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ASSOCIATION PATTERNS BETWEEN RAINFALL AND TURBIDITY IN A MEDITERRANEAN RIVER: THE CASE OF THE LLOBREGAT RIVER (BARCELONA, SPAIN)

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The variation in rainfall in the Llobregat River basin (Barcelona, Spain) and its cyclicality has been studied previously, but not the influence of rain on turbidity. For the first time, the potential correlation between the two variables was evaluated, using a long time series of over 200,000 records from 1995 to 2020. On most days the turbidity was less than 100 NTU, surpassing 500 NTU only on very few days (approx. 5%). The significant linear correlation between rain and turbidity indicates a relationship between both variables, although of low magnitude. Turbidity oscillations were also observed according to the season and year. The time series analysis of data from 39 meteorological stations in the river basin revealed that turbidity can be explained by the rainfall of the previous 1-4 days (1 day maximum).

INTRODUCTION

Mediterranean rivers are characterized by irregularity of flow, extreme hydrological fluctuations, and a profound transformation arising from human activity (Estrany *et al.*, 2010). Of the many parameters measured in river water, turbidity stands out for the complexity of its relationships with physical-chemical, microbiological or ecological parameters.

Turbidity is an optical determination of water clarity. Suspended solids and dissolved colored material reduce water clarity by creating an opaque, hazy, or muddy appearance. Turbidity measurements are often used as an indicator of water quality, based on clarity, and estimated total suspended solids in water (Fondriest Environmental, 2014).

High turbidity in source water is a problem for the purification and disinfection of drinking water, leading to higher costs and often temporary closure of treatment plants (Sabater *et al.*, 2012). In industrial processes, turbidity can contribute to clogged tanks and pipes. The particles can also scour machines, potentially damaging them (WHO, n.d.).

Therefore, knowledge of turbidity behavior in rivers can improve water management efficiency. Suspended solids can be comprised of organic and inorganic materials such as sediment, algae, and other contaminants. However, specific factors can affect turbidity levels in a body of water, such as water flow, point source pollution, land use and resuspension (Fondriest Environmental, 2014). Rainfall, the source of the river water, is another factor, especially when the climate is unpredictable, as occurs in the Mediterranean.

The issue of climate is currently of special interest, as climate-related problems are expected to decrease the future quality of life of the world population. The city of Barcelona, highly dependent on an already stretched water supply, is not exempt from these problems and therefore, in a context of climate change, the study of how source water quality is related to meteorological variables becomes even more important (Sabater *et al.,* 2012). Previous studies have been carried out on the variation of rainfall in the Llobregat River basin and its cyclicality, but not on rain-associated patterns of turbidity; see, for example, "Forecasting Local Daily Precipitation Patterns in a Climate Change Scenario" (Abaurrea and Asín, 2005).

In this study, we focused on some climatic variables and analyzed their behavior and interaction. Variables such as temperature and precipitation refer to the city of Barcelona, whereas stream flow refers to the Llobregat River, which partly supplies the city's water. It is of great importance to foresee how climate change will affect the Mediterranean region, which includes, on a local level, the flow of the Llobregat River (Lopez *et al.,* 2019; X Jiménez-Albán, 2019).

Barcelona has a Mediterranean climate characterized by relatively wet and mild winters, and dry summers. The rainiest seasons are autumn, spring, and winter. The highest temperatures coincide with the three to five months of aridity in the summer, when the area is under the influence of a subtropical anticyclone. There are few days with extreme temperatures, cold or hot, so the maximum and minimum annual averages in Barcelona are moderate, typical of a mild Mediterranean climate (X Jiménez-Albán, 2019; Sabater el al, 2014).

The average annual number of rainy days is 90. However, it is important to clarify that rain rarely lasts for an entire day, and a completely overcast sky is less common than in a continental climate; several consecutive days of rain are also unusual. Summer storms can be strong, but tend to be short, the clouds quickly giving way to clear skies. Snow in Barcelona is a highly exceptional event. The climatic projection for the next years up to 2100 indicate that the river flow will not decrease but the rain regime will change and become more irregular (X Jiménez-Albán, 2019).

DESCRIPTION OF TIME SERIES

A time series of data was provided by the staff of the drinking water treatment plant (DWTP) of Sant Joan Despí (Barcelona), and consists of the hourly turbidity (NFU) measured at regular intervals (hours) by means of an automatic turbidity sensor in the collection of water from the Llobregat River. Turbidity values are validated by plant technicians and stored in a computer system. More than 222,768 hourly turbidity data have been collected and aggregated daily using their mean.

Another data series was obtained from the network of 39 automatic meteorological stations of the Meteorological Service of Catalonia (METEOCAT) located in the river basin (CE, CL, CN, CR, D2, D3, DI, H1, MQ, MS, MV, MW, R1, U3, U4, UF, UG, UI, V5, VO, VP, VT, VU, VV, W4, WM, WN, WP, WV, WW,WY, XA, XB, XC, XF, XL, XT, Y9, Z8), which measure the amount of rain at regular intervals. Accumulated precipitation was calculated from historical data from 1995 to 2020, and linked to the historical series of turbidity values taken at the nearest hour.

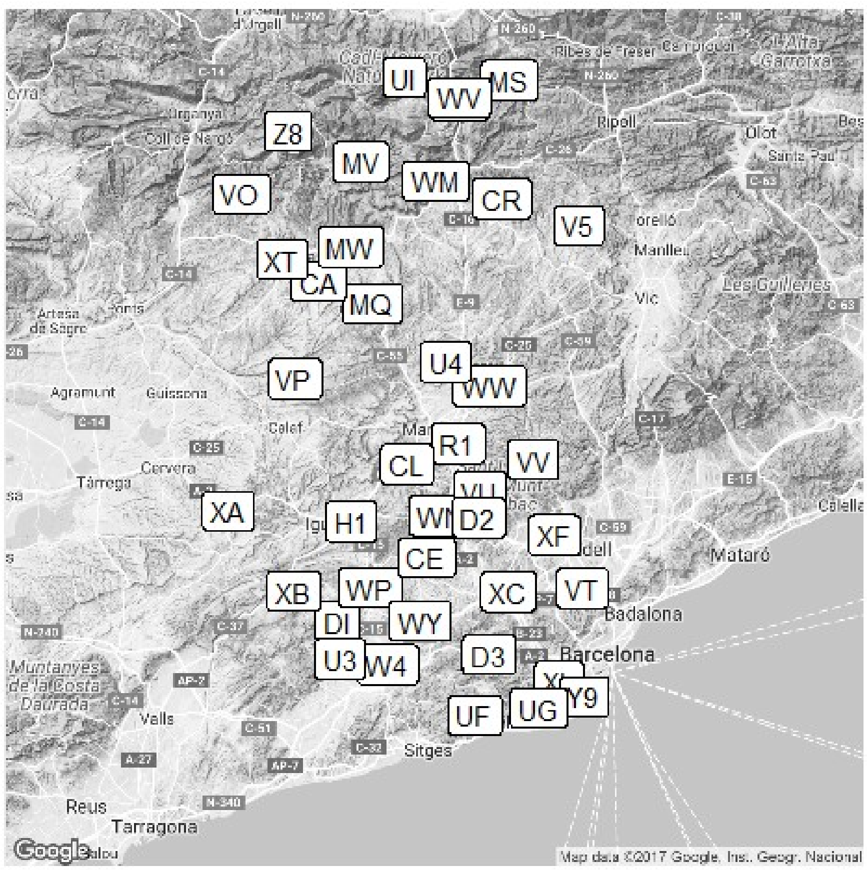

Figure 1: METEOCAT stations in the Llobregat River basin (from Google maps)

The generated database was verified, and the last observation carried forward method was used to impute any missing data, obtaining a reasonably stable time series for this research work. Values of accumulated rain and turbidity were added daily for 9,282 days, although the turbidity data do not begin until 1997 (see Figure 2).

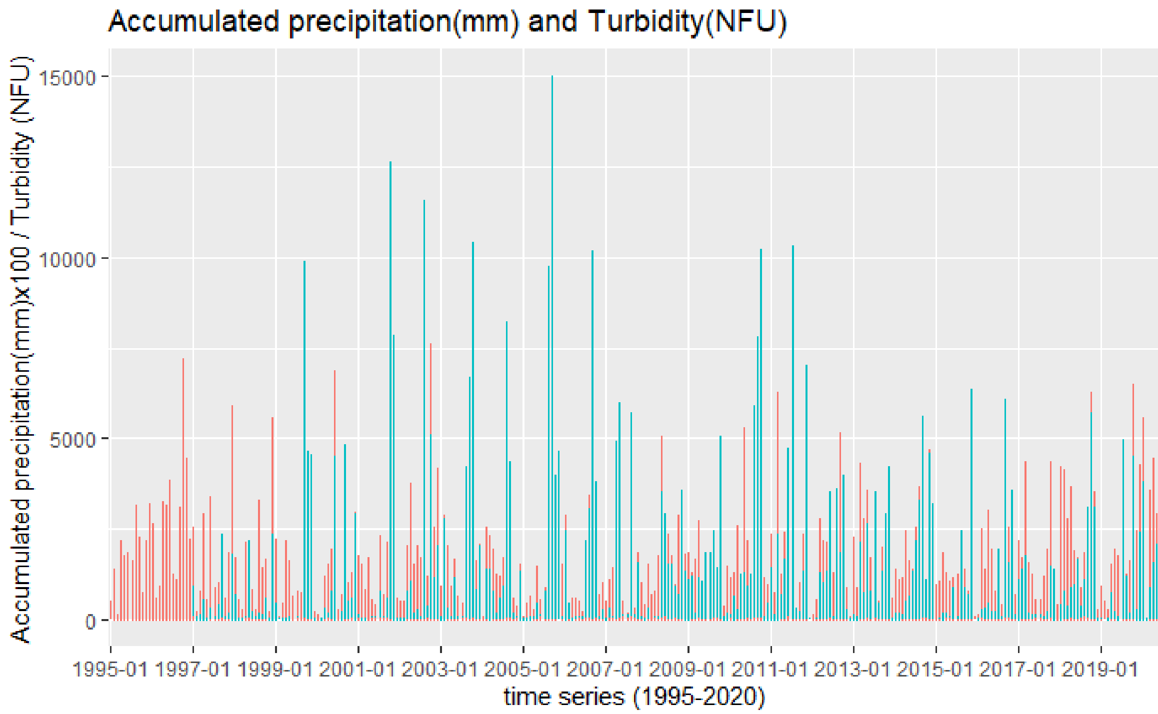

Figure 2: Time representation of accumulated precipitation (mm, red color) and turbidity (NFU, blue color) in the study period 1995-2020.

Looking at Figure 2, which jointly depicts the daily time series of turbidity and accumulated precipitation, it is very hard to spot a pattern of behavior linking the two variables. We therefore carried out a descriptive analysis of the data in search of a relationship or trend that may explain the turbidity behavior of the river and consequently the need for purification of water for consumption.

The main objective of this study was to describe the stored and revised time series, and then identify any association between the precipitation measured by the meteorological stations with the turbidity of river water, looking for possible patterns or trends over time.

METHODOLOGY

The usual methodology for the description and study of time series was used (Wilks, 2011; Jimenez-Alban, 2020). For the descriptive part, methods included frequency histograms, and boxplot representations by year and month.

To correlate the rain and turbidity series, Pearson's correlation was applied, as well as the logarithmic transformation of turbidity with accumulated precipitation. The estimation of the correlation has been complemented with its statistical test. A cross-correlation function (CCF) was used to assess whether there was a pattern of relationship between rainfall before the turbidity value and the turbidity. An additive model was also applied to study the episodes of high turbidity in the DWTP and identify if there was a trend over time.

The chi-square statistical test has been used to compare proportions, for example when comparing different events of interest between days.

A significance level of 0.05 has been considered in the different statistical contrasts carried out. Different libraries of software R version 3.6.1 were used to carry out the analyses in this study.

RESULTS AND DISCUSSION

Once the long time series were processed and refined, the statistical methodology mentioned above was applied and the following results were obtained.

Descriptive study of the time series of accumulated rain and turbidity from 1995 to 2020

Figure 3 shows a frequency histogram representing the observed turbidity distribution, truncated to 500 NTU. Values >500 NTU represent less than 5% of the total. It can be seen that the turbidity was less than 100 NTU on most days, rarely surpassing 500 NTU, a high threshold value used in water purification.

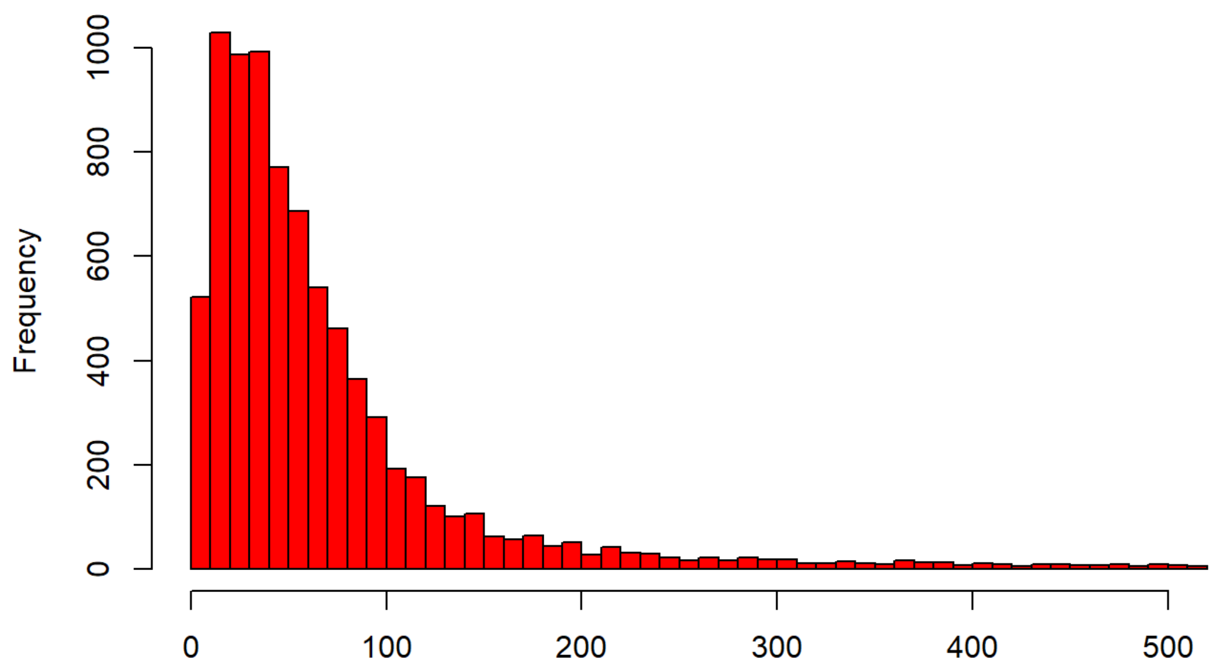

Figure 3: Histogram of daily turbidity (NFU) in the time series 1995-2020 (truncated to 500 NTU)

The turbidity and rainfall data are presented in a series of boxplots, showing the annual and monthly variations of turbidity (Figures 4 and 5, respectively) and precipitation (Figures 6 and 7, respectively). It can be seen that rainfall fluctuates considerably, peaking in the spring and autumn months. Turbidity increases in autumn, and was particularly variable in 2018, which was an unusually rainy year (Figure 6).

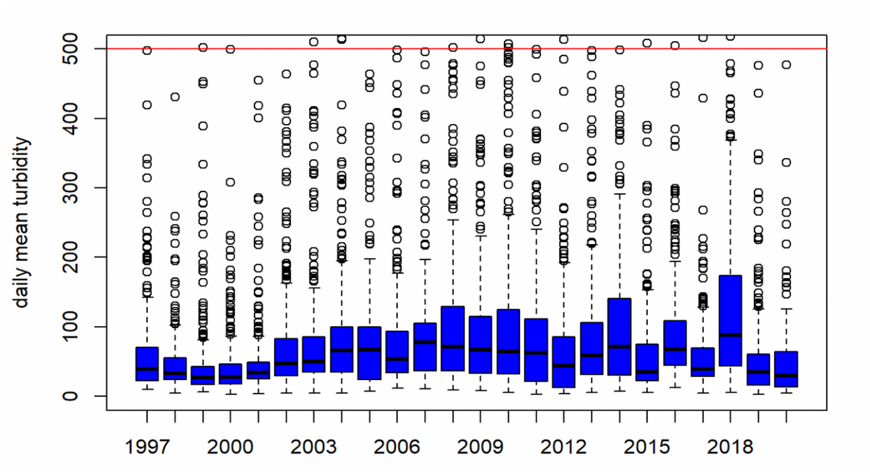

Figure 4: Boxplot of daily turbidity (NFU) by year in the time series 1995-2020

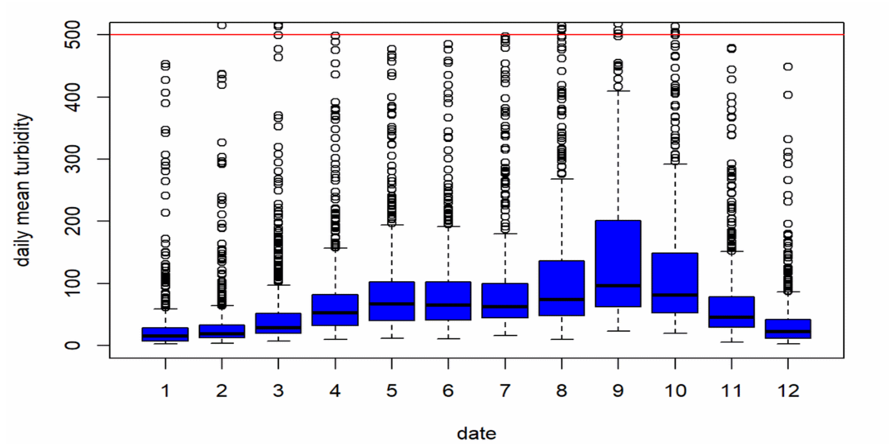

Figure 5: Boxplot of daily turbidity (NFU) by month in the time series 1995-2020

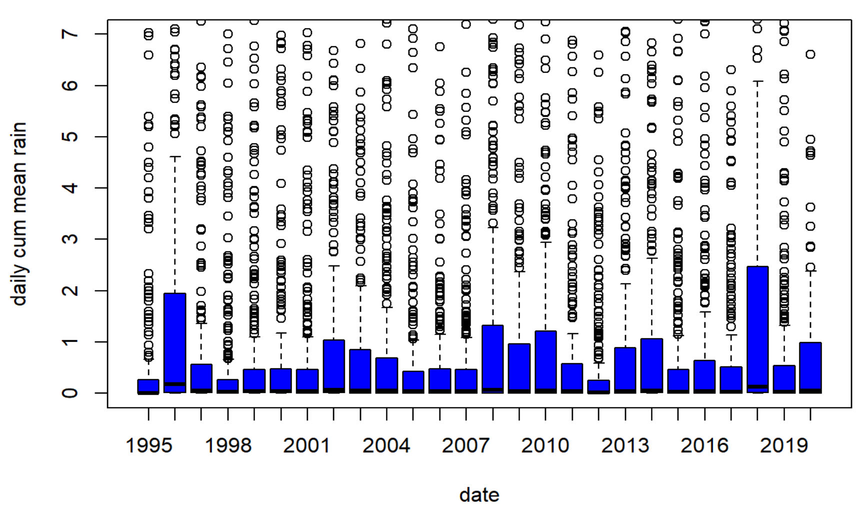

Figure 6: Boxplot of daily turbidity (NFU) by year in the time series 1995-2020

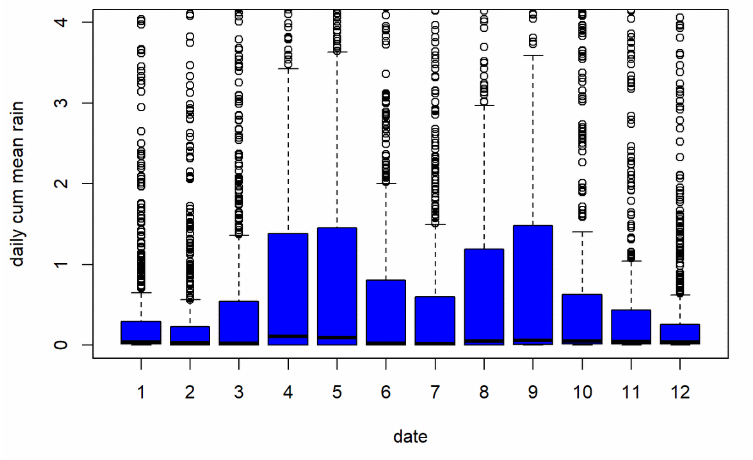

Figure 7: Boxplot of daily turbidity (NFU) by year in the time series 1995-2020

Correlation between the variables of average accumulated rainfall and average daily turbidity

A scatterplot (Figure 8) depicting the relationship between the daily accumulated rain and turbidity reveals a correlation index value that is low (r = 0.34) but significant (p<0.001), which indicates that a relationship exists between the two variables.

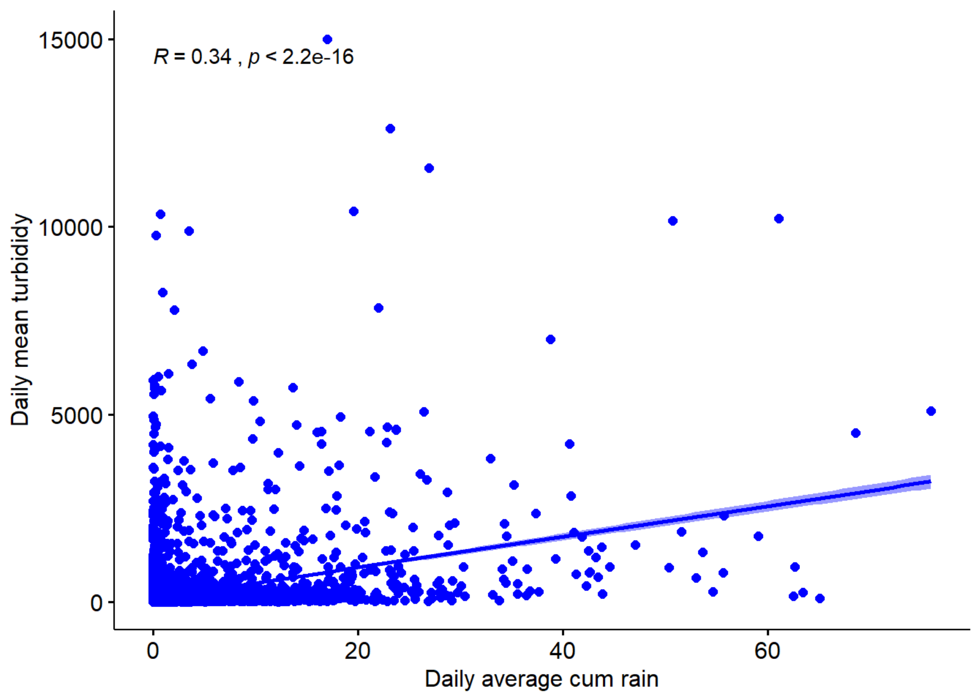

Figure 8: Scatterplot depicting the relationship between the daily accumulated rain and turbidity (R= correlation)

Autocorrelation between turbidity and cross-correlation function (CCF)

Using a CCF (Figure 9), it was found that the turbidity can be explained by the rainfall in the previous 1-4 days (1 day maximum). An explanation is that recent rain collects in the river before it reaches the point where the turbidity is observed (see Figure 1).

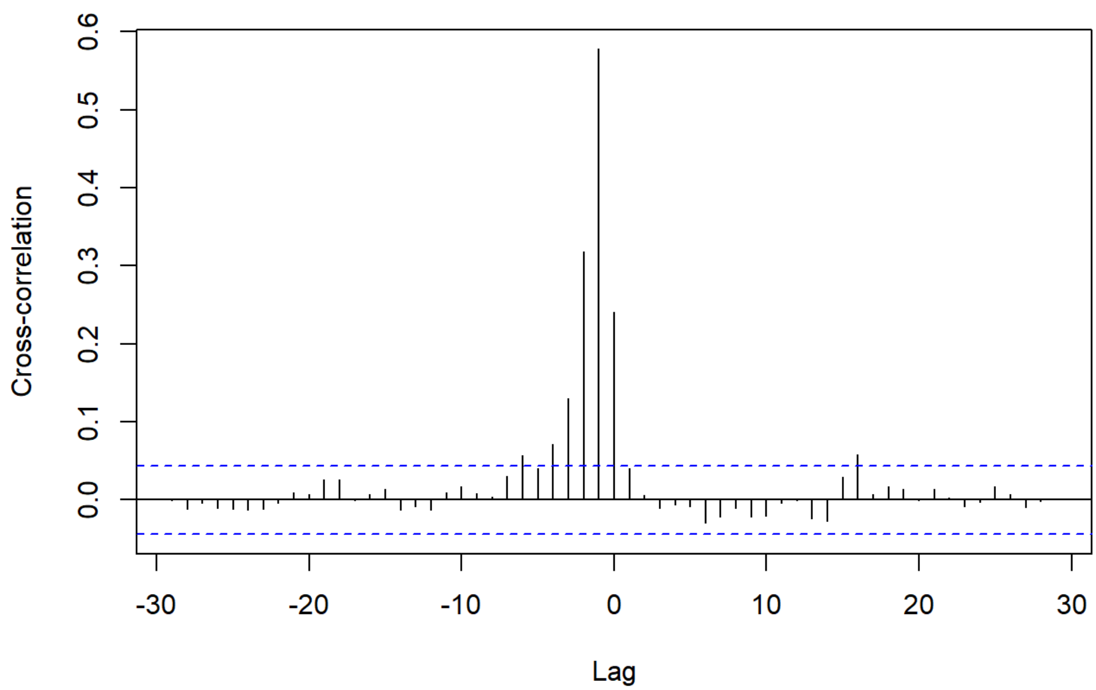

Figure 9: Cross-correlation between daily turbidity (NFU) by year in the time series 1995-2020

Trend in the number of high turbidity episodes (>500 NTU)

In the analyzed time series, out of a total of 9,282 days, 451 (4.9 %) had a turbidity greater than 500 NTU (Table 1).

Table 1: Number of days with turbidity > 500 NTU

	Frequency	Percent	Cum. percent
T<=500	8831	95.1	95.1
T>500	451	4.9	100.0
Total	9282	100.0	100.0

A chi-square test revealed that the number of days with exceptionally high turbidity differed by year (p-value <2.2e-16). Thus, 2008, 2014 and 2018 featured about 29-30 episodes of turbidity > 500 NTU, whereas 2001 and 2019 only had 12 days (Table 2 and Figure 10).

Table 2: Days with turbidity > 500 (T) NTU per year

YR	T<=500	T>500	YR	T<=500	T>500
1999	345	20	2009	345	20
2000	352	14	2010	346	19
2012	347	19	2011	336	29
2013	345	20	2012	347	19
2001	353	12	2013	345	20
2002	351	14	2014	336	29
2003	339	26	2015	351	14
2004	344	22	2016	345	21
2005	337	28	2017	354	11
2006	345	20	2018	336	29
2007	346	19	2019	353	12
2008	336	30			

Additionally, months 9 and 10 were detected to have significantly more days of high turbidity than the other months ($p < 0.05$).

To determine if there was a trend in the number of days / year with turbidity > 500 NTU, an analysis based on a time series decomposition method was performed (Figure 11), but no pattern was discerned, perhaps because the series is not long enough.

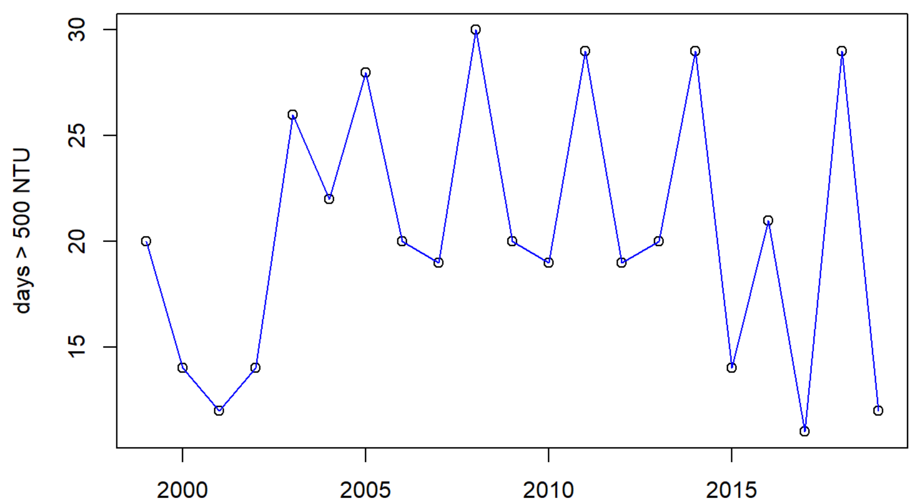

Figure 10: Days with > 500 NTU (turbidity) by year in the time series 1995-2020

We can see from the time graph (Figure 11) that this time series could probably be described using an additive model, as the random fluctuations in the data are reasonably constant in size over time. A non-seasonal time series consists of a trend component and an irregular component, which can be separated by estimation. To estimate the trend component of a non-seasonal time series that can be described using an additive model, it is common to apply a smoothing method, such as calculating the simple moving average of the time series. To estimate the trend component more accurately, the data can be smoothed with a simple moving average of a higher order, which requires some trial and error to find the correct amount of smoothing. The result of decomposition using a simple moving average of order 6 can be seen in Figure 11.

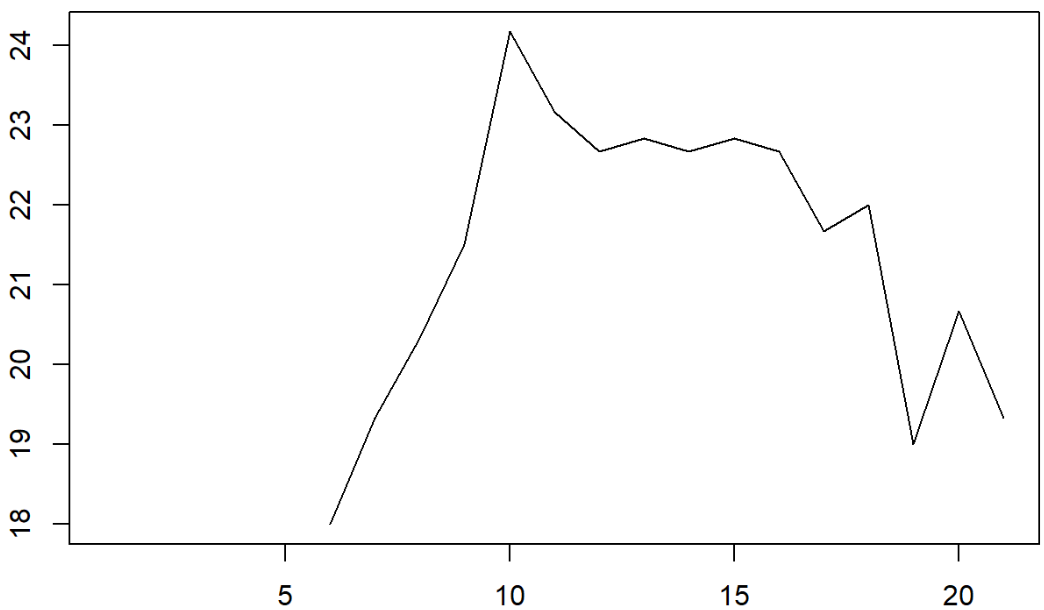

Figure 11: Simple moving average of order 6 for time series of days with > 500 NTU (turbidity) by year (X=years 1995-2020, Y=days with > 500 NTU (turbidity) decomposed)

In Figure 11, a differential behavior can be detected before and after 2000 (year 10). In the period leading up to 2000, the number of high turbidity episodes seems to increase, whereas they decrease between 2000 and 2020. However, there are too few data to capture a clear trend.

CONCLUSIONS

This study represents the first attempt to measure the relationship between rainfall and turbidity in the Llobregat River, which was permitted by the availability of a long time series of data, consisting of more than 200,000 records from 1995 to 2020.

Turbidity is a variable of great importance, as it is an indicator of the state of the river and can affect the amount of water available for consumption.

On most days, the turbidity was less than 100 NTU, reaching more than 500 NTU only on exceptional days (approx. 5%). A significant linear correlation was observed between rain and turbidity, which indicates that a relationship exists between the two variables, although of little magnitude.

Rainfall in the area undergoes considerable fluctuations, with peaks in the spring and autumn months, whereas turbidity shows a notable increase in the autumn. Turbidity was more variable in 2018, which was a particularly rainy year.

Although the relationship between rainfall and turbidity is complex, the analysis of the time series revealed that turbidity can be explained by the rain of the previous 1-4 days (1 day maximum), as recorded in 39 meteorological stations of the Llobregat River basin.

No trend was detected in the number of days with high turbidity per year, perhaps because the series are not long enough.

The study provides useful data about the behavior of the Llobregat river, which can be used to optimize the management of water supply and other activities.

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Author Credit Statement

Pere López-Brosa, Javier Méndez-Viera: Conceptualization, Methodology. Toni Monleón-Getino: Software, Methodology. Miquel Paraira, Marta Gantzer: Data curation. Pere López: Visualization, Investigation. Francisco Lucena, Miquel Paraira, Marta Gantzer: Supervision. Toni Monleón, Javier Méndez, Pere López-Brosa: Writing- Reviewing and Editing, Writing- Original draft preparation.

REFERENCES

Abaurrea, J., Asín, J. 2005. Forecasting Local Daily Precipitation Patterns in a Climate Change Scenario. Climate Research 28 (3), 183–97.

Bernhardt, J. C., Koller, M., Lichtenberger A. Mediterranean Rivers in Global Perspective. 2019. In Mediterranean. Rivers in Global Perspective (Mittelmeerstudien 19; Paderborn 2019).

Brosa, P., Monleón-Getino, A., Méndez J., Lucena-Gutiérrez, J. 2019. Turbidity Forecasting in the Delaware River. Journal of Research in Environmental and Earth Science 5 (2), 01–09.

Christopher, W., Barber, D. 1998. Bayesian Classification with Gaussian Processes. *Transactions on Pattern Analysis and Machine Intelligence* 20 (12). IEEE, 1342–51.

Estrany, J., García C., Alberich, R. 2010. Streamflow dynamics in a Mediterranean temporary river. Hydrological Sciences Journal 55 (5)

Fondriest Environmental, Inc. Turbidity, Total Suspended Solids and Water Clarity. Fundamentals of Environmental Measurements. [See at:

https://www.fondriest.com/environmental-measurements/parameters/water-quality/turbidity-total-suspended-solids-water-clarity/] .

Jiménez-Albán, X., Monleón-Getino, A. 2021 Statistical models for climate change in the bodies of water of the Mediterranean. Journal of Environmental Hydrology 29 (1), 1-10

Monleón-Getino T. 2020. BDSBIOST3. R library for Machine learning and advanced statistical methods for omic, categorical analysis and others [See at: https://github.com/amonleong/BDSbiost3]

Monleón-Getino, A. 2017. Big Data: Hacia La Cuarta Revolución Industrial. Universitat de Barcelona, 1–66.

Peña, D. 2005. Análisis de Series Temporales. Alianza Editorial. Spain.

Rodríguez, R., Navarro, X., Casas M.C., Ribalaygua, J., Russo, B., Pouget, L., Redaño, A. 2014. Influence of Climate Change on Idf Curves for the Metropolitan Area of Barcelona (Spain). International Journal of Climatology 34 (3), 643–54.

Sabater, S., Ginebreda, A., Barceló, D. et al. 2012. The Llobregat: The Story of a Polluted Mediterranean River. The handbook of environmental chemistry 21. Springer-Verlag, Berlin.

Sabater, S., Muñoz, I., García-Berthou, E., Barceló i Cullerés, D. 2014. Multiple Stressors in Mediterranean Freshwater Ecosystems: The Llobregat River as a Paradigm. Contributions to Science, 161–69.

Tianqi, C., He, T., Benesty, M., Khotilovich V., Tang, Y. 2015. Xgboost: Extreme Gradient Boosting. R Package Version 0.4-2, 1–4.

Van Hecke, T. 2010. Time Series Analysis to Forecast Temperature Change. Mathematical Scientist 35 (2), 63–69.

WHO. Fact Sheet 2.33: Turbidity Measurement. In Fact sheets on environmental sanitation. [See at: http://www.who.int/water_sanitation_health/hygiene/emergencies/fs2_33.pdf]

Wilks, D. 2011. Statistical Methods in the Atmospheric Sciences. Vol. 100. Academic press.

Wilks, D.S. 2011. *Statistical Methods in the Atmospheric Sciences*. Vol. 100. Academic press.

Xuebin, Z., Harvey, K. D., Hogg, W. D. and Ted R Yuzyk. 2001. Trends in Canadian Streamflow. *Water Resources Research* 37 (4). Wiley Online Library: 987–98.

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