Title: Links between climate and DBPs

Deliverable 6.2

WP 6 EXPOSURE – Human exposure in the population



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ABSTRACT	This deliverable is related to Task 6.3 of the DoA and aims to investigate the influence of extreme weather events on trihalomethanes (THM) formation in drinking water systems in Cyprus, Ireland and Spain, three European countries with historically high THM levels. Using hydrometeorological indicators such as river flow, reservoir level, the Standardized precipitation Evapotranspiration Index (SPEI 1), and temperature, we explored the relationship between climatic variability and THM levels. Extreme events were defined as river flow, reservoir volume below the percentile 10 (low river flow, as a proxy of drought/water scarcity) and above the percentile 90 (high river flow as a proxy of unusually high water abundance). Descriptive trends highlighted the prominence of brominated THMs in Nicosia´s (Cyprus) desalinated water. However, scarce sample availability in Ireland and Cyprus limited robust statistical analysis. In Barcelona (Spain), high river flow appeared to dilute bromide precursors in the Llobregat system, reducing total THM levels, while both high and low reservoir level in the Ter system increased total THMs. SPEI 1 was more predictive in riverine than in reservoir-based systems. Our findings suggest that operational factors, such as source water blending and treatment strategies may buffer the immediate impacts of extreme weather on THM formation in the studied systems. These results highlight the need for adaptive water management and further research on long-term climate impact across diverse system typologies. The uneven delivery across case studies highlights the difficulty to conduct this type of assessment in light of the currently available datasets and the need to create open access databases with long-term information on drinking water quality, treatment and source to advance the knowledge in this field.		

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EXECUTIVE SUMMARY

While climate change effects on the hydrological cycle and source water quality are increasingly recognized, there is very limited qualitative evidence indicating how extreme weather events may affect the concentration of chemicals in finished drinking water. We evaluated the impact of extreme weather events on trihalomethane (THM) formation in drinking water systems across three countries: Cyprus, Ireland and Spain, that are known for high THM levels in Europe. We used hydrological parameters such as river flow or reservoir level, temperature, and the Standardized Precipitation Evapotranspiration Index (SPEI 1), to assess the potential links between hydrometeorological extreme events and THM formation. River flow and reservoir volume were used as markers of water availability because they integrate the precipitation in the relevant basin and informs about the resulting water available to supply the population.

In Ireland, we studied several water systems including Wexford, where THM levels exceeded EU regulatory limits, and Waterford, Galtee and Ardfinnan, which showed lower variability. No further analysis was performed due to the scarce number of samples collected. In the descriptive assessment, no clear extreme weather-driven pattern was identified.

In Cyprus, we examined two cities: Nicosia, which relies primarily on desalinated water and Limassol, which blends desalinated, surface and groundwater. In Nicosia, total THM (THM4) levels frequently exceeded EU regulatory limits, predominantly driven by brominated THMs, which are known for their higher genotoxicity as compared to chloroform. However, due to the lack of detailed data on water source percentage, treatment plant distance/residence time, and operational strategies, and because samples were collected only at the final tap, further analysis with SPEI 1 or similar indices was not feasible.

In Barcelona, Spain, two distinct Drinking Water Treatment Plants (DWTPs) were analysed: the Llobregat River-based and the Ter Reservoir-based system. Extreme events were defined statistically, using the percentile 10 and percentile 90 of river flow and reservoir volume to represent, respectively, low river flow/reservoir volume (as a proxy of drought/water scarcity) and high river flow/reservoir volume (as a proxy of unusual water abundance). Results showed that high river flow were associated with reduced THM levels in Llobregat DWTP, most probably by diluting bromide precursors, thus shifting the THM speciation from brominated to chlorinated species. Conversely, unusually high and unusually low reservoir levels increased THM levels in the Ter DWTP. The SPEI-1 index proved more effective in capturing the effects of extreme weather in the river-based system, where water quality fluctuations were more immediate, whereas the reservoir acted as a buffer against these changes.

Overall, the study findings show no strong direct influence of extreme weather events on THM formation in Barcelona, suggesting that operational factors such as treatment strategies and source mixing are more influential than short-term meteorological fluctuations. This highlights the importance of focusing on operational improvements and source water protection as primary measures to reduce THM formation, while also recognizing the potential impact of climate change on long-term water quality trends. Further research is needed to replicate our findings in other settings and drinking water systems with a lower degree of human intervention on treatment and source management, and expand to other water quality parameters.

The uneven delivery across case studies - the full analytical approach was mainly achieved for Barcelona, while Ireland and Cyprus remained more exploratory due to data limitations- illustrates the difficulty to conduct this type of assessment in light of the currently available datasets and the need to create or make available open access databases with long-term information on drinking water quality, treatment, and source to adequately answer the research question.

This Deliverable is related to Task 6.3 of the DoA.

1.0 Introduction

1.1 Disinfection by-products and Public Health interest

Access to safe drinking water is a fundamental human right and a critical public health need, increasingly under pressure from global environmental change (1). Disinfection is a key step in drinking water treatment, essential for controlling microbial contamination, and it has been one of the most impactful public health interventions of the 20th century (2,3). However, chemical disinfection leads to unintended formation of disinfection byproducts (DBPs) through reaction with natural organic matter (NOM) or inorganic ions such as bromide or iodide present in raw water (4–6).

Among the more than 800 DBPs identified, trihalomethanes (THM) are the most prevalent and among the first regulated chlorination DBPs (4,7). Although regulatory standards vary internationally (8–10), regulatory limits for total THM are set at 80 µg/L in the United States and 100 µg/L in Europe (8,11). Long-term THM exposure has been consistently associated with an increased risk of bladder cancer (12,13) and some studies suggest a potential link to adverse pregnancy outcomes (10,14,15).

THM formation is influenced by a combination of source water quality and operational factors, including the concentration and type of natural organic matter (NOM), temperature, pH, bromide and chlorine dose as well as the residence time within the distribution system (16–18). Surface waters are generally richer in NOM, increasing THM formation compared to groundwater (16). THM formation can vary due to spatial factors such as water source (reservoir, river, lake,…) and temporal factors (such as seasonal change or extreme events like drought or heavy rainfall…), infrastructure (e.g. treatment) and environmental conditions (e.g., temperature, precipitation, soil type, other chemicals present…) (19,20).

Some of the highest reported THM levels in Europe have been found in Ireland, Cyprus and Barcelona , Spain (21,22). Water source differs substantially across the three study regions, influencing THM formation. Cyprus relies on approximately 65% surface water, supplemented by 31% of seawater, which contributes to elevated bromide levels and a shift toward brominated THM species (7). Ireland primarily uses surface water, about 82%, some of it sourced from high peatlands, rich in NOM making it particularly susceptible to THM formation. In contrast, Spain relies more heavily on groundwater, around 60%, which typically contains lower NOM levels. However, in the Metropolitan Area of Barcelona, surface water is the dominant source, aligning THM formation dynamics more closely those in Cyprus and Ireland (21).

1.2 Climate change and extreme weather events

While climate change effects on the hydrological cycle and source water quality are increasingly recognized (23–26), there is little knowledge about the impacts on finished drinking water quality. A degradation in drinking water quality in the context of climate change has been suggested (27), leading to potential public health risks. However, there is very limited qualitative evidence indicating how extreme weather events may affect the concentration of chemicals in finished drinking water.

Extreme weather events such as heavy rainfall, flash flood, drought or dry spell periods critically challenge drinking water production and they are expected to become more frequent according to future climate projections (28). Extreme rainfall for instance, can increase runoff from urban and agricultural areas, leading to higher loads of dissolved organic carbon, nutrients and turbidity in source waters, acting as precursors of THM formation. In contrast, drought periods can concentrate NOM and bromide due to lower dilution capacity, further elevating DBP formation potential. As an example, TOC levels could rise for up to three weeks after a rewetting phenomenon (29).

Extreme weather events are reported to affect THMs levels in DWTPs due to their influence across the entire water production mesosystem. Storms and heavy rainfall have some controversial results, as it does not increase the THM formation potential in stormy spring time (30). However, they have been

shown to sediments, organic matter, turbidity and pathogens and can potentially decrease clarifier performance as well as elevating the treatment costs.

Predictions estimate that a 1.8ºC increase in water temperature, combined with high TOC will increase THM formation by up to 50% in Scotland (31). In times of drought or contamination from flooding, utilities may be compelled to switch to alternative sources that may have higher THM precursor loads or salinity, such as brackish water or low-flow rivers, complicating treatment and increasing risk.

1.3 DBP formation under water work operational resilience mechanisms

Infrastructure strain during extreme weather such as pump failure, power outage or overwhelmed intake systems, can reduce process stability and compromise optimal disinfection practices, therefore, DBP levels. Reducing THM formation depends primarily on source water characteristics. Filtration, sedimentation, decay and flocculation are key processes used to remove TOC. However, it is essential to differentiate TOC by polarity, as not all TOC fractions are equally reactive. In addition, total dissolved nitrogen is expected to increase due to atmospheric nitrogen deposition and inefficient agricultural practices (32). Sand filtration reduces THM concentrations, whereas active carbon filtration may not be so efficient depending on the age of the filter (16).

In cases of high TOC caused by runoff from flash flood, Saint Joan-Despí DWTP in Barcelona switches from surface to groundwater sources (16,33). Using alternative sources within an interconnected network is a common mitigation strategy. In both Barcelona and Cyprus, desalinated water is used as supplementary source. However, desalination carries significant environmental impact. It is energy-intensive, often reliant on fossil fuels, and contributes to marine ecosystem stress due to brine discharges. These impacts are often overlooked in the global change scenarios, despite their interaction with ocean warming and acidification (34).

Reducing residence time in the distribution system is another strategy to limit THM formation, as longer contact times between residual chlorine and organic matter can increase DBP concentrations. Smaller water treatment plants, which serve fewer users, often exhibit higher THM levels due to longer storage and less frequent water turnover. In Cyprus, where water scarcity is persistent issue, household storage tanks are commonly used, which can further extend retention times and elevate DBP levels (35).

Together, these operational adjustments, sources switching, advanced filtration, and distribution management, form key components of climate-resilient water supply systems, but must be balanced with environmental, economic, and public health considerations.

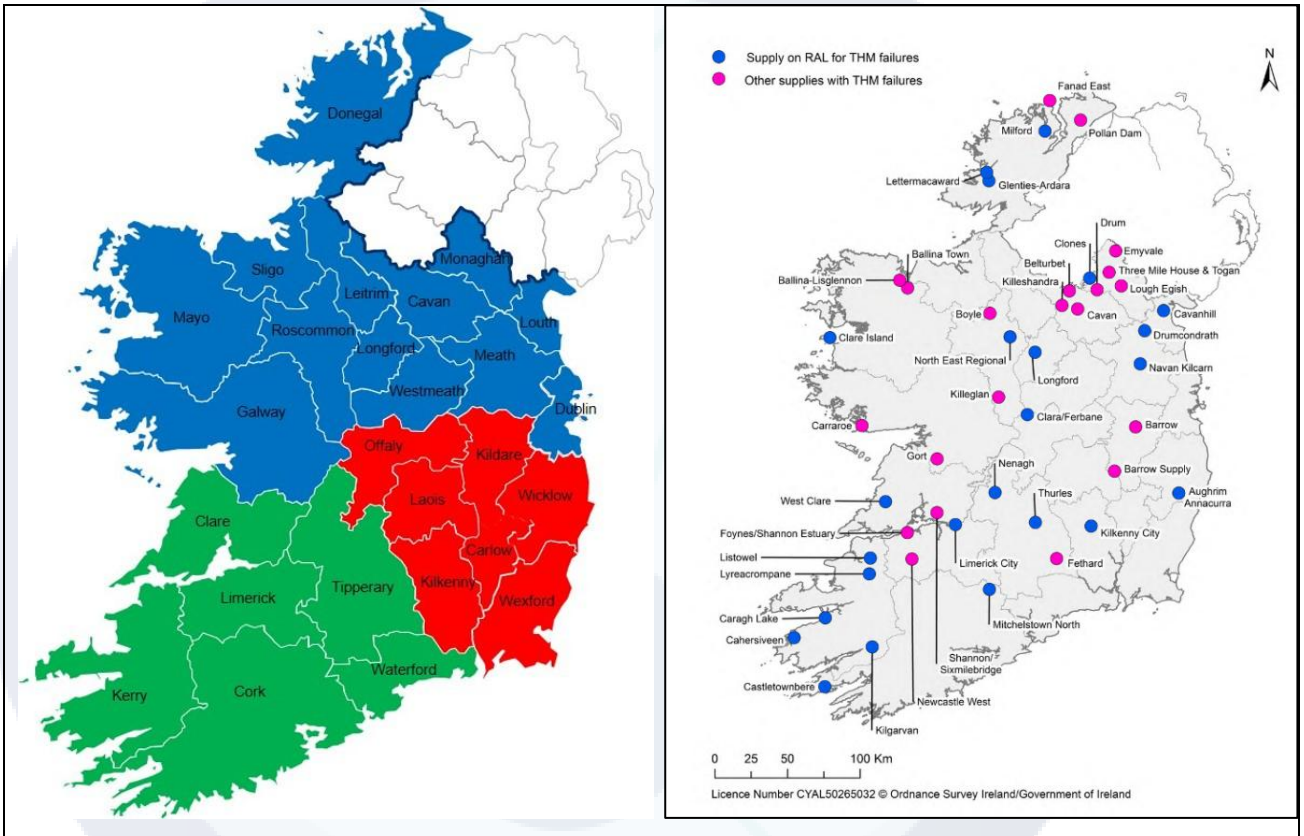
2.0 Ireland Case Study

Until 2015, Ireland´s drinking water services were managed in a decentralized manner by local authorities under the Water Services Act (2007-2014). This system suffered from inefficiencies and inconsistencies in planning, operations and maintenance. It also relied on a dual funding model: domestic water services were financed through central taxation, while non-domestic users were billed by local authorities. In response to these structural weaknesses, the state-owned utility Irish water (Uisce Éireann) was established in 2013, marking a shift to a centralized, unified system. One of its key initiatives is the National Water Resources Plan, a 25-year strategy aimed at delivering a sustainable, secure, and reliable water supply across the country (36).

One of the most pressing challenges in Ireland´s water sector is its aging infrastructure, particularly water distribution network. Ireland has the highest water leakage rate in Europe. In 2018, leakage was estimated at 46%, with a target reduction to 25% by 2023 (36).

Ireland has a long-standing issue with elevated THM concentrations, making it a national health and compliance concern. In 2015, the European Commission initiated infringement proceedings against Ireland for breaching the Drinking Water directive. And in 2024, the European Court of Justice ruled that Ireland must fully implement measures to ensure compliance. As of 2023, the average THM exceedance was 125 µg/L (37).

Figure 1. Regional division of water management and THM4 audit in 2023, Ireland.



Sourced from: Water IE and EPA

Ireland is highly dependent on surface water, which accounts for approximately 82% of its drinking water supply (21). Groundwater provides the remaining 18-25%, and in some rural counties, it accounts for up to 50%. In areas not served by public water schemes, residents rely on private wells and springs. Roughly

20% of Ireland´s land area is covered by peatlands, which store over 75% of the country´s soil organic carbon. However, only 15% of these peatlands are classified as near-intact, meaning most have been degraded due to drainage or land use changes (38). Peat-rich catchments, especially in the west, contain high levels of dissolved organic matter (DOM), a well-known precursor for THM formation.

Climate change is expected to exacerbate the pressures on Ireland´s water sector. Increases in rainfall intensity, longer dry periods and rising temperatures may alter the quantity and quality of sources waters (31). These changes can enhance the mobilization of dissolved organic carbon (DOC) from peatlands and soils, increasing THM precursors and placing additional pressure on treatment infrastructure already in construction and remodeling due to the aging decentralized infrastructure.

Therefore, in this section, we aim to investigate the influence of extreme weather events, measured by the drought Standardized Precipitation Evapotranspiration (SPEI 1) index, on the trihalomethanes formation in final drinking water from no peatland regions such as Tipperary, Wexford and Waterford.

2.1 Methodology

2.1.1 Hydrologic and climate data source

We obtained drinking water quality databases through Dublin City University from 2010 to 2024 of the following indicators: total trihalomethanes (μg/L) at the final tap water for regulatory purpose analyses and other quality parameters such as pH, conductivity (μS/cm), bromate (mg/L), hardness (as $CaCO_3$) and total organic carbon (TOC, mg/L).

The main predictor was the Standardized Precipitation-Evapotranspiration Index (SPEI-1), a validated composite scale used to capture drought and high precipitation conditions. The data was collected from the official SPEI calculator from the SPEI Global Drought Monitor (39). To create the variable, we obtained the monthly median of SPEI-1 from the geographic area near the county respectively Figure 2. Then, we merged the SPEI 1 data with the water quality data, assigning each month a unique SPEI1 value. The SPEI scale is centered around 0, with positive values indicating increasing wetness. A SPEI value of ≥ 1.5 is considered severely wet while a value of ≤ - 1.5 is classified as severe drought.

2.1.1 Study area

We selected three counties in the southeast of Ireland: Tipperary, Wexford and Waterford, to capture areas that are not classified as high peatland zones (38). Peatlands are typically associated with elevated levels of natural organic matter, which when chlorinated during water treatment, leads to higher THM formation. Wexford and Waterford are coastal counties with estuarine influences, while Tipperary is an inland county. This selection allows for comparison of coastal versus inland supply characteristics under similar regulation but different operational conditions and source. From each county, we selected the water supply scheme where data with the most complete data, including the East Waterford Water Supply Scheme, Ardfinnan Regional, Galtee Regional and Wexford Town. In the 2023 EPA water report, boil water notices were issued in several areas, including Waterford and Tipperary, primarily due to disruptions from industrial action affecting treatment operations.

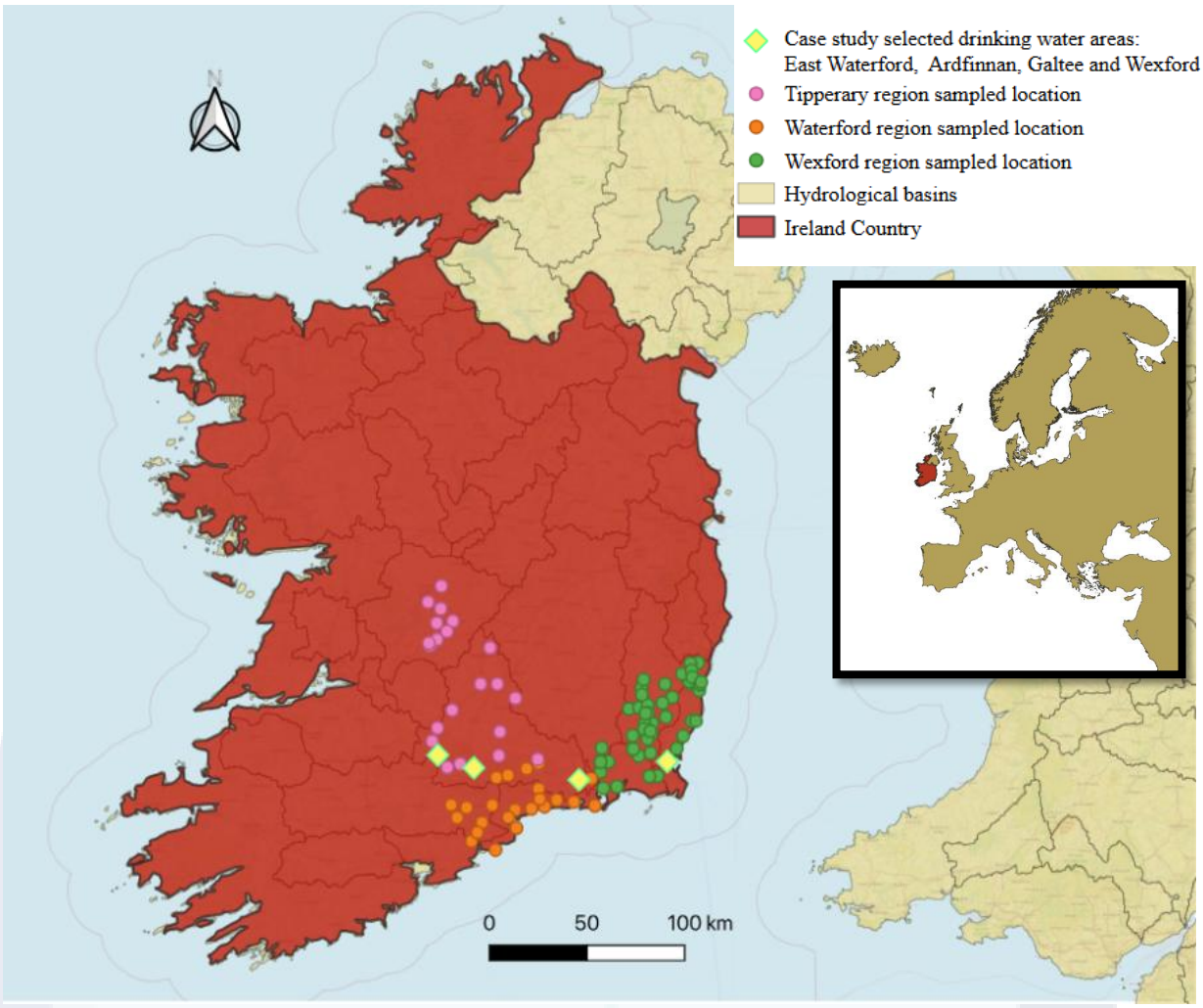
Waterford city is supplied from the Adamstown reservoir, sourced waters include the River Clodiagh and River Mahon and Ballyshunnock reservoir (40). Treatment processes consist of coagulation, flocculation, clarification, filtration and disinfection.

The Ardfinnan Regional Public Water supply sources raw water from 2 mountain streams. Water treatment includes coagulation, flotation, rapid gravity filtration, pH correction, chlorination, fluoridation (41).

Galtee Regional public water is a mixed source: the Muskry stream, the spring mount wells and the College Stream, this last one is used as a supplementary water source when dry weather. Water treatment includes coagulation, clarification, filtration, disinfection and fluoridation (42).

The main water source for Wexford Town is the Sow River, with the intake located at Edenvale. During peak demand, supply is augmented by the Coolree impoundment reservoir. The treatment plant, which previously reported water losses of 35 to 40% in 2014, employs coagulation, sedimentation, rapid gravity filtration, chlorination and fluoridation (43).

Figure 2. Ireland case study sampled location and drinking water selected areas for study



Map produced using QGIS. Basemap data from OpenStreetMap; contour lines generated from watershed data

2.1.2 Statistical analyses

Data cleaning was standardized:values below limit of detection (LOD) were imputed as LOD/2, and duplicated dates or missing data were removed. For SPEI 1, we used the threshold ≥ |1.5| to classify conditions as normal or severe drought or wet. To maintain uniformity, GAM modelling was initially planned but was not performed due to limited outcome data.

2.2 Results

A summary of the descriptive statistics is provided in Table 1. Note that measurements were taken from the final tap water, which introduces some intra-network variability due to potential differences in distribution network length, storage conditions, and household plumbing. This heterogeneity should be considered when interpreting local trends and comparisons.

Table 1. Summary of descriptive statistics of THM4, SPEI_1 and other covariates, Ireland.

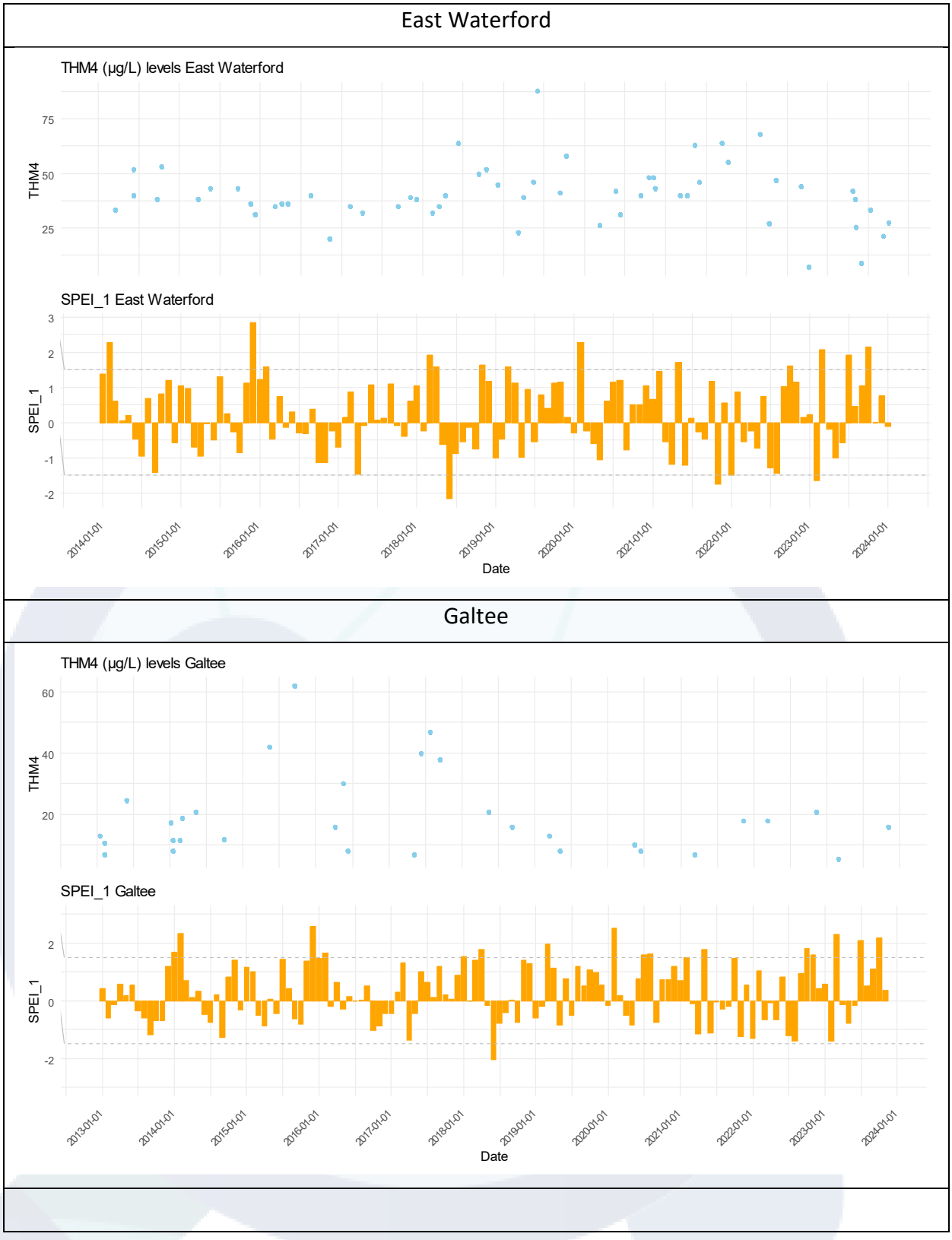
East Waterford	THM4	TOC	pH	Conductivity	Bromate	Hardness	SPEI_1
Total N	58	51	369	370	12	-	118
Me (P25, P75)	40 (34, 46)	1.47 (1.2, 1.9)	8.44 (8.1, 8.7)	196 (184, 205)	1.3 (1.3, 1.3)	-	0.1 (-0.6, 1.1)
Min/Max	7/88	0.42/5.89	6.0/9.2	91/275	1.1/1.7	-	-2.2/2.8
Galtee	THM4	TOC	pH	Conductivty	Bromate	Hardness	SPEI_1
Total N	33	24	214	211	8	6	131
Me (P25, P75)	16 (10,21)	1.2 (0.9, 1.6)	7.6 (7.3, 7.8)	135 (125, 152)	1.3 (1, 1.6)	42.5 (41.3,43.8)	0.2 (-0.5,1.1)
Min/Max	5.5/62	0.3/3.3	6.5/8.9	14/721	1/3	21/65	-2.1/2.6
Ardfinnan	THM4	TOC	pH	Conductivty	Bromate	Hardness	SPEI_1
Total N	34	29	208	202	15	4	132
Me (P25, P75)	19 (10,38)	1.5 (0.8,1.7)	7.3 (7.2,7.4)	115 (93,139)	1.3 (1,2)	320 (245,326)	0.1 (-0.6, 1.0)
Min/Max	4/78	0.3/2.7	6.7/7.9	69/616	1/ 2.1	27/333	-2.3/2.8
Wexford	THM4	TOC	pH	Conductivty	Bromate	Hardness	SPEI_1
Total N	32	33	181	182	3	-	130
Me (P25, P75)	67.5 (58,84)	2.8 (2.3, 4.3)	7.4 (7.2, 7.6)	369 (323, 294)	2.3 (2.2, 8.3)	-	-0.01 (-0.7, 0.9)
Min/Max	5.6/190	2.3/15.9	6.5/8.1	165/595	2/14.3	-	-1.9/2.8

Due to the scarcity of outcome data, the highest number of entries recorded was 58 for East Waterford over a 10 years period. This limited sample size constraint for a robust statistical modelling in relation to climatic predictors such as SPEI. As a result, multivariate modelling was not feasible.

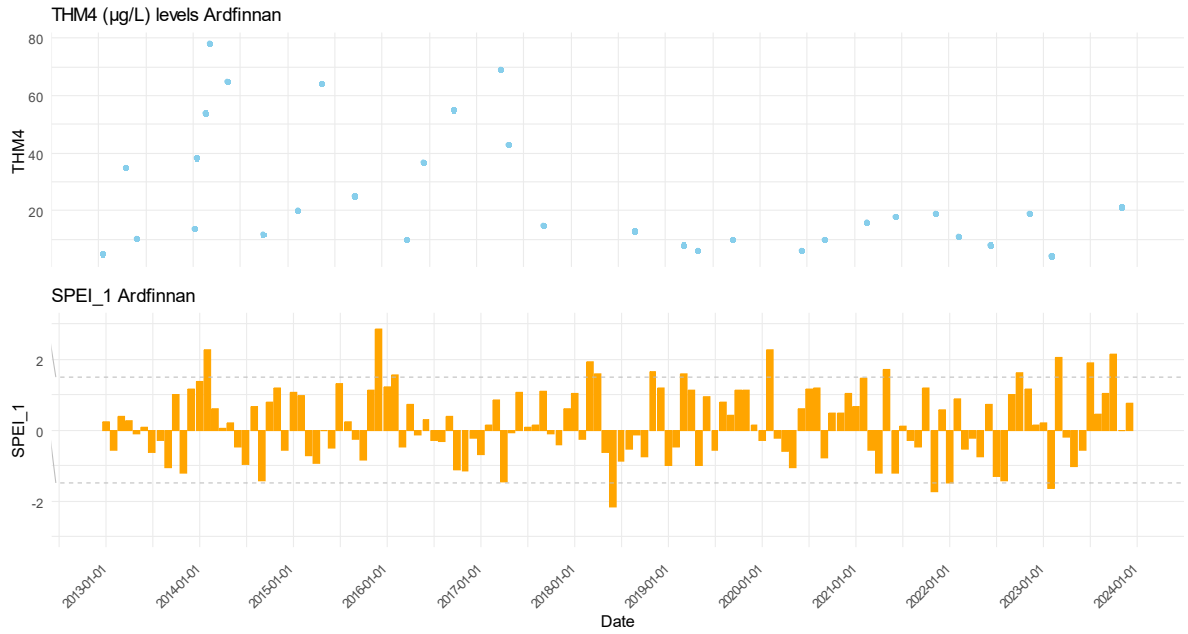
No consistent seasonal pattern was identified over the 10 to 14 years, mostly due to non-systematic sampling intervals and the influence of local operational factors. However, Wexford City emerged as a concerning region, reporting THM4 levels exceeding legal limits, reaching a peak of 190 µg/L in 2021, while this may represent an outlier, it is noteworthy that the next highest measurement was still 110 µg/L, suggesting recurrent exceedances issues in the area (Figure 3). This region also showed higher levels of TOC, bromate and conductivity values, compared to the 4 study areas, which may indicate suboptimal disinfection management. In contrast, Galtee, Waterford and Ardfinnan reported a decreasing trend in THM4 concentrations over the years, possibly reflecting operational improvements of shifts in raw water quality management (Figure 3).

When comparing THM4 levels with the SPEI-1 index, which reflects short-term drought/ wetness stress, no strong extreme climate event signal was visually evident. Inspection of trends across locations suggested that extreme meteorological conditions did not correspond clearly with variations in THM concentrations. In Galtee and Ardfinnan THM4 levels peaks prior to 2018 with 62 and 78 µg/L levels respectively (Figure 3), appeared to be more strongly associated with operation conditions rather than with extreme weather events. Likewise, in Wexford or Waterford, no apparent temporal alignment was observed between elevated THM4 levels and SPEI1 extremes. This suggests that at least over the timeframe and resolution of the current dataset, local treatment practices, source water characteristics, and infrastructure conditions may have a more substantial influence on THM4 formation than short-term extreme weather variability.

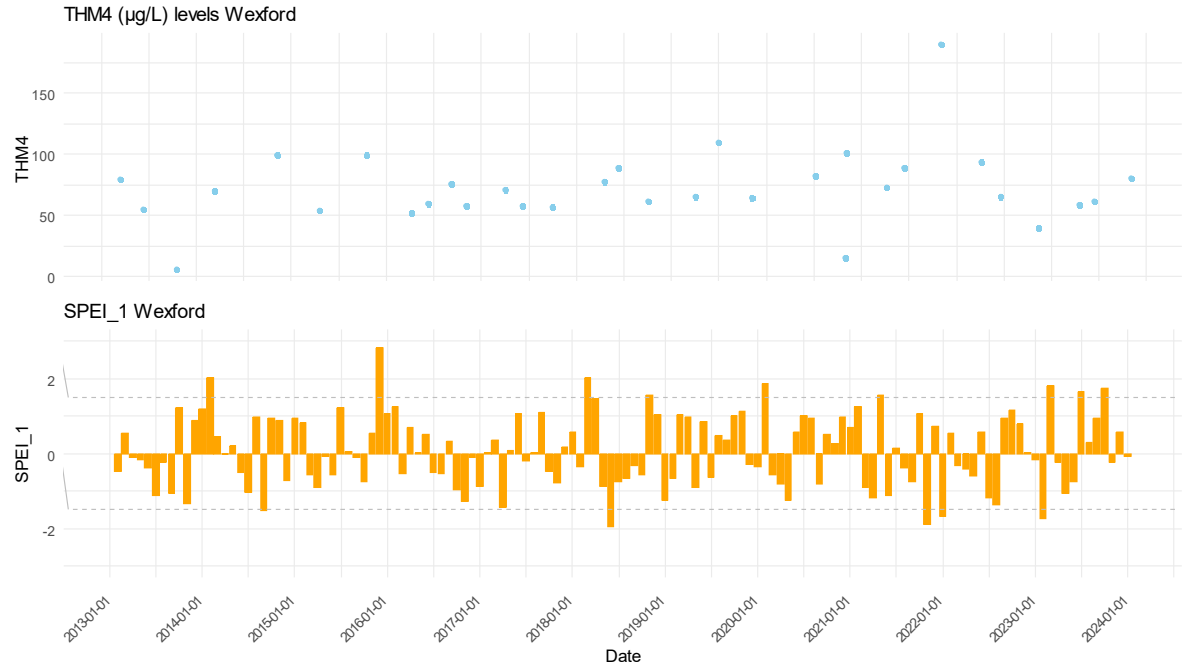
Figure 3. THM4 levels and SPEI_1 from the different sites of the study, Ireland.



Ardfinnan



Wexford



2.3 Discussion

Findings from this analysis highlight the disparity of regional variability in THM4 concentrations across the monitored areas. Wexford City showing the highest levels, exceeding legal limits, while other areas such as Galtee, Waterford and Ardfinnan exhibit a decreasing trend. The results suggest that the levels of organic matter as well as bromide and conductivity, along with treatment effectiveness play a crucial role in determining THM formation, however, as we did not have further information, results are preliminary.

Despite the public accessibility of water quality data, we encountered substantial limitations in data continuity and granularity, the scarcity of THM4 levels from the same geographic point is a barrier to conduct a robust statistical analysis. For instance, East Waterford, the most data-rich area, had only 58 entries over a 10 years period, which highlights the infrequency of sampling and its implications for assessing exposure and risk. Furthermore, as the Irish water system is undergoing structural and operational improvements in their long-term National Water Plan, it presents a dynamic environment that challenges to analyse isolated drivers whether they are hydrological or operational.

Although this study aimed to explore the relationship between short-term extreme weather events, measured by the SPEI 1 index and the THM4 formation, the available data did not support a clear association. Visual comparisons between THM4 levels and SPEI-1 trends did not reveal any consistent alignment with extreme weather events. This absence of a detectable relation could be due to limited resolution, irregular sampling or the mixing influence of treatment and operational drivers. Therefore, no firm conclusions can be drawn about the impact of meteorological extremes on THM4 formation based on current evidence. Nevertheless, this remains a critical area for future research, particularly in the context of projected increases in temperature, extreme weather events and elevated concentrations of organic matter mobilization under climate change, needing operational transparency, integrated climate and water quality datasets and more frequent and harmonized monitoring of THM4.

3.0 Cyprus Case Study

Cyprus, as part of the Mediterranean region, has been identified as a hotspot for extreme climatic events. These changes have significant public health implications, particularly concerning air pollution, heat waves, and water scarcity and potential future zoonotic diseases (44,45). Geographically, Cyprus is dominated by two mountain ranges: The Troodos Mountains in the central part of the island and the Kyrenia Range in the north. The island experiences an intense Mediterranean climate characterized by strong seasonal variations with hot-dry summers, rapidly changing weather conditions during spring and autumn and short, rainy winters. Over the last 116 years, there has been a notable decline in annual rainfall accompanied by a shift of precipitation pattern that has increased the frequency of extreme weather events such as heavy rainfall, heat waves and prolonged drought. Additionally, rising evapotranspiration rates have contributed to desertification. Human activities, including high drinking water demands during the summer tourism season and extensive agriculture use, have led to reservoirs depletion and freshwater quality deterioration due to overexploitation. As a result, Cyprus has the highest water stress index in Europe (44,46).

The country´s infrastructure is vulnerable to climate-related extreme event such as heavy rainfall, sea level rise, flooding and strong wind. Flash floods, triggered by intense rainfall events, reminds an urgent concern, though no evidence links them directly to climate change(46). As example, drought which peaked in the winter of 2007, 2008 and 2018 (35)

Looking at future projections, Nicosia is expected to experience an increase of two months in the numbers of hot days per year (defined as days exceeding 38 C) by the end of the century(46). Over the past decade, the number of hot days and warm nights has already increased. Cyprus relied heavily on rain supplied water until 1997(35). To delve deep into the matter, almost 90% of the rain water returns to the atmosphere due to evapotranspiration (35). And the decline in rainfall over the last three decades, has forced Cypriots to seek for alternative water sources, such as desalination, which is highly energy-intensive. While desalination provides a reliable drinking water supply, it also contributes to biodiversity lost, rising sea salinity and further environmental stress caused by increased temperature and drought conditions(34). Until 2001, water supply was restricted in Cyprus, with mains water being switched on only 2-3 times per week and every household having installed a water storage tank to provide current water supply for 2 days(35). Those restrictions have been going on and off after 2008, as desalinated water was a partial solution.

To ensure the safety and quality drinking water, disinfection is required throughout the distribution network, typically using chlorination or chloramination (14,22,47). However, these processes lead to the formation of disinfection-by-products (DBPs) some of which have been linked to health risk (13). Notably, Cyprus has some of the highest levels of trihalomethanes (THMs) in Europe(22). Since 1997, the country has increasingly relied on desalinated seawater for drinking water supply, with more than 95% of desalination plants utilizing reverse osmosis technology. Studies have reported higher levels of iodinated THM in drinking water sourced from seawater and brackish groundwater, both sources present in Limassol (48).

This study aims to assess and compare the impact of extreme climatic event such as drought, heavy precipitation and high temperature on THM formation in the final drinking water in Nicosia and Limassol.

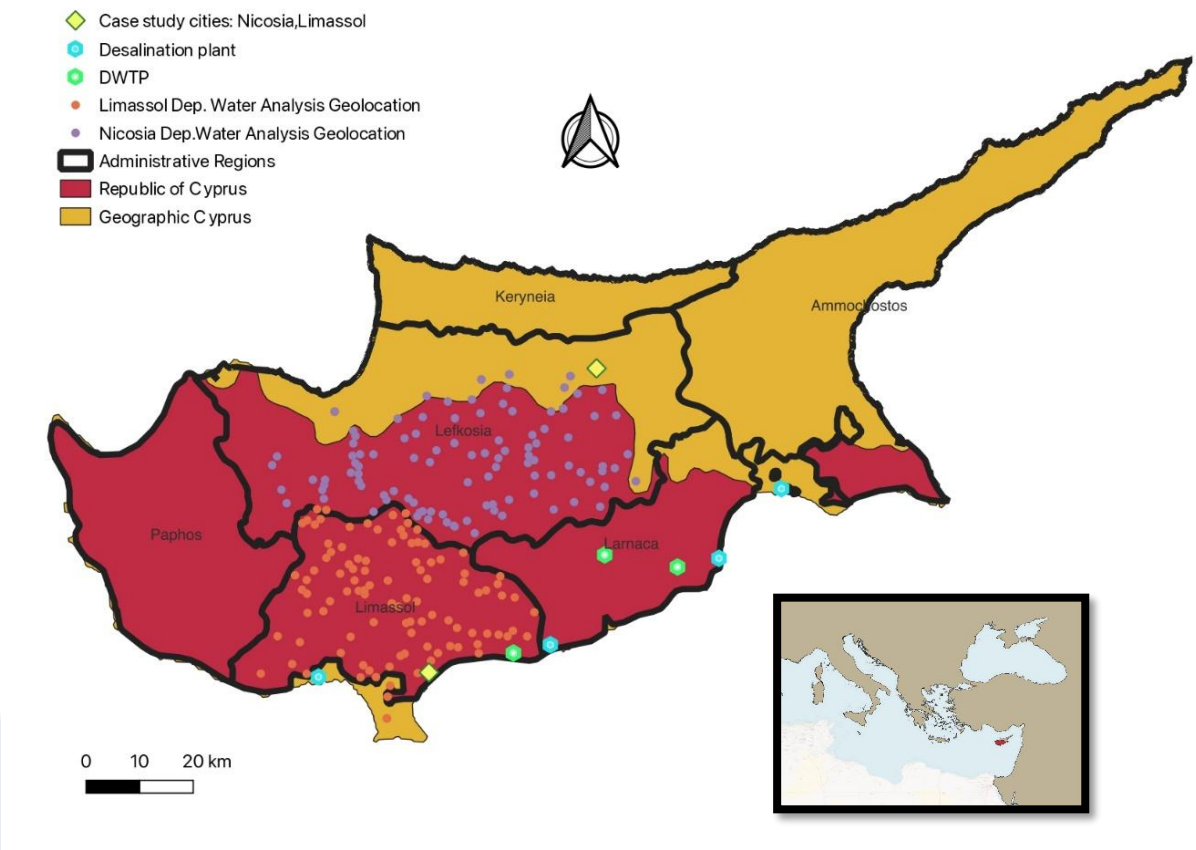
3.1 Methodology

3.1.1 Study area

Water supply management in Cyprus falls under the jurisdiction of the Water Development Department (WDD) in the Republic of Cyprus (excluding northern parts). There are 5 main desalination plants and

other desalination plants operated by private entities. This study focuses on the two largest urban area: Nicosia and Limassol. Limassol is the most populated municipality, followed by Strovolos in Nicosia (11).

Figure 4. Cyprus map with study sampled places and drinking water treatment plants geolocation



Map produced using QGIS. Basemap data from OpenStreetMap; contour lines generated from Watershed data and simplemaps

Nicosia is the capital and it divided into 29 administrative units, referred to as neighborhoods or quarters (49). Nicosia is the only Capital in Europe that has a buffer zone wall to divide the two portions of the capital (35). Nicosia´s drinking water supply comes from different sources with varying mixing ratios:

- The Kornos Water Treatment Plant (which can be supplied from the Lefkara and Dipotamos dams). At the treatment plant, a chlorine dioxide system has been installed, which operates when there is a high concentration of organic load or high temperatures that may cause elevated concentrations of trihalomethanes.
- The Tersefanou Water Treatment Plant (supplied by the Southern Conveyor Project, i.e., from the Kouris Dam, Kalavasos Dam, Vasilikos Desalination Plant, Moni Wastewater Treatment Plant). The mixing ratio of the incoming water is irregular. Into the final water reservoir also flows water from the Larnaca and Dhekelia desalination plants (again at irregular ratios). At the Tersefanou treatment plant, there is an activated carbon filter system that operates whenever deemed necessary. In addition, by the first quarter of 2026, a chlorine dioxide system will also be installed.

Limassol is divided into 18 quarters, with its drinking water supply primarily coming from (49):

- The Limassol Water Treatment Plant (mainly supplied by the Kouris Dam). At the treatment plant, both an activated carbon filter system and a chlorine dioxide system are being installed.
- Episkopi Desalination Plant.
- Vasilikos Desalination Plant.
- Germasogeia Aquifer boreholes.
- Kouris Aquifer boreholes.
- It is also planned, at the beginning of 2026, to construct and operate a water treatment plant for the Garyllis aquifer, a desalination plant at the Limassol Port, as well as a new desalination plant in the Episkopi area (within 2026).

3.1.2 Hydrologic and climate data source

We obtained drinking water quality databases through the University of Cyprus, from 2010 to 2021 with the following indicators: chloroform, bromodichloromethane, dibromochloromethane, bromoform concentrations and total trihalomethanes (μg/L) at the final tap water for regulatory purpose analyses, no other parameters such as total organic carbon (TOC), residence time, bromide or conductivity were available.

The main predictor was the Standardized Precipitation-Evapotranspiration Index (SPEI-1), a validated composite scale used to capture drought and high precipitation conditions. The data was collected from the official SPEI calculator from the SPEI Global Drought Monitor (39). To create the variable, we obtained the monthly median of SPEI-1 from the geographic area where water was extracted for both Nicosia and Limassol, 5 and 2 geolocation points respectively Figure 4. SPEI data was retrieved for 2010-2024 periodand with the water quality data, assigning each month a unique SPEI1 value. The SPEI scale is centered around 0, with positive values indicating increasing wetness. A SPEI value of ≥ 1.5 is considered severely wet while a value of ≤ - 1.5 is classified as severe drought.

WDD has already stated the predictors they usually use for drought, where Standardized Precipitation Index (SPI) is included as one of the six but with a limited use as it is only reliable for complete hydrological years.

3.1.1 Statistical analyses

Data cleaning was standardized, with values below limit of detection (LOD) imputed as LOD/2, and duplicated dates or missing data were removed. For SPEI 1, we used the threshold ≥ |1.5| to classify conditions as normal or severe drought or wet. To maintain uniformity, GAM modelling was initially planned but was not performed due to limited granularity and metadata gaps.

3.2 Results

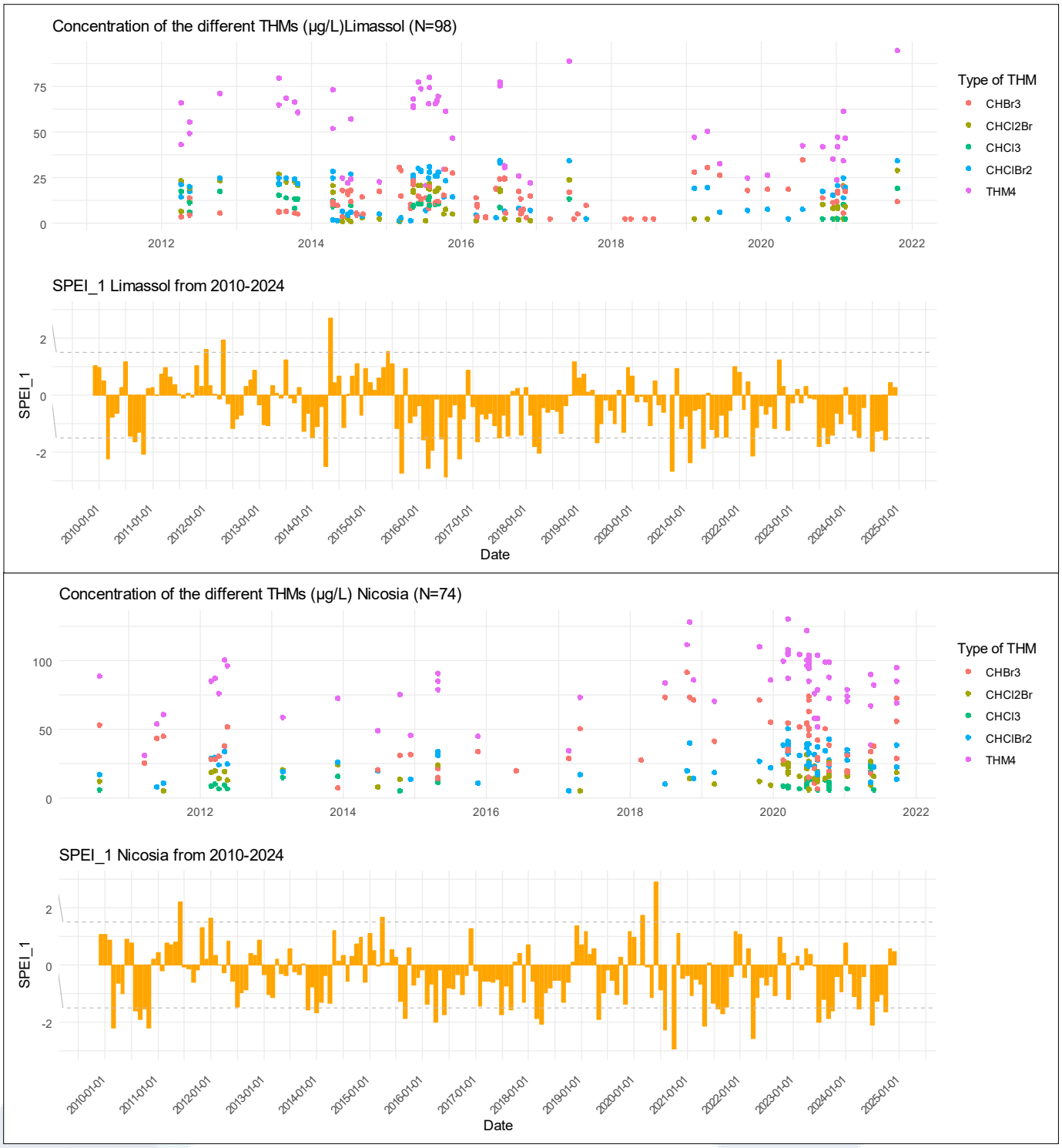
In Nicosia, THM4 concentrations reached a maximum of 130.2 μg/L with an interquartile range of 70.3 to 99.2 μg/L, exceeding the regulatory limits in several instances, particularly during 2020. Given that three desalination plants supply drinking water to Nicosia, these elevated levels are consistent with expectations of increased brominated THM formation, as desalinated water is characterized by a higher bromide content. In contrast, Limassol, had a larger sample size, with globally lower THM4 levels, peaking at 94.8 μg/L and an interquartile range of 18.7 to 65.4 μg/L. The speciation profile showed relatively higher proportions of CHCl2Br and CHClBr2, suggesting limited bromide availability in the source water. This aligns with known reaction pathway which brominated species shift toward CHBr3 under higher bromide concentrations.

Exploring the SPEI_1 index, for Nicosia the driest and wet months are concentrated in 2020 and 2022 which coincides with the highest THM4 values. However, other peak moments of THM4 such as end of 2018 are not classified as excessively dry or wet. Still further analysis should be performed to correlate

results. For Limassol, there is a fluctuation between 2012 to 2021 of the THM4 which is not translated in SPEI_1 index of dry or wetness, whereas this tendency is corrected afterwards (Figure 5). This observation suggests that short-term extreme weather conditions, measured by SPEI_1, are not directly associated with peak THM formation in the Cyprus dataset.

Due to the limited granularity and inconsistency sampling frequency, and the absence of detailed metadata, no further modelling analysis was performed. Therefore, findings from the case study remain exploratory, highlighting the need for systematic monitoring and more integrated datasets to better understand and manage THM risks in complex supply systems such as those relying on desalination.

Figure 5. THM levels (2010-2021) and SPEI_1 level (2010-2024) in Nicosia and Limassol, Cyprus.



A summary of the descriptive statistics is provided in Table 2.

Table 2. Summary of descriptive statistics of THM species (µg/L) and SPEI_1, Cyprus.

Nicosia (N=74)	CHCl3	CHCl2Br	CHClBr2	CHBr3	THM4	SPEI_1
Total N	34	58	67	68	71	134
LOD/NA	25/15	10/6	3/4	2/5	-/3	-
Me (P25, P75)	8.8 (6.7, 12.5)	16.0 (13.7, 21.5)	27.4 (20.1, 33.7)	34.9 (27.1, 51.7)	85.6 (70.3, 99.2)	-0.34 (-0.99, 0.33)
Min/Max	5.3/22.3	5.4/31.40	2.5/50.1	6.3/91.6	13/130.2	-4/1.64
Limassol (N=98)	**CHCl3**	**CHCl2Br**	**CHClBr2**	**CHBr3**	**THM4**	**SPEI_1**
Total N	31	38	57	80	82	115
LOD/NA	7/60	22/38	14/27	15/3	-/16	-
Me (P25, P75)	11.2 (9.9, 13.6)	18.8 (17.0, 21.0)	21.2 (11.8, 26.2)	14.0 (10.0,18.7)	34.9 (18.7, 65.4)	-0.43 (-1.03,0.19)
Min/Max	6.3/21.4	5.1/29.1	5.0/34.5	5.1/34.9	5.1/94.8	-3.36/1.36

3.3 Discussion

This case study highlights the complexity of managing THM in water systems, particularly in regions reliant on desalination. Nicosia supplied by three desalination plants, showed elevated THM4 levels, frequently exceeded the EU regulatory limits, with a peak value of 130.2 µg/L and a high interquartile range. This is consistent with the higher bromide content in seawater, which remains in the desalinated water, and promotes the formation of brominated THMs. However, the raw water quality alone does not fully explain the elevated THM4 concentrations, as operational factors such as the distance from treatment plants, residence time and rechlorination likely play a role. The lack of detailed data on the entire water treatment process challenges the understanding to relative contributions of each driver.

Limassol showed generally lower THM4 levels, dominated by intermediate species of THM4: CHCl2Br and CHClBr2, indicating a lower bromide availability, which may be sourced from blending desalinated and surface water sources. This shift in speciation is valuable for understanding exposure profiles, as more brominated THM have greater toxicity profiles.

In terms of extreme weather events, our study did not perform any analysis. No direct relationship was observed, in our available data, SPEI-1 extreme did not match the THM4 peak clustered around 2013-2015. This suggests that short-term extreme weather events may not be a primary driver of THM variability in these systems, especially when source switching and operational drivers are likely to have a stronger influence.

Several limitations should be considered when interpreting the results of this case study. Temporal and spatial inconsistencies in data collection were noted, with Nicosia showing more frequent data after 2020, while in Limassol data was concentrated mainly between 2014-2018 and 2020-2021, limiting the ability to detect consistent trends over time. Additionally, sampling was conducted at various points such as the outlet, intermediate and final tap water locations of the network, affecting the accuracy of the data. Inconsistencies in reporting data posed challenges, as some LOD values were reported as LOD <1, others <5 and some as 0. To maintain uniformity, all values <5 were adjusted to LOD/2, which led to a loss of granularity in the dataset. Furthermore, 8.9% of Nicosia samples and 12.9% of Limassol data, THM4 data

was not the summary of all the different species of THM, which was difficult to correct due to the LOD issue. We accounted for the LOD/2 to summarize final THM4.

In conclusion, this case study highlights the complexities of managing THM4 in Cyprus, where the water supply is heavily reliant on desalination. The elevated THM4 concentrations observed in Nicosia, mostly brominated THMs, underlines the importance of improving operational factors to mitigate the formation of more toxic brominated THMs. Despite the lack of detailed relationship with extreme weather events, improving source water management, treatment strategies and operational efficiencies remains critical to reducing THM4 levels. Future research should focus on systematic monitoring of bromide and THM speciation to better understand the influence of source water variability, climate change and operational factors on final drinking water quality. Additionally, addressing the data limitations highlighted in this study will be essential to gain understanding of the extreme weather events on THM formation.

4.0 Barcelona Case Study

Barcelona, located in the Mediterranean Basin, has long been recognized as one of the European urban areas with persistently high concentration of THM in its drinking water (21,22). This has contributed to widespread public distrust in tap water, driven more by organoleptic deficiencies such as taste and odor, often associated with chlorine, than by recognised direct toxicological risks (50). Consequently, bottled water consumption has increased, raising the environmental footprint without producing significant improvements in life expectancy or disability-adjusted life years (51).

At the same time, the Mediterranean Basin is a climate change hot-spot, where environmental pressures intersect with dense human activity, amplifying vulnerabilities in water resources (52,53). The region is undergoing significant hydrological transformations, including a long-term decline in total precipitation, increased seasonal irregularity and extended dry periods. The years 2021 to 2023 marked the driest sequence since 1835, highlighting the region´s escalating susceptibility to aridification and water scarcity (28,53,54). By late 2023, water restriction was imposed in the metropolitan area of Barcelona, focusing primarily on non-essential uses, such as irrigation of green spaces, street cleaning and certain agricultural withdrawals. These measures had a significant impact on public perception and urban water governance.

In Barcelona, where bottled water is already widely used due to lingering mistrust of tap water, these supply constraints heightened concerns about long-term water security. As climate models projects up to a 25% reduction in available freshwater resources in Spain over the coming decades, and Barcelona´s situation exemplified the growing vulnerability of Mediterranean cities to water quality challenges like THM as well as issues of availability, resilience and sustainability. Addressing these challenges will require integrated and forward-looking water management strategies that reinforce supply reliability, mitigate upstream pressures and restore public confidence in the urban water system.

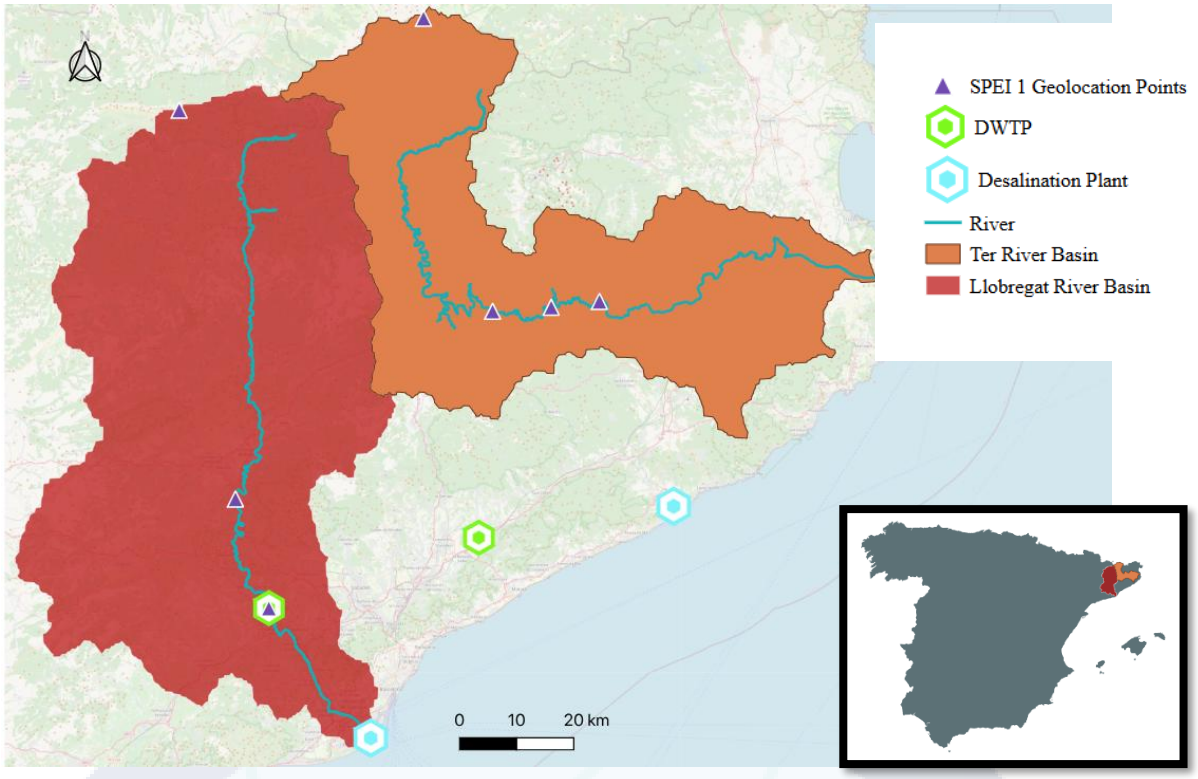
This study aims to investigate the impact of extreme weather events, intensified by climate change, on the formation and levels of THM in Barcelona´s drinking water system, to better understand the risk presented to water quality and to inform adaptive management strategies.

4.1 Methodology

4.1.1 Study area

The metropolitan area of Barcelona is a densely populated region with more than 5,5 M inhabitants located in the Mediterranean coast in northeast Spain (55). The Mediterranean climate is characterized by mild, humid winters and dry, hot summers (56). Barcelona experiences biannual rainy periods (spring, autumn), which often lead to flash floods. Llobregat and Ter Rivers (56), sourced in the Pre-Pyrenean mountains (53,57,58), are the main drinking water supplies, treated at three DWTPs: Ter (Cardedeu), Llobregat (Abrera), and Sant Joan Despí. This study focuses on the two DWTPs managed by the public company Ens d'abastament d'Aigua Ter Llobregat (ATL): Llobregat and Ter DWTPs (Figure 6). To manage water demand and availability, the two rivers have been interconnected since 2010. Additionally, desalinated seawater is supplied to Llobregat DWTP from El Prat desalination plant since 2009 and to Ter DWTP from Tordera desalination plant since 2002.

Figure 6. Barcelona case study, geocoordinates of SPEI selected areas.



Map produced using QGIS. Basemap data from OpenStreetMap; contour lines generated from Watershed data

The northern and central parts of the Llobregat basin are characterized by a mix of pines forest, agricultural lands, industrial areas, and potash mines (57), which increases the salinity in the river, making the Llobregat River rich in bromide and organic matter (16,56). To mitigate the formation of brominated THMs, an electrodialysis reversal (EDR) plant was installed at Llobregat DWTP in 2009 (7,59). In contrast, the upstream section of the Ter River is dominated by riparian forests of deciduous trees (58). Ter River´s flow is highly regulated by three connected reservoirs (Sau, Susqueda and Pasteral), which also function as artificial sediment cells (60). Water from the Pasteral reservoir is supplied to Ter DWTP through several gates, with each gate compartment analyzed prior to select the optimal water layer, reducing the need for extensive treatment.

4.1.1 Hydrological and meteorological data source

ATL provided data for both Llobregat and Ter DWTPs from 2010 to 2024, including concentrations of chloroform (CHCl3), bromodichloromethane (CHCl2Br), dibromochloromethane (CHClBr2), bromoform (CHBr3) and total trihalomethanes (THM4, µg/L) measured at the DWTP outlet. Raw water parameters at the DWTPs inlet included Llobregat River flow (m^3/s), Ter reservoir volume (hm^3), temperature (ºC), and water quality indicators such as conductivity (µS/cm), ammonia (mg/L), nitrite (mg/L), nitrate (mg/L), pH, total organic carbon (TOC, mg/L), ultraviolet absorbance (UV Abs, abs/m), and bromide (mg/L). Water samples were analyzed every 4-5 days in Llobregat DWTP and weekly in Ter DWTP. Operational variables such as percentage of water processed by EDR system at the Llobregat DWTP and the percentage of water from secondary sources (e.g., desalinated water), were provided for both DWTPs.

We also collected data on the Standardized Precipitation-Evapotranspiration Index (SPEI-1), a validated composite scale used to capture drought and high wet conditions. Data was sourced from the official SPEI calculator from the Spanish National Research Council (CSIC) website (39). To create the variable, we

calculated the median SPEI-1 from three to four geographic locations by basin (Figure 6). For the Llobregat basin, we selected the geolocation coordinates from the river source, the confluence with its main affluent, the Cardener River, and Llobregat DWTP. For the Ter basin, we selected the river source and the three reservoirs to calculate the median value. The SPEI-1 is calculated weekly using data from a one-month period, with data points for the 1st, 9th, 16th and 23rd of each month. We merged the SPEI-1 data with the water quality data, applying a one-week lag, and assigning each week a unique SPEI-1 value. The SPEI scale is centered around 0, with positive values indicating increasing wetness. A SPEI value of ≥ 1.5 is classified severely wet, while a value of ≤ - 1.5 indicates severe drought.

4.1.2 Statistical analyses

We assessed the relationship between extreme weather events and THM formation using two complementary approaches. The first approach used temperature and hydrological indicators as main predictors: Llobregat River flow at the inlet (m^3/s) for Llobregat DWTP, and reservoir volume for Ter DWTP. The second approach relied on the meteorological SPEI-1 as a proxy for drought and extreme wet conditions. Given the differences in catchment characteristics, raw water profiles, and treatment, separate analyses were conducted for each DWTP, also reported previously by heteroscedasticity issues (7). Values below the limit of detection (LOD) were imputed LOD/2, and duplicated data were removed.

To avoid multicollinearity, we selected representative water quality indicators based on the Spearman correlations plot, prioritizing consistency across both DWTP (Figure 7). For instance, nitrate was used as a proxy for nitrogen species due to its correlation with ammonia and nitrite. TOC was chosen over UV absorbance; and conductivity served as a proxy for bromide. Final models included as covariates the percentage of water source (defined by the proportion of main river water for each DWTP), conductivity, TOC, pH and a nitrogen parameter (nitrate was used in Ter DWTP since most ammonia values were below the limit of detection) (Figure 8 and Table 3). The percentage of EDR treated water was included only for Llobregat DWTP, as a site-specific parameter.

We developed separate models for each THM species: CHCl3, CHCl2Br, CHClBr2, CHBr3 and THM4. CHCl3 was excluded from Llobregat models and CHBr3 was excluded in Ter models due to consistently negligible levels. We applied Generalized Additive Models (GAMs) to explore nonlinear association between hydrometeorological predictors and THM concentrations. In the exploratory analysis, models incorporated cubic regression splines on river flow or reservoir volume (k=2) and on time (k=60) to account for seasonal and long-term trends. In the final models, main predictors (temperature and water flow or volume) were converted to categorical variables based on the 10th and 90th percentiles (P10, P90), included as dummy variables. These models retained the time spline and the same set of covariates (TOC, pH, conductivity and ammonia/nitrate, source of water; and EDR for Llobregat plant). All models were stratified by water source and in the Llobregat DWTP, also by EDR treatment, to assess their role as potential effect modifiers on THM formation. We maintained same threshold for the categorical extreme weather events. Lag structures were evaluated but they did not improve model fit and were therefore not retained.". However, a one-week lag was applied in the merging of SPEI-1 data to account for the temporal delay in THM response to meteorological conditions.

SPEI-1 was analyzed separately and categorized, based on the SPEI-1 ≥ |1.5| threshold values, into normal or extreme conditions (drought and wetness). Models included the same covariates and the time spline as above. All data analysis was conducted using statistical software R Studio version 4.4.1. and the spatial representations by QGIS 3.22.

Figure 7. Spearman correlation plot for both study sites in Barcelona

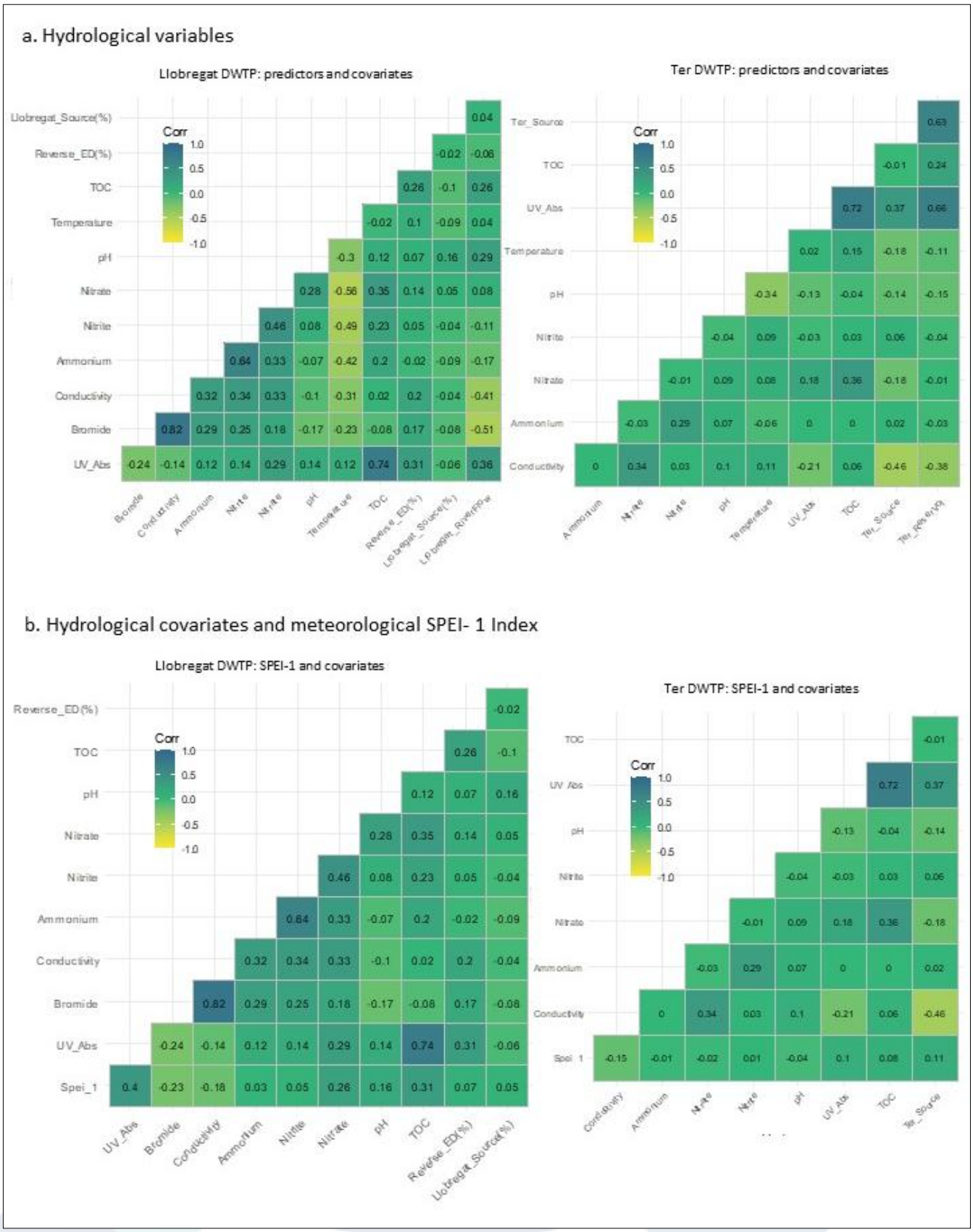


Figure 8. Conceptual model for both drinking water treatment plants, Barcelona case-study.

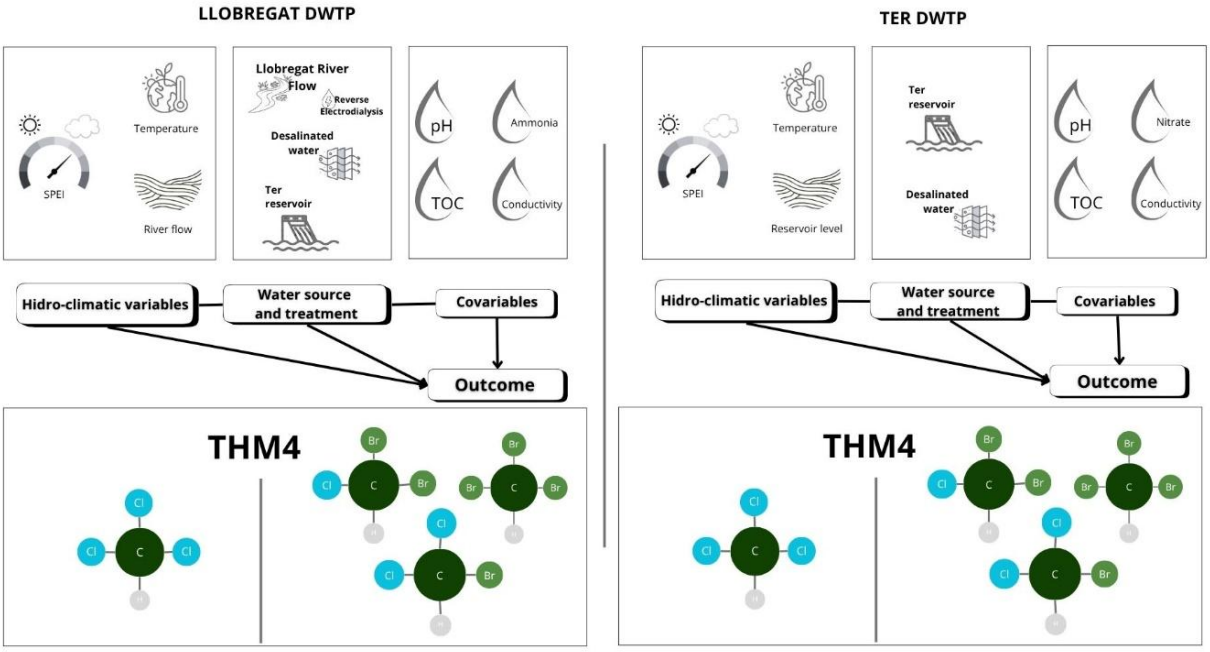


Table 3. Regression Model for predictor of THM levels across water treatment plants

$$THM = \beta_a * s(time) + \beta_b * Predictors + \beta_c * Covariates + \beta_d * Source$$

Where:

β_a, β_b, β_c, β_d: Estimated regression coefficients β corresponding to each variable group.

THM: Represents different types of THM, including THM4, CHCl3, CHCl2Br, CHClBr2, CHBr3

s(time): A spline function of time, with 60 basis functions, used to capture non-linear temporal pattern of seasonality and trend within a GAM model.

Predictors: The main predictors including temperature. For Llobregat DWTP, Llobregat River flow is included; for Ter DWTP, the Sau-Susqueda-Pasteral reservoir level is used. In the second model, the SPEI 1 index is used as the categorical predictor.

Covariates: Based on Spearman correlation analysis, the covariates include: conductivity, ammonia or nitrate, pH, TOC. For Llobregat DWTP, the percentage of water treated by EDR is also included.

Source: Llobregat DWTP accounts for two secondary sources whereas Ter DWTP relies on one secondary source.

4.2 Results

4.2.1. Hydrological trends in Ter and Llobregat basin

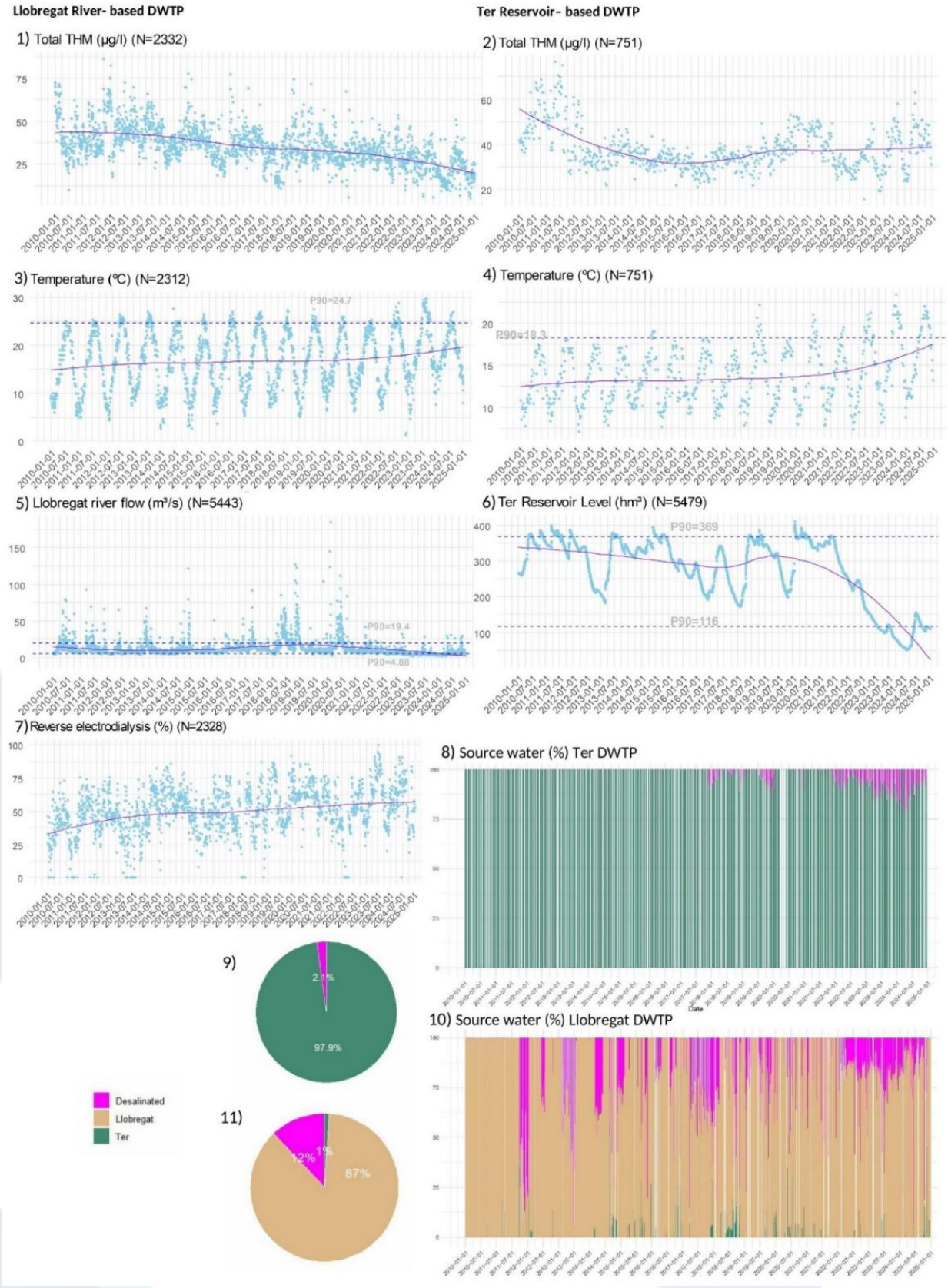
A descriptive summary of variables under study is provided in Table 4. The Llobregat River flow had a median of 8.3 m^3/s with significant variability according to the interquartile range (IQR: 6.5 - 11.8 m^3/s). In the Ter basin, reservoir volume showed moderate fluctuation (IQR: 217 - 348 hm^3), with a median of 305 hm^3. Over the 15-year period, THM level declined by approximately 20µg/L (Figure 9), while raw water temperature increased by + 0.3 °C annually at both study sites (Figure 9). In Llobregat DWTP, bromide, ammonia and conductivity increased notably during the last 18 months, coinciding with the drought period which is likely driven by concentration effects during drought conditions (Figure A1). In contrast, the Ter DWTP showed a shift in trends between 2017 and 2018, with increasing concentrations of nitrate, TOC and conductivity (Figure A2).

Table 4. Summary of descriptive statistics of the variables continuous and categorical, Barcelona.

PARAMETERS		LLOBREGAT PLANT			TER PLANT	
		N	Median (P25-P75)		N	Median (P25-P75)
Chloroform (CHCl3, µg/L)		2331	<0.5 (<0.5, 1.4)		751	23.0 (19.0, 24.7)
Bromodichloromethane (CHCl2Br, µg/L)		2331	3.0 (2.0, 4.4)		751	8.8 (7.8, 10.0)
Dibromochloromethane (CHClBr2, µg/L)		2331	10.5 (8.0, 13.0)		751	2.6 (2.0, 3.7)
Bromoform (CHBr3, µg/L)		2331	17.4 (13.0, 22.9)		751	<0.5 (<0.5, <0.5)
Total trihalomethane (THM4, µg/L)		2331	34.3 (27.8, 41.7)		751	35.8 (31.4, 42.1)
Predictors						
Continuous	Temperature (°C)	2312	17.0 (12.0, 22.0)		751	13.4 (11.0, 16.4)
	River flow (m3/s)	5443	8.3 (6.5, 11.8)		-	-
	Reservoir volume (Hm3)	-	-		5479	305 (217, 348)
	Standardized Precipitation Evapotranspiration Index (SPEI 1)	5445	-0.1 (-0.8, 0.7)		5479	-0.1 (-0.8, 0.7)
Categorical		All sources (N)	Only Llobregat (N)	Llobregat+ Desalinated (N)	All sources Ter (N)	
	High temperature (≥P90)	232	76	141	74	
	Normal temperature (<P90)	2080	1060	766	677	
	Low river flow/reservoir volume (≤P10)	544	16	207	548	
	High river flow/reservoir volume (≥P90)	545	95	50	548	
	Normal river flow/reservoir volume (>P10, <P90)	4354	1038	653	4383	
	SPEI 1 ≤-1.5 (severe drought)	271	42	64	376	
	SPEI 1 ≥ 1.5 (severe wet)	389	71	73	369	
	SPEI 1 <|1.5|	4782	1036	773	4734	
Covariates		N	Median (P25-P75)		N	Median (P25-P75)
Conductivity (µS/cm)		2317	1331 (1166, 1491)		749	408 (388, 433)
Total Organic Carbon (TOC, mg/L)		2299	3.2 (2.8, 3.7)		749	2.6 (2.4, 3.0)

Ammonia (mg/L)	2331	0.1 (0.1, 0.2)	757	0.1 (0.1, 0.2)
Nitrate (mg/L)	2309	7.5 (5.9, 9.7)	751	4.2 (<0. 5, 6.0)
pH	2315	8.1 (8.0, 8.2)	749	8.0 (7.9, 8.0)
Operational variables				
Electrodialysis Reversal (EDR, %)	2219	40.8 (39.4, 62.0)	-	-
Desalinated water (%)	1048	22.0 (14.7, 34.3)	219	6.6 (4.2, 9.6)
Ter water (%)	272	6.0 (3.7, 10.5)	-	-

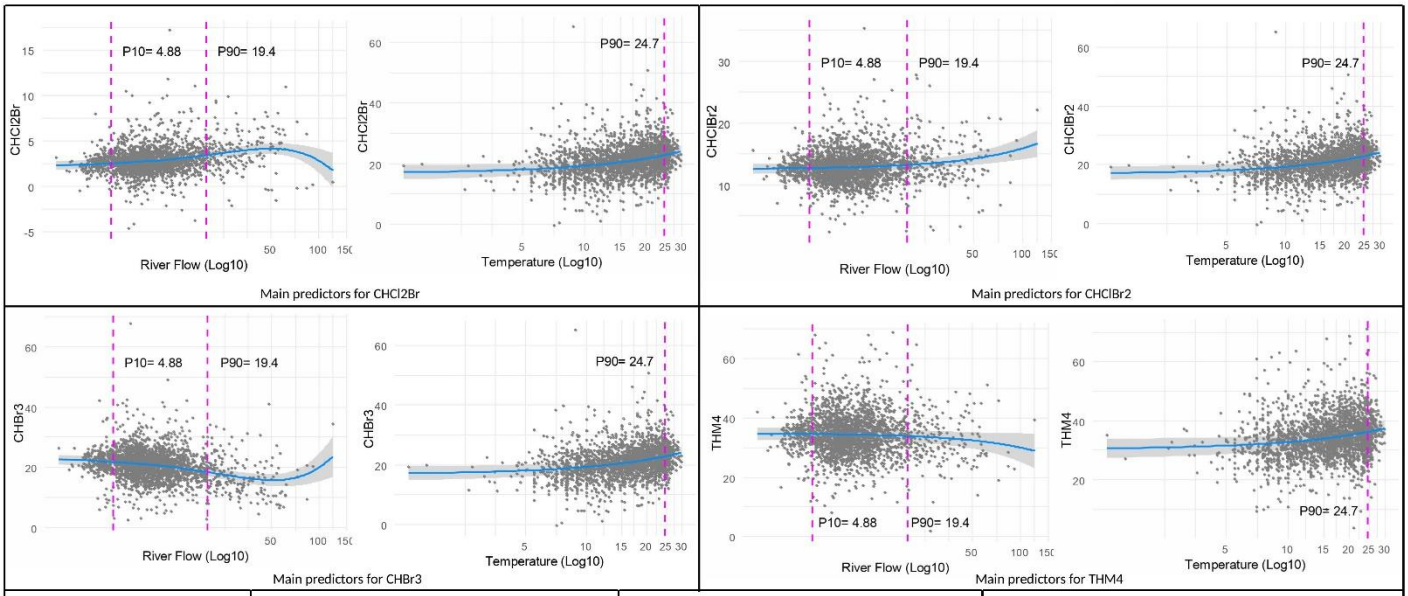
Figure 9. Descriptive statistic of the main outcome (THM4) and variables (Temperature, River Flow, Reservoir Level and Reverse Electrodialysis).



4.2.2. Llobregat DWTP (River-based)

The analysis conducted across the full range of temperature and flow values showed a non-linear association between river flow and THM species, showing different patterns by THM species. Temperature was positively associated with most THM species [THM4 by 0.24 (CI 95%: 0.08, 0.39)] except for CHCl2Br, which showed no significant associations (Figure 10).

Figure 10. Main predictors (Temperature and Flow) in continuous models for Llobregat DWTP



Outcome	Temp Continuos	% Llobregat Source	Other Covariates
	Coef (95%CI)	Coef (95%CI)	
CHCl2Br	-0.01 (-0.04, 0.02)	-0.04 (-0.05, -0.04)	Cond^, NH4^, pH*, TOC*,EDR*
CHClBr2	0.12 (0.07, 0.18)	0.03 (0.02, 0.04)	Cond^, NH4^, pH, TOC*, EDR
CHBr3	0.24 (0.14, 0.35)	0.06 (0.04, 0.07)	Cond*, NH4, pH^, TOC*, EDR^
THM4	0.24 (0.08, 0.39)	-0.13 (-0.16, -0.11)	Cond*, NH4^, pH, TOC*, EDR^

The models with extreme events showed that extreme high temperature (P90 ≥24.7 °C) did not have a significant effect on THM species. For instance, β coefficient for THM4 was -0.25 (CI 95%: -1.51, 1.01) (Table 5). However, high river flow (P90 ≥ 19.4 m^3/s), was inversely associated with THM4 (β: -1.41, CI 95%: -2.77, -0.05) and CHBr3 (β:-2.64, CI 95%: -3.61, -1.67) while positively associated with CHClBr2 (β: 0.79, CI 95%: 0.28, 1.29) and CHCl2Br (β:0.74, 95%CI: 0.46, 1.02) (Table 5).

Given the consistent influence of water source on THM formation in the exploratory analyses (Figure 10), we stratified the models to assess whether it might act as an effect modifier. We stratified the data into two main subgroups: one solely based on Llobregat River water versus mixed sources (river + desalinated seawater), while maintaining the same P10 and P90 flow threshold. Results revealed evidence of effect modification for specific THM species. For intermediate THM such as CHCl2Br and CHClBr2, high river flow was positively associated in samples sourced only from the Llobregat River, but showed null association in the mixed-source group (Table 5). This loss of significance suggests an interaction, where source water composition alters the effect of hydrological extreme on chlorinated THM formation. In contrast, the association between high flow and CHBr3 remained consistently negative across both subgroups, which indicates no significant effect modifier. For the THM4, we observed a stronger negative association in the

mixed-source group compared to the only Llobregat River sourced water group, pointing to a possible quantitative modification (Table 5).

Operational factors also played a role, such as the increasing use of EDR, averaging 50-60% (Figure 9), which was inversely associated with CHBr3 and THM4, but positively linked to CHCl2Br (Table 5). Desalinated water use peaked above 90% in some summer periods such as in 2013 and 2024, and was directly associated with CHCl2Br and the THM4 (Table 5). Additionally, other covariates such as TOC emerged as a consistently positive predictor across all THM species, reinforcing the importance of organic matter in THM formation. Conductivity and pH were positively associated with brominated species, while nitrate levels were positively associated with CHCl2Br and CHClBr2 (Table 5, Figure 10).

The SPEI-1 index exhibits a linear relationship with the THMs (Annex Figure 1), with results at the Abrera DWTP aligning closely with those observed for hydrological parameters (Table 5). Severe wet conditions measured by SPEI-1, were positively associated with higher CHCl2Br and CHClBr2 concentrations, by 0.52 (CI 95%: 0.24, 0.79) and by 0.59 (CI 95%: 0.10, 1.09), respectively (Table 5). On the contrary, it was negatively associated with CHBr3: -1.11 (CI 95%: -2.06, -0.16). The magnitude of the association was higher than the hydrological parameter (high river flow). In addition, the pattern was consistent even when we segregate the data by water source for the chlorinated THMs. However, no association was found during severe drought conditions.

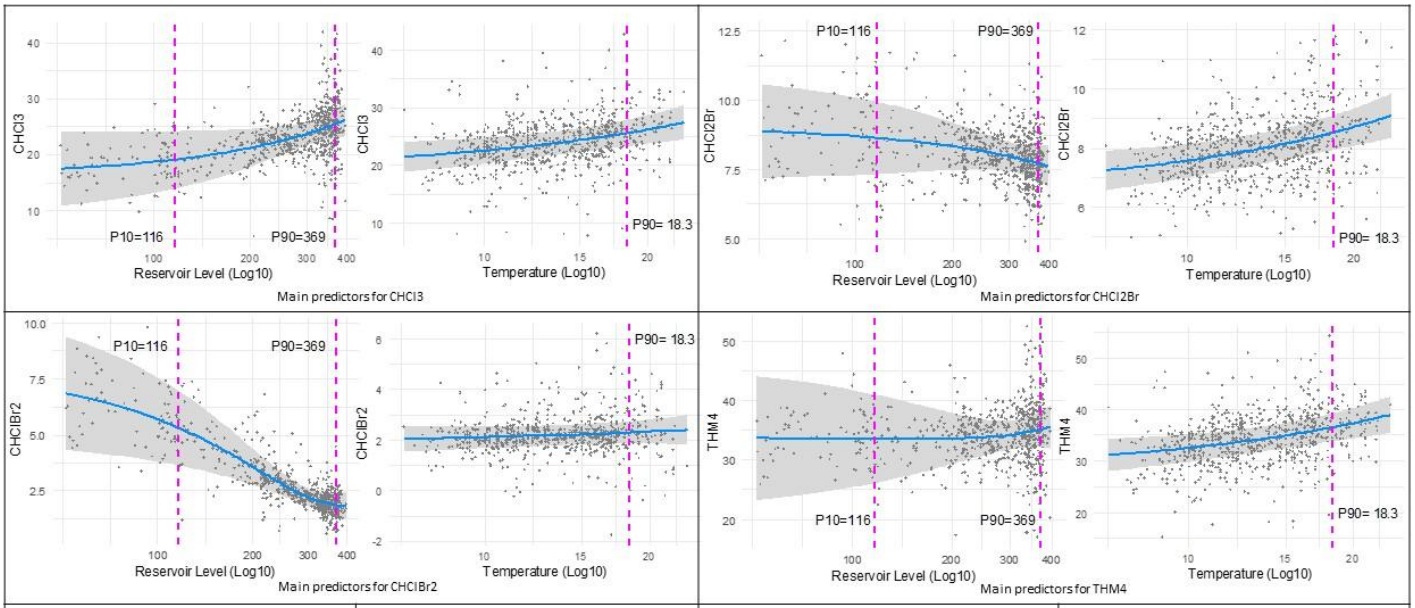
These findings in Llobregat DWTP highlight the role of extreme weather conditions, capture by flow mediated dynamics and SPEI 1, are modulating THM species formation

4.2.3. Ter DWTP (Reservoir-based)

The exploratory analysis with the main predictors as a continuous variable in the TER DWTP, THMs species, such as THM4, were positively associated with temperature by 0.35 (CI 95%: 0.07, 0.63), except for CHClBr2 which was not significant (Figure 11). Continuous reservoir levels also showed a linear association with THM species, which allowed for stratification by P10 and P90.

In our extreme weather events model, extreme high temperature, defined by P90 ≥18.3 °C did not show an effect on the THM species, for instance the association with THM4 was 0.87 (CI 95%: -1.06, 2.81) (Table 5). In contrast, low reservoir levels (P10 ≤ 116 hm3), significantly increased all THM species, most notably CHCl3 by 2.99 (CI 95%: 0.29, 5.69) and THM4 by 4.08 (CI 95%: 0.83, 7.33). In addition, high reservoir levels (P90 ≥ 369 hm^3), increased THM formation, such as CHCl3 by 1.63 (CI 95%: 0.33, 2.92) and THM4 by 1.64 (CI 95%: 0.09, 3.19). Other factors, such as TOC and pH were the main positively influencing THM formation (Table 5, Figure 11).

Figure 11. Main predictors (Temperature and Flow) in continuous models for Ter DWTP



Outcome	Temp Continuos	% Ter Source	Other Covariates
	Coef (95%CI)	Coef (95%CI)	
CHCl3	0.27 (0.04, 0.50)	0.11 (-0.04,0.25)	Cond, NO3, pH, TOC*
CHCl2Br	0.09 (0.03, 0.15)	-0.02 (-0.05, 0.02)	Cond, NO3, pH, TOC
CHClBr2	0.01 (-0.04, 0.06)	-0.13 (-0.16,-0.10)	Cond, NO3, pH, TOC
THM4	0.35 (0.07, 0.63)	-0.20 (-0.37, -0.02)	Cond, NO3, pH, TOC*

In Ter DWTP, the SPEI-1 index also exhibits a linear relationship with THMs concentrations (Figure A2), although, associations were less consistent with the hydrological findings observed for reservoir volume (Table 5). Notably, THM4 levels declined significantly during both severe drought and wet conditions, by -1.82 (CI 95%: -3.39, -0.24) and -2.15 (CI 95%: -3.83, -0.46) respectively. These findings suggest that SPEI 1 may capture broader climatic influences that do not directly correlate with local reservoir storage.

Table 5. Llobregat and Ter drinking water treatment plant (DWTP). Change ((β coefficient) in trihalomethane (THM) concentrations by percentile 10 and 90 (P10, P90) of river flow and reservoir level relative to normal (>P10, <P90) and temperature ≥P90 relative to <P90. The column at the right indicates THM concentration change by SPEI extremes relative to normal values.

Analysis group by water source	Outcome[1]	N	River flow/ Reservoir volume		Temperature	N	SPEI 1	
			Low (≤P10) b (95%CI)	High (≥P90) b (95%CI)	High (≥P90) b (95% IC)		≤-1.5 (Severe Drought) b (95%CI)	≥ 1.5 (Severe Wet) b (95%CI)
Llobregat plant, all data[2]	CHCl2Br	2262	0.32 (-0.02, 0.65)	0.74 (0.46, 1.02)	-0.15 (-0.41, 0.11)	2264	-0.06 (-0.38, 0.25)	0.52 (0.24, 0.79)
	CHClBr2		0.19 (-0.42, 0.80)	0.79 (0.28, 1.29)	-0.34 (-0.80, 0.13)		-0.03 (-0.59, 0.54)	0.59 (0.10, 1.09)
	CHBr3		-0.37 (-1.54, 0.81)	-2.64 (-3.61, -1.67)	0.30 (-0.59, 1.20)		0.09 (-1.00, 1.18)	-1.11 (-2.06, -0.16)
	THM4		0.09 (-1.55, 1.74)	-1.41(-2.77, -0.05)	-0.25 (-1.51, 1.01)		-0.78 (-2.31, 0.74)	0.91(-0.42,2.24)
Llobregat plant, only Llobregat River[3]	CHCl2Br	1119	0.02 (-0.64, 0.68)	1.22 (0.96, 1.49)	-0.11 (-0.40, 0.17)	1119	-0.31 (-0.66, 0.04)	0.59 (0.30, 0.87)
	CHClBr2		-0.40 (-2.09, 1.29)	0.92 (0.25, 1.59)	0.01 (-0.73, 0.75)		-0.30 (-1.18, 0.58)	1.37 (0.66, 2.07)
	CHBr3		-2.60 (-5.53, 0.33)	-3.46 (-4.63, -2.29)	1.41 (0.13, 2.69)		-0.04 (-1.60, 1.51)	-0.51 (-1.76, 0.74)
	THM4		-3.08 (-7.13, 0.98)	-0.77 (-2.38, 0.84)	1.36 (-0.41, 3.12)		-0.60 (-2.71, 1.51)	1.69 (-0.01, 3.39)
Llobregat plant, river + desalinated[3]	CHCl2Br	890	0.23 (-0.17, 0.62)	-0.05 (-0.64, 0.54)	0.18 (-0.21, 0.58)	891	0.25 (-0.28, 0.78)	0.73 (0.27, 1.18)
	CHClBr2		0.20 (-0.43, 0.82)	-0.52 (-1.47, 0.43)	-0.07 (-0.70, 0.57)		-0.03 (-0.92, 0.86)	0.01 (-0.72, 0.74)
	CHBr3		0.58 (-0. 77, 1.93)	-2.81 (-4.85, -0.76)	-0.40 (-1.77, 0.97)		-0.44 (-2.32, 1.43)	-2.42 (-3.98, -0.87)
	THM4		1.32 (-0.48, 3.12)	-4.36 (-7.08, -1.64)	0.13 (-1.70, 1.95)		-0.36 (-2.85, 2.14)	-0.09 (-2.19, 2.01)
Ter plant, all data[4]	CHCl3	745	2.99 (0.29, 5.69)	1.63 (0.33, 2.92)	1.56 (-0.05, 3.18)	745	-1.78 (-3.10, -0.46)	-1.74 (-3.15, -0.33)
	CHCl2Br		1.35 (0.67, 2.04)	0.10 (-0.23, 0.43)	0.33 (-0.08, 0.75)		0.004 (-0.34, 0.35)	-0.20(-0.57, 0.16)
	CHClBr2		0.59 (0.05, 1.13)	-0.04 (-0.30, 0.21)	-0.21 (-0.53, 0.11)		0.15 (-0.11, 0.41)	-0.10 (-0.37, 0.18)
	THM4		4.08 (0.83, 7.33)	1.64 (0.09, 3.19)	0.87 (-1.06, 2.81)		-1.82 (-3.39, -0.24)	-2.15 (-3.83, -0.46)

[1]CHCl3 = chloroform, CHCl2Br = bromodichloromethane, CHClBr2 = dibromochloromethane, CHBr3 = bromoform, THM4 = Sum of all trihalomethanes

[2]Adjusted for source, conductivity, ammonia, pH, Total Organic Carbon (TOC), and % Electrodialysis Reversal (EDR).

[3]Adjusted for conductivity, ammonia, pH, TOC, and %EDR.

[4]Adjusted for source, conductivity, nitrate, pH, and TOC.

4.3. Discussion

The full analytical approach was mainly achieved for Barcelona, while Ireland and Cyprus remained more exploratory due to data limitations. The uneven delivery across case studies showcases the difficulty to conduct this type of assessment in light of the currently available datasets and the need to create (or make available) open access databases with long-term information on drinking water quality, treatment, and source. Available time series for Barcelona (15 years) was shorter than expected (at least 20 years), which represents a limitation to provide generalizable conclusions at longer term. Given the paucity of relevant data, the analysis was conducted at the utility level rather than at the local/regional/national scale as initially conceived in the DoA. Given the different data needs in this task and WP5, after discussions to explore integrative approaches, independent analyses were finally conducted.

The evaluation in Barcelona assessed the influence of extreme hydrologic and weather events on THM formation in two contrasting drinking water production systems in the Barcelona Metropolitan Area: a river-fed system (Llobregat plant) and a reservoir-based system (Ter plant). By combining long-term monitoring with event-based modeling, we identified how certain extreme hydrometeorological events, along with operational factors, modulate both THM formation and species profiles.

Over the 15 years study period, THM4 levels declined across both plants, reflecting operational upgrades and improved treatment efficiency. Notably, the overall influence of extreme events on THM concentration appeared modest in magnitude, their impact on THM speciation was more pronounced. Our findings provide a more nuanced understanding of how extreme river flow and reservoir volume affect THM formation.

The Llobregat plant, a dynamic riverine system with highly flexible operational capabilities such as extensive source blending and EDR technology, demonstrates substantial adaptability to extreme hydrometeorological conditions. High river flow events were associated with reduced levels of brominated THMs (e.g., CHBr3), while concurrently increased chlorinated species such as CHCl2Br and CHClBr2. These effects remained even after adjusting for covariates such as EDR usage and stratification by water source. This speciation shift is likely driven by precursor dilution (lower bromide) and increased TOC from surface runoff, especially when pure Llobregat river water is treated. This altered ratio of precursors may exert a more direct influence on THM levels beyond what operational strategies alone can buffer. This shift towards less brominated species also implies a lower presence of more toxic THM, especially relevant for public health.

EDR emerged as a key operational factor, contributing not only to the reduction of the overall THM4 but also to shift in speciation toward less brominated THMs. The ability of EDR to consistently lower bromide levels suggests its strategic value in mitigating climate-sensitive formation pathways, particularly those driven by high temperature and elevated bromide availability.

The composition of the source water acted as a significant effect modifier. When desalinated seawater was blended with river water, the association was notably attenuated between high flow and increased chlorinated THM species. This highlights the role of source water management in buffering treatment plants against fluctuations in natural hydroclimatic events and how important is to account for blending regimes in risk modeling.

In contrast, low river flow conditions showed no significant effect on THM levels. This lack of effect may be attributable to the combined buffering capacity of EDR and the strategic use of desalinated water during dry periods, both of which reduce bromide content and thereby decouple THM formation from temperature-driven kinetics. Accordingly, the relatively weak temperature effect observed in our models

likely reflects successful operational decoupling of key chemical precursors from environmental conditions.

The Ter plant, supplied by a system of interconnected reservoirs, is operationally less complex than Llobregat system. However, like the Llobregat plant, the continuous temperature model showed a significant association with THM formation, whereas extreme temperature events model did not. This discrepancy suggests that gradual and sustained temperature increases might be more influential than short-term extremes. And noted in previous literature, effects of extreme weather events vary depending on their duration, timing and the intensity, which may explain the lack of consistent patterns under binary extreme event classification.

Both low and high extreme reservoir volumes were significantly associated with increased THM formation, though likely via different pathways. Low reservoir volumes may lead to the concentrate organic precursors, enhancing THM formation. Notably, most of those extreme low reservoir events were registered over the recent years coinciding with periods where blending desalinated seawater system was mostly used, and therefore altering water composition. Conversely, extreme high reservoir volumes were registered over the 15 years period, and this increase of THM formation, may reflect vertical mix of water in the proper reservoir, as it mobilizes organic matter from deeper layers or resuspend accumulated material from the bottom of the reservoir, particularly during storm-driven inflows, increasing TOC levels and precursors reactivity. Both extremes pose potential risks to source water quality through different pathways. However, it is important to note that within the interconnected three-reservoir system, raw water quality is routinely monitored at multiple depths in the two upstream reservoirs. This monitoring informs the selection of intake gates, allowing operators to choose the water layer with the most favorable quality before it is transferred to the final reservoir, functioning as a large mixing basin prior to treatment in the drinking water plant.

The SPEI-1 index showed associations with THM species, particularly in Llobregat plant, suggesting it may serve as a proxy for climate influence in river-based systems. However, in the Ter plant, associations between SPEI-1 and THM were less aligned with hydrological measures, likely due to the buffering effect of reservoir storage. Longer-term indices (such as SPEI-3 or SPEI-6) would better capture long-term meteorological variations, but neither appropriate for short-term extreme weather events.

We acknowledge several limitations in our modeling approach that may have impacted the detection and interpretation of extreme weather effects on THM formation. The use of a high-order spline, allowed us to model non-linear responses and preserve data granularity. However, it may have attenuated some of the variability attributable to extreme weather events, limiting our ability to detect their independent effect, this could help explain the relatively small effect attributed to hydrological parameters. The modest effect may reflect either a true buffering effect of treatment systems or a methodological constraint in detecting episodic impacts within a smoothed temporal framework. Additionally, temporal resolution of the data, with sampling occurring every 4-5 days to weekly, may have constrained our ability to fully capture rapid changes during short-duration extreme events. Mediterranean weather is characterized by flash floods and it is already reported in literature that even if there is an initial phase of increasing concentrations of TOC and other matters by runoff, the water quality during the events could also change. Therefore, this limitation reduces the sensitivity of the models. Although collinearity was not detected, high correlation between key variables warrants cautious interpretation such as between Ter River water percentage and reservoir volume (r=-0.63) (Figure 7). The interaction may have enhanced the individual effect those variables into the final model of THM formation. However, the inclusion of those variables was essential for predicting THM and including the interaction effect in the models made no difference. Finally, other operational factors known to influence THM formation, such as free chlorine

concentration, residence time or storage duration, were not included due to data limitations. These variables are important to be integrated into future studies.

Future research should also consider post-drought rewetting events, which may have triggered increased TOC levels and subsequent THM formation (40), highlighting the need to view extreme weather impacts not as isolated episode but within a broader hydrological context. To better capture these dynamics, we recommend the use of complementary modeling approaches, such as seasonal-trend decomposition, random forest models, generalized additives mixed models, or weighted regression techniques paired with high-frequency monitoring (29). These could enhance the detection of complex interactions between extreme weather events, source water quality and treatment operations.

In conclusion, our study applied a long-term analysis of two contrasting drinking water plants to assess how extreme weather events influence THM formation and speciation. While the overall effect of extreme conditions were modest, distinct patterns emerged depending on water source and treatment configuration. The Llobregat plant with its flexible use of EDR treatment and source mixing, appeared to buffer THM formation under extreme weather events. In contrast, the Ter system, reliant on reservoir dynamics such as selective withdrawal and artificial sedimentation cell combining three reservoir system with less operational flexibility, showed greater sensitivity to volume extremes. These findings highlight the importance of integrating source water characteristics, advanced treatment technologies and long-term monitoring to improve climate resilience in drinking water systems. Future research should aim to capture short-term events with higher-frequency data and explore broader operational variables to enhance predictive capacity. Studies in other settings with less intervened drinking water production systems are needed to understand the effect of extreme weather events on drinking water quality in different contexts.

ANNEX

Figure A1: Llobregat DWTP all the different variables concentration time series and SPEI-1 relationship with THM4

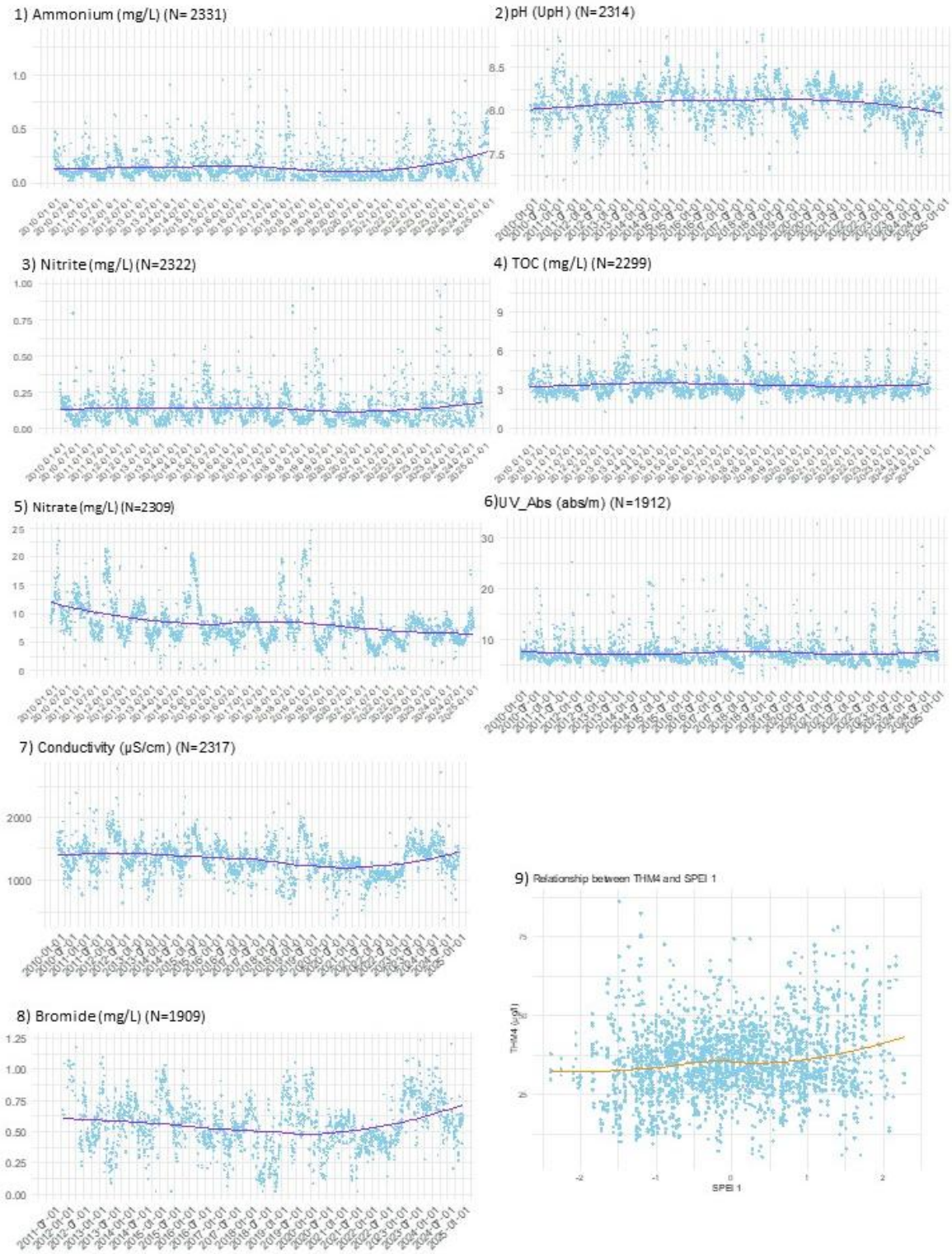
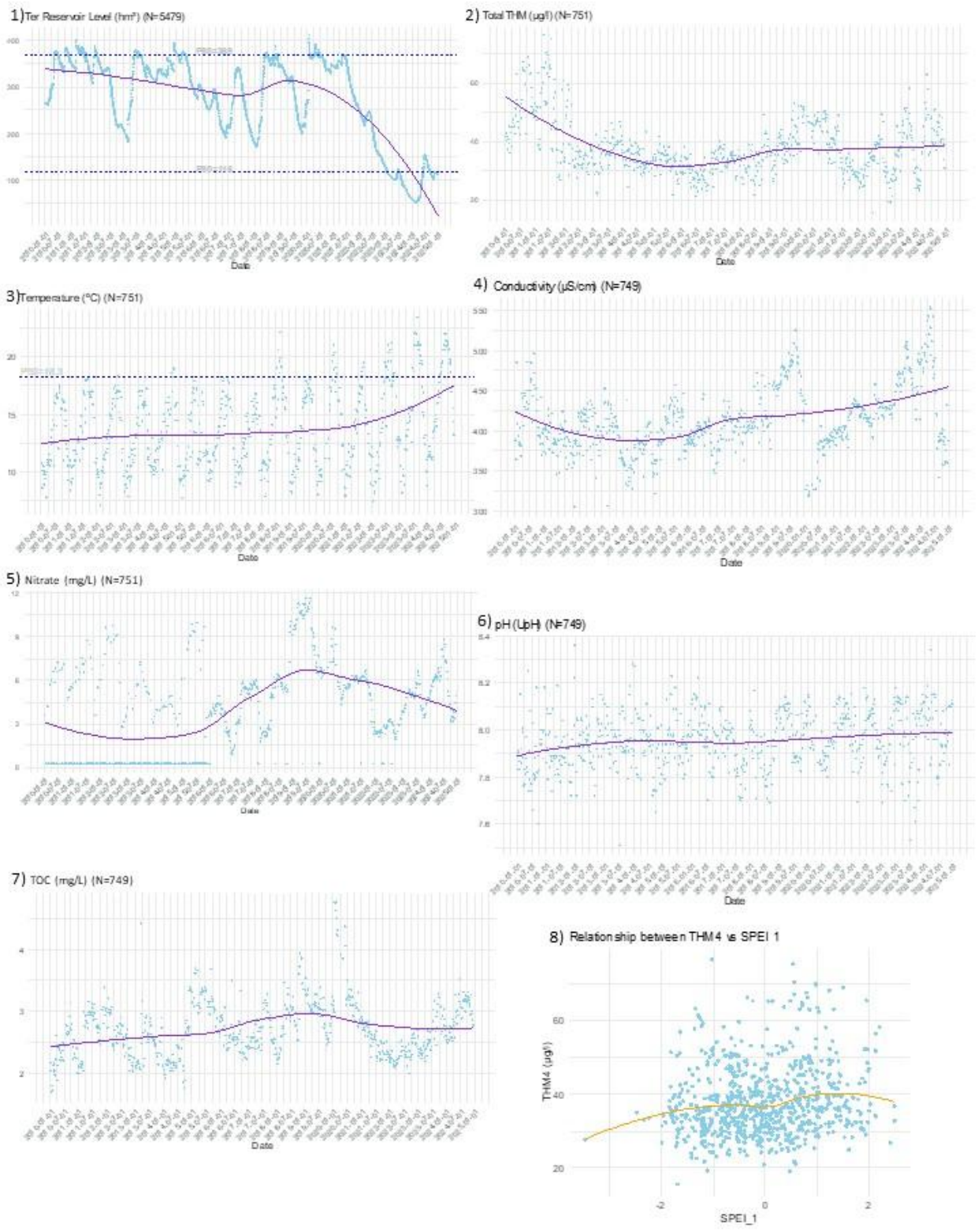


Figure A2: Ter DWTP all the different variables concentration time series and SPEI-1 relationship with THM4



REFERENCES

1. WHO. Resolution adopted by the General Assembly on 28 July 2010: 64/292. The human right to water and sanitation [Internet]. 2010 [citado 24 de febrero de 2025]. Disponible en: https://documents.un.org/doc/undoc/gen/n09/479/35/pdf/n0947935.pdf

2. Phillips MT, Owers KA, Grenfell BT, Pitzer VE. Changes in historical typhoid transmission across 16 U.S. cities, 1889-1931: Quantifying the impact of investments in water and sewer infrastructures. Azman AS, editor. PLoS Negl Trop Dis. 18 de marzo de 2020;14(3):e0008048.

3. CDC. Control of Infectious Diseases [Internet]. Morbidity and Mortality Weekly Report; 1999. Disponible en: https://www.cdc.gov/mmwr/PDF/wk/mm4829.pdf

4. Richardson SD, Plewa MJ. To regulate or not to regulate? What to do with more toxic disinfection by-products? J Environ Chem Eng. agosto de 2020;8(4):103939.

5. Hu J, Song H, Karanfil T. Comparative Analysis of Halonitromethane and Trihalomethane Formation and Speciation in Drinking Water: The Effects of Disinfectants, pH, Bromide, and Nitrite. Environ Sci Technol. 15 de enero de 2010;44(2):794-9.

6. Srivastav AL, Patel N, Chaudhary VK. Disinfection by-products in drinking water: Occurrence, toxicity and abatement. Environ Pollut. diciembre de 2020;267:115474.

7. Valenti-Quiroga M, Daunis-i-Estadella P, Emiliano P, Valero F, Martin MJ. NOM fractionation by HPSEC-DAD-OCD for predicting trihalomethane disinfection by-product formation potential in full-scale drinking water treatment plants. Water Res. diciembre de 2022;227:119314.

8. EU. DIRECTIVE (EU) 2020/2184 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 16 December 2020 on the quality of water intended for human consumption (recast) [Internet]. Disponible en: https://documents.un.org/doc/undoc/gen/n09/479/35/pdf/n0947935.pdf

9. Sadiq R, Rodriguez M. Disinfection by-products (DBPs) in drinking water and predictive models for their occurrence: a review. Sci Total Environ. 5 de abril de 2004;321(1-3):21-46.

10. Benítez JS, Rodríguez CM, Casas AF. Disinfection byproducts (DBPs) in drinking water supply systems: A systematic review. Phys Chem Earth Parts ABC. octubre de 2021;123:102987.

11. World Health Organization. Guidelines for drinking-water quality. 4th ed. 2011 [citado 10 de abril de 2024]; Disponible en: https://iris.who.int/handle/10665/44584

12. Villanueva CM, Cantor KP, Cordier S, Jaakkola JJK, King WD, Lynch CF, et al. Disinfection Byproducts and Bladder Cancer: A Pooled Analysis. Epidemiology. mayo de 2004;15(3):357-67.

13. Grellier J, Rushton L, Briggs DJ, Nieuwenhuijsen MJ. Assessing the human health impacts of exposure to disinfection by-products — A critical review of concepts and methods. Environ Int. mayo de 2015;78:61-81.

14. Nieuwenhuijsen MJ, Smith R, Golfinopoulos S, Best N, Bennett J, Aggazzotti G, et al. Health impacts of long-term exposure to disinfection by-products in drinking water in Europe: HIWATE. J Water Health. junio de 2009;7(2):185-207.

15. Nieuwenhuijsen MJ, Martinez D, Grellier J, Bennet J, Best N, Iszatt N, et al. Chlorination Disinfection By-Products in Drinking Water and Congenital Anomalies: Review and Meta-Analyses.

16. Platikanov S, Puig X, Martín J, Tauler R. Chemometric modeling and prediction of trihalomethane formation in Barcelona's water works plant. Water Res. agosto de 2007;41(15):3394-406.

17. Albanakis C, Tsanana E, Fragkaki AG. Modeling and prediction of trihalomethanes in the drinking water treatment plant of Thessaloniki, Greece. J Water Process Eng. octubre de 2021;43:102252.

18. Kim HC, Yu MJ. Characterization of natural organic matter in conventional water treatment processes for selection of treatment processes focused on DBPs control. Water Res. noviembre de 2005;39(19):4779-89.

19. Delpla I, Rodriguez MJ. Variability of disinfection by-products at a full-scale treatment plant following rainfall events. Chemosphere. enero de 2017;166:453-62.

20. Parr TB, Inamdar SP, Miller MJ. Overlapping anthropogenic effects on hydrologic and seasonal trends in DOC in a surface water dependent water utility. Water Res. 1 de enero de 2019;148:407-15.

21. Evlampidou I, Font-Ribera L, Rojas-Rueda D, Gracia-Lavedan E, Costet N, Pearce N, et al. Trihalomethanes in Drinking Water and Bladder Cancer Burden in the European Union. Environ Health Perspect. enero de 2020;128(1):017001.

22. Villanueva CM, Evlampidou I, Ibrahim F, Donat-Vargas C, Valentin A, Tugulea AM, et al. Global assessment of chemical quality of drinking water: The case of trihalomethanes. Water Res. 15 de febrero de 2023;230:119568.

23. Michalak AM. Study role of climate change in extreme threats to water quality. Nature. 21 de julio de 2016;535(7612):349-50.

24. Samaniego L. Permanent shifts in the global water cycle. Science. 27 de marzo de 2025;387(6741):1348-50.

25. Bonte M, Zwolsman JJG. Climate change induced salinisation of artificial lakes in the Netherlands and consequences for drinking water production. Water Res. agosto de 2010;44(15):4411-24.

26. Sun Q, Yan Z, Wang J, Chen JA, Li X, Shi W, et al. Evaluating impacts of climate and management on reservoir water quality using environmental fluid dynamics code. Sci Total Environ. octubre de 2024;947:174608.

27. Delpla I, Jung AV, Baures E, Clement M, Thomas O. Impacts of climate change on surface water quality in relation to drinking water production. Environ Int. noviembre de 2009;35(8):1225-33.

28. Polade SD, Gershunov A, Cayan DR, Dettinger MD, Pierce DW. Precipitation in a warming world: Assessing projected hydro-climate changes in California and other Mediterranean climate regions. Sci Rep. 7 de septiembre de 2017;7(1):10783.

29. Delpla I, Bouchard C, Dorea C, Rodriguez MJ. Assessment of rain event effects on source water quality degradation and subsequent water treatment operations. Sci Total Environ. marzo de 2023;866:161085.

30. Delpla I, Jones TG, Monteith DT, Hughes DD, Baurès E, Jung AV, et al. Heavy Rainfall Impacts on Trihalomethane Formation in Contrasting Northwestern European Potable Waters. J Environ Qual. julio de 2015;44(4):1241-51.

31. Valdivia-Garcia M, Weir P, Graham DW, Werner D. Predicted Impact of Climate Change on Trihalomethanes Formation in Drinking Water Treatment. Sci Rep. 10 de julio de 2019;9(1):9967.

32. Wang M, Bodirsky BL, Rijneveld R, Beier F, Bak MP, Batool M, et al. A triple increase in global river basins with water scarcity due to future pollution. Nat Commun. 6 de febrero de 2024;15(1):880.

33. Benítez-Cano D, González-Marín P, Gómez-Gutiérrez A, Marí-Dell'Olmo M, Oliveras L. Association of drought conditions and heavy rainfalls with the quality of drinking water in Barcelona (2010–2022). J Expo Sci Environ Epidemiol. enero de 2024;34(1):175-83.

34. Xevgenos D, Marcou M, Louca V, Avramidi E, Ioannou G, Argyrou M, et al. Aspects of environmental impacts of seawater desalination: Cyprus as a case study. Desalination Water Treat. enero de 2021;211:15-30.

35. Park EJ. Strategy of Water Distribution for Sustainable Community: Who Owns Water in Divided Cyprus? Sustainability. 29 de octubre de 2020;12(21):8978.

36. Leakage reduction programme | Projects | Uisce Éireann (formerly Irish Water) [Internet]. [citado 23 de abril de 2025]. Disponible en: https://www.water.ie/projects/local-projects/leakage-reduction-programme

37. EPA. Drinking Water Quality in Public Supplies 2023. julio de 2024; Disponible en: https://www.epa.ie/publications/compliance--enforcement/drinking-water/annual-drinking-water-reports/drinking-water-quality-in-public-supplies-2023.php

38. O'Driscoll C, Sheahan J, Renou-Wilson F, Croot P, Pilla F, Misstear B, et al. National scale assessment of total trihalomethanes in Irish drinking water. J Environ Manage. abril de 2018;212:131-41.

39. Beguería S, Latorre B, Reig F, Vicente-Serrano SM. Global SPEI database [Internet]. Disponible en: https://spei.csic.es/spei_database/#map_name=spei01#map_position=1475

40. Dunne N. Drinking Water Audit Report: East Waterford Water Supply Scheme [Internet]. EPA; 2018 abr p. 11. Report No.: DW2018/43. Disponible en: https://www.epa.ie/publications/compliance--enforcement/drinking-water/audit-reports/waterford-county/Adamstown.pdf

41. Doyle C. Site Visit Report: Ardfinnan Regional [Internet]. EPA; 2023 nov p. 7. Report No.: SV28199. Disponible en: https://www.epa.ie/publications/compliance--enforcement/drinking-water/audit-reports/tipperary/Ardfinnan-Audit-01112023.pdf

42. Roche M, Doris Y. Drinking Water Audit Report: Galtee Regional Water Treatment Plant [Internet]. EPA; 2015 nov p. 6. Report No.: DW2015/156. Disponible en: https://www.epa.ie/publications/compliance--enforcement/drinking-water/audit-reports/tipperary/Galtee-Regional.pdf

43. Doris Y. Drinking Water Audit Report: Wexford Town Public Water Supply [Internet]. Wexford: EPA; 2014 sep p. 7. Report No.: DW2014/229. Disponible en: https://www.epa.ie/publications/compliance--enforcement/drinking-water/audit-reports/wexford/WexfordTownAudit.pdf

44. Hadjinicolaou P, Giannakopoulos C, Zerefos C, Lange MA, Pashiardis S, Lelieveld J. Mid-21st century climate and weather extremes in Cyprus as projected by six regional climate models. Reg Environ Change. septiembre de 2011;11(3):441-57.

45. Lazoglou G, Papadopoulos-Zachos A, Georgiades P, Zittis G, Velikou K, Manios EM, et al. Identification of climate change hotspots in the Mediterranean. Sci Rep. 30 de noviembre de 2024;14(1):29817.

46. Cyprus, 2018 7th National Communication and 3rd Biennial report under the UNFCCC of Cyprus.

47. Kalita I, Kamilaris A, Havinga P, Reva I. Assessing the Health Impact of Disinfection Byproducts in Drinking Water. ACS Est Water. 2 de marzo de 2024;4(4):1564-78.

48. Ioannou P, Charisiadis P, Andra SS, Makris KC. Occurrence and variability of iodinated trihalomethanes concentrations within two drinking-water distribution networks. Sci Total Environ. febrero de 2016;543:505-13.

49. Water Development Department [Internet]. [citado 22 de abril de 2024]. Disponible en: http://www.moa.gov.cy/moa/wdd/wdd.nsf/index_en/index_en?opendocument

50. Font-Ribera L, Cotta JC, Gómez-Gutiérrez A, Villanueva CM. Trihalomethane concentrations in tap water as determinant of bottled water use in the city of Barcelona. J Environ Sci. agosto de 2017;58:77-82.

51. Villanueva CM, Garfí M, Milà C, Olmos S, Ferrer I, Tonne C. Health and environmental impacts of drinking water choices in Barcelona, Spain: A modelling study. Sci Total Environ. noviembre de 2021;795:148884.

52. Diffenbaugh NS, Giorgi F. Climate change hotspots in the CMIP5 global climate model ensemble. Clim Change. octubre de 2012;114(3-4):813-22.

53. Estrada L, Garcia X, Saló-Grau J, Marcé R, Munné A, Acuña V. Spatio-temporal patterns and trends of streamflow in water-scarce Mediterranean basins. Hydrol Earth Syst Sci. 17 de diciembre de 2024;28(24):5353-73.

54. Lana X, Serra C, Casas-Castillo MDC, Rodríguez-Solà R, Prohom M. Two Centuries of Monthly Rainfall in Barcelona (NE Spain): Disparity Trends, Correlation of Autumnal Rainfall with the WeMO Index and Its Contribution to Annual Amounts. Climate. 19 de octubre de 2024;12(10):166.

55. L'àrea metropolitana [Internet]. [citado 26 de febrero de 2025]. Población - L'àrea metropolitana - Àrea Metropolitana de Barcelona. Disponible en: https://www.amb.cat/web/area-metropolitana/coneixer-l-area-metropolitana/poblacio

56. Godo-Pla L, Emiliano P, Poch M, Valero F, Monclús H. Benchmarking empirical models for THMs formation in drinking water systems: An application for decision support in Barcelona, Spain. Sci Total Environ. abril de 2021;763:144197.

57. Versini PA, Pouget L, McEnnis S, Custodio E, Escaler I. Climate change impact on water resources availability: case study of the Llobregat River basin (Spain). Hydrol Sci J. 25 de octubre de 2016;61(14):2496-508.

58. SabaterH S, Armengol J. The Ter, a mediterranean river system in Spain. Limnetica. 1992;8:141-9.

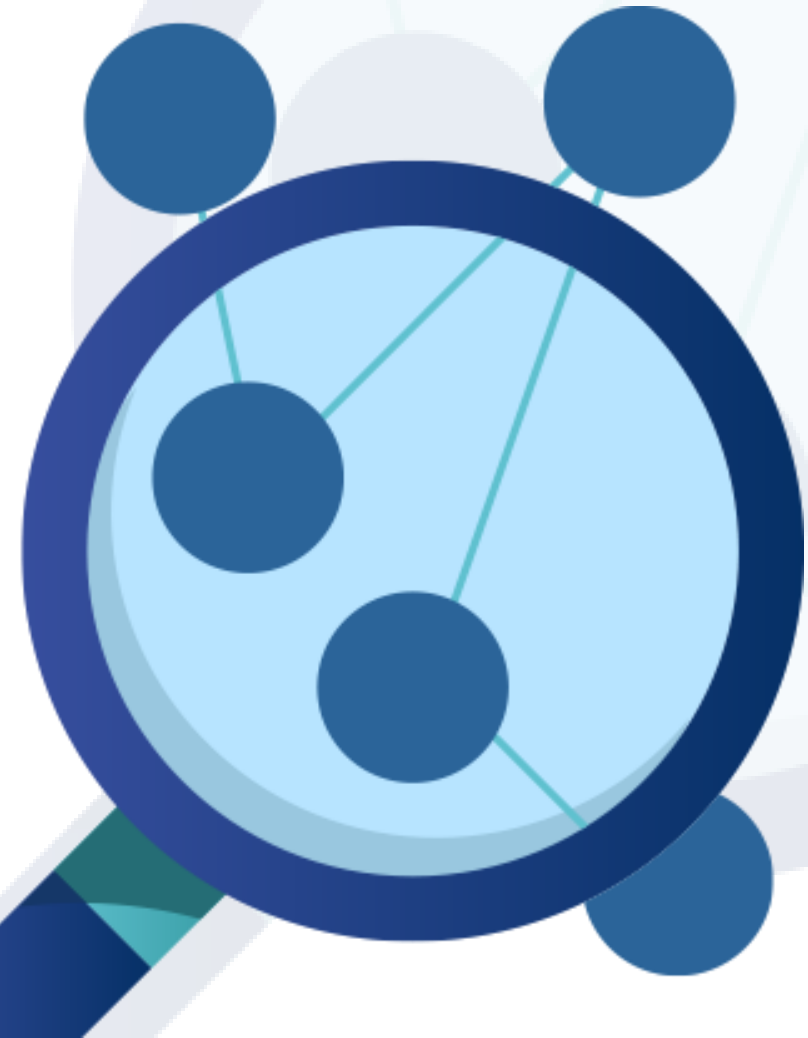
59. Valero F, Barceló A, Medina ME, Arbós R. Barcelona, three years of experience in brackish water desalination using EDR to improve quality. New O&M procedures to reduce low-value work and increase productivity. Desalination Water Treat. enero de 2013;51(4-6):1137-42.

60. Fernandez-Turiel JL, Gimeno D, Rodriguez JJ, Carnicero M, Valero F. Factors influencing the quality of a surfce water supply system: The Ter River, northeastern Spain. Fresenius Environ Bull [Internet]. 2003;12(1). Disponible en: https://www.researchgate.net/publication/286885812

intoDBP will create innovative tools and strategies to improve water quality management for safe human use and a healthy environment. It focuses on catchment protection and forecasting, transformative drinking water treatment, and real-time monitoring to combat the effects of climate and global change. In particular, intoDBP focuses on pollution and risks related to disinfection byproducts (DBPs). By developing and applying advanced, integrated, and cost-effective sensors and analytical methods, intoDBP will expand knowledge on water quality and DBP precursors to better understand its formation and human exposure in Europe. intoDBP monitoring results will feed into numerical forecasting tools to predict source water changes and formulate climate change adaptation pathways at catchment and treatment scale. intoDBP also develops transformative options for advanced and cost-effective upgrade of water treatment and disinfection.

In the intoDBP consortium researchers, small and large enterprises, communication experts and public services join forces to generate interdisciplinary solutions, that will generate a renewed perspective of drinking water surveillance, support decision-making and governance, and increase system resilience. intoDBP will implement and validate its cross-cutting products in four complementary case studies from three European countries where compliance with DBP regulation currently is an acknowledged challenge. The direct and visible positive impact of intoDBP in the case studies will foster rapid product adoption at a European and global scale, thus strengthening Europe's position and role in the global water market.

Reaching out beyond the water sector itself, intoDBP will directly engage society through surveys to analyze exposure to DBPs, collect data about catchment protection initiatives, create awareness and promote sustainable consumer behavior such as reducing bottled water consumption.



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