chía	4°49,806′ N	74°3330′ W	Chía	2010-01	65,000,000	11,000,000
4	Engativá Downstream	4°43,194′ N	74°9667′ W	Engativá	2016-02	110,000,000	2,000,000
9	Downstream Quebrada Honda	4°37,427′ N	74°23,469′ W	El socorro	2012-01	24,000,000	4,800,000
10	Downstream Rio Frío	4°50,167′ N	74°4852′ W	Zipaquirá -	2010-01	46,000,000	18,000,000
					2016-02	17,000,000	270,000
11	Downstream Rio Fucha	4°39,732′ N	74°9757' W	Bogotá	2009-01	150,000,000	3,400,000
13	Downstream Rio Tunjuelo	4°37,956′ N	74°13,608′ W	Bogotá –	2008-02	170,000,000	12,000,000
					2019-01	39,000,000	8,600,000
14	Upstream of Chía	4°56,668′ N	74°1003′ W	Chía -	2007-01	24,000,000	20,000,000
14					2019-01	1,700,000	820,000
18	Upstream Salto Tequendama	4°33,049′ N	74°16,796′ W	Soacha	2009-01	240,000,000	150,000
21	Gibraltar Pump	4°38,865′ N	74°11,118′ W	Bogotá	2009-01	870,000,000	21,000,000
	Juan Amarillo	4°44,303′ N	74°7655′ W	Denetí	2008-02	190,000,000	12,000,000
22	By Pass			bogota –	2014-02	200,000,000	22,000,000
23	Soacha cannel	4°35,467′ N	74°14,716′ W	Soacha	2019-01	<240,000,000	11,000,000
27	Engativa Discharge	4°43,303′ N	74°8952′ W	Engativá	2019-02	200,000,000	41,000,000
28	Jaboque Discharge	4°43,352′ N	74°9047′ W	Bogotá	2015-01	24,000,000	98,000
	Chía Municipal Discharge	4°51,615′ N	74°2356′ W	Chía -	2008-02	25,000,000	1,700,000
29					2014-02	16,000,000	4,600,000
30	Cota Municipal Discharge	4°47,841′ N	74°5760′ W	Cota -	2010-01	200,000,000	53,000,000
					2019-02	150,000,000	34,000,000
31	San Ant. Tequendama Municipal Discharge, Quebrada La Cuy	4°37,353′ N	74°21,237′ W	Soacha	2018-01	160,000,000	20,000,000
20	El Cortijo	4°43,817′ N	74°7781′ W	Bogotá -	2009-01	220,000,000	12,000,000
39					2016-02	170,000,000	8,200,000
42	LG Pte. La Balsa Station	4°49,744′ N	74°4226′ W	Cajica -	2014-01	2,400,000	820,000
					2019-02	2,400,000	290,000
42	LG Pte. La Virgen Station	4°47,949′ N	74°5765′ W	Cota -	2007-01	73,000,000	9,800,000
43					2019-01	2,400,000	500,000
53	La Ramada	4°42, 915′ N	$74^\circ 9305' \mathrm{W}$	Funza	2010-01	14,000,000	6,700,000
54	LG La Isla	4°38,668′ N	74°13,249′ W	Tenjo	2009-01	92,000,000	3,300,000
55	LG Las Huertas	4°35,173′ N	74°15,228′ W	Bogotá	2016-02	87,000,000	5,000,000
56	LG Pte. Cundinamarca	4°41,748′ N	74°10,327′ W	Bogotá	2014-01	>24,000,000	6,900,000
57	LM Hacienda San Francisco	4°40,157′ N	74°10,204′ W	Normandia	2008-02	98,000,000	3,500,000

POINTS ID	STATION NAME	COORDINATES				TC	E. coli
		Latitude	Length	- MUNICIPALITY	Year	MPN/100 mL	MPN/100 mL
58	LM Vuelta Grande	4°44,785′ N	74°7728′ W	Bogotá –	2014-02	20,000,000	20,000,000
					2019-01	2,400,000	580,000
59	EL salitre WWTP	4°44,191′ N	74°7593′ W	Bogotá –	2008-02	150,000,000	13,000,000
					2014-02	170,000,000	22,000,000
60	Mondoñedo bridge	4°32,546′ N	74°16,290′ W	Mosquera –	2008-02	87,000,000	2,700,000
					2016-02	110,000,000	7,200,000
67	Quebrada Honda	4°37,584′ N	74°23,333′ W	El socorro –	2007-01	6,500,000	1,400,000
					2019-02	98,000	840
68	Quebrada La Tenería	4°53,864′ N	74°1121′ W	Cajica –	2014-02	240,000,000	240,000,000
					2019-02	100,000,000	7,500,000
70	Rio Tunjuelo	4°37,607′ N	74°13,397′ W	Bogotá	2008-01	240,000,000	11,000,000
72	Rio Balsillas	4°37,077′ N	74°15,078′ W	Mosquera	2019-01	16,000,000	1,900,000
74	Rio Chicú	4°46,415′ N	74°6971′ W	Tenjo -	2007-01	2,400,000	430,000
					2019-02	2400	310
75	Rio Frío	4°50,501′ N	74°4799′ W	Zipaquirá –	2011-01	58,000,000	9,600,000
					2019-02	9900	100
76	Rio Fucha	4°39,870′ N	74°9197′ W	Bogotá -	2009-01	450,000,000	20,000,000
					2019-01	100,000,000,000	55,000,000
79	Rio Soacha	4°35,743′ N	74°14,595′ W	Soacha -	2009-01	160,000,000	11,000,000
					2019-02	92,000,000	26,000,000

Table 1. Cont.

4. Discussion

The above results allow us to develop an analysis of the possible causes and triggers affecting the state of the basin. In the current investigation, most of the 35 stations located along the middle basin of the Bogotá River showed high levels of total coliforms and *E. coli*, exceeding the limits allowed and established at the national and international levels. For example, the WHO guidelines recommend that the amount of total and fecal coliforms should be 0 UFC (colony forming units)/100 mL for water supply sources [36]. Similarly, the results presented by the World Water Quality Monitoring Program show contamination by these pathogenic microorganisms affecting approximately one-third of the river sections in Asia, Africa, Asia and Latin America [37].

These results coincide with the study carried out by Ochoa-Herrera et al. (2020), who analyzed the water quality of 18 rivers located in Quito, the capital province of Pichincha, Ecuador, by means of microbiological parameters, where high levels of contamination by total coliforms and *Escherichia coli* are evidenced [38]. The maximum values of these enterobacteria, reported in the current study, in the different water bodies are shown in Table 1.

The initial station of the river system is Quebrada La Tenería No. 68, which reports a high degree of contamination from fecal coliforms since it receives a large part of the sewage waters from the municipality of Cajicá [39].

The municipality of Cajicá currently uses a combined sewer system, wherein only 48% of the wastewater and rainwater that collect are treated before being discharged into the river. Another important factor is that the Calahorra WWTP, which receives most of the municipal wastewater, can only treat ~50% of the wastewater received [40]; this has prompted strategies for extending the capacity of the plant. Likewise, hydraulic adaptation work has been conducted in the river, which may account for the lower values that have been reported recently.

Following this water along its trajectory through the municipality of Chía, the values remain above the provisions established in Executive Order 1594 of 1984 and Agreement 43 of 2006, which sought to establish measures for improving the quality of water in the

Bogotá River basin by 2020. This failure may be due to deficiencies in wastewater treatment, ultimately leading to direct discharges into water bodies. The municipality of Chía built a treatment plant in 1989, but the plant was not sufficient for the 68% population increase experienced since 2000, 78% of which corresponds to the urban population. Even when the treatment plan covers 83.6% of the sewer system [41], it only manages to properly treat 30–40% of the wastewater produced. In particular, due to the excessive increase in urban population, wastewater flow rates have also increased, exceeding by far the hydraulic capacity of the plant. Currently, a large part of the urban area is covered by the Chía I WWTP, which can only treat 2.36 m³/s; this has caused a negative impact on the environment and the population at large [42].

In addition to the discharges from the WWTP into the Bogotá River, 11 domestic discharge points, five rainwater discharge points, and one industrial discharge point have also been identified [41]. To mitigate this issue, the municipal government built the Chía II treatment plant, seeking to treat 70% of the wastewater that reaches the Frio River, a body of water that is also deeply affected by municipal discharges and that flows into the Bogotá River. The Chía II plant began operation testing in February 2020 [43].

The next station at Puente de la Balsa (No. 42) is highly impacted by pollutants, since it receives significant discharges, including discharges from the Chía I WWTP. In addition, industrial and rural domestic discharges have been identified in this section, a situation worsened by the high number of water hyacinths found in this area of the river, which causes greater retention of suspended particles [44].

In the next section of the river system, the Rio Frio and downstream and Rio Frio stations No. 75 and No. 10, which were built to evaluate the behavior of the Frio River, an effluent of the Bogotá River, reported lower pollutant concentrations in some periods, especially for the first station. This is commonly caused by the dynamics between the hydraulic, morphological, and water quality characteristics of the water body [45], which, in the case of the Rio Frio, constitutes a fluvial and alluvial valley. For this reason, the area usually becomes flooded during the rainy season [46]. This process can help to dilute pollutants, as is supported by the fauna still present in the area. In addition, another influencing factor that may affect the first section of the river is that it flows through the municipality of Chía, where the river system does not receive significant urban discharges. Here, some of the wastewater produced in this municipality is treated by the Chía I WWTP, which mitigates its impact in this area. However, as evidenced by the data, low contamination concentrations are not constant. This may be because the river receives domestic and industrial discharges as it passes through the municipality of Cajicá and the entrance to Chía. Nevertheless, the downstream Rio Frio station (No. 10) exhibits an opposite dynamic, generated by the multiple discharges it receives. In fact, in 2018, 35 wastewater discharge points were identified—three were agricultural, 15 were rainwater, 15 were domestic water, and two were industrial [41]. The construction of the Chía II WWTP is supposed to mitigate this situation, but we will not know how efficient it is until the plant becomes operational.

The Frio River originates in the Páramo de Guerrero in the northeastern area of Zipaquirá and constitutes a structural axis for agricultural development and growth, since it flows through several irrigation districts and provides continuity to agricultural activities [47]. According to reports, this water source has not yet been considered as an alternative source of drinking water because it exhibits high concentrations of lead and heavy metals. In fact, the 2016 Quality Index issued by the Regional Autonomous Corporation (CAR) states that near the river mouth between the Frio and the Bogotá rivers, the water quality decreases by 20%, which is a level considered to be unpleasant for developing the ecosystem and aquatic life in said body of water [41]. Likewise, researchers have identified issues in the area, such as deforestation, eucalyptus trees, pasturelands, single-crop farming, e.g., potatoes and flowers, invasive acacia species, and inadequate canalization, which also trigger contamination through phytosanitary products, chemicals, and agricultural waste runoffs [47]. Although a significant decrease in pollutant concentrations is expected, the projections from the Chía development plan remain uncertain, due to the conurbation of the municipalities surrounding the city of Bogotá. Furthermore, to foster municipal urban development, the construction of 6–12-story buildings and an area of ~300 ha have been approved for urban expansion [48]. This will undoubtedly boost population growth and, in turn, increase wastewater generation, thus affecting the new plant's effectiveness.

As was observed at the station in the municipality of Cota, No. 30, in the first two years, large total coliform concentrations were reported. However, these concentrations somewhat decreased in 2012-01 and 2014-01, before increasing again and maintaining similar values. For fecal coliforms, such as *E. coli*, a significant increase in concentrations was observed. At this point, this behavior was related to different situations occurring in this municipality. Cota has an active Wastewater Treatment Plant (WWTP) located in Vereda El Rozo. The municipal sewer system covers 97.65% of its urban area and 68.56% of its rural area, using a combined system. However, there are still several natural drains and spillways (fences) in the rural areas [49]. Despite this sewer network coverage, wastewater treatment is still not optimal. For example, the El Rozo WWTP can only treat 13.96% of the wastewater produced in the area. In addition, this plant underwent an optimization process in 2016, during which time it remained nonoperational and did not treat any wastewater at all. However, even after these enhancements, it still has not been able to effectively meet the demand [50]. According to the Environmental Report issued by the municipality, 85.94% of the area discharges wastewater directly into the Bogotá River from the Pueblo Viejo discharge point. For this reason, the construction of a new WWTP has been planned. This new treatment plant was expected to start operations at the end of 2019. At the time of writing, no reports of its commissioning have yet been received. In addition, 73 discharge points have been identified, of which only 5 have been officially permitted [49]. One of the conflicts that also significantly impact water source contamination is the location of the municipality of Cota, which has been experiencing accelerated urban and industrial expansion. For example, this municipality hosts numerous industrial parks, such as Siberia [51]. Furthermore, their industrial discharges have not been characterized and, according to the latest analysis conducted in 2014, they constitute the largest pollutant load in the river due to the lack of a treatment system and the mixing that takes place within the sewer system, wherein domestic wastewater, industrial wastewater, and rainwater are mixed before being directly discharged into the Bogotá River [49]. According to Agreement 43 of 2006, this section of the river is expected to reach Class-IV quality parameters, which includes restricted agricultural and livestock use, especially considering that this section is used to supply irrigation and drainage to the La Ramada district. Still, according to a 2016 report, only 20% of this objective is being fulfilled [49].

Next in the watercourse, the Puente La Virgen station, No. 43, is located within the municipality of Cota. According to the study conducted, contamination at this point in the river is due to an invasion from the riparian buffer zone, which the municipal Territorial Organization Plan (POT) sets at 100 m for the Bogotá River. During this study period, both fillings and droughts were evident in areas surrounding the water body. In addition, this area has become a dumping ground for wastewater, garbage, and chemical waste from industrial establishments dedicated to grazing, farming, and some secondary sector industries [52]. This decrease may be due to the fact that the Regional Autonomous Corporation (CAR) has recently established a protection and conservation treatment area under the Central Savannah Association of Municipalities. Nevertheless, since this basin constantly suffers from moderate water stress, it still remains under conditions of contamination [53].

The performance of the Rio Chicú station, No. 74, is noteworthy, given that, in fact, this is one of the stations with the lowest concentrations. This may be due to the fact that the Chicú river is located in the municipality of Tabio, which has a wastewater treatment plant (WWTP) that reduces the sludge and microorganisms found in this body of water, thus complying with the maximum permissible values. In addition, since 2016, the municipal government managed the Tabio Territorial Organization Scheme before the

relevant authorities, in accordance with the new Basin Organization and Management Plan (POMCA) guidelines for the Bogotá River [54].

In the case of the LM Vuelta Grande station No. 58, it continues to exceed the values allowed by the current regulations. According to an assessment conducted in 2015, the urban municipality of Tenjo has a wastewater treatment plant and uses two main purification processes: an anaerobic piston-flow reactor (RAP) and an oxidation pond. As these treatment units lack sufficient capacity to treat the total amount of wastewater generated throughout the year, all excess wastewater is left untreated and is discharged directly into the Bogotá River, where it eventually reaches the LM Vuelta Grande station No. 58. In addition, the oxidation pond presents some deformities caused by gases emanating from the decomposing organic matter due to poor maintenance, which reduces the hydraulic capacity of the pond [55].

In the case of the Juan Amarillo station No. 22, this receives its name from the eponymous wetlands; these wetlands work as a buffer pond and are used to prevent flooding of the Juan Amarillo River. The outlet or discharge from this river to the Bogotá River is located downstream. The increase in concentrations at the monitoring point is due to multiple erroneous connections making direct contributions to the wetlands, as well as to the amount of bovine and hog feces generated in the reserve [56]. This section of the river is afflicted by a lack of environmental awareness, illegal settlements and dwellings, fraudulent actions by people seeking to avoid paying utility bills, the growth and development of neighboring buildings, and total ignorance of the applicable environmental regulations [57].

Another station that shows unusual circumstances is the one located at the El Salitre WWTP, given the values recorded at the WWTP. Overall, these values are not justifiable as they should be in compliance with the regulations, since the effluent discharges are of water that is previously treated by the WWTP. Hence, this treatment plant is not playing its part properly. This may be due to the fact that the Bogotá urban drainage system (Salitre Channel–Salitre WWTP–Bogotá River) lacks a comprehensive scheme, which destabilizes the plant during contamination peaks. In addition, the Salitre channel exhibits low flow-rate speeds due to backwater and water storage effects, thus leading to the sedimentation of solids and organic matter. However, the structure and functionality of the plant are also inefficient, since it is not able to treat water received during the first few minutes of rainfall, which contains large pollutant loads from garbage and waste [58]. Currently, the El Salitre WWTP is being expanded and optimized to treat 7.0 m³/s and prevent at least 450 t/month of garbage from reaching the Bogotá River. If this is successful, the pollution levels reported in previous years are expected to decrease [59].

The Cortijo station No. 39 was evaluated; it can be determined that here, the concentrations were caused by a number of cement industries operating in the area that use water to wash their aggregates and clean their equipment and plants. The waters are discharged completely untreated, or with low-quality treatment, into the Bogotá River, thus increasing the presence of sludge and, in turn, significantly increasing organic matter. Given the high load of organic matter transported by this tributary and the inefficient treatment of the El Salitre WWTP, the Rio Bogotá reach high levels of contamination [44].

The dynamics of the Jaboque station No. 28 show that concentrations did not undergo massive changes over time. This is because this station is located in the Jaboque wetlands, which are separated from the Bogotá River by dams to prevent river waters from flowing into the wetlands. This way, the wetlands discharge into the river but not the other way around, thus preventing the wetlands from functioning as buffer zones. In addition, at least 95% of the sewer wastewater was reduced due to the creation of the Capital District Wetlands Policy, as per Executive Order 624 of 2007 [60], wherein these wetlands were declared a wildlife sanctuary. For this reason, their contamination rates are minimal and fully comply with the corresponding regulations [61].

As it passes through the town of Engativá, the river system is faced with a problem; this section of the river flows through a community with no environmental awareness, in addition to the wastewater discharges from domestic, commercial, and industrial activ-

ities [27], coupled with inadequate solid waste management. Hence, a large part of this waste ends up on the Bogotá riverbed, causing the proliferation of disease vectors, offensive odors, and general deterioration around the area [62].

The community of Engativá has a significant hydrological system consisting of either the Salitre or Juan Amarillo river, in addition to three wetlands—Jaboque, Santa María, and Juan Amarillo. Near these buffer zones, there are hazardous areas that are prone to landslides and flooding, as well as to sewer, garbage, and excrement discharges produced by the surrounding population [63]. This improper management of liquid and solid waste (burning and agglomeration) produced by anthropic activities leads to favorable environments for the spread of pests, mosquitoes, rodents, bad odors, vector-borne diseases, and the continuous deterioration of the environment [62].

The population of the community of Engativá is ~797,000 inhabitants (11.6% of the total population of Bogotá), representing the third-largest region in terms of population. In addition, 20,579 Bogotá businesses operate in this area, representing 9% of all city businesses. The businesses operating in this community are mostly service-based (73%), industry (19%), and construction (5%) businesses [64].

In the case of the Ramada station, No. 53, this is an irrigation and management station for swamps and ponds within the Bogotá River basin program. Hence, this agricultural area is being contaminated with water from the Bogotá River, thus negatively impacting the environment due to the contamination levels reported in its middle basin [65]. Considering that Executive Order 1594 from 1984, which still remains in effect, establishes that the most probable number (MPN) should not exceed 5000 for total coliforms and 1000 MPN/100 mL for fecal coliforms when the water resource is used for irrigating fruits that are consumed unpeeled and for short-stemmed vegetables. The water quality is now expected to be in a better condition even when there are no records because, since 2019, the Regional Autonomous Corporation has been working on the recovery of the Bogotá River to prevent its degradation, especially in agricultural areas [66].

The Fucha River Basin, which originates in the El Delirio forest reserve in the Cruz Verde Páramo, flows into the Bogotá River, covering an area of 12,991 urban and 4545 rural ha, corresponding to the eastern hills of the city [34]. This basin includes the communities of San Cristóbal, Antonio Nariño, Los Mártires, and Rafael Uribe. This is the apparent reason for the maximum values of fecal coliforms obtained due to domestic, commercial, and industrial wastewater discharges. Many of these populations are illegal settlements, Strata 1 and 2, with a serious shortage of infrastructure and public spaces [67].

The Fucha River collects all the sewer wastewater from downtown Bogotá, and, from the industrial zone (Américas, Calle13), the wastewater from numerous slaughterhouses and the community of Fontibón is collected, comprising a total area of 16,390 ha that discharges directly into this river [34].

Due to the aforementioned issues, the Fucha River currently ranks as the second most polluted river basin in the city. The discharges from this river into the Bogotá River are calculated as being 65% industrial waste and 35% domestic waste. On a daily basis, the Fucha River discharges at least 590 t of solids and 274 t of biological waste into the Bogotá River, of which 107 t comes from dwellings and the rest comes from businesses and industries [34].

Our analysis confirmed the degradation of water quality for agricultural use. In fact, the concentrations of coliforms follow an exponential trend, which is related to the behavior of the Fucha River index [35]. However, the Territorial Organization Plan for the Fucha River comprises an ecological corridor that seeks to preserve natural channels within the city. However, this micro-basin has few green areas due to its high level of urbanization and industrialization, which fact has also brought about complex usage conflicts that have hindered the proper management and recovery of the river [68].

Continuing the analysis, the Tunjuelo River basin represents the largest of the three rivers flowing through the capital city. It originates in Los Tunjos Lake in the Sumapaz Páramo, at an altitude of ~3450 masl. The river basin is formed by three main channels—the

Mugroso, Chisacá, and Curubital rivers—with a length of 73 km. It is located in the southeastern part of the city of Bogotá and runs through the municipality of Soacha. The river basin covers an area of 41,534 ha, including the communities of Usme, Ciudad Bolívar, Kennedy, Tunjuelito, Rafael Uribe, San Cristóbal, Puente Aranda, Antonio Nariño, Bosa, and the municipality of Soacha [69]. The Tunjuelo River basin plays a critical role in supplying water to the southern areas of the city of Bogotá [70]. This basin is classified into the upper, middle, and lower basins, with the upper and middle areas being rural, while the lower basin is mostly urban. The upper basin is located between Lake Tunjos in the Sumapaz Páramo and the La Regadera dam. The middle basin extends from the La Regadera dam to the Cantarrana dam, very close to Quebrada Yomasa. The lower basin covers the area from the Cantarrana dam to the mouth of the Bogotá River. This area reports the greatest anthropic incidence, leading to higher contamination rates [69].

The Tunjuelo River faces various socio-environmental conflicts, such as the application of pesticides in crop areas, contamination by tanneries, mining activities, contamination due to its proximity to the Doña Juana sanitary landfills, agricultural activities in the conservation areas, danger due to hydraulic phenomena, land use issues, legal and illegal settlements, and extraction of construction materials, among others [70].

According to reports from the downstream Tunjuelo River station No. 13, the pollutant load at this point is mainly generated by the pollutants provided by the Tunjuelo River as it flows into the Bogotá River. A large percentage of the domestic, industrial, and commercial wastewater from the city's sewer system is discharged into the Tunjuelo River [71]. Alternatively, a large part of the leachate produced by the Doña Juana landfill eventually falls into the Tunjuelo River, a situation that worsens whenever the river flow decreases at times of drought and due to anthropic actions in the upper river basin. In addition, the pollution load carries mining wastewater and solid waste, which has turned this river into a complete sewer [72]. Although there is a leachate treatment system in the landfill, it can only treat 15 L per second, which falls short of the 25 L per second actually generated in 2017. This means that many pollutants that remain untreated or that are partially treated are discharged directly into the Tunjuelo River, which, starting from this point, runs through four other communities before flowing into the Bogotá River [73].

On the other hand, at the Balsillas River Station, No. 72, another contributor to the contamination of the Bogotá River basin is the Balsillas River sub-basin, which is part of its middle river basin. This body of water is a contributor of high-impact pollutants associated with the presence of coliforms. In addition, heavy metals are also an important factor because most of the activities developed in the area use raw materials with a high content of elements such as cadmium and lead in their production processes [74].

After this point, the municipality of Soacha is the main contributor of pollutants to this river. The municipality is located in the southern part of the Bogotá savannah, bordering the city of Bogotá to the west, at an altitude of 2600 masl. The municipal territory has a total area of 184.45 km², with an urban area of 19 km², a rural area of 165.45 km² and a population of approximately 535,000 inhabitants [75]. The Soacha River is highly polluted, as seen in the results from the Río Soacha station, No. 79, due to the presence of TC in its alluvial aquifers and fans. This is mainly due to biological and industrial factors and an average concentration of biodegradable organic matter that is outside the limits established by the regulations [76].

Next is the station of Puente Variante Mondoñedo Bridge, No. 60; in this area, the Bogotá river has already passed through several communities in the upper and middle basin, including the city of Bogotá DC and the municipality of Soacha, among others, receiving large amounts of domestic and industrial wastewater [77]. These values far exceed the water quality objectives established by the Regional Autonomous Corporation (CAR) for the year 2020 in Agreement 43 of 17 October 2006, "by which the water quality objectives for the Bogotá river basin to be achieved by the year 2020 are established", thus setting a maximum value of 7 mg BOD/L and a maximum permissible TC concentration value of 2.0×10^4 (MNP/100 mL) for this Class-II zone [78].

When evaluating the upstream Salto Tequendama station, No. 18, upon reaching the Tequendama Falls, due to the geomorphology of the area, which forms a natural 257-m-high waterfall [79], and the hydraulic characteristics of the water body at this point, the flow rate of the river increases, dragging garbage, colloidal solids, and dissolved solids from the upstream basin. This may account for the high levels of coliforms recorded in this section of the river [80]. Agreement 43 of 2006, issued by the Regional Autonomous Corporation (CAR), sets forth a maximum limit of 2.0×10^4 (MPN/100 mL) for Class IV. However, the values historically recorded by this station well exceed these objectives, as defined by the Corporation [78]. At Tequendama Falls, the Bogotá River leaves the savannah and enters the Tequendama archeological site in the province of Cundinamarca. The oxygenation it receives through this waterfall allows the river to recover part of its macrobiotic life [81].

As reported at the Quebrada La Cuy municipal discharge point, at this stage, high levels of TC and *E. coli* concentrations are recorded, mostly due to fecal contamination from animals. In 2010, the Regional Autonomous Corporation of Cundinamarca conducted a hog farm census of the area. The results revealed that 17,921 hogs were kept in 117 farms, none of which evidenced optimum waste-disposal systems. The discharges generated by hog farms in the area, in addition to producing bad odors, also directly affect the water in the middle basin of the Bogotá River and the waters near this section, which are used for animal consumption [82].

Finally, the Quebrada Honda No. 67 station is located in the last sections of the middle Bogotá River basin; the Quebrada Honda stream acts as a dissolution system for the pollutants that reach this point, considerably reducing both TC and *E. coli* levels. The Quebrada Honda stream is located within the Tequendama province in the department of Cundinamarca, mainly encompassing the municipalities of Tena and Bojacá. This sub-basin covers an area of ~1979.56 ha and runs at a height of 800–2550 masl [83]. These ameliorating effects are mainly due to the fact that a large part of the Quebrada Honda sub-basin is located in a protected forest reservation [84]; consequently, the anthropic effects on this body of water are minimal.

These agreements and measures were implemented to protect the Guacheneque Páramo, where the Bogotá River originates, as well as to manage the different industrial, agricultural, and livestock discharges, repair the river and its riverbed, and commission WWTPs [85]. As the consequences from river basin contamination increase, legal actions have become the go-to mechanisms for protecting environmental rights, even leading to work aimed at cleaning up the Bogotá River [85].

Throughout the entire middle basin of the Bogotá River, higher levels of coliforms and E. coli than the ones provisioned in Executive Order 1594 from 1984 on water and wastewater have been recorded. These standards establish a limit of 2.0×10^4 MPN/100 mL for TC and 2.0×10^3 MPN/100 mL for *E. coli*. All assessments included in this study are compared against these benchmark values. As evidenced in the aforementioned regulations, none of the sampling points comply with maximum permissible limits, except the Rio Frio station, No. 75, from 2009-02 to 2019-02, the downstream Jaboque station, from 2008-02 to 2019-02, the Quebrada Honda station, No. 67, from 2011-02 to 2019-02, and the Rio Chicú station, No. 74, from 2011-01 to 2019-02, where a decrease in fecal coliforms (E. Coli) is evidenced. The latter case is probably due to the conditions of the rivers that flow into this section of the river basin, as well as to a decrease in the contributions from the different municipal activities. For this reason, the water body becomes re-aerated, increasing by small amounts the presence of dissolved oxygen, especially after 109 km of the Bogotá River, exactly where it meets the Frio River [86]. Oxygenation helps the aerobic microorganisms in the water to breathe, which can then fulfill their function of naturally decontaminating the water. For this reason, the physicochemical conditions and the biological activity of the tributaries and effluents of this water resource are extremely significant [87].

5. Conclusions

This study concludes that, in the case of the middle Bogotá River basin, TC and *E. coli* concentrations are significant, since they exceed the permissible values established by current regulations. The analysis conducted for each year from 2007 to 2019 evidenced contamination in the water body, especially in the El Salitre WWTP, downstream Engativá, downstream Rio Fucha, and downstream Rio Tunjuelo stations, among others. Nevertheless, TC and *E. coli* concentrations have decreased in four stations—Rio Frio, Quebrada La Honda, the Jaboque discharge, and Rio Chicú—mainly due to the oxygenation, geomorphology, and aeration processes where anthropic impacts are minimal. In these sections of the Bogotá River, due to the natural characteristics of the water body and contributions from its tributaries, the concentration levels of these pollutants are considerably reduced.

Even though specific sections of the riverbed have been recovered over the years through different environmental programs conducted by the Regional Autonomous Corporation (CAR), as well as via an increased environmental awareness in some areas, the current state of the middle basin of the Bogotá River remains unsatisfactory. In fact, its current condition is unacceptable due to the different activities that occur near the riparian buffer zone of the river, which brings about uncontrolled domestic, industrial, and/or commercial wastewater discharges, an increased number of illegal settlements, and poor adherence to the Territorial Organization Plan (POT) in different municipalities. Likewise, inappropriate organic and inorganic solid waste management also favors the development of these fecal concentrations found in the surface waters of the river.

All these variables affecting the middle basin of the Bogotá River have a negative impact on public health and the environment, since this water is used to supply drinking water to a few communities outside Bogotá, as well as irrigation systems for crops intended for human consumption, causing gastrointestinal diseases to the human body due to its high content of coliforms and other toxic substances. For this reason, more WWTPs are expected to be implemented in the municipalities bordering the river, and significant improvements in the treatment capacities of each unit are required. In addition, new technologies should be implemented, such as solar water disinfection technologies in individual units and phytoremediation, where plant species such as algae are used to reduce the number of microorganisms favoring the development of communities.

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Appendix A



Figure A1. Bogotá River monitoring stations. Source: prepared by the authors, 2021.

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