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Physicochemical Parameters in the Generation of Turbidity Episodes in a Water Supply Distribution System

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Abstract: Water is necessary for the development and support of human life. The ability of water to supply the different populations has different origins: water taken from river diversions, water from underground catchments, water from lakes and reservoirs, water from the recirculation of treated water, etc. Episodes of turbidity and color changes in the water supply in pipe distribution systems are non-isolated problems that occur in many cities and towns. In particular, sedimentation in water supply pipelines and the subsequent resuspension of these particles in the system have created the need to investigate the processes and variables that promote turbidity episodes, including why, when, and where these episodes occur. In this study, different physicochemical parameters were investigated and analyzed in the water supply distribution network of the city of La Coruña (northwest Spain) through a pipe monitoring panel under real operating conditions. The supply waters come from the Mero river basin, a basin made up of siliceous materials, a unique condition with respect to the majority of studies that have been carried out using waters coming from basins made of basic materials. In this case, the relationships between different variables were studied, including the number of particles, particle size, turbidity, color, concentration of particulate materials, and mineralogy. In this article, only those parameters that are better correlated have been noted. The results revealed a predominant relationship between color and the concentration and mineralogy of particulate materials, as well as between turbidity and the number and size of particles.

Keywords: water quality; turbidity; water supply networks; sedimentation; color

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1. Introduction

Drinking water is water that can be used for human consumption. Thus, parameters such as pH, temperature, concentrations of dissolved species, type of dissolved species, turbidity, etc., must be controlled in order to comply with certain regulatory limits. These parameters are not constant, but can vary with the season of the year [1–3].

The city of La Coruña is located in the northeast of the Iberian peninsula on the left bank of the Mero River, whose mouth ends in the Burgo estuary. The city and its adjoining municipalities house 400,000 inhabitants, a number that increases in the summer.

To guarantee sufficient resources to meet demand, the Abegondo-Cecebre Reservoir was established, which has a total volume of approximately 22 hm^3; recently, water has also been stored in the old mining pit of Meirama, at the head of the Barces river basin.

The Cañas drinking water treatment plant (DWTP) is located on the Barcés River, and the A Telva DWTP is located 7 km downstream of the reservoir.

The water distribution network consists of pipes with different characteristics: fiber cement, grey cast iron, and ductile cast iron with cement mortar or PVC coating. From A Telva, the pipe system distributes water to different points in the city of La Coruña and its neighboring municipalities (Figure 1).

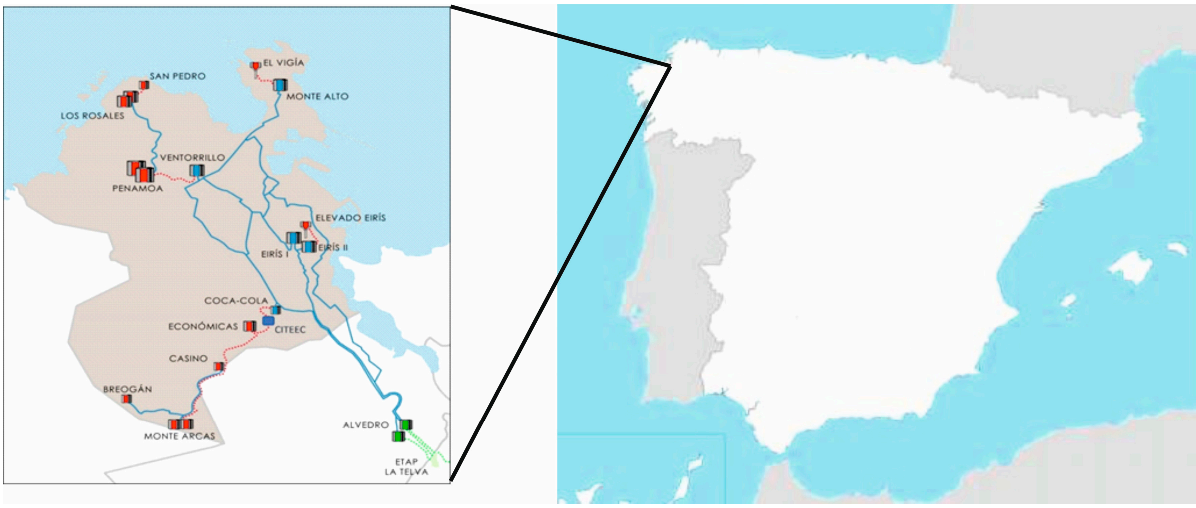

Figure 1. Simplified diagram of the pipeline distribution network from A Telva to La Coruña.

When episodes of turbidity and color change began to occur, actions were immediately carried out to analyze and characterize different sections of pipes in the distribution network that were being replaced. This provided a preliminary analysis of the sediment and resuspended particles in the distribution network which were causing episodes of water turbidity and discoloration.

The occurrence of similar problems in other distribution systems corroborates that turbidity is not a unique problem of the pipe network of La Coruña [1,2], but is similar to events in other distribution and supply systems in different cities and urban centers, which leads us to assume that the problem is very relevant.

The study carried out follows the methodology applied by other authors, although in this, case the waters that serve as supplies come from silica basins, a fact that is not stated in other studies that have been consulted. Generally, the problem of sedimentation in pipes is associated with the formation of carbonates. The previously conducted studies analyzed water from basins containing carbonated or sulfated materials (calcites, dolomites, gypsum, etc.) [4].

Thus, the general problems that cause turbidity can be classified into three types:

(a) Problems associated with the resource itself: direct pumping of water from river catchments to supply areas without initial filtration or the direct pumping of groundwater from underground sedimentary aquifers with poorly designed filtration. In both cases, the collected water carries suspended materials (mechanical action) or dissolved materials that can precipitate (chemical action); this occurs in many cities of Latin America, India, etc. Turbidity problems are associated with water from sedimentary basins loaded with silt that can infiltrate into usable aquifers or that is suspended in the river itself.

(b) Problems associated with the purification process: this process is influenced by discharges of dissolved species and pollutants in different tributaries and rivers and the use of treatment methods that inadequately remediate various discharged products and pollutants, causing inefficiency, such as that which occurs in urbanized and industrialized areas. Variations in water composition make it necessary to dynamically adapt the treatment approaches [5].

(c) Problems associated with the distribution piping system, such as the lining materials of the pipes, which can cause or favor turbidity as a function of two parameters: (a) the type of material, and (b) the age of the pipe. This is the case for many areas, both inside and outside of Spain [6–8].

Not all solutions to the above problems are satisfactory, and the same problems reappear over time, which suggests that the origin of turbidity and color episodes is not unique, but a combination of the three above causes.

2. State of Knowledge

Regarding the three causes listed above, there is abundant literature regarding the adhesion and behavior of particles on surfaces under fluid flow.

The existing studies can be classified according to three approaches: (a) hydraulic effects, (b) chemical effects, and (c) biological effects. These studies analyzed the composition of the sediments that are produced in distribution piping systems, the mechanisms of adhesion and formation of flocs and colloids, the resuspension processes of sediments, and their relationship with turbidity [1,9].

From a hydraulic point of view, several experimental studies have shown that the sedimentation rate of particles is greatly affected by the roughness and friction factor [10]. Thus, a distinction is made between fluid velocity and sedimentation velocity, which are related parameters. The movement and settling of rigid particles in various media, including under the effect of the boundary layer, have been investigated by Clift et al. [11], Lai and Nazaruff [12], Friedlander and Johnstone [13], Kneen and Strauss [14], Owen [15], Liu and Agarwal [16], and McCoy and Hanratty [17], among others.

From a chemical and biological point of view, studies have addressed the composition of materials likely to form sediment in pipes. Different cations dissolved in water, especially iron and manganese, are naturally derived from the dissolution of minerals due to redox reactions and the erosion of the source basin near the rock–water interface [18–23].

With respect to the mechanisms of the chemical formation of particles in the liquid phase, the adhesion and the formation and resuspension of colloidal flocs have been studied in laboratory tests by applying cell techniques (jar test) [24–28].

Some authors have studied the formation of flocs of aluminum, with cations other than manganese and iron, in certain pipes [24,29,30]. In certain renovated sections of the distribution network, the sediments were analyzed, and the precipitation of mainly iron, manganese, and aluminum oxides verified that there was no bacteriological activity.

Biologically, some metals improve the absorption of nutrients in living organisms [31], according to the mineral species present in water and the capacity of the organism to mobilize nutrients in various compounds through the action of different catalytic enzymes [32]. Therefore, the concentrations of metal ions are also very important with regards to the absorption and accumulation of nutrients [32,33].

From a mechanical point of view, the resuspension of sediments is related to the shear stress in the lower surface of the network. A sudden increase in velocity leads to an increase in shear stress, and when the shear stress is large enough to overcome the resistance (called critical shear stress), the settled particles begin to move. Shields and Migniot [25] formulated two equations for water with a free surface, and Berlamont [25] formulated one equation for water in pipes.

From the above literature review, it can be seen that sediment is highly complex and its appearance and composition vary considerably in drinking water distribution systems, even when a single water source is used.

Despite this complexity, there are several common components in most sediments that predominantly control sediment properties. In general, elemental minerals include several types of species (Fe, Ca, Al, Mn) that are generally found in drinking water distribution systems, but their quantity differs considerably [34–38].

3. Materials and Methods

For this study, a bypass was built in the water supply distribution network of the city of La Coruña (Spain) that connects the network with a monitoring panel (Figure 2) at the CITEEC point, as shown in Figure 1. The list of instruments installed is as follows:

- Unik 5000 pressure sensors, with a measurement range of 0–5.5 bar and an output signal of 4 to 20 mA, installed at the input and output of the panel.
- One AquaTrans ultrasonic flowmeter (AT 600), with an adjustable measuring range.
- One SIEMENS SITRANS FM MAG 5000/6000 flowmeter, with an adjustable measuring range.

- One Particle Sense particle counter from Pi Instruments, with an internal datalogger that allows for the recording of up to 8 selectable particle size ranges between 2 and 100 microns.
- One multiparametric measurement system for the physical–chemical monitoring of drinking water (micro::station, S::CAN), equipped with an internal datalogger and the following sensors:
    - ○ A pH sensor (PH::lyser V2) that collects measurements within the range of 2–14 pH units with a response time of 30 s and a resolution of 0.01 pH units.
    - ○ A Conductivity and temperature sensor (Condu::Lyser V2) for recording within the ranges 0–500,000 µs/cm and –20 to 130 °C, with an accuracy of ±0.10% and a response time of 60 s.
    - ○ A free residual chlorine sensor (Chlori:lyser V1) with temperature and pH compensation for recording concentrations in the range 0–2 mg/L, with a resolution of 0.01 mg/L and a response time of 120 s.
    - ○ A dissolved oxygen sensor (Oxy::lyser V1) with a temperature compensator, which collects measurements in the range 0−25 mg/L with an accuracy of 0.02 mg/L and a drift < 1% year.
    - ○ A spectrometric probe (Spectrum:lyser V2) with a stabilization time of 60 s and an accuracy of 0.01% for the measurement of:
        - ✓ Color: Range 0–500 Hazen units.
        - ✓ Turbidity: Range 0–100 NTU.
        - ✓ NO_3: Range 0–100 mg/L.
        - ✓ COD: Range 0–50 mg/L.
        - ✓ TOC: Range 0–100 mg/L.
- One Arduino Datalogger system (2 GB), which controls the opening of the solenoid valves and stores the data records of the pressure sensors and flow meter.
- Two GV solenoid valves (21HT5K0Y160), used to regulate the water supply to the monitoring equipment.

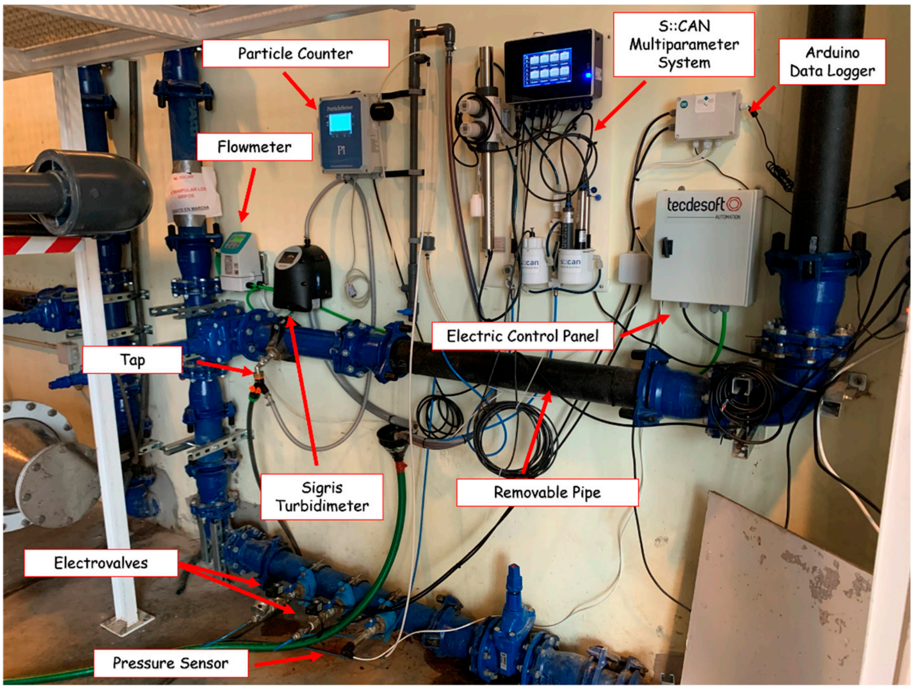

Figure 2. Distribution of relevant elements in the piping panel.

The water supply in the panel was monitored for a year (2020). The equipment installed in the panel provided usable information for a preliminary analysis of the turbidity and discoloration episodes detected in the network.

4. Results and Discussion

The generation of turbidity in pipes is associated with the sedimentation of particles in the water supply distribution system. The sedimentation of particles on a pipe wall in a developed turbulent flow is a fairly common phenomenon.

With respect to the mechanisms of chemical formation of settleable particles formed within the liquid phase, the adhesion and formation of colloidal flocs have been studied as a primary cause of the formation of suspended materials in water generating discoloration and turbidity.

Overall, sediment is the cause of episodes of turbidity and discoloration of water. There are several common components of most sediments that predominantly control their properties. In our case, the detected components were Fe, Mn, and Al.

The relationship between different parameters measured in the panel was analyzed to obtain a pattern of predictable behavior in the distribution system. The variables and parameters that were measured continuously were turbidity, pH, electrical conductivity, dissolved oxygen, temperature, residual chlorine, number of particles/mL, particle size, nitrates, total organic carbon, dissolved organic carbon, and color.

After a year of monitoring, we analyzed the correlations between the different measured parameters to preliminarily quantify and qualify the suspended material in the water, causing these episodes of turbidity. Thus, this study focused on the analysis of the relationships between turbidity and color using different parameters, of which we highlight the following:

Turbidity—number of particles/mL ratio;
Turbidity—particle size ratio;
Turbidity—color ratio;
Color—cation concentration relationships;
Color—particle size ratio.

While the panel is a point in the network at which turbidity episodes can be recorded, it provides only partial, and not total, information regarding what happens in the entire distribution system.

4.1. Turbidity—Number of Particles/mL Ratio

Of all the parameters measured, perhaps the most intuitive relationship that can be established initially is that of turbidity with the number of particles/mL. Note that the turbidity is produced by material that is suspended and transported in the water, that is, not dissolved material, but material that is formed from coagulation or flocculation and that may have sedimented [39]. Several authors have analyzed the importance of the number of suspended particles in turbidity episodes [12]. It should be noted that depending on temperature, pressure, and concentration, the dissolved material transported in water can form flocs that sediment out in the tanks of the distribution network by gravity, as well as in the pipes themselves by mechanical mechanisms or electrostatic adhesion [16,17].

Figure 3 shows the correlation between the total number of particles/mL produced during the year of monitoring regarding turbidity.

Figure 3 shows that after a certain turbidity value, the number of particles/mL tends toward an asymptotic value, such that the increase in turbidity is independent of the increase in the number of particles/mL. An acceptable correlation can be seen.

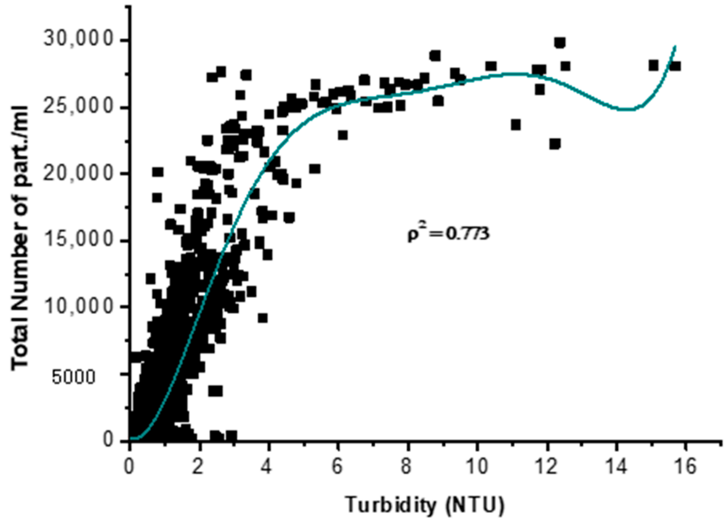

Figure 3. Graph of the total number of particles/mL with respect to turbidity.

4.2. Turbidity—Particle Size Ratio

As we have just seen, there is a direct relationship between turbidity and the total number of particles/mL. However, when considering the relationship between the number of particles/mL of a given size with respect to turbidity (Figures S1–S5), different behavior is observed. The correlation coefficient is also shown in these figures.

Figure S1 shows the number of particles/mL between 2 and 5 microns, with respect to turbidity. The relationship is not biunivocal, since for the same number of particles/mL, there can be two different turbidity values.

Figures S2–S5 show the relationships for the number of particles/mL between 5 and 10 microns, 10 and 15 microns, 15 and 25 microns, and 25 and 50 microns, respectively. In these cases, an increase in turbidity is observed with the number of particles/mL.

Although well-defined trends exist in each case, the influence of each of the different particle sizes on the turbidity variation must be assessed as a whole. Accordingly, there is a substantial difference between particles with sizes greater than and less than 5 microns.

Figure 4 shows the ratio of the number of particles/mL less than 5 microns to that of particles greater than 5 microns, with respect to turbidity. A descending graph can be observed, which indicates that the lower the ratio, the higher the turbidity, which is reasonable: turbidity will increase with a higher relative number of larger particles.

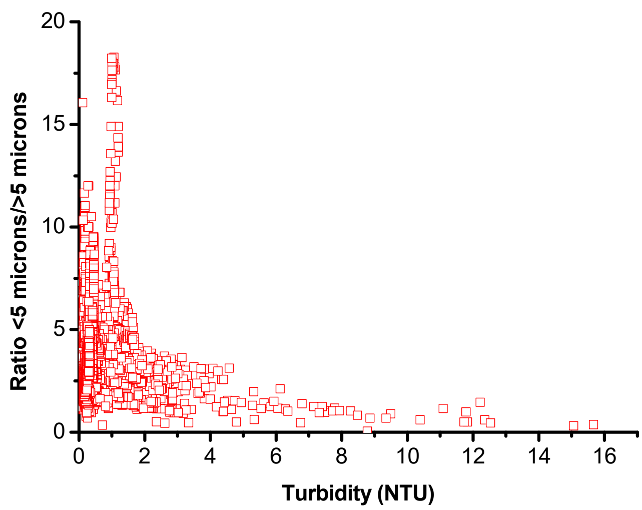

Figure 4. Graph of the ratio of the number of particles/mL less than 5 microns to the number of particles/mL greater than 5 microns with respect to turbidity.

4.3. Turbidity—Color Ratio

One of the most subjective indicative parameters is color. The measurement of color in quantifiable units provides a limit for establishing compliance with current regulations.

However, color is a subjective parameter depending on the observer, since a certain person can perceive a different color than another, even when a water sample is in compliance with the regulated limit.

Figure 5 presents the relationship between color and the measured turbidity. There is no good correlation, since high turbidity is not synonymous with greater discoloration. Thus, to corroborate this finding, tap water samples were taken at various times when there were turbidity episodes and under normal conditions; the results verified that the color (or color perception) depends on the composition of the water.

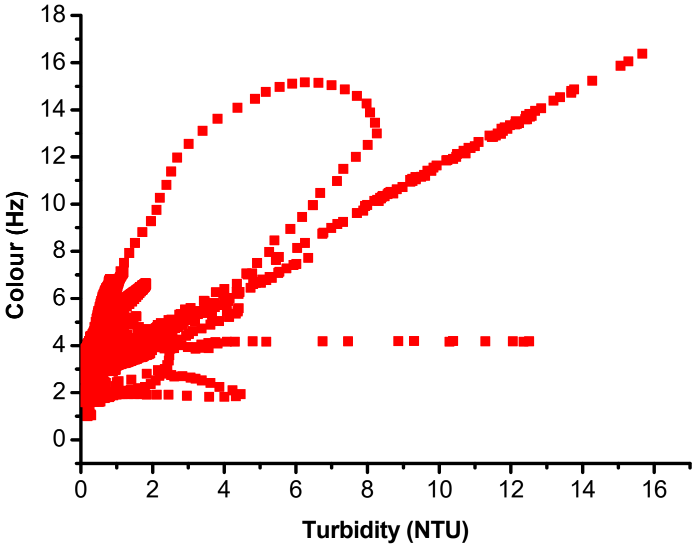

Figure 5. Graph of color with respect to turbidity.

Figure 6 shows photographs of three samples and the corresponding measurements of color (measured in Hazen units), turbidity, and concentrations of particulate iron, particulate manganese (oxides), and particulate aluminum (hydroxide). The sample with greater turbidity (9.2 NTU) has a light color (26 Hazen units) due to the higher concentration of particulate aluminum (7.73 mg/L) compared to particulate iron (3.97 mg/L) and particulate manganese (0.519 mg/L), whose oxides and hydroxides have a gelled appearance.

However, the third sample, which contains more particulate iron (12.28 mg/L) and particulate manganese (2.98 mg/L) compared to particulate aluminum (2.48 mg/L), presents a more earthy color with a higher Hazen unit value (52 Hazen units) than the previous sample, but a lower turbidity (5.25 NTU), which corroborates that turbidity and color are not directly related, but rather depend on the type or nature of metals in the water.

In this case, particulate matter rather than dissolved matter is relevant. As described below, dissolved metals do not have a predominant effect on turbidity or color. In contrast, the particulate matter present in water is the cause of its discoloration [40,41].

4.3.1. Color—Cation Concentration Relationships

Below 5 Hazen units of color, the water does not show discoloration. The change in water color is associated with high concentrations of iron cations and particulate manganese, while with high concentrations of particulate aluminum, gelation is observed (aluminum hydroxide), as shown in Figure 6. However, turbidity is not directly proportional to color (Figure 6). On the other hand, when the calculated concentrations of dissolved Fe, Mn, and Al cations were plotted against color (Figures S6–S8), no clear correlation was observed.

Sample A	Sample B	Sample C
1.33 NTU <6 Hazen units	9.20 NTU 26 Hazen units	5.25 NTU 52 Hazen units
Mn_{part} =0.054 mg/L	Mn_{part} = 0.519mg/L	Mn_{part} = 2.98 mg/L
Al_{part} =0.003 mg/L	Al_{part} =7.73 mg/L	Al_{part} = 2.48 mg/L
Fe_{part} =0.019 mg/L	Fe_{part} = 3.97 mg/L	Fe_{part} = 12.28 mg/L

Figure 6. Color appearance of collected samples; color vs. turbidity.

4.3.2. Color–Particle Size Ratio

Lastly, Figure 7 and Figures S9–S13 show the relationships between particle size and color. It can be seen that there is no marked trend showing an acceptable correlation, such as occurs between particle size and turbidity. This fact indicates that the color is not related to the morphometric parameters of the particles, as explained above. In Figure S14, it can also be seen that there is no clear relationship between the ratio of particles smaller than 5 microns and larger than 5 microns with respect to color.

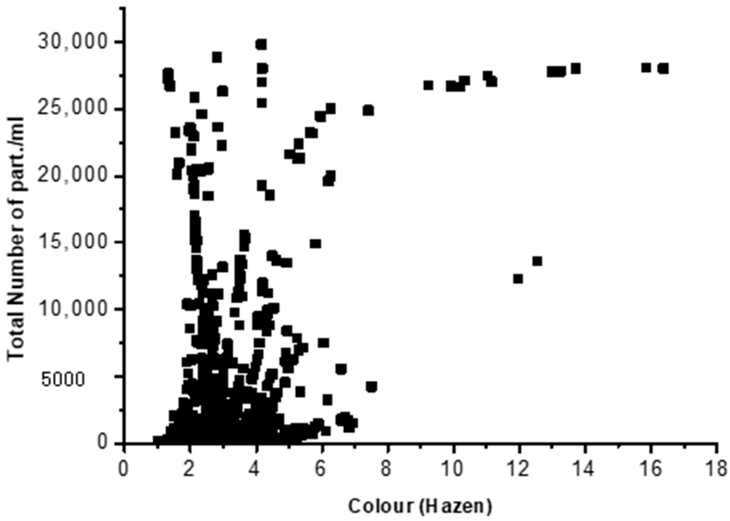

Figure 7. Graph of the total number of particles/mL with respect to color.

On the other hand, the temporal evolution of turbidity, number of particles in their different granulometries, and color have been analyzed in order to determine some pattern of behavior throughout the year.

In Figures 8–10, the temporal evolutions of the turbidity, the number of particles, and the color, respectively, are represented.

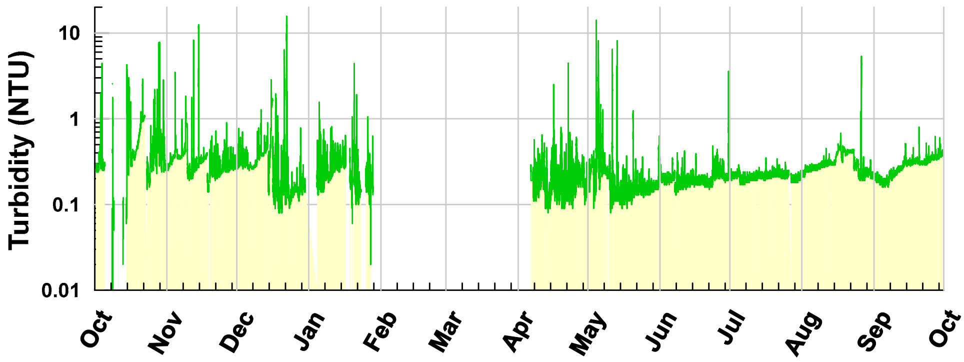

Figure 8. Time evolution of turbidity 2020/2021.

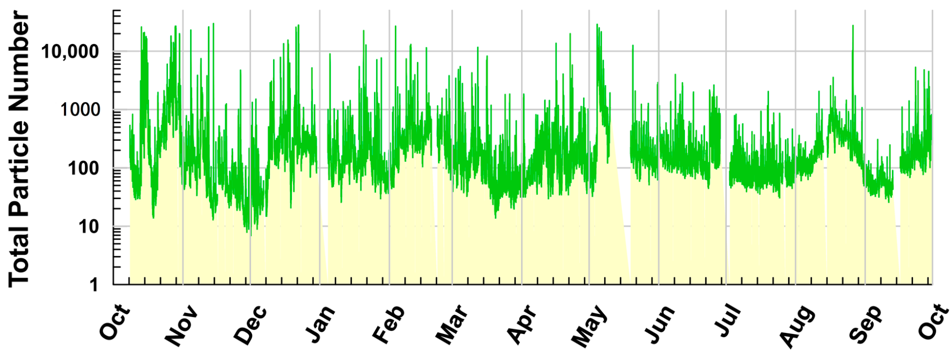

Figure 9. Time evolution of total particle number 2020/2021.

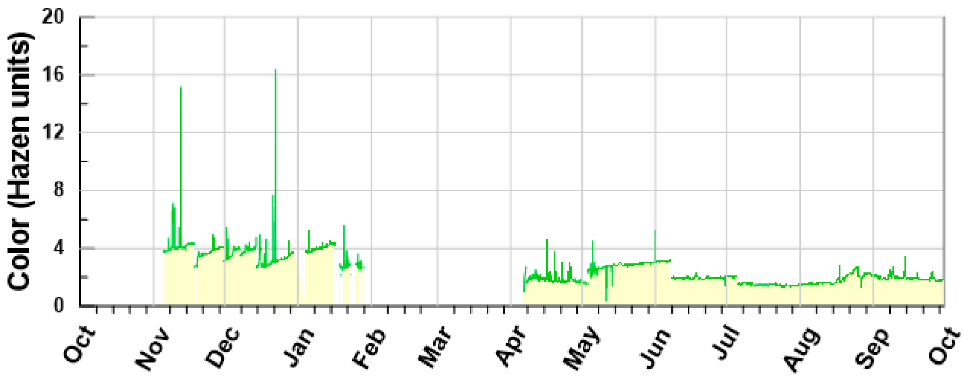

Figure 10. Time evolution of color 2020/2021.

A pronounced temporal variability is observed in the three parameters due to the different actions occurring in the treatment plant. Any action carried out in the plant is transmitted in the instrumented panel. There are some gaps in the graphs because the instrumentation was under maintenance, or it failed.

Figures S15–S19 show the temporal evolutions of the number of particles/mL between 2 and 5 microns, 5 and 10 microns, 10 and 15 microns, 15 and 25 microns, and 25 and 50 microns, respectively. Again, the same variability as for the other parameters is observed.

In Table 1 a statistical analysis of the above parameters has been carried out. The substantial difference in the number of particles/mL in the different granulometric intervals between percentile 5 and percentile 95 can be verified, with a median very dissimilar from the average.

Table 1. Statistical parameters.

Parameter	Mean	Mode	Min.	Q1	Median	Q3	Max	P5	P10	P90	P95	P99
Turbidity (NTU)	0.29	0.20	0.01	0.19	0.23	0.31	1567	0.13	0.15	0.41	0.49	1.41
Color (Hazen units)	2.52	1.96	0.32	1.84	2.07	3.11	1638	1.47	1.54	3.96	4.07	4.36
Total Particle number	458	64	7	77	141	300	29,830	34	47	711	1491	7213
Range 2–5 µm	325	43	20	57	102	220	15,601	27	36	536	1120	5160
Range 5–10 µm	92	12	6	14	28	55	12,631	5	8	125	257	1353
Range 10–15 µm	25	3	0	3	7	15	9986	1	2	34	64	327
Range 15–20 µm	7	1	0	1	1	3	13,932	0	0	8	16	87
Range 25–50 µm	0	0	0	0	0	0	1304	0	0	1	1	6

5. Conclusions

This study provides an initial basis for broader research on the origin of the turbidity episodes in water supply distribution pipelines. In this case, a bypass built in the water distribution network of the city of La Coruña (northeast Spain) was monitored by means of an instrument panel of pipes.

Different variables and selected parameters were monitored based on studies conducted by various authors. Although it is premature to make conclusive statements, certain relationships were observed between the different parameters studied: (a) turbidity and number of particles/mL—turbidity increases with the number of particles up to a certain value; (b) turbidity and particle size—after a given number of particles/mL, turbidity increases with particle size; (c) influence of the number of particles/mL greater than 5 microns on turbidity—turbidity increases with the proportion of the number of particles/mL greater than 5 microns, with respect to the number of particles/mL less than 5 microns.

Notably, it was confirmed that water discoloration and turbidity do not have a direct relationship, but that color is more closely related to the composition of particulate material in the water (concentration of Fe, Mn, or Al). Currently, a broader analysis is not presented because a large sample population is not available for sample collection during turbidity episodes. Currently, there is no instrumentation available for the continuous measurement of particulate cation concentrations, which means that sample collection during turbidity and/or discoloration episodes depends on the operational availability of the collection systems.

Future research will focus on the sampling of particulate material in periods of turbidity in order to analyze the chemical composition of said material. For this, it will be necessary to install programmed equipment that obtains samples from a diversion when the turbidity or the size of the particles exceeds a preset value.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14213383/s1, Figure S1. Graph of the number of particles/ml from 2 to 5 microns with respect to turbidity. Figure S2. Graph of the number of particles/ml from 5 to 10 microns with respect to turbidity. Figure S3. Graph of the number of particles/ml from 10 to 15 microns with respect to turbidity. Figure S4. Graph of the number of particles/ml from 15 to 25 microns with respect to turbidity. Figure S5. Graph of the number of particles/ml from 25 to 50 microns with respect to turbidity. Figure S6. Graph of colour with respect to the dissolved Fe concentration. Figure S7. Graph of colour with respect to the dissolved Mn concentration. Figure S8. Representation of the colour with respect to the dissolved Al concentration. Figure S9. Graph of the number of particles/ml from 2 to 5 microns with respect to colour. Figure S10. Graph of the number of particles/ml from 5 to 10 microns with respect to colour. Figure S11. Graph of the number of particles/ml from 10 to 15 microns with respect to colour. Figure S12. Graph of the number of particles/ml from 15 to 25 microns with respect to colour. Figure S13. Graph of the number of particles/ml from 25 to 50 microns with respect to colour. Figure S14. Graph of the ratio of the number of particles/ml less than 5 microns to the number of particles/ml greater than 5 microns with respect to colour. Figure S15. Time evolution of the number of particles/ml from 2 to 5 microns. 2020/2021. Figure S16. Time evolution of the number of particles/ml from 5 to 10 microns. 2020/2021. Figure S17. Time evolution of the number of particles/ml from 10 to 15 microns. 2020/2021. Figure S18. Time evolution of the number of particles/ml from 15 to 25 microns. 2020/2021. Figure S19. Time evolution of the number of particles/ml from 25 to 50 microns. 2020/2021.

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