



UNIONE EUROPEA
Fondo Sociale Europeo



REACT EU



UNIVERSITÀ
DEGLI STUDI
DI BRESCIA

*DEPARTMENT OF CIVIL ENGINEERING, ARCHITECTURE, LAND AND
ENVIRONMENT AND MATHEMATICS*

*DOTTORATO IN INGEGNERIA CIVILE, AMBIENTALE, DELLA COOPERAZIONE
INTERNAZIONALE E DI MATEMATICA*

Research project co-financed by the European Union under the PON R&I 2014-2020 Program, FSE
REACT-EU resources, Action IV.5 "Doctorates on Green topics"

ICAR/03 – Environment and Health Engineering

CYCLE

XXXVII

**IMPACTS OF EXTREME WEATHER ON THE
VARIABILITY OF CRITICAL PARAMETERS IN DRINKING
WATER SUPPLY SYSTEMS: INSIGHTS FROM
OPERATIONAL EXPERIENCE**

Academic year 2023/2024

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Serial no. 740068

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ACKNOWLEDGEMENT

First, I would like to express my deepest gratitude to Professor Sabrina Sorlini, who has been a guiding light throughout my PhD journey. She provided strategic insights and step-by-step guidance, from proposing the research topic and methodologies to applying legal regulations in practice. She taught me how to synthesize information and approach problems from a broader perspective. I sincerely appreciate her dedication and invaluable support throughout my research.

I would also like to thank the Department of Civil Engineering, Architecture, Land and Environment and Mathematics, University of Brescia, as well as under the PON R&I 2014-2020 Program, FSE REACT-EU resources, Action IV.5 "Doctorates on Green topics" which provided me with an excellent academic environment, fostering my research mindset and granting me access to advanced knowledge in environmental protection and water supply systems.

Moreover, I am profoundly grateful to the A2A water cycle company for trusting, supporting, and offering me opportunities for growth and learning throughout my journey here. The experiences I have gained not only helped me develop professionally but also ignited my passion for environmental protection, especially in safeguarding the pristine waters of Mompiano source a mission I am truly honored to contribute to. A special thank Silvia Arici, our leader at the chemistry laboratory, for her clear guidance and strategic direction in my work. Her dedication and inspiration have not only shaped my path but also instilled a deep appreciation for water protection in all team members.

I would also like to extend my gratitude to the Faculty of Environmental Engineering (FEE), Hanoi University of Civil Engineering (HUCE) for their valuable support during the data collection process in Vietnam. Their assistance was instrumental in helping me obtain critical data, which enriched my research and provided a broader perspective on climate change impacts on water supply systems.

I am also grateful to Nicola for his creative and intelligent solutions throughout our collaboration. His patience, support, and thorough explanations have helped me overcome challenges and significantly expand my knowledge.

I sincerely thank Robi, Antonio, Paolo, and my colleagues who accompanied me on sampling trips, whether to remote locations hundreds of kilometers away or under scorching sun and heavy rain. Your companionship has been an immense source of motivation throughout this journey.

I am also incredibly appreciative of Cristiana, Barbara, Leida, Linda, Sami, and Silvia B for their detailed guidance and unwavering support, both professionally and in daily life. Your kindness has made me feel truly fortunate to be part of this environment.

Additionally, I would like to express my gratitude to my fellow Master's colleagues Marika, Erick, and Simonre who have shared my passion for research and the protection of Brescia's water systems.

Lastly, I extend my most heartfelt thanks to my colleagues, my family, my husband, and my children for their unwavering support and encouragement. The dedication and support of everyone have been instrumental in helping me complete this PhD journey. Once again, thank you all from the bottom of my heart!

Sincerely,
Tran Thi Kim Hoan

ABSTRACT

Climate change is increasingly recognized as a major threat to the safety and sustainability of drinking water supply systems worldwide. Extreme weather events such as heatwaves, heavy rainfall, prolonged droughts, and flooding significantly impact water sources, treatment processes, and distribution networks, leading to variations in water quality parameters and increased operational challenges. This dissertation investigates the effects of climate-induced extreme weather events on drinking water quality, focusing on the variability of key parameters and risk management strategies in water supply systems. A multi-method approach was employed, including an extensive literature review, surveys of water service managers in Italy and Vietnam, and an in-depth case study in Brescia, Italy.

The research highlights the increasing frequency and severity of climate-related challenges in drinking water systems. Key concerns include microbial contamination, elevated turbidity levels in source water, and rising water temperatures, which accelerate chemical reactions and microbial activity within distribution networks. The study also examines the integration of real-time monitoring systems, which have transformed water quality management by enabling immediate risk assessment and response. In this context, operational monitoring, as outlined in D.Lgs. 18/2023, ensures continuous compliance with safety standards by focusing on the functionality of risk control measures, unlike traditional analytical monitoring, which provides long-term water quality assessments.

A key advancement in this field is the development of Early Warning Systems (EWS). By continuously monitoring pH, conductivity, and turbidity, EWS can rapidly detect unexpected changes in water systems. For instance, a sudden increase in turbidity may indicate contamination or structural issues, prompting immediate intervention. These systems not only enhance responsiveness but also simplify long-term monitoring programs by prioritizing critical indicators. Furthermore, EWS can be integrated with automated controls, such as valves or discharge systems, to mitigate risks in real time. However, the effectiveness of such systems depends on robust data management and interpretation, requiring statistical methods to process raw data into actionable insights. The creation of comprehensive databases and control charts is crucial for informed decision-making and strengthening supply system reliability.

Through surveys of water service providers in Italy and Vietnam, the study identifies regional variations in climate risk perceptions and adaptive capacities. While both countries face similar climate-driven challenges, their ability to mitigate risks differs due to variations in regulatory frameworks, financial resources, and technological advancements. Italian water providers emphasize regulatory compliance with European Union directives on water quality and emerging contaminants, whereas Vietnamese managers highlight infrastructure limitations and the urgent need for investment in resilient water treatment technologies.

The case study in Brescia, Italy, provides a detailed examination of climate variability's direct impacts on a drinking water supply system. Data analysis reveals that heavy rainfall events correlate with spikes in turbidity and microbial indicators, necessitating increased disinfection efforts and stricter microbiological control at the source. To address these challenges, this dissertation proposes several adaptation strategies to enhance drinking water system resilience. First, real-time water quality monitoring should be integrated with advanced sensor technologies and data analytics to

enable early detection of contamination and fluctuations in key parameters. Second, microbial monitoring technologies must be improved by implementing new detection tools that significantly reduce incubation times, allowing for faster bacterial identification and improved response times compared to conventional methods. Additionally, the implementation of Water Safety Plans (WSPs) is essential, promoting a proactive, risk-based approach to water quality management that incorporates climate resilience into system planning and operations. Finally, regulatory and policy enhancements should focus on strengthening climate adaptation guidelines in the drinking water sector, ensuring that national standards align with international best practices. These measures collectively contribute to a more adaptive and robust water supply system, capable of mitigating climate-induced risks and ensuring long-term sustainability. In conclusion, this research underscores the urgent need for climate-adaptive strategies in drinking water management. Without timely interventions, climate-induced water quality deterioration poses significant risks to public health and service reliability. The proposed measures, if effectively implemented, can contribute to a more resilient and sustainable drinking water supply system, capable of withstanding future climatic uncertainties. Further research is recommended to explore the long-term effectiveness of adaptation strategies and develop predictive models that integrate climate projections with water quality dynamics.

Sommario

Il cambiamento climatico è sempre più riconosciuto come una delle principali minacce alla sicurezza e alla sostenibilità dei sistemi di approvvigionamento idrico potabile in tutto il mondo. Eventi meteorologici estremi come ondate di calore, forti piogge, siccità prolungate e inondazioni hanno un impatto significativo sulle fonti idriche, sui processi di trattamento e sulle reti di distribuzione, determinando variazioni nei parametri di qualità dell'acqua e maggiori sfide operative. Questa tesi di laurea esamina gli effetti degli eventi meteorologici estremi indotti dal clima sulla qualità dell'acqua potabile, concentrandosi sulla variabilità dei parametri chiave e sulle strategie di gestione del rischio nei sistemi di approvvigionamento idrico. È stato impiegato un approccio multi-metodo, che include un'ampia revisione della letteratura, sondaggi sui gestori dei servizi idrici in Italia e Vietnam e uno studio di caso approfondito a Brescia, Italia.

La ricerca evidenzia la crescente frequenza e gravità delle sfide legate al clima nei sistemi di approvvigionamento idrico potabile. Le principali preoccupazioni includono contaminazione microbica, elevati livelli di torbidità nell'acqua di sorgente e aumento delle temperature dell'acqua, che accelerano le reazioni chimiche e l'attività microbica all'interno delle reti di distribuzione. Lo studio esamina anche l'integrazione di sistemi di monitoraggio in tempo reale, che hanno trasformato la gestione della qualità dell'acqua consentendo una valutazione e una risposta immediate al rischio. In questo contesto, il monitoraggio operativo, come delineato nel D.Lgs. 18/2023, garantisce la conformità continua agli standard di sicurezza concentrandosi sulla funzionalità delle misure di controllo del rischio, a differenza del monitoraggio analitico tradizionale, che fornisce valutazioni della qualità dell'acqua a lungo termine.

Un progresso fondamentale in questo campo è lo sviluppo di sistemi di allerta precoce (EWS). Monitorando costantemente pH, conduttività e torbidità, gli EWS possono rilevare rapidamente cambiamenti imprevisti nei sistemi idrici. Ad esempio, un improvviso aumento della torbidità può indicare contaminazione o problemi strutturali, richiedendo un intervento immediato. Questi sistemi non solo migliorano la reattività, ma semplificano anche i programmi di monitoraggio a lungo termine dando priorità agli indicatori critici. Inoltre, gli EWS possono essere integrati con controlli automatizzati, come valvole o sistemi di scarico, per mitigare i rischi in tempo reale. Tuttavia, l'efficacia di tali sistemi dipende da una solida gestione e interpretazione dei dati, che richiede metodi statistici per elaborare i dati grezzi in informazioni fruibili. La creazione di database e grafici di controllo completi è fondamentale per un processo decisionale informato e per rafforzare l'affidabilità del sistema di fornitura.

Attraverso sondaggi sui fornitori di servizi idrici in Italia e Vietnam, lo studio identifica variazioni regionali nelle percezioni del rischio climatico e nelle capacità di adattamento. Mentre entrambi i paesi affrontano sfide simili dovute al clima, la loro capacità di mitigare i rischi differisce a causa di variazioni nei quadri normativi, nelle risorse finanziarie e nei progressi tecnologici. I fornitori idrici italiani sottolineano la conformità normativa con le direttive dell'Unione Europea sulla qualità dell'acqua e sui contaminanti emergenti, mentre i gestori vietnamiti evidenziano le limitazioni infrastrutturali e l'urgente necessità di investimenti in tecnologie di trattamento delle acque resilienti. Il caso di studio di Brescia, Italia, fornisce un esame dettagliato degli impatti diretti della variabilità climatica su un sistema di approvvigionamento idrico potabile. L'analisi dei dati rivela che gli eventi di forti piogge sono correlati a picchi di torbidità e indicatori microbici, rendendo necessari maggiori

sforzi di disinfezione e un controllo microbiologico più rigoroso alla fonte. Per affrontare queste sfide, questa tesi propone diverse strategie di adattamento per migliorare la resilienza del sistema idrico potabile. In primo luogo, il monitoraggio della qualità dell'acqua in tempo reale dovrebbe essere integrato con tecnologie di sensori avanzate e analisi dei dati per consentire il rilevamento precoce della contaminazione e delle fluttuazioni nei parametri chiave. In secondo luogo, le tecnologie di monitoraggio microbico devono essere migliorate implementando nuovi strumenti di rilevamento che riducano significativamente i tempi di incubazione, consentendo un'identificazione batterica più rapida e tempi di risposta migliorati rispetto ai metodi convenzionali. Inoltre, l'implementazione di Water Safety Plans (WSP) è essenziale, promuovendo un approccio proattivo e basato sul rischio alla gestione della qualità dell'acqua che incorpori la resilienza climatica nella pianificazione e nelle operazioni del sistema. Infine, i miglioramenti normativi e politici dovrebbero concentrarsi sul rafforzamento delle linee guida per l'adattamento climatico nel settore dell'acqua potabile, assicurando che gli standard nazionali siano allineati alle migliori pratiche internazionali. Queste misure contribuiscono collettivamente a un sistema di approvvigionamento idrico più adattivo e robusto, in grado di mitigare i rischi indotti dal clima e garantire la sostenibilità a lungo termine. In conclusione, questa ricerca sottolinea l'urgente necessità di strategie di adattamento al clima nella gestione dell'acqua potabile. Senza interventi tempestivi, il deterioramento della qualità dell'acqua indotto dal clima pone rischi significativi per la salute pubblica e l'affidabilità del servizio. Le misure proposte, se implementate in modo efficace, possono contribuire a un sistema di approvvigionamento idrico potabile più resiliente e sostenibile, in grado di resistere alle future incertezze climatiche. Si raccomandano ulteriori ricerche per esplorare l'efficacia a lungo termine delle strategie di adattamento e sviluppare modelli predittivi che integrino le proiezioni climatiche con le dinamiche della qualità dell'acqua.

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ABBREVIATIONS

Abbreviation	Definition
A2A S.p.A	Drinking water treatment company in Italy
AD	Anno Domini
AMAP	Municipalized Water Company of Palermo
AOC	Assimilable Organic Carbon
ARPA	Regional Agency for Environmental Protection
As	Arsenic
BAC	Biologically Activated Carbon
BDCM	Bromodichloromethane
BOD	Biological Oxygen Demand
BrO ₃	Bromate
BYT	Ministry of Health in Vietnam
CC	Climate Change
CeNSiA	The National Center for Water Safety
CH	Chloral Hydrate
Cl ₂	Chlorine Gas
ClO ₂	Chlorine Dioxide
ClO ₃ -	Chlorate
CNBr	Cyanogen Bromide
DBCM	Dibromochloromethane
DBPs	Disinfection By-Products
DCAA	Dichloroacetic Acid
DCAN	Dichloroacetonitrile
DO	Dissolved Oxygen
DOM	Dissolved Organic Matter
DWSs	Drinking Water Supply Systems
DWTPs	Drinking Water Treatment Plants
EBCT	Empty Bed Contact Time
EQS	Environmental Quality Standards
EU	European Union
EWS	Early Warning Systems
FAO	Food and Agriculture Organization
F	Fluoride
Fe	Iron
FeCl ₂ ,	Iron (II) Chloride
FeCl ₃	Iron (III) Chloride
FeSO ₄	Iron (II) Sulfate
GAC	Granular Activated Carbon
GCI	Gray Cast Iron
GDP	Gross Domestic Product
H ₂ O ₂	Hydrogen Peroxide
H ₂ S	Hydrogen Sulfide
HAAs	Haloacetic Acids
HAcAms	Haloacetamides
HANs	Haloacetonitriles
Hg	Mercury
HKs	Haloketones
HNM	Halonitromethanes

HRT	Hydraulic Retention Time
IDEXX	Water Testing Technology Company
IPCC	Intergovernmental Panel on Climate Change
IOM	Intracellular Organic Matter
ISPRA	Institute for Environmental Protection and Research
ISS	Institute Superiore di Sanita
ISTAT	Italian National Institute of Statistics
ISTISAN	Reports from the Institute Superiore di Sanita
IWA	International Water Association
KMnO ₄	Potassium Permanganate
KNMI	Royal Netherlands Meteorological Institute
MIB	2-Methylisoborneol
Mn	Manganese
NaOCl	Sodium Hypochlorite
NAs	N-Nitrosamines
NDMA	N-Nitrosodimethylamine Acids
NH ₂ Cl	Chloramines
NH ₃	Ammonia
NO ₃	Nitrate
NOM	Natural Organic Matter
NTU	Nephelometric Turbidity Units
OECD	Organization for Economic Co-operation and Development
O ₃	Ozone
O ₂	Oxygen
PAA	Peracetic Acid
PAC	Powdered Activated Carbon
PACl	Poly Aluminium Chloride
Pb	Lead
PCA	Principal Component Analysis
PFAS	Per- and Polyfluoroalkyl Substances
PFASs	Examples: PFOS and PFNA
PFPeA	Perfluoropentanoic Acid
PFPS	Perfluoropentane Sulfonate
PhACs	Pharmaceutical Active Compounds
PLC	Programmable Logic Controller
QCVN	Unknown (Needs clarification)
ReMaF	Unknown (Needs clarification)
RO	Reverse Osmosis
SDGs	Sustainable Development Goals
SMAT	Water Utility Company in Italy
TCNM	Trichloronitromethane
TCAA	Trichloroacetic Acid
TDS	Total Dissolved Solids
Total THMs	Total Trihalomethanes
TOC	Total Organic Carbon
UF	Ultrafiltration
UN	United Nations
UPS	Uninterruptible Power Supply
US EPA	United States Environmental Protection Agency
USGCRP	U.S. Global Change Research Program

UV	Ultraviolet
WHO	World Health Organization
WMO	World Meteorological Organization
WSPs	Water Safety Plans
WSTPs	Water supply treatment plants

CHAPTER 1: CLIMATE CHANGE AND DRINKING WATER SUPPLY SYSTEM

Introduction

Human activities are significantly altering the climate, leading to profound shifts in global weather patterns. The Intergovernmental Panel on Climate Change (IPCC 2022, n.d.) reports that human influence on climate systems has intensified the frequency and severity of extreme weather events worldwide. Although climate change is a global phenomenon, its impacts vary across regions, manifesting as severe cold, droughts, heatwaves, floods, and wildfires. These disruptions affect established precipitation and temperature patterns, posing serious risks to natural ecosystems and human infrastructure, including drinking water supply systems (DWSs). Current Global Climate Models (GCMs) highlight these regional differences: rainfall patterns are decreasing in areas such as Africa and Southern Europe, while Northern Europe and North America are experiencing more frequent and intense precipitation events (Garnier & Holman, 2019a); (Juana et al., 2013). Global temperatures are projected to rise by over 1.5°C within the next 50 years, with profound implications for water resources, agriculture, and public health (IPCC, 2018). Observations from recent decades, including reports from the World Meteorological Organization (WMO), confirm that global temperatures have reached unprecedented highs, intensifying pressure on water systems. Notably, WMO reported that the hottest years in recorded history have occurred in the early 21st century. For example, in 2015, global temperatures were the highest ever documented, with an anomaly of approximately 0.76°C above the 20th-century average (Michel Jarraud WMO, 2015).

Extreme weather events such as floods, droughts, storms, heatwaves, and wildfires are becoming increasingly frequent and severe, significantly affecting drinking water supply systems. These events not only cause substantial damage to infrastructure but also deteriorate water quality, increasing risks to public health. Flooding events transport debris, organic materials, and pollutants from rivers into water sources, increasing turbidity and contamination levels. Examples include Central Vietnam (2020) and Bangalore, India (2022), which experienced catastrophic flooding, disrupting water supply infrastructure (Giri, 2021). In Emilia-Romagna, Italy (May 2023), heavy rains caused rivers such as Savio and Lamone to overflow, leading to the evacuation of 36,000 residents and contamination of drinking water sources (ARPAE Emilia-Romagna, Guy Carpenter, n.d.). Venice (2019) suffered a historic flood, with water levels reaching 1.87 meters, the highest in over 50 years, damaging infrastructure and increasing treatment costs (Bernhard Mühr, Susanna Mohr & Michael Kunz, n.d.).

In August 2011, Tropical Storm Irene struck eastern New York and nearby US states, significantly impacting public drinking water systems. Numerous water suppliers issued boil water advisories, primarily due to physical damage to distribution networks (Friedman et al., 2024). Beyond direct infrastructure damage, extreme storms and strong winds can also disrupt electrical grids, affecting the ability to produce and distribute safe drinking water (S. Liu et al., 2016). For instance, in 2008, Hurricane Ike led to power outages for approximately 2 million customers across the USA (Schmidlin, 2011). Many public water supply systems lost power but continued operations using backup generators, while others experienced failures in water production, pumping, and monitoring systems. Nine days of post-landfall, 25 public water systems were still under boil water advisories, and 13 relied on electrical generators (Schmidlin, 2011). Additionally, power failures led to the breakdown of sewage treatment plants and pumping stations in some areas, resulting in overflows and the discharge of untreated or partially treated sewage into waterways. Similarly, after Hurricane Sandy

in 2012, certain parts of New York experienced water shortages for up to 11 days, leaving residents without access to run water, forcing them to leave their homes for drinking water and preventing them from flushing toilets (Schmeltz et al., 2013).

Cyclones can also trigger waterborne disease outbreaks due to contamination of drinking water sources. Following Cyclone Aila in India in 2009, a cholera outbreak was reported, with fecal contamination of water supplies identified as a major cause (Bhunia & Ghosh, 2011). In contrast, a similar outbreak was anticipated after Cyclone Sidr in Bangladesh in 2007 but was prevented due to effective food and safe drinking water distribution, along with timely healthcare interventions (Kabi & Khan, 2017). Rory Villaluna, as the head of the National WASH (Water, Sanitation, and Hygiene) said that Storms and hurricanes bring strong winds and heavy rainfall, often damaging water infrastructure and causing pipeline bursts and contamination of drinking water with floodwaters, as seen with Typhoon Haiyan in the Philippines (Rory Villaluna, 2013)

In contrast, prolonged droughts significantly reduce reservoir and groundwater levels, leading to increased concentrations of pollutants, salts, and heavy metals. Vietnam's Central Highlands faced water shortages due to prolonged dry lead to groundwater levels declined, farmers resorted to deepening existing wells or digging new ones to access water (Worldbank, 2019), Italy experienced one of its most severe droughts in 70 years, causing the Po River, a major water source, to reach record-low levels, raising concerns for agricultural and urban water supply (Montanari et al., 2023). Heatwaves and wildfires also exacerbate water crises. Heatwave with summer of 2019 in European was marked by two major heatwaves in June and July, with temperatures reaching unprecedented levels in several countries, including France, Belgium, and Germany. The June heatwave was characterized by a strong Saharan air mass intrusion, while the July event was amplified by soil moisture deficits from the preceding heatwave caused severe evaporation in reservoirs, worsening water scarcity (Sousa et al., 2020). Wildfires in California (2020) released ash and hazardous chemicals into water bodies, complicating water treatment and increasing costs (Gregory Pierce, Peter Roquemore, and Faith Kearns, 2021). These examples demonstrate that extreme weather events disrupt drinking water supply systems, underscoring the urgent need for enhanced water management, protection measures, and climate adaptation strategies.

Regulatory and policy frameworks play a crucial role in mitigating climate-related water risks. The European Union Directive 2020/2184 mandates that drinking water suppliers implement risk management frameworks that consider climate change effects. In Italy, Legislative Decree (D.Lgs.) 18/2023 requires water service providers to integrate climate risk assessments into Water Safety Plans (WSPs), ensuring that water utilities are prepared for climate-driven contamination risks, extreme weather disruptions, and infrastructure vulnerabilities. Despite these regulations, there remains a gap between policy enforcement and real-world adaptation efforts, particularly regarding real-time monitoring, climate-responsive treatment strategies, and risk-based adaptation measures.

1.1 Research problem and challenges

As climate change drives more frequent and intense weather events, drinking water supply systems (DWSs) must adapt to new challenges. Issues include increased turbidity, contamination, and reduced water availability, which can exceed the operational capacities of Drinking Water Treatment Plants (DWTPs). The IPCC reports that extreme precipitation has increased globally, but storm frequency trends remain uncertain, complicating planning for DWS resilience (Meuleman et al.,

2007). Further complexity arises from phenomena like El Niño, which disrupts weather patterns, increasing the likelihood of tropical cyclones, droughts, and wildfires in vulnerable regions (Cai et al., 2018).

Climate variability, notably El Niño events, adds another layer to this complexity, creating severe and unpredictable weather conditions globally. During El Niño years, the Pacific Ocean's altered temperatures can precipitate tropical cyclones, droughts, wildfires, and floods, disproportionately affecting certain regions. Recent studies predict a potential doubling in the frequency of El Niño events due to greenhouse warming, leading to greater climate variability and extreme conditions in vulnerable areas (Cai et al., 2018).

The impacts of climate change on water availability and quality are profound. Extreme weather events like droughts reduce water levels, causing contaminant concentrations to rise, while heavy rains increase turbidity and introduce pollutants that complicate water treatment (Delpla et al., 2009a); (Khan et al., 2015a); (Van Vliet et al., 2023). These pressures can surpass the operational capacities of existing drinking water treatment plants (DWTPs), compromising water quality standards and public health outcomes. Increased turbidity and contamination during extreme weather events can lead to a surge in waterborne diseases. Studies have documented increased cases of gastrointestinal illness following heavy rainfall or flooding, often due to the breakdown of potable water supplies and the presence of pathogens like *Cryptosporidium* and *Giardia* in drinking water sources (Ryan C. Graydon et al., 2022); Watkins, 2012; (Delpla et al., 2009a).

Globally, developing countries face heightened vulnerabilities due to limited infrastructure and resources for addressing water quality issues. The World Health Organization's (WHO) 2011 Drinking Water Guidelines offer recommendations for managing drinking water safety. Recent editions of these guidelines focus primarily on establishing and implementing systems to manage water quality risks. While the guidelines provide some direction on handling water quality during emergencies and disasters, their main emphasis is on everyday management, considering the typical variations in climate. As a result, the guideline values for many chemical contaminants assume long-term, continuous exposure. The guidelines address extreme weather events only briefly. The WHO acknowledges that over time, climate change may increase the intensity of weather events, including more frequent and prolonged periods of high temperatures, droughts, heavy rainfall, and severe storms. Scientific consensus indicates that ongoing greenhouse gas warming throughout the 21st century is likely to lead to more frequent, longer-lasting heatwaves and more intense rainfall events across many regions (IPCC, 2014). These climate-related changes increase existing risks and introduce new ones for both natural and human systems.

Evidence also shows a rise in both the frequency and intensity of extreme heat events globally, alongside more frequent heavy rainfall in several areas (Cool et al., 2019). Thus, certain regions may become more prone to intense rainfall, while others may experience heightened drought risks. Studies suggest that climate change is already responsible for about 75% of moderate daily hot extremes and roughly 18% of moderate daily precipitation extremes (Fischer & Knutti, 2015). WHO guidelines indicate that such events may cause changes in water quality, affecting sediment load, chemical composition, organic carbon content, and microbial quality (WHO, 2023). A systematic review found 87 instances of waterborne disease outbreaks related to extreme weather, with heavy rain and flooding frequently preceding these outbreaks due to contamination of drinking water sources (Cann et al., 2013). Developing countries are especially vulnerable to extreme weather impacts due to limited

resources, infrastructure, and disaster preparedness (IPCC, 2007) Although WHO's Water Safety Plans (WSPs) apply broadly across different water supply situations, many extreme weather events may exceed the capacities of standard risk management plans. This highlights the need for updated guidelines that specifically address the impacts of extreme weather on drinking water quality.

Moreover, global water demand is expected to rise by 55% by 2050, driven primarily by urbanization, industrial activities, and energy production (OECD, 2012). Water scarcity is currently at a global level; specifically, the amount of water has doubled compared to the population in the last century, and more regions are reaching the limits where water supply services can no longer be provided sustainably. Therefore, population growth and economic development are exerting unprecedented pressure on renewable water resources. Water scarcity is defined as the lack of freshwater resources to meet human and environmental needs in each area. According to the Food and Agriculture Organization (FAO), it can be classified as follows: One component is the physical component, which occurs when the demand for water exceeds the available supply in each region, due to water limitations and increased consumption. The second type is economic water scarcity, which occurs when infrastructure is inadequate or there is ineffective management of available water resources, leading to limited access to resources. Although these issues are distributed unevenly across the territory, there are areas with physical scarcity, as well as areas where leaks along the network reduce supply capacity.

Water scarcity has wide-reaching effects, from food security threats to public health risks. First, it poses a direct threat to food security by limiting agricultural productivity. Agriculture relies heavily on water for irrigation, so when water resources are insufficient, crop yields decrease, leading to higher food prices and reduced access to essential goods. Second, inadequate access to clean water and sanitation services creates significant health risks, as poor water quality promotes the spread of waterborne diseases, endangering public health. Finally, water scarcity causes substantial economic losses, particularly in sectors heavily reliant on water, such as agriculture, industry, and tourism. The World Bank estimates that poor water management could cost countries up to 6% of their GDP, driven by diminished agricultural productivity and increased healthcare expenses related to waterborne illnesses. These trends underscore the urgency of integrated water management strategies that account for both current and future climate-related pressures. Effective responses require multi-sectoral coordination, innovation in water-saving technologies, and climate-resilient infrastructure. The future holds significant challenges for water management, as climate change amplifies disparities between water-rich and water-poor regions. Addressing these challenges demands not only improved planning but also comprehensive policies that prioritize sustainable water use amid ongoing and future climate uncertainties.

Inadequate data for tracking water quality during extreme events further hampers efforts to develop predictive models. Climate science typically focuses on large-scale projections, while water quality research is localized, resulting in a gap in cohesive models that integrate both fields (Michalak, 2016). Effective adaptation requires more comprehensive monitoring, interdisciplinary research, and advanced models that capture the nuanced impacts of climate change on water quality (Wu et al., 2020).

Moreover, there exists a disconnect between climate science and water quality research. Climate science typically emphasizes large-scale patterns and long-term projections, while water quality research is often localized and focused on specific water bodies or regions. This divide

complicates efforts to develop cohesive models that integrate both global climate trends and localized water quality impacts, ultimately restricting our ability to predict and manage climate-related risks to drinking water systems. (Michalak, 2016).

The main reason of this research is The Legislative Decree of February 23, 2023, No. 18, (implements Directive (EU) 2020/2184 concerning the quality of water intended for human consumption. Article 8 of this decree establishes that drinking water managers must conduct a risk assessment and management process across the entire water supply chain, from collection to distribution. Specifically, paragraph 1, letter (a), requires consideration of the results of the risk assessment for water catchment areas, as stipulated by Article 7. Letter (d) of the same paragraph mandates the identification of hazards and dangerous events in the drinking water supply system, including a risk assessment that also takes into account the impacts of climate change. “Identifies hazards and dangerous events within the scope of the water supply system, including an assessment of the risks they could pose to human health through the use of water, also taking into account the risks resulting from climate change”.

To address these challenges, there is an urgent need for enhanced monitoring, integrated research, and advanced predictive models ((Wu et al., 2020). Although some studies have examined the effects of specific weather conditions on water quality, tools that effectively combine climate and water quality data for extreme events remain largely unavailable. Developing such tools requires comprehensive data collection, interdisciplinary research, and models that can simulate the complex dynamics of climate impacts on water systems.

The combined effects of climate change, extreme weather events, and water scarcity necessitate a proactive approach to drinking water management. Addressing these challenges requires strengthening water governance policies, enhancing early warning systems and real-time monitoring, and improving technological adaptation strategies to ensure sustainable and climate-resilient water management

1.2 Scope of the Study

This study focuses on the impacts of climate change on drinking water supply systems (DWSs) in Italy and Vietnam. While existing research broadly addresses climate effects on water quality, in-depth studies on specific water systems remain limited (Paul et al., 2019). The study examines both groundwater-dependent and surface water systems, evaluating how extreme weather events affect:

- Changes in raw water quality caused by extreme weather events.
- Technological adaptation strategies such as real-time monitoring and predictive risk assessments.

The research also explores various adaptive strategies, including technological advancements, operational measures, and Policy recommendations to improve climate-resilient water governance frameworks. A case study on the Mompiano water treatment plant (Brescia, Italy) is included to provide real-world insights into monitoring and mitigation strategies.

1.3 General overview of thesis aims and research questions

This section provides a brief overview of the thesis objectives and research questions, offering context for the subsequent in-depth analysis presented in later chapters

This thesis aims to explore the implications of climate change on drinking water supply systems (DWSSs), with a particular focus on how extreme weather events influence water quality and system resilience. Through a combination of literature analysis, field-based case studies, and real-time monitoring, the research addresses both scientific and managerial dimensions of climate-related challenges in water management. The ultimate goal is to provide actionable insights that support the development of more climate-resilient water supply systems, particularly in the contexts of Italy and Vietnam.

The research is guided by the following key questions:

1. How does climate change affect water quality and availability in drinking water supply systems?
2. Are current international and national standards sufficient to address these emerging risks?
3. What technical and managerial adaptations can enhance the resilience of DWSSs to climate-related impacts?

These questions are examined in detail later in the thesis, particularly in Chapter 2 (items 2.7), which presents the identified research gaps, refined research questions, and the methodological approach for addressing them.

1.4 Structure of the Thesis

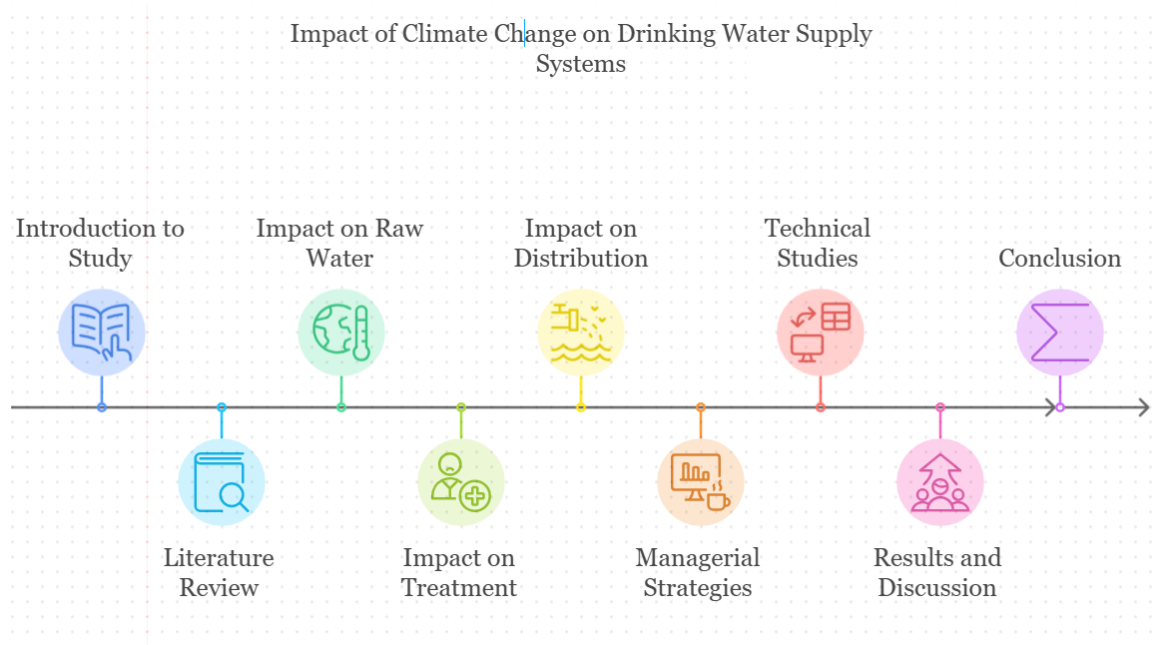


Figure 1. 1 Impact of climate change on Drinking Water Supply Systems

Chapter 1 provides an overview of the study, including its background, objectives, and significance. It highlights climate change's impact on drinking water systems and the challenges posed by extreme weather events. International and EU regulations, including the new water standards in Italy, Vietnam are also introduced.

Chapter 2 presents a literature review on climate change impacts on water resources, treatment technologies, and distribution networks. It discusses key technical challenges and existing adaptation strategies.

Chapter 3 (Detailed Analysis):

This chapter will present detailed case studies from Italy and Vietnam, illustrating how different regions are experiencing and addressing the impacts of climate change on their DWSS. Each case study will provide insights into local challenges and control measures.

Chapter 4 (Technology):

Presents case studies of drinking water treatment systems in various regions of Italy, including:

Detailed descriptions of water supply systems, raw water quality, and strategies to address anomalies and each case study is analyzed to derive practical lessons for management and operation.

Chapter 5 Focuses on real-time data from the Mompiano water treatment plant in Brescia

The development and implementation of measures to control the impact of climate change on water supply systems. The motivation for this research stems from the primary goal of ensuring the safety and efficiency of water supply plants through timely HACH monitoring and intervention. This monitoring activity is inherently linked to high-frequency measurements, generating a wealth of valuable data. Processing history data not only aids in assessing the current operational framework of control measures but also lays the foundation for integrating early warning systems based on online monitoring. These systems enable continuous sampling and rapid detection of critical in monitored parameters, thereby facilitating effective measures to mitigate or eliminate associated risks.

The fundamental concept of early warning systems involves limiting the complexity of the monitored parameters by prioritizing physicochemical parameters (pH, conductivity, turbidity, temperature), which serve as indirect indicators of undesirable changes in the system. These parameters are not only easy to measure but also provide representative data reflecting system variations.

Chapter 6 Analyzes results from Chapter 5, such as the correlations between parameters (temperature, rainfall, microorganisms) and the effectiveness of tools like IDEXX coliert allows the identification of certain bacteria using an improved technique that allows obtaining results, with shorter incubation times than classical HPC methods. This chapter underscores that early warning systems are strategic solutions. It will discuss the successes and challenges faced in adapting DWSS to climate change and provide recommendations for future actions based on these experiences.

1.5 Regulatory and water quality

Water quality standards can be used to address climate change impacts in several ways. New Water quality standards may be established as climate-driven pollutant loading issues emerge and existing water quality standards can be updated to reflect current climate change concepts and data. This chapter will delve into the policies related to DWSS and climate change. It will cover international, national, and local policies, regulations, and guidelines that govern water supply systems and their adaptation to climate change. Focus on the comparison of critical parameters concentration correlation standard of Water Quality issued by new legislation.

1.5.1 International standards

Water is an essential resource that not only supports human and ecosystem health and is essential for food and energy production and transportation services, but also provides cultural, aesthetic, and recreational values (Miller & Belton, 2014)

Therefore, many national as well as international laws, regulations, and resolutions are in place to protect and guarantee the safe provision of this natural resource, one of which are the Sustainable Development Goals (SDGs), which were established in 2015 by the United Nations General Assembly and are intended to be achieved by the year 2030.

Among the 17 Sustainable Development Goals (SDGs) established by the United Nations, one specifically emphasizes ensuring the availability and sustainable management of clean water and universal access to safe sanitation, represented in SDG 6, "Clean Water and Sanitation" (United Nations, 2022). In 2020, the United Nations reported that about 2.2 billion people lacked safe and reliable access to drinking water (United Nations Children's Fund et al., 2019).

Achieving SDG 6 presents a significant challenge for the global community, especially as climate change intensifies and is projected to continue affecting water resources (United Nations, 2015). Thus, it is crucial to evaluate how climate change will impact water availability and demand to adjust water supply systems and introduce preventive measures against its adverse effects early on.

1.5.2 European standards

Beyond the SDGs, The European Union has enacted several legislative measures to manage water quality and resource conservation, notably the Water Framework Directive 2000/60/EC, which was established in 2000. This directive sets strict chemical and quantitative standards for various water bodies, including surface and groundwater, with a focus on ecosystem protection, pollution reduction, and flood and drought management. EU member states must integrate these standards into national laws (European Parliament, 2014).

Another crucial regulation, the Drinking Water Directive 2020/2184, effective from January 2021, prescribes minimum quality standards for drinking water, applicable to systems serving over 50 individuals or providing more than 10 cubic meters of water per day. It requires regular testing for 48 microbiological, chemical, and indicator parameters and allows for additional or stricter limits at the national level (European Parliament, 2020). This directive emphasizes risk-based preventive strategies across the supply chain, from catchment areas to point-of-use, including assessments of climate change impacts. By January 2029, all water supply systems must complete risk assessments, to be reviewed every six years.

The first edition of these volumes was published from 1983 to 1984, followed by the second edition from 1993 to 1997, the third from 2004 to 2008, and the most recent fourth edition, published in 2011 and revised in 2022.

This latest edition of the Guidelines expands upon the concepts, approaches, and information introduced in previous editions, addressing topics in greater detail, such as:

- Drinking water safety, including minimum procedures, specific guideline values, and guidelines for use.

- Microbial risks, which are a significant concern in both developing and developed countries, promoting a preventive approach to ensuring the microbial safety of drinking water and emphasizing the importance of protecting source waters.

- Climate change, which introduces changes in water temperature and precipitation patterns, prolonged droughts, and more frequent extreme weather events. Recognizing and managing these impacts has become an integral part of water resource management strategies.

- Chemical contaminants in drinking water, providing information on substances not previously included (e.g., anatoxins, cylindrospermopsins, saxitoxins) and updating those already included based on new scientific evidence (e.g., asbestos, bentazone, chromium, iodine, manganese, microcystins, nickel, silver, tetrachloroethylene, trichloroethylene) (see Annex 1).

- The primary chemicals responsible for significant adverse health effects, including arsenic, fluoride, lead, nitrate, selenium, and uranium.

It is the responsibility of each country to make final decisions on ensuring the distribution of quality drinking water, utilizing the WHO guidelines as a foundational reference to address various local issues.

In addition, to achieve SDG target 6.1, the WHO recommends the implementation of water safety plans (WSPs), as outlined in its drinking water quality guidelines ((WHO, 2023). This 'comprehensive approach to risk assessment and management' involves multiple steps that address each part of the water supply chain

This "comprehensive approach to risk assessment and management" involves multiple steps that address each part of the water supply chain from source to tap. WSPs are tailored for each individual water supply system, covering one or more water sources (either surface or groundwater), the surrounding catchment, abstraction and treatment systems, storage, and the distribution network.

The European Union has adopted this framework and requires Member States to use a risk-based approach. However, it divides the assessment into separate components: risk assessments for catchments, supply systems (including abstraction, treatment, storage and distribution) and domestic distribution systems, as set out in Directive (EU) 2020/2184 on drinking water quality (Article 7).

Although the WHO guidelines recognize that climate change may affect water quantity and quality, there is no specific provision for this in the WSPs; rather, climate change is considered an additional factor that may require adaptation of the guidelines. However, the WHO has issued separate guidance on 'Climate-resilient Water Safety Plans' ((WHO, 2023), which suggests points at which climate-related factors can be incorporated. These include forming the team (Module 1), describing the system (Module 2), assessing hazards and risks under current control measures (Modules 3 and 4), planning for additional control measures and long-term investments (Module 5), and preparing management protocols (Modules 8 and 9).

Interestingly, EU Directive 2020/2184 specifies that climate change risks should be assessed as part of the risk assessment of the supply system (Art. 9, No. 2 (c)), although it does not require this for the risk assessment of the catchment area.

WHO's guidance advises that system descriptions should include elements such as "reliability of source yields (taking into account seasonal and annual variability, such as droughts)", "historical water quality data and its relationship to source yields", "climate projections that could affect water

supply", "effects of current and future climate on water quantity and quality", and "trends in land use and population growth that could affect water resource supply or demand". Thus, drinking water utilities need to understand (1) the magnitude and uncertainty of potential climate changes, (2) their impacts on water quantity and quality, and (3) the scope and effectiveness of potential control measures.

Climate change could alter the likelihood or intensity of certain problems or affect microbiological concentrations. A key aspect of *Legionella* management, for example, is regular water sampling and implementation of WSPs to monitor and mitigate risks (Environmental Management of *Legionella* in Domestic Water Systems: Consolidated and Innovative Approaches to Disinfection Methods and Risk Assessment).

As a member of the UN and the EU, Italy is required to incorporate these established goals and guidelines into its national legislation. In October 2022, the European Commission proposed significant updates to this directive, along with amendments to related directives such as the Groundwater Directive and the Environmental Quality Standards Directive.

These amendments focus on revising the lists of pollutants to be monitored in surface water (e.g. significant direct costs are expected from adding ibuprofen, glyphosate, PFAS and bisphenol A to the list of priority substances, and amending Environmental Quality Standards (EQS) for polycyclic aromatic hydrocarbons (PAHs), mercury and nickel, and groundwater (PFAS), reflecting the need to address emerging pollutants and better manage water quality in the face of new environmental challenges). This update aims to ensure that quality standards for these substances are regularly reviewed and that more data becomes available on an ongoing basis, thereby improving the overall monitoring and management of water resources in Europe. (European Commission website on the Water Framework Directive). Each Member in Europe is required to comply with EU directives, including those on water quality, although they may face unique geographical, geochemical, economic and social challenges.

1.5.3 Italian National Standards

Italy's regulatory approach to water quality aligns with EU standards, particularly through Legislative Decree No. 18 of 23 February 2023, which incorporates the requirements of Directive (EU) 2020/2184. Enforced from March 21, 2023, this decree supersedes Legislative Decree 31/2001 and introduces significant updates, harmonizing Italian standards with EU guidelines to enhance water quality and safety.

1.5.3.1 Key Updates from Legislative Decree 18/2023

A major innovation introduced in the 2023 decree is the adoption of a risk-based approach to water safety, focusing on a comprehensive assessment of risks from water extraction points to internal building distribution systems. This approach, reflecting WHO's principles, includes climate change as a key risk factor. Italian National Institute of Health guidelines on Water Safety Plans (WSPs) support this framework, promoting equitable access to safe drinking water.

1.5.3.2 Detailed Overview of WSP Implementation and Definition

The minimum requirements for the parameter values to assess the quality of water intended for human consumption have been partially updated. Therefore, it was deemed appropriate to compare the current legislation (Legislative Decree 18/2023) with the previous one (Legislative Decree

31/2001) to specifically identify the changes made and the new parameters introduced, along with their corresponding parametric values.

Regarding microbiological parameters (Annex I, Part A, Legislative Decree 18/2023), no new parameters were added or parameter values changed compared to the previous legislation, which is therefore confirmed in the new decree, in line with the provisions of EU Directive 2020/2184.

The 2023 decree updates parametric requirements for assessing water quality, with comparisons to the previous regulation (Legislative Decree 31/2001) revealing adjustments in several microbiological and chemical parameters:

Microbiological Parameters (Annex I, Part A): The decree maintains previous microbiological standards, with no changes to parameter values, consistent with EU Directive 2020/2184.

Chemical Parameters (Annex I, Part B): Several chemical limits were revised, and new substances were added due to emerging health concerns. Key additions include antimony, Bisphenol A, chlorate, chlorite, chromium, haloacetic acids, lead, microcystins, PFAS, selenium, and uranium, addressing scientific evidence on their toxicity.

As for chemical parameters (Annex I, Part B, Legislative Decree 18/2023), several parameters have undergone changes in the maximum limit, and others have been regulated for the first time. Specifically, Table 1.1 compares the parameters with modified maximum limits between sets of regulations.

Table 1.1 Comparison of Parametric Values Between Different Regulations

Parameter	Unit of Measurement	Parametric Value (D. lgs. 31/2001 and amendments)	Parametric Value (D. lgs. 18/2023)	Parametric Value (EU Directive 2020/2184)
Antimony	µg/L	5	10	10
Boron	mg/L	1	1.5	1.5
Chlorite	mg/L	0.2	0.25	0.25
Copper	mg/L	1	2	2
Selenium	µg/L	10	20	20
Vanadium	µg/L	50	140	-
Total THMs	µg/L	30	30	100
Chromium	µg/L	50	25	25
Lead	µg/L	10	5	5
Turbidity	NTU	<1 NTU	-	-
Bisphenol A	µg/L	NA	2.5	Not specified
Chlorate	mg/L	-	0.25 (if the disinfection method does not generate chlorite)	Not specified
Haloacetic Acids (HAAs)	µg/L	NA	60 (measured exclusively if disinfection methods susceptible to generate haloacetic acids are used)	Not specified
Microcystin-LR			1 µg/L (measured exclusively in the case of increasing disinfection of cells suitable for the formation of microscopic cysts with liver-toxic properties)	
Total PFAS			0.5 µg/L (measured only for perfluorooctanoic substances, for the development of operational plans and obtaining technical treatment plans)	
Sum of PFAS			0.1 µg/L (measured only for perfluorooctanoic substances, for the development of operational plans and obtaining technical treatment plans – Annex 3, Pt. 3)	
Uranium			30 µg/L	

It can be observed that the maximum limits for antimony, boron, chlorite, copper, selenium, and vanadium have been increased, while the value for total trihalomethanes (TTHMs) has remained unchanged and is maintained lower than the indications provided by the EU Directive, which allows Member States to apply lower parametric values if deemed appropriate, without compromising the disinfection process. In the case of parameters such as chromium and lead, the maximum limit has been reduced, but it is specified that these more restrictive limits must be met starting from January 2026 for chromium and January 2036 for lead. Until these dates, the limit in force will remain that of the previous regulation for both parameters.

Table 1. 2 Lists new parameters with their regulatory concentration limits, aligned with EU Directive 2020/2184 guidelines.

New Parameters	Unit of Measure	Parameter Value (D.lgs. 18/2023)	Parameter Value (EU Directive 2020/2184)
Bisphenol A	µg/l	2.5	2.5
Chlorate	mg/l	0.25*	0.25
Haloacetic Acids (HAAs)	µg/l	60	60
Microcystin-LR	µg/l	1	1
Total PFAS	µg/l	0.5	0.5
Sum of PFAS	µg/l	0.1	0.1
Uranium	µg/l	30	30

* In cases where the disinfection method used does not generate chlorate, the parameter value of 0.25 mg/l must be met by January 12, 2026, at the latest. When a disinfection method that produces chlorate is used, particularly chlorine dioxide, a parameter value of 0.70 mg/l applies. Where possible, water utility managers should aim for lower values without compromising disinfection. This parameter is measured only if the specific disinfection methods in question are used.

Chemical parameters update

The chemical parameters have undergone a major revision, with the modification of the values for some parameters but above all with the introduction into the list of new substances for which studies have demonstrated their toxicity for humans and therefore the need to be regulated.

The following table lists the newly introduced parameters and those for which the concentration limit value has been revised, namely: antimony (Sb), Bisphenol A, chlorate (ClO_3^-), chlorite (ClO_2^-), chromium (Cr), haloacetic acids (HAAs), lead (Pb), Microcystin-LR, PFAS, selenium (Se) and uranium (U).

The indicator parameters, regulated in Annex I of Legislative Decree 18/2023, Part C, have not undergone any changes either in the number of parameters listed or regarding the maximum limits compared to the previous legislation

Also, in Annex I of Legislative Decree 18/2023, Part D, the parameters to be monitored for a proper risk assessment and management of internal building distribution systems are specifically listed (as shown in Table 1.3), following the guidelines established by the WHO in the Guidelines for Drinking-water Quality, which were then transposed into the national guidelines for the implementation of WSPs. Annex II, Part A, defines the general objectives and requirements for the control and monitoring programs for water intended for human consumption. Regarding operational monitoring, Italian regulations fully adhere to EU Directive 2020/2184, confirming the same reference values for both the turbidity of water leaving the water supply plant

Table 1. 3 Parameters for risk assessment in internal distribution systems. Source: D. Lgs. 18/2023, annex1, Part D.

Parameter	Unit of Measurement	Parameter Value	Notes
Legionella	UFC/l (colony-forming units)	< 1000	This parameter value is defined for the purposes of articles 9 and 14. Actions prescribed by these articles may be considered even below the parameter value, particularly in cases of infections and outbreaks. In these cases, the source of the infection must be confirmed, and the *Legionella* species identified.
Lead (Piombo)	µg/l	5	The parameter value of 5.0 µg/l must be met by January 12, 2036, at the latest. Until this date, the parameter value for lead is 10 µg/l. Managers of internal distribution systems must strive to reach the lower value of 5.0 µg/l as soon as possible, and in any case no later than January 12, 2036.

Legionella | UFC/l (colony-forming units) | < 1000 | This parameter value is defined for the purposes of articles 9 and 14. Actions prescribed by these articles may be considered even below the parameter value, particularly in cases of infections and outbreaks. In these cases, the source of the infection must be confirmed, and the *Legionella* species identified.

Lead (Piombo) | µg/l | 5 | The parameter value of 5.0 µg/l must be met by January 12, 2036, at the latest. Until this date, the parameter value for lead is 10 µg/l. Managers of internal distribution systems must strive to reach the lower value of 5.0 µg/l as soon as possible, and in any case no later than January 12, 2036.

Establishment of CeNSiA and AnTeA

The following have been established at the ISS: the National Center for Water Safety (CeNSiA) and the centralized information system called the Dynamic Territorial Register of Drinking Water (AnTeA). The functions of CeNSiA will primarily include:

- Approval of WSPs.
- Issuance of authorizations for the introduction of ReMaF on the national market.
- Management of the centralized information system AnTeA, based on guidelines provided by the Ministry of Health and the Ministry of the Environment and Energy Security, with the support of ISPRA;
- Production and communication of evidence to ensure universal and equitable access to drinking water and safe sanitation services.

AnTeA's system was established with the following objectives:

- Ensure the acquisition, processing, analysis, and sharing of data related to the monitoring and control of the quality of water intended for human consumption.

- Ensure communication, integration, and sharing of data between the competent environmental and health authorities at the national, regional, and local levels, and between these authorities and the drinking water operators.
- Ensure adequate public access to information.
- Ensure the availability, updating, and accessibility of information to the European Commission, the European Environment Agency, and the European Centre for Disease Prevention and Control.
- Ensure the exchange of information for respective purposes with ARERA, ISTAT, and other national institutions, as well as with WHO.

Minimum Requirements for Chemical Reagents and Active or Passive Filtration Materials Used in the Treatment of Water for Human Consumption

Chemical reagents and active and passive filtration materials (ReMaF) used in the treatment of water for human consumption must be compatible with the characteristics of the water with which they come into contact and must not, over time: compromise its safety or suitability for human consumption, alter its color, odor, or taste, promote microbial growth, or release contaminants into it at levels higher than acceptable.

Furthermore, starting January 12, 2036, only ReMaF that comply with current regulations, have been authorized by CeNSiA, and registered in the AnTeA system will be allowed to be introduced into the national market and used throughout the entire water supply chain. A ReMaF authorized by another EU Member State may be placed on the national market if it has undergone a sanitary evaluation by a recognized technical-scientific body, based on criteria that ensure an equivalent level of safety for human health as that provided by this decree.

Information to the Public

The new degree reiterates that water supply service providers must ensure that users are provided with adequate and up-to-date information regarding production, management, and quality of the drinking water supplied. Such information should be made available to all users periodically and in the most appropriate and easily accessible manner (e.g., on bills or through digital media).

The main objective is to strengthen consumer trust in the water supplied and water services, encouraging increased use of tap water. Additionally, this would contribute to significantly reducing waste production and the use of new plastic.

1.5.3.4. In-Depth Look at the Implementation and Definition of WSPs

As mentioned in previous sections, WHO introduced a global risk assessment and management approach that covers all components of the water supply chain, from abstraction to the consumer. The evolution of knowledge regarding risk analysis has highlighted several critical issues in strategies that only check the conformity of the final product, shifting the focus to a broader risk assessment and management approach for the entire water supply chain.

In Legislative Decree 18/2023, specifically in Annex VI, the minimum criteria for approving a WSP for drinking water supplies are presented, in line with WHO provisions and transposed into national guidelines for risk assessment and management in the water supply chain according to the Water Safety Plan model (Luca Lucentini, 2024) issued by the Institute Superiore di Sanità

Evaluating the drinking water supply system and the associated risks is crucial to identify all potential events and hazards that could affect the water supply chain, causing negative health impacts on consumers. Hazards can be microbiological, physical, chemical, or radiological in nature and should be clearly identified to apply appropriate protective measures. A dangerous or potentially dangerous event is a situation or condition that occurs and whose consequences pose a risk in the water used or consumed. These events may arise naturally or may be triggered by predictable factors.

The most adopted approach to risk assessment is semi-quantitation, based on combining the probability of a hazard or dangerous event occurring with the potential impact it could have on human health or the environment. At the end of the evaluation, a numerical score from 1 to 25 is assigned, corresponding to the severity of the risk. Table 1.4 presents an example of a semi-quantitative risk assessment matrix proposed by WHO guidelines.

Table 1. 4 Presents an example of a semi-quantitative risk assessment matrix proposed by WHO guidelines

Source: Report ISTISAN 14/21 of the ISS, 2014

Degree of Probability	Insignificant (no impact or insignificant impact)	Minor (little significant impact)	Compliance of an organoleptic type	Compliance with legal or reference values	Very Severe (serious /catastrophic effects on health)
Rare (e.g., once every 5 years)	1	2	3	4	5
Unlikely (e.g., once a year)	2	4	6	8	10
Moderately Probable (e.g., once a month)	3	6	9	12	15
Probably (e.g., once a week)	4	8	12	16	20
Almost Certain (e.g., once a day)	5	10	15	20	25
Grade	<6: Low	6-9:	10-15:	>15:	
Classification	Low	Medium	High (significant)	Very High	

Within the broader assessment of real or potential risks, it is recommended to focus on emerging hazards and/or scenarios that, based on available data, seem most plausible. Among the emerging risk factors for water intended for human consumption are all those chemical substances that were previously monitored but had significantly low concentration levels compared to the prescribed limits or were even undetectable. These substances are referred to as “emerging contaminants” because the risk they pose to human health and the environment is not yet fully understood. Specifically, this includes pharmaceuticals (e.g., non-steroidal anti-inflammatory drugs,

antidepressants, antifungals, antivirals, and antibiotics), personal care and hygiene products (such as sunscreens with ultraviolet filters), perfluorinated compounds, pesticide degradation products, and nanomaterials (e.g., fullerenes, titanium dioxide).

At the end of the risk assessment of dangerous events, a series of control measures are defined for managing priority risks, which should be included in an improvement plan. The introduction of operational monitoring is crucial in managing issues and unforeseen events that may affect the drinking water supply chain. Its actions must be conducted in real time and, when possible, preventively, giving the resource manager sufficient time to implement the appropriate countermeasures as defined in the WSP to address the problem. In this regard, critical limits need to be established that can signal the potential ineffectiveness of a control measure before it compromises the quality of water intended for human consumption.

The operational monitoring plan can be supported by modern sensor technologies, online monitoring systems, and early warning systems (EWS) to quickly detect malfunctions in water treatment or potential contamination events. What is crucial in choosing to adopt this type of monitoring system is that it is not necessary to monitor all potential chemical or microbiological hazards. It is more effective to monitor specific variables that are easy to measure, and whose sudden changes act as an early warning for the operator about a possible alteration in water quality characteristics (e.g., turbidity, pH, temperature, electrical conductivity).

Lastly, the development of an emergency plan for the entire drinking water system is foreseen, which should be integrated into the WSP. This represents the strategy to be adopted in managing emergency scenarios that are beyond the control of the resource management entity, and for which it was not possible to foresee preventive and containment measures within the WSP, such as in the case of water crises caused by extreme events or earthquakes.

When discussing, as in this case, vulnerability scenarios, it is inevitable to focus on the potential impact of climate change on the drinking water system. The main consequences can significantly affect both the quality and quantity of the distributed water, especially during emergencies, as well as the physical impact on infrastructure. In this regard, in 2010, WHO developed “Guidelines for Managing Water Services During Extreme Weather Events,” (L Sinisi and R Aertgeerts, 2011) in which the role of WSPs becomes central for correctly managing the risks induced by climate change

1.5.3.5 New water scarcity Provision: Drought decree

The ongoing challenges of water scarcity and drought, which increasingly impact various regions of the country and result in significant repercussions for both the drinking water sector and the social and economic fabric, have prompted the Italian Government to implement immediate measures for effective management. Recently, the Italian government issued Decree Law No. 39 of April 14, 2023, titled “Urgent Provisions for Addressing Water Scarcity and Strengthening and Adapting Water Infrastructure” (Drought Decree). This decree encompasses a range of measures aimed at tackling the water emergency, reducing water wastage, enhancing and adapting water infrastructure, and bolstering the resilience of water systems against climate change.

To address the significant reduction in precipitation, a Crisis Management Committee for water scarcity has been established. This committee will oversee direction, orientation, and monitoring of efforts to manage the crisis. Its initial task will be to conduct a review of all projects

and interventions requiring urgent implementation to address the water crisis in the short term. Subsequently, the Committee will coordinate and promote the execution of essential interventions for mitigation, enhancement, and adaptation of water infrastructure, with the goal of increasing the resilience of water systems to climate change and minimizing water losses.

A special Commissioner has been appointed at the national level to execute the emergency interventions identified by the Crisis Management Committee. This Commissioner will ensure the proper application of measures aimed at rationalizing consumption and eliminating waste, oversee the appropriate use of reservoir volumes for potable, irrigation, industrial, and hydroelectric purposes, and regulate flows sourced from reservoirs within the limits established by water extraction concessions.

A streamlined procedure has been established for the construction of tanks designed to collect rainwater for agricultural use, with a specified maximum volume. Furthermore, to promote rational and sustainable management of water resources, the reuse of treated wastewater for irrigation purposes in agriculture is permitted until the end of the current year (2023), applicable to facilities that were operational as of the decree's effective date. Additionally, modifications to the regulation of desalination plants and the strengthening of penalties for illegal water extraction are planned.

1.5.4 Vietnamese National standard for domestic water supply

Vietnamese standards in QCVN 01-1:2018/BYT are tailored to the country's specific regulatory and environmental context, with stricter or less strict limits for certain parameters.

For several contaminants, like vanadium, bisphenol A, PFAS, and microcystin-LR, Vietnam does not specify limits, unlike the EU and WHO standards.

Vietnam adopts stricter limits for parameters like ammonia, selenium, and chromium, ensuring safer drinking water for the population.

Vietnam's standard for domestic water supply:

The concept of "Water Safety Plans" (WSPs), introduced by the World Health Organization (WHO), is a crucial framework for managing risks to ensure the safety of drinking water. The WSP methodology involves assessing and managing risks at every stage of the water supply chain, from source to tap. This includes identifying hazards, implementing control measures, and regularly monitoring water quality.

WSPs became mandatory for municipal water systems in Vietnam, and they are also required for rural water supply systems. And the key challenges include insufficient local guidance for WSP development (87% of utilities reported this issue) and inadequate funding for implementation (43%). They need better guidance, and training remain (Nguyen et al., 2023)

In Vietnam, the standards for domestic water supply are outlined in QCVN 01-1:2018/BYT, issued by the Ministry of Health. These standards set specific requirements for water quality, ensuring that it is safe for daily activities, such as bathing, laundry, and cooking, though additional treatment (e.g., boiling, filtering) may be necessary for drinking. Annex QCVN 01-1 :2018/BYT

Table 1. 5 Comparison of Water Quality Standards (Vietnam vs. WHO)

Parameter	Vietnam (QCVN 01-1:2018/BYT)	WHO Guidelines for Drinking-water quality	Comparison
E. coli	0 CFU/100 mL	0 CFU/100 mL	Vietnam's standard matches WHO's. Both require E. coli to be undetectable, indicating that Vietnam meets this critical microbial safety standard.
Total Coliforms	≤ 3 CFU/100 mL	0 CFU/100 mL	Vietnam allows a slightly higher limit, but microbial safety measures, though WHC tolerance approach.
pH	6.5 - 8.5	6.5 - 8.5	Both standards are aligned, ensuring water acidity/alkalinity is within safe levels for human consumption
Arsenic (As)	≤ 0.01 mg/L	≤ 0.01 mg/L	Vietnam fully complies with WHO guidelines for arsenic, a critical contaminant often found in groundwater.
Lead (Pb)	<0.01 mg/L	≤ 0.01 mg/L	Vietnam matches WHO's standard, reflecting strong regulations for preventing lead contamination
Fluoride (F)	≤ 1.5 mg/L	≤ 1.5 mg/L	Both standards are identical, ensuring safe fluoride levels to prevent dental and skeletal fluorosis.
Nitrate (NO ₃)	≤ 50 mg/L	≤ 50 mg/L	Vietnam follows WHO standards, preventing harmful nitrate levels that can affect infant health (blue baby syndrome).
Ammonia (NH ₃)	≤ 0.3 mg/L	≤ 1.5 mg/L	Vietnam's stricter limit demonstrates a more conservative approach to ammonia content in drinking water
Iron (Fe)	≤ 0.3 mg/L	≤ 0.3 mg/L	Vietnam aligns with WHO in controlling iron levels to avoid unpleasant taste and staining.
Mercury (Hg)	≤ 0.001 mg/L	≤ 0.006 mg/L	Vietnam adopts a more stringent standard, providing stronger protection against mercury contamination
Manganese (Mn)	≤ 0.3 mg/L	≤ 0.4 mg/L	Vietnam's regulation is stricter than WHO's, offering enhanced safety.
Turbidity	≤ 2 NTU	≤ 5 NTU	Vietnam's stricter limit ensures clearer water, reducing the likelihood of microbial contamination.
Total Dissolved Solids (TDS)	≤ 1000 mg/L	≤ 1000 mg/L	Both standards are identical, ensuring water is free from excessive dissolved substances that can affect taste and health.

Comparison and Vietnam's Application in table 1.5

-Vietnam's compliance: In terms of core microbial and chemical safety, Vietnam's QCVN 01-1:2018/BYT largely matches WHO standards, ensuring public health protection through stringent controls on key contaminants like E. coli, arsenic, lead, and fluoride.

- Stricter standards: Vietnam's tighter regulations on parameters such as ammonia, mercury, and manganese reflect a more cautious approach in safeguarding against specific chemical risks, compared to the broader global WHO guidelines.

- Areas for improvement: While microbial safety standards are mostly met, the total coliform limit is slightly higher in Vietnam than WHO's ideal. Vietnam could further improve by aligning more closely with WHO's zero-tolerance approach for total coliforms in all drinking water samples.

In conclusion, Vietnam's water safety standards are comprehensive and generally aligned with WHO's globally recognized guidelines, though there is room for stricter microbial safety measures, particularly concerning total coliforms. The QCVN standards demonstrate that Vietnam is committed to providing safe water but can benefit from continuous updates to address evolving environmental and public health challenges.

1.6 Conclusion

Chapter 1 has provided a comprehensive overview of the impacts of climate change on drinking water supply systems (DWSs), particularly in the context of increasing extreme weather events. Studies and reports from the IPCC, WMO, and other organizations highlight the significant changes in temperature, precipitation patterns, and the frequency of natural disasters, all of which directly affect water quality and availability.

The effects of climate change on water supply systems have been illustrated through real-world events worldwide, including severe flooding in Vietnam and India, prolonged droughts in Italy and China, and hurricanes and typhoons disrupting water infrastructure in the U.S. and the Philippines. These events not only cause interruptions in water supply but also degrade water quality, increasing contamination risks and the spread of waterborne diseases.

Furthermore, this chapter has introduced key regulatory frameworks at the international, European, and national levels, including EU Directive 2020/2184, Italy's Legislative Decree 18/2023, and Vietnam's QCVN 01-1:2018/BYT, which aim to manage and safeguard drinking water quality against climate-related risks. However, despite the existence of these policies, challenges remain in their practical implementation, particularly in real-time water quality monitoring, climate-responsive treatment strategies, and improving the resilience of water supply systems.

Given these challenges, this research aims to assess climate change's effects on drinking water quality, explore adaptation strategies, and enhance the resilience of water supply systems through advanced monitoring technologies and sustainable management strategies.

The topics covered in this chapter establish a foundation for further in-depth analysis in the following chapters:

- Chapter 2 will provide a literature review on climate change impacts on water resources, treatment technologies, and distribution networks.
- Chapter 3 will present case studies from Italy and Vietnam, illustrating how different regions experience and address climate change impacts on DWSs.

- Chapters 4 and 5 will focus on technological monitoring solutions and real-time data from the Mompiano water treatment plant (Brescia, Italy) to assess risk control measures.
- Chapter 6 will analyze the findings, evaluate the effectiveness of monitoring tools, and propose strategies to enhance the resilience of drinking water supply systems against climate risks.

In conclusion, this chapter has set the stage for the research by outlining the background, challenges, and regulatory context related to climate change and water supply systems. The following chapters will develop deeper into the scientific and practical aspects of this issue, offering solutions to enhance the safety, sustainability, and resilience of drinking water systems in the face of climate change.

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CHAPTER 2: LITERATURE REVIEW, RESEARCH GAPS, RESEARCH QUESTIONS AND OBJECTIVES

2.1 Introduction

The causes of climate change can be considered complex interactions between the earth, the atmosphere, the oceans, and the land systems. Therefore, changes in any of these systems can be natural and man-made, depending on the greenhouse gases (GHG), aerosol levels, land use and ground cover, and atmospheric compounds that affect absorption, dispersion, and radiation in the atmosphere and on the surface of the earth.

Climate change is a global issue with significant environmental and social implications. According to preliminary data from the Copernicus Climate Change Service of the European Union, the global average temperature reached 17.15°C on July 22, 2024, surpassing the previous day's record of 17.09°C. In other words, Earth experienced its two hottest consecutive days. Unusually high winter temperatures in Antarctica contribute to pushing global temperatures to new milestones. The temperature record marks a milestone that climate scientists do not expect to remain unbroken for long, as human activities continue to drive climate change by releasing pollution from fossil fuels into the atmosphere. Bob Henson, a meteorologist at Yale Climate Connections, stated that while it is not surprising for records to be broken, the sharp rise in temperatures over the past two years is still "stunning." People across the globe are facing the impacts of extreme heat this week and throughout the summer. California, USA, recorded temperatures above 37°C in many areas on July 22, increasing the risk of wildfires in the region. Temperatures soared to 47.8°C in Al Dhaid, a city in northeastern Dubai. Southern France remains sweltering, while heat warnings have been issued in many areas of Spain and Portugal. Climate change not only causes global warming but also increases the frequency and intensity of extreme weather events such as floods, droughts, heatwaves, and wildfires (Compaoré et al., 2023). Flooding causes soil erosion, introducing pollutants from agricultural, urban, and industrial areas into water sources, raising turbidity, organic matter, and harmful microorganisms. Droughts reduce water flow, concentrate pollutants, and create conditions favorable for harmful algae, while heatwaves accelerate organic matter decomposition, reduce dissolved oxygen levels, and support the proliferation of pathogenic microorganisms (Delpla et al., 2009a).

This literature review will provide a thorough overview of current state of information about impacts of climate change on drinking water supply systems. Dividing two definitions separate with Climate change impacts on water resources globally will provide scope: broad and comprehensive, encompassing all water systems worldwide, including surface water, groundwater, and the hydrological cycle and focus on examines the overarching effects of climate change on water availability, distribution, and hydrological patterns. This includes changes in precipitation, river flows, droughts, and floods, as well as impacts on water quantity and ecosystems dependent on water as

- Increased variability in rainfall patterns leading to droughts and floods.
- Melting glaciers and reduced snowpack affecting river flows and freshwater availability.
- Rising sea levels causing saltwater intrusion into coastal aquifers.
- Shifts in water availability impacting agriculture, energy production, and biodiversity.

The focus is on global water sustainability, equitable resource allocation, and large-scale water management challenges due to climate change.

And Climate Change Impacts on Source Water Quality will provide narrower scope, specifically targeting the quality of water sources used for human consumption, agriculture, and industry (e.g., rivers, lakes, reservoirs, and aquifers). We just focus addresses how climate change affects the chemical, biological, and physical quality of water sources. This includes contamination risks, ecosystem degradation, and changes in pollutant concentrations.

- Warmer temperatures promote algal blooms in lakes and reservoirs, reducing water quality.
- Increased runoff from extreme rainfall events introducing pollutants (e.g., pesticides, sediments, and pathogens) into water bodies.
- Changes in flow patterns affecting the dilution and transport of contaminants.
- Coastal flooding leads to saltwater intrusion, degrading freshwater quality.

The focus is on safeguarding water quality for public health, ecosystem services, and industrial/agricultural use, with emphasis on monitoring, treatment, and management of specific contamination risks.

While both definitions explore the impacts of climate change on water, Climate change impacts on water resources globally focuses on macro-level changes in water availability and distribution, whereas Climate Change Impacts on Source Water Quality is in on water quality issues critical for human use and ecosystem health. Both are interconnected, as quantity issues often influence quality, and vice versa. Effective climate strategies must integrate both perspectives to ensure holistic water resource management.

Climate change impacts on drinking water supply systems: the effects of climate change on drinking water supply systems will be specifically covered Climate Change Impacts on Source Water Quality, including modifications to water treatment technologies and distribution systems. Other factors will also be examined that could affect the reliability and safety of drinking water supplies.

Strategies for adapting to the climate change effects on drinking water supply system: this section will explore different strategies including actions to improve water efficiency and conservation, modifications in water management practices and other adaptive measures.

The first section will study the changes that have occurred due to changing climate starting from the causes that have generated them up to their influence on qualitative and quantitative characteristics of water. The influence on hydrological cycle is specifically studied since it influences sources of water supply that feed the system for treatment and distribution of drinking water. Changes in precipitation patterns, snowpacks and melting patterns, changes in evapotranspiration, changes in river flow, drought patterns and increasingly widespread flood phenomenon. Variation in temperature, turbidity, chemical and microbiological variation of water supply sources are all consequences of climate change. The growth of cyanobacterial colonies is a major issue that is closely tied to climate change. All these above-mentioned effects will be studied thoroughly in the light of scientific literature

2.2 Climate change impacts water resources globally

Climate change profoundly affects water resources worldwide by altering the delicate balance of the hydrological cycle. These changes manifest in the following ways:

Increased variability in rainfall patterns leading to droughts and floods.

Climate change leads to more erratic rainfall, with some regions experiencing excessive precipitation while others face prolonged droughts.

The average annual global precipitation has slightly increased over the past century due to higher atmospheric moisture. The frequency and intensity of extreme precipitation events are also likely to rise in most parts of the world as global temperatures continue to increase followed by United States Global Change Research Program (USGCRP, 2017)

Climate change is significantly altering global rainfall patterns, leading to changes in surface water flow. Climate models predict reduced rainfall in Africa and Southern Europe (Juana et al., 2013), while Northern Europe and North America may experience increases. (Garnier & Holman, 2019a);(Barriopedro et al., 2011)

Intensified and more frequent rainfall can cause soil erosion and flooding, introducing sediment, nutrients, and pesticides into water sources, which degrades water quality, harms aquatic ecosystems, and raises drinking water treatment costs. (X. Wang et al., 2018b)

Conversely, climate-change-induced droughts can also diminish water quality. Low flow during droughts, combined with rising temperatures, increases concentrations of dissolved substances and biological oxygen demand (BOD) in rivers while reducing dissolved oxygen (DO), negatively impacting aquatic ecosystems(Whitehead et al., 2009). In urban areas, heavy rainfall can overwhelm combined sewer systems, leading to chemical and microbial contamination of surface waters, which can pollute drinking water supplies and cause waterborne diseases(Khan et al., 2015b) Additionally, reduced flow means less water to dilute wastewater, resulting in higher downstream pollutant concentrations, complicating efforts to improve water quality standards. Climate change also disrupts estuarine flow patterns, causing saltwater intrusion into coastal aquifers, which contaminates freshwater resources, threatening human health and coastal ecosystems(Whitehead et al., 2009)

In the Mekong Delta, the hydrological system has transitioned from a nearly undisturbed state to one heavily influenced by human activities, with saltwater intrusion into surface and groundwater systems becoming a recent adverse issue. This phenomenon poses a severe threat to freshwater supplies and degrades ecological environments (K. T. Nguyen et al., 2019)

Increased irrigation demands driven by higher crop water needs due to rising temperatures can lead to greater exploitation of deep groundwater for agricultural use, exacerbating saltwater intrusion into deep groundwater in the Mekong Delta (Ngo-Duc et al., 2014)Wagena and Easton (2018) highlighted that climate change could significantly harm water quality in the Susquehanna River Basin, Chesapeake Bay. They found that total nitrogen increased by 8.9% and sediment by 25.8% under climate change conditions compared to current levels. (X. Wang et al., 2018b) Similarly, compared to current sediment loads in the Neshanic River Basin (Central New Jersey), Giri et al. (2019a, b) observed a 10% increase in sediment load due to future climate change. (Giri, 2021). Moreover, Wang et al. (2018) reported a 6% rise in total phosphorus compared to baseline reference conditions due to climate change in the Chao and Bai River Basins, China.

Melting glaciers and reduced snowpack affecting river flows and freshwater availability

The decline of glaciers and snow, which serve as natural water reservoirs, is leading to reduced river flows in many regions, posing significant challenges to water supply systems, a critical issue previously discussed. In the Himalayas, often called "Asia's Water Tower" or the "Third Pole,"

snowmelt plays a vital role in sustaining the flow of major rivers like the Mekong. However, rapid warming due to climate change is accelerating glacier melt and reducing snow accumulation, directly affecting the Mekong's flow and impacting water resources in downstream areas like the Mekong Delta. (Su et al., 2019) Additionally, new dam constructions could explain about 62% of the changes in the annual streamflow during 2010-2014, whereas climate change used to contribute over 80% of the changes during 1992-2009. Operations of upstream dams can help increase streamflow in the dry season and reduce streamflow in the wet season (D. Li et al., 2017) the construction of dams along the Mekong River basin, particularly upstream, alters river flow patterns, increasing dry-season flows but reducing wet-season flows. This, combined with climate change, creates complex hydrological shifts that affect water availability in downstream regions. River flow also plays a critical role in mitigating saltwater intrusion in the Mekong Delta. Strong flows during the rainy season push seawater back, maintaining freshwater supplies for agriculture, domestic use, and ecosystems. However, reduced river flows heighten the risk of saltwater intrusion, threatening freshwater resources (Xiao et al., 2021). Globally, climate change impacts river flows differently causing increases in high-latitude and equatorial regions while decreasing flows in mid-latitude and subtropical regions driven by changes in precipitation, temperature, and hydrological dynamics (Nigel W. Arnell, 1999)

Rising sea levels causing saltwater intrusion into coastal aquifers.

Rising sea levels, one of the most serious consequences of climate change, have far-reaching negative impacts on global water resources. Saltwater intrusion is a primary issue, as higher sea levels push saline water further inland, contaminating coastal freshwater supplies and disrupting agricultural production, as seen in vulnerable regions like the Mekong Delta in Vietnam (Xiao et al., 2021). Methods such as environmental isotope techniques, groundwater flow and salt transport models, and technical measures are being employed to assess and manage saltwater intrusion. Additionally, rising sea levels heighten the risk of coastal flooding, threatening lives and properties, especially in densely populated, low-lying coastal cities (Hanson et al., 2011). Economic damages from coastal flooding are projected to increase from \$27 trillion in 2010 to \$80 trillion by 2050 based on land use and from \$46 trillion to \$158 trillion based on population growth (Jongman et al., 2012). Altered river flow patterns also result from sea level rise, affecting downstream freshwater availability and coastal ecosystems. Furthermore, sea level rise compromises drinking water quality through saltwater intrusion and pollution of freshwater sources (Vineis et al., 2011). Addressing these challenges is complicated by uncertainties in climate change and sea level rise predictions, limitations in forecasting models, and insufficient reliable data on climate, hydrology, and water quality. These obstacles underscore the importance of international collaboration in research, data sharing, and the development of comprehensive adaptation strategies to mitigate the global impacts of climate change on water resources.

Shifts in water availability impacting agriculture, energy production, and biodiversity

Changes in water resources can have significant impacts on agriculture, energy production, and biodiversity.

In agriculture, the depletion of groundwater due to climate change and overexploitation severely affects irrigation activities, particularly under drought conditions, reducing crop yields and threatening food security (Kløve et al., 2014). At the same time, water quality is impacted by increased soil erosion and nutrients and pesticide runoff into water sources, complicating irrigation practices.

These changes may force farmers to switch to different crops or adjust their farming methods (X. Wang et al., 2018b)

For energy production, hydropower plants that depend on river and lake flows are vulnerable to changes in water flow caused by climate change, leading to reduced electricity output. Droughts can deplete reservoirs, compromising energy production capacity (Giri, 2021). Additionally, the expansion of bioenergy crop cultivation (e.g., corn, sugarcane, soybeans for biofuel) often involves the heavy use of fertilizers to maximize growth and yield. However, excessive fertilizer use can lead to leaching, where nutrients and chemicals from fertilizers (such as nitrates and phosphates) seep into groundwater. This contaminates water resources, posing environmental risks and health hazards when polluted groundwater is consumed

Regarding biodiversity, ecosystems dependent on groundwater, such as wetlands and riparian zones, face significant changes in species composition and functionality due to declining groundwater levels and stream flows (Kløve et al., 2014). Freshwater ecosystems are also threatened as changes in water temperature, flow, and quality adversely affect aquatic species, disrupting food chains (Whitehead et al., 2009). According to Polemio and Walraevens (2019), in coastal areas, saltwater intrusion caused by rising sea levels and reduced freshwater availability can significantly impact ecosystems. These changes also alter habitats for many species, particularly those with low dispersal abilities and long reproductive cycles. (Polemio & Walraevens, 2019)

Additionally, water pollution is exacerbated by the runoff of contaminants from soil and urban areas, combined with wastewater from agricultural and industrial activities, worsening water resource challenges. Human activities, such as dam construction, water extraction, and land-use changes, further amplify the impacts of climate change on water resources. Moreover, extreme weather events like droughts and floods not only increase the risk of pollution but also significantly reduce water quality.

Refined version: Numerous studies have been conducted globally and regionally to assess the impacts of climate change on drinking water resources, treatment systems, and distribution networks. These studies have provided valuable insights into how different climatic variables such as rising temperatures, shifts in precipitation, and extreme weather events affect water quality and availability.

However, despite this growing body of knowledge, several important research gaps remain. Many existing studies tend to focus on specific components of the water supply chain such as raw water quality or treatment performance without offering a comprehensive view across the entire system, from source to tap. Furthermore, limited attention has been given to the integration of real-time monitoring technologies and climate-related risk assessments within operational water utilities, particularly in comparative studies involving countries with differing infrastructures, such as Italy and Vietnam.

This research aims to address these gaps by building on existing literature and incorporating multiple data sources, including empirical field data (e.g., surveys, water quality data, and online monitoring device outputs), operational monitoring results, and stakeholder feedback. By comparing findings between Italy and Vietnam, this study offers new insights into adaptive strategies, real-time risk management, and climate-resilient water governance. These contributions are intended to

strengthen the ongoing scientific debate on climate change impacts in the drinking water sector and provide a useful foundation for further research and policymaking.

2.3 Climate Change impacts on quality effects on water base

Climate change exerts multifaceted effects on the quality of drinking water sources, driven primarily by variations in temperature, precipitation, and the increasing frequency of extreme weather events. These impacts manifest across a range of water bases, including surface waters, shallow and deep groundwater, bank filtration systems, and karstic aquifers, each responding uniquely due to their intrinsic hydrogeological characteristics. This chapter presents the effects of climate change on water quality based on water base type, to highlight specific vulnerabilities and adaptation needs.

2.3.1 Surface waters

Climate change has complex and multifaceted effects on surface water quality, particularly with regard to drinking water sources. According to Compaoré et al. (2023), climate change primarily through variations in temperature and precipitation profoundly influences the quality of surface catchments and aquifers, the effectiveness of drinking water purification processes, and the final quality in the distribution system. These climatic stressors alter the physical, chemical, and biological parameters of source waters, increasing levels of pollutants such as dissolved organic matter (DOM) and disinfection by-products (DBPs), both of which pose public health risks (Whitehead et al., 2009).

Erratic rainfall patterns and intense precipitation events exacerbate soil erosion and nutrient runoff, introducing microorganisms and contaminants into surface waters (Giri, 2021). These changes challenge water treatment operations by reducing the efficiency of coagulation and sedimentation and increasing the demand for advanced treatment technologies. Additionally, adaptation measures such as watershed management, wetland restoration, and the adoption of technologies like membrane filtration and ozonation are becoming increasingly necessary to protect water quality (Delpla et al., 2009).

Flooding and heavy rainfall events significantly alter the microbiological quality of surface water. Increases in coliforms (e.g., *Escherichia coli*), bacteriophages, enteric viruses, and *Pseudomonas* have been observed under changing temperature and precipitation conditions (Delpla et al., 2009; Khan et al., 2015b). A systematic review by Levy et al. (2016) identified approximately 30 studies linking heavy rainfall with outbreaks of diarrheal diseases. This risk is expected to intensify under climate change scenarios (WHO, 2011; Schijven et al., 2013), as land use in upstream watersheds heavily influences runoff quality (Hofstra, 2011).

Flood-related risks include flash flooding, infrastructure damage, landslides, and sediment transport, especially as global temperatures increase by 1.8°C (Delpla et al., 2009). Rising sea levels and urban expansion in low-elevation coastal zones (LECZs) of Asia and Africa exacerbate these risks, increasing exposure to flood hazards and undermining resilience strategies (Schijven et al., 2013).

Greenhouse gas emissions are a major driver behind intensified precipitation extremes globally. Radiative forcing alters seasonal precipitation patterns, leading to increased rainfall in Northern Europe and drying trends in Southern Europe (EEA, 2020). Similar patterns are evident in Southwestern Australia, Southern Africa, and Western North America (Seneviratne et al., 2021). The

IPCC confirms that extreme precipitation has increased across North America, Europe, and Asia, often creating greater seasonal disparities in water availability.

Prolonged droughts, driven by reduced precipitation and higher evaporation, worsen water scarcity and concentrate pollutants, thereby degrading water quality and increasing treatment burdens. Reduced flows limit dilution capacity and raise concentrations of DOM, nutrients, and pathogens. For example, in the Tame River (UK), phosphorus levels rise during summer low-flow periods, increasing algal blooms and reducing dissolved oxygen (DO), which harms aquatic ecosystems. These effects elevate treatment costs impact recreation and commercial water use. Under high-emission scenarios, water quality degradation could lead to economic losses exceeding \$1.4 billion in the U.S. by 2050 (Van Vliet et al., 2023; Fant et al., 2017).

Climate-induced changes in snowmelt and rainfall patterns are disrupting river and stream hydrology an essential component of surface water systems. Earlier snowmelt and increased winter flows are followed by significantly reduced summer flows, which both degrade water quality and complicate supply timing (Skaland et al., 2022; Arnell, 1999). Lower flows reduce dilution capacity, while higher flows mobilize sediments and contaminants. Studies from Northern and Central Europe show that peak flows are project to shift nearly a month earlier by 2070, further increasing eutrophication risks and straining water treatment systems.

Events such as the severe 2003 drought in the Rhine and Meuse Rivers illustrate how temperature-driven reductions in DO and increased microbial oxygen demand worsen water quality. A 3°C increase can reduce DO saturation by about 10%, threatening aquatic ecosystems (Kløve et al., 2014). Rising sea surface temperatures also disrupt marine ecosystems by altering species composition and reducing nutrient circulation. Climate change further complicates pesticide dynamics: changing soil moisture conditions affect pesticide breakdown and mobility, increasing their presence in surface waters, as shown in Mediterranean regions (Louchart et al., 2005).

Higher temperatures and nutrient enrichment from runoff foster eutrophication and harmful algal blooms, increasing microbial proliferation and the burden on water treatment infrastructure. DOM released by decomposing soil organic matter during floods promotes microbial growth while diminishing the effectiveness of sunlight disinfection. This scenario leads to greater production of DBPs during treatment (Lipczynska-Kochany, 2018).

Land use also modulates the impact of climate change on surface water quality. Forests, wetlands, and riparian zones improve water quality, while intensive agriculture contributes to non-point pollution from nutrients and pesticides (Wilson & Weng, 2011; López-Ballesteros et al., 2023; Cunha et al., 2016a). In urban areas, soil impermeability increases runoff and introduces pollutants from industrial and residential sources into surface waters (Delpla et al., 2009).

In Europe, 72% of water supplies come from surface sources, though this varies regionally. Florence and Naples primarily use river water, while Milan sources groundwater from 433 wells. Understanding the localized vulnerabilities of such systems is essential as climate change differentially affects Italy's regions

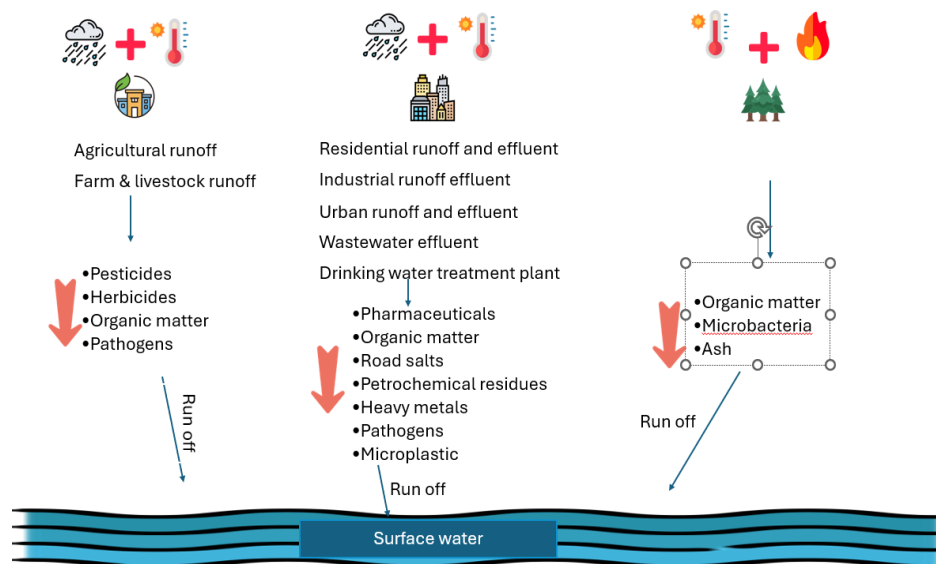


Figure 2. 1 Climate change impacts on source water quality (Compaoré et al., 2023)

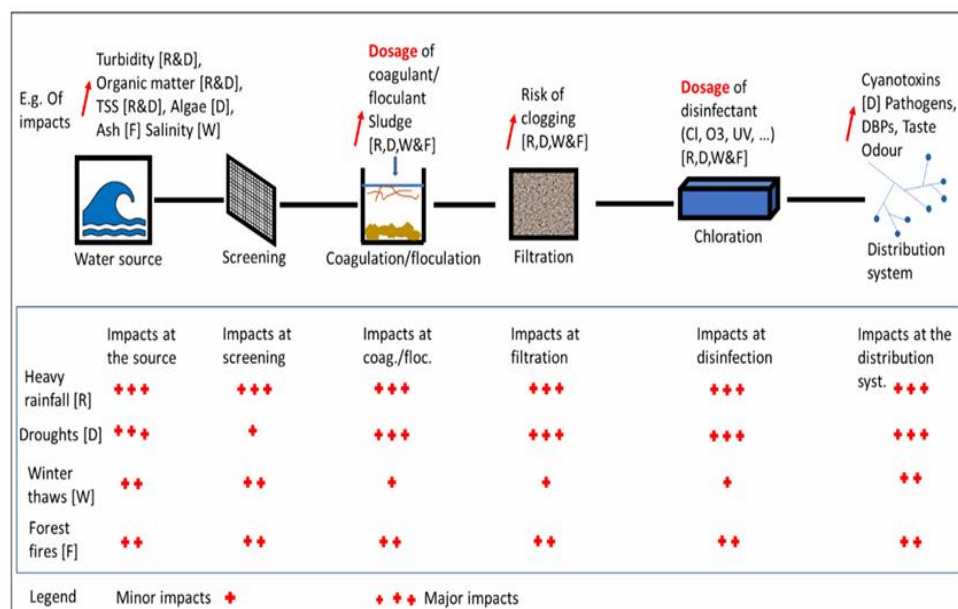


Figure 2. 2 Examples of the impact of the most recurrent climatic hazards on a typical drinking water treatment plant (DWTP) (Compaoré et al., 2023)

Effects of Climate Change on Lakes and Artificial Reservoirs Rising water temperatures, driven by climate change (CC), are profoundly altering water quality, ecosystem dynamics, and hydrological processes. This warming trend, observed across Europe, North America, and Asia since the 1960s, has led to surface water temperature increases ranging from 0.2°C to 2°C, primarily due to atmospheric warming (B.C Bates, n.d.). Projections suggest that European lakes may experience an average temperature increase of about 2°C by 2070, with shallow lakes being particularly susceptible to higher summer temperatures, while deeper lakes face prolonged winter warming due to their greater heat storage capacity. For instance, a study at Hongfeng Lake, China, revealed that a 2°C winter temperature rise resulted in a 6% increase in algal growth. Such blooms deplete dissolved oxygen (DO) levels, suffocating fish and other organisms while destabilizing ecosystems. Temperature shifts further disrupt migration patterns, life cycles, and species distributions, often favoring heat tolerant

organisms and leading to ecological imbalances (Giri, 2021) Tibetan lakes, for instance, have experienced a doubling of average turbidity since 2000 due to increased sediment input from accelerated glacier melting and the expansion of lakes (Mi et al., 2019). Similarly, in Cambodia's Tonle Sap Lake, despite a reduction in sediment runoff from the Mekong River, turbidity levels have risen. This paradox is attributed to hydrodynamic changes resulting from the lake's shrinkage, which has facilitated sediment resuspension from the lakebed (Z. Wang et al., 2021)

The effects of climate change on water bodies have been particularly observed in lakes and artificial reservoirs. Among the most significant effects is the increased frequency of algal blooms. Literature links this phenomenon to eutrophication processes, driven by high nitrogen and phosphorus concentrations in the water, often originating from agricultural runoff or urban wastewater discharges. The intensification of these blooms, exacerbated by higher temperatures, promotes rapid algal growth (Rodrigues et al., 2021). Another phenomenon associated with climate change is the increased turbidity and sediment resuspension, degrading water quality. This phenomenon depends on morphological and climatic factors such as wind, currents, and temperature increases, influencing water stratification and the activity of organisms (Mi et al., 2019). Rising temperatures also disrupt the ecological balance of lake environments. For instance, increased temperatures boost benthic biomass and macroinvertebrate populations, while greater activity of benthic organisms leads to increased sediment resuspension (Niemistö et al., 2012). While artificial reservoirs generally respond to climate changes better than natural lakes due to managed water volumes, they can also adapt through optimized intake depths for potable water treatment. Lastly, climate change has heightened concerns about microplastic pollution in surface waters

2.3.2 Shallow Ground water source

Shallow groundwater systems are highly vulnerable to climate change due to their proximity to surface activities. Model of (Benz et al., 2024) Warming temperatures (up to +3.5°C by 2099) alter microbial ecology and geochemical reactions, increasing the survival of pathogens and mobility of contaminants like nitrates and pesticides (Lotfi et al., 2020);

Evapotranspiration and Groundwater Vulnerability under Climate Change Climate change significantly alters the hydrological cycle, particularly by increasing evapotranspiration rates due to rising air temperatures. Evapotranspiration, which combines evaporation from soil and transpiration from vegetation, plays a critical role in regulating groundwater recharge. Higher temperatures elevate atmospheric water demand, leading to greater water loss from soils and reducing the net infiltration available to replenish aquifers (Lotfi et al., 2020)

This process is especially critical in arid and semi-arid regions, where limited rainfall, combined with higher evapotranspiration, intensifies groundwater depletion. As soil moisture decreases and precipitation becomes more irregular, groundwater recharge is further inhibited (Padrón et al., 2020). Empirical studies show that even in regions with stable rainfall, increased evapotranspiration alone can lead to significant drops in groundwater levels.

Reduced recharge weakens the resilience of shallow aquifers, while over-extraction in response to drought exacerbates depletion. Moreover, declining groundwater levels in coastal regions increase the risk of saltwater intrusion, compromising the quality of freshwater reserves (Holger Treidel, 2011). Key causes include the over-extraction of groundwater, which lowers groundwater levels and allows seawater to infiltrate coastal aquifers; rising sea levels due to climate change,

increasing hydraulic pressure and pushing saltwater further inland; reduced freshwater flow from rivers caused by droughts and altered rainfall patterns; and extreme weather events like storms and tsunamis, which force saltwater inland, leading to the salinization of land, surface water, and groundwater(Xiao et al., 2021)

Additionally, reduced dry season flows impact groundwater recharge, leading to declining groundwater levels and issues like saltwater intrusion in coastal areas. Low flows also exacerbate water pollution, as diminished dilution capacity raises pollutant concentrations. These seasonal changes complicate water supply management, forcing treatment facilities to handle fluctuating water volumes, poorer quality raw water, and potential flood damage. For example, studies in Norway reveal increased winter flows and reduced summer flows due to climate change, with projections suggesting peak flows may occur nearly a month earlier in much of Northern and Central Europe by 2070. Such disruptions highlight the pressing need for adaptive strategies to manage seasonal variability in water systems effectively. (Skaland et al., 2022)

Moreover, increased concentrations of pollutants due to reduced dilution and longer retention times can further degrade water quality (Kløve et al., 2014).

Projections suggest that evapotranspiration rates could rise by up to 7.3% in mountainous and dryland regions, with the most pronounced impacts during the summer months (Lotfi et al., 2020). These trends underscore the need for adaptive groundwater management strategies that account for changing climate patterns and the critical role of evapotranspiration in determining water availability.

Land use changes and agriculture amplify non-point source pollution risks (López-Ballesteros et al., 2023) Additionally, shallow aquifers in urban areas face risks from leaking sewer networks and industrial discharges, intensified by flooding.

High evapotranspiration rates concentrate pollutants and reduce aquifer recharge, especially in arid regions (Padrón et al., 2020). Land use changes and agriculture amplify non-point source pollution risks (López-Ballesteros et al., 2023). Additionally, shallow aquifers in urban areas face risks from leaking sewer networks and industrial discharges, intensified by flooding.

2.3.3 Deep wells source

Deep aquifers are relatively buffered from short-term climatic changes but still experience long-term quality degradation. Rising temperatures promote hypoxic conditions and nutrient release (iron, manganese), altering water chemistry (Treidel et al., 2011).

Evapotranspiration and reduced recharge can lower deep water tables, potentially increasing drawdowns and salinity, particularly in coastal zones (Holger Treidel, 2011). Deep well systems require adaptive withdrawal management to avoid thermal impacts and preserve aquifer quality (Khan et al., 2015).

Although deep confined aquifers are generally less sensitive to direct climatic influences due to their slow recharge rates and geological isolation, they are not immune to long-term climate impacts. These aquifers often contain fossil groundwater that is not renewable on human timescales, and once depleted, recovery is unlikely. (Delpla et al., 2009b)

Climate change can indirectly affect deep groundwater systems through increased anthropogenic extraction in response to surface water shortages and declining shallow aquifers. Increased pumping to meet growing demands may lead to long-term drawdowns, reduce pressure

heads, and mobilize naturally occurring substances such as arsenic, fluoride, or salinity from surrounding formations. (Delpla et al., 2009)

Changes in surface temperature can influence groundwater temperatures at shallow to intermediate depths (10–15 meters), and projections show that mean groundwater temperature in temperate zones may increase under future warming scenarios. These thermal changes can affect water quality and geochemical equilibria, including microbial dynamics. (Kløve et al., 2014) Deep aquifers may exhibit delayed responses to changes in recharge conditions. (Invik et al., 2017) However, a prolonged decline in recharge due to shifts in precipitation patterns can eventually disrupt the water balance of deeper groundwater systems. For instance, reduced recharge may increase the contribution of older, deeper flow paths to groundwater abstraction, which can alter water chemistry and mineral content. (Polemio & Walraevens, 2019) (Maurizio Barbieri et al., 2021)

Case studies also reveal that increased Sr/Ba ratios in spring and groundwater samples are associated with deeper flow paths and recharge pattern changes induced by climate variations. Even deep wells may eventually show signs of water stress due to long-term climate trends, especially when coupled with intensified human withdrawal. (Maurizio Barbieri et al., 2021)

In summary, while deep aquifers may seem more resilient, they are vulnerable to indirect and long-term impacts of climate change, including increased extraction pressure, thermal shifts, and gradual quality degradation over time.

2.3.4 Bank filtration

Bank filtration systems are climate-sensitive, as their performance depends on river flow and temperature. High river discharge from intense rainfall can reduce filtration time, impairing the natural attenuation of pollutants. In contrast, low flows reduce infiltration, limiting supply. Temperature changes influence redox conditions, affecting the mobility of metals and organic compounds. Coastal and saline areas face the additional risk of saltwater intrusion, compromising the filtration process (Xiao et al., 2021). Strategies such as adaptive pumping and pretreatment are essential.

Climate change affects the quality of surface water, the primary source for bank filtration. Rising surface water temperatures reduce dissolved oxygen (DO) solubility, which plays a key role in the chemical and biological processes within the riverbed and aquifer zone. Lower DO can diminish the effectiveness of natural pollutant removal in the filtration process.

Extreme weather events such as floods and droughts expected to increase in frequency and intensity under climate change can cause significant shifts in surface water quality. Flooding events increase suspended solids, organic matter, and microbial pollutants entering rivers, while droughts concentrate dissolved contaminants due to reduced dilution. These disruptions may exceed the natural attenuation capacity of the bank filtration system.

Changes in nutrient loads, particularly nitrogen and phosphorus, are also expected. Higher temperatures accelerate organic matter mineralization and nutrient release, while more intense rainfall promotes erosion and runoff of nutrients into rivers. Elevated nutrient concentrations encourage algal and cyanobacterial blooms, which can impair water taste and odor and even introduce harmful cyanotoxins, making post-filtration treatment more challenging.

Micropollutants such as pesticides from agriculture may become more mobile and persistent

due to altered precipitation and temperature patterns, increasing the risk of contamination in bank filtration systems. The transport and degradation of these compounds are highly climate-sensitive, requiring enhanced monitoring.

Groundwater the second key component of the bank filtration process is also vulnerable. Changes in precipitation and evapotranspiration affect aquifer recharge near riverbanks. Lower groundwater levels can reduce filtration efficiency and elevate saltwater intrusion risks in coastal settings. Groundwater temperature may also rise due to warming air temperatures, altering redox conditions and microbial processes that govern contaminant breakdown.

Finally, the interaction between surface water and groundwater is critical for bank filtration effectiveness. Climate change can modify the hydraulic gradient and exchange dynamics between rivers and adjacent aquifers, impacting both the volume and quality of water captured by infiltration wells.

In summary, climate change affects surface water quality, groundwater recharge, and the complex interactions between them all of which influence the performance and reliability of bank filtration systems. Continuous source water monitoring and adaptive management strategies, including pre-treatment upgrades and hydraulic control, are essential to ensure safe drinking water under changing climate conditions.

2.3.5 Karstic water source

Karstic water sources, formed in fractured carbonate rock, represent one of the most complex and sensitive hydrogeological systems on Earth. These regions are characterized by high permeability, rapid groundwater flow through fissures and conduits, and limited natural filtration. Karst aquifers are particularly vulnerable to climate change due to their direct dependence on short-term recharge events (typically months to a few years), which strongly influence both water quantity and quality.

Globally, carbonate rocks are present across all continents. Asia holds the largest surface area of karst (18.6%), while Europe especially the Mediterranean region has the highest karst proportion (21.8%). Countries like China and Russia contain the largest absolute areas of karst landscapes, supporting large populations and complex water demand patterns (Gold-scheider et al., 2020)

In karst aquifers, rapid and shallow groundwater flow makes them highly responsive to fluctuations in precipitation and recharge. These systems are primarily calcium-bicarbonate dominated and exhibit low mineralization, but are extremely sensitive to external stressors. Climate change-induced shifts in snow cover, rainfall, and temperature influence the recharge-discharge dynamics of karst springs (Maurizio Barbieri et al., 2021)

A case study in the fractured carbonate aquifers of the Central Apennines in Italy specifically the Sibillini Mountains provides insight into these dynamics. Key springs such as Capodacqua (S1), Pescara (S2), and Foce (S3) exhibit different geochemical behaviors depending on their position within the aquifer. S1 and S2 emerge from the epiphreatic zone and are characterized by rapid flow through karst conduits, while S3, which emerges from the deeper basal aquifer, shows slight sulfate enrichment.

Climate change can modify hydrogeological conditions and water chemistry in karst systems. For example, the ratio of strontium to barium (Sr/Ba) in spring water has been observed to rise during recharge phases, indicating hydrodynamic changes in aquifer pressure regimes. Declining recharge may increase the contribution of deeper flow paths, elevating ion concentrations and overall water

hardness. (Maurizio Barbieri et al., 2021)

Moreover, intense storm events expected to increase under climate change can disrupt the geochemical stability of karst springs and shift their composition toward that of lowland riverine systems, particularly through rapid flushing of pollutants and mobilization of sediments.

Aside from climate stressors, increasing population pressure adds another layer of complexity to karst water management. Over-extraction and land use changes further impact the quantity and quality of groundwater in these fragile systems.

In summary, karstic water sources are uniquely sensitive to both natural and anthropogenic pressures. Climate change affects their recharge patterns, geochemistry, and spring discharge behavior. Continuous water quality monitoring and the protection of karst aquifers especially those in protected mountain areas and national parks are critical to ensuring sustainable groundwater use in a warming climate.

2.4 Climate change effects on Drinking water supply system

2.4.1 Impacts of Climate Change on Water Treatment Systems

This chapter describes conventional treatment processes (chemical, physicochemical, and biological) and their efficiency in responding to variations in water quality characteristics. It examines the production of potable water from conventional water sources and addresses climate-induced impacts on treatment systems in figure 2.1b

Conventional Treatment Processes

2.4.1.1 Chemical Processes

Ensuring safe drinking water has always relied on effective treatment processes to control microbial and chemical contamination. However, climate change has increasingly worsened water quality challenges, pushing the need for improvements in treatment methods. Higher temperatures, changing rainfall patterns, and more frequent extreme weather events contribute to issues like increased microbial contamination, algal blooms, and greater water turbidity.

Disinfection remains a crucial step in water treatment to meet microbiological safety standards and ensure safe consumption. Chemical oxidants are essential in this process-not only for final disinfection but also in earlier treatment stages like pre-oxidation. These oxidants serve multiple purposes: aiding coagulation, disinfecting, oxidizing and removing metals like iron and manganese, and eliminating odors, tastes, hydrogen sulfide (H₂S), and color.

In typical surface water treatment systems that use clarification and flocculation (Figure 2.3), oxidants/disinfectants are added at three key stages. During the pre-oxidation phase (or rapid mixing), they help with disinfection, improve coagulation, and address various chemical contaminants.

An intermediate oxidation/disinfection stage can also be performed before filtration to prevent bacterial growth.

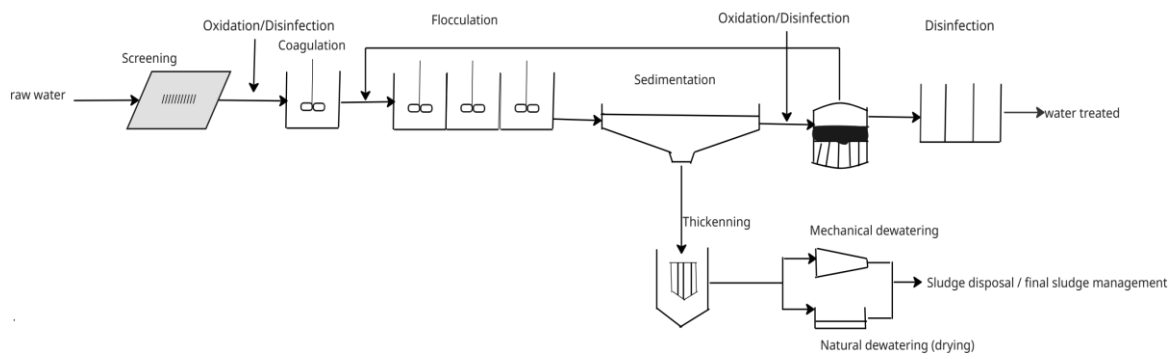


Figure 2. 3 Clarification and flocculation: oxidants/disinfectants are added at three key stages (Paolo Roccaro, University of Catania book *Impatti dei Cambiamenti climatici sull'approvvigionamento di acqua potabile sicura*, 2023)

2.4.1.2 Types and Characteristics of Chemical Disinfectants

Chlorine is the most widely used disinfectant in drinking water treatment because it effectively kills harmful microorganisms like bacteria and viruses. Its strong oxidizing properties allow it to destroy microbial cells, making it a reliable, cost effective, and easy-to-use solution. Additionally, chlorine can leave a residual amount in the water distribution system, helping to prevent recontamination.

However, chlorine also has some drawbacks. It reacts with organic matter in water to form harmful disinfection by-products (DBPs), such as trihalomethanes (THMs), including chloroform, bromodichloromethane, chlorodibromomethane, and bromoform (Han et al., 2020). Chlorine can also cause unpleasant tastes and odors and may react with sediments in pipes, leading to corrosion and encouraging biofilm growth on pipe walls.

Chlorine is commonly used in three forms:

- Chlorine gas (Cl_2)
- Sodium hypochlorite (NaOCl)
- Calcium hypochlorite ($\text{Ca}(\text{OCl})_2$)

All these forms release hypochlorous acid (HOCl) when dissolved in water, which is the active disinfectant:

- $\text{Cl}_2 + \text{H}_2\text{O} \rightarrow \text{HOCl} + \text{H}^+ + \text{Cl}^-$
- $\text{NaOCl} + \text{H}_2\text{O} \rightarrow \text{HOCl} + \text{Na}^+ + \text{OH}^-$
- $\text{Ca}(\text{OCl})_2 + 2\text{H}_2\text{O} \rightarrow 2\text{HOCl} + \text{Ca}^{2+} + 2\text{OH}^-$

At a pH of 7.5, hypochlorous acid is most effective. However, chlorine can still react with natural organic matter (NOM) to form DBPs like THMs and haloacetic acids (HAAs), both of which are regulated by European Directive 2020/2184.

To maintain disinfectant levels over long distances, chloramines (NH_2Cl) are often used. They produce fewer THMs than chlorine but can create other by-products, such as nitrosamines (e.g., NDMA), which also need monitoring.

Another disinfectant, chlorine dioxide (ClO_2), is widely used in Italy, especially for pre-oxidation. It is produced on-site due to its instability through the reaction:

- $2\text{NaClO}_2 + \text{Cl}_2 \rightarrow 2\text{ClO}_2 + 2\text{NaCl}$

Advanced Oxidation and Disinfection in Water Treatment

Chlorine dioxide is commonly used in water treatment because it helps reduce the formation of harmful disinfection by-products (DBPs) such as trihalomethanes (THMs) and haloacetic acids (HAAs). However, it can also lead to the formation of other by-products that must be carefully monitored and controlled to ensure water safety.

Ozone (O_3) is another powerful disinfectant, widely used to remove contaminants and micropollutants from water. While effective, ozone can produce bromate (BrO_3^-), a harmful by-product that is strictly regulated due to its health risks. Additionally, ozone can break down organic materials into potentially toxic compounds, complicating the treatment process. Conversely, oxygen (O_2) is abundant in the environment but reacts too slowly to be effective in standard water treatment. However, when combined with chemical oxidants, oxygen can assist in reducing the formation of harmful DBPs.

Advanced Oxidation Processes (AOPs) and Other Disinfectants

Potassium permanganate ($KMnO_4$) is often used as a pre-oxidant to remove iron, manganese, odors, and taste from water. A key advantage of potassium permanganate is that it does not produce DBPs, making it a safer option for initial treatment stages. Hydrogen peroxide (H_2O_2) is another oxidant, primarily used for the removal of hydrogen sulfide (H_2S), though its broader application in water treatment is limited.

Advanced Oxidation Processes (AOPs) rely on highly reactive hydroxyl radicals ($\bullet OH$) to break down pollutants. These radicals are capable of degrading complex organic molecules, making AOPs highly effective in water purification. Common AOP methods include:

- Ozone (O_3) alone
- Ozone combined with Hydrogen Peroxide (O_3/H_2O_2)
- Ultraviolet (UV) light
- UV combined with Hydrogen Peroxide (UV/H_2O_2)
- Fenton reactions (a combination of iron and hydrogen peroxide)

Ozonation is particularly effective at destroying algae but can also release organic substances such as humus and biopolymers. These substances may lead to the formation of DBPs like THMs and HAAs. Pre-ozonation can help control THM levels by removing extracellular organic matter before it enters the main treatment processes. However, excessive ozonation can increase the formation of harmful by-products like N-nitrosamines (NAs). During the summer, when algae levels are high, more intracellular organic matter (IOM) is released, reducing the effectiveness of ozonation and increasing the potential for DBP formation.

While ozonation is effective at removing pharmaceuticals and personal care products, it can also make water more toxic if not properly managed. The success of AOPs is influenced by several water quality factors, including pH, chemical oxygen demand (COD), total organic carbon (TOC), iron (Fe), manganese (Mn), and light transmittance.

Challenges of Advanced Oxidation Processes

Despite their effectiveness, AOPs come with certain challenges. Natural organic matter (NOM) in the water can consume hydroxyl radicals, weakening the oxidation process and reducing overall efficiency. Additionally, AOPs can generate harmful by-products, which, in some cases, may be more toxic than the original pollutants they are designed to remove.

Peracetic acid (PAA) is another disinfectant that offers a safer alternative as it does not produce toxic DBPs, making it suitable for drinking water treatment. However, PAA poses handling risks due to its flammable and explosive nature at high temperatures, limiting its use primarily to wastewater treatment applications.

Oxidant Effectiveness in Water Treatment (from strongest to weakest):

Oxidant	Standard Potential (V)
Hydroxyl Radical	2.80
Ozone	2.07
Peracetic Acid	1.81
Hydrogen Peroxide	1.78
Potassium Permanganate	1.68
Chlorine Dioxide	1.57
Chlorine	1.36

Figure 2. 4 The hierarchy of oxidants commonly used in water treatment ((Paolo Roccaro, University of Catania inbook Impatti dei Cambiamenti climatici sull approvvigionamento di acqua potabile sicura, 2023)

2.4.1.3 Essential Factors in Disinfection and the Impact of Climate Change

The success of water disinfection relies on two main factors: the disinfectant concentration (C) and the contact time (t) between the disinfectant and pathogens. Together, these form the C·t value, a critical indicator of how much disinfectant is needed to effectively inactivate harmful microorganisms. Standard C·t values help determine the appropriate dosage for specific pathogens, ensuring water safety.

Disinfection efficiency is often explained through kinetic models like Chick's Law, which describes how microorganisms are eliminated over time:

$\ln\left(\frac{N}{N_0}\right) = -k \cdot t$ Here, N_0 is the initial number of microorganisms, N is the number remaining after time t , and k is the reaction rate constant. This model highlights how disinfection progresses over time.

Temperature plays a significant role in this process. Warmer conditions, driven by climate change, can:

- Speed up disinfectant breakdown, reducing its effectiveness.
- Increase natural organic matter (NOM) in water, which reacts with disinfectants.
- Lead to more brominated disinfection byproducts (DBPs) due to saltwater intrusion in coastal areas.

To account for more complex disinfection dynamics, Haas and Hom (1972) expanded Chick's model:

The reaction rate "k" (reaction constant) can be integrated into the formula:

$$\ln\left(\frac{N}{N_0}\right) = -kC^n t^m$$

(where "N₀" is the initial concentration of microorganisms).

where "k" is the die-off coefficient, n and m are experimentally determined factors that reflect how disinfectant concentration and contact time affect microbial inactivation.

Disinfectant decay over time is modeled by the first-order decay equation:

$\frac{dC}{dt} = -k_a C$ where "k_a" is the first-order decay coefficient. Disinfectant decay is temperature dependent.

Where is the decay rate constant. Higher temperatures increase this decay rate, weakening disinfection effectiveness.

Optimizing Disinfection Performance

To maximize disinfection efficiency:

- Proper mixing ensures even distribution of the disinfectant.
- Hydraulic reactors are designed to prevent water from bypassing the treatment system (avoiding short-circuiting).
- Monitoring residual disinfectant levels (like chlorine, ozone, or hydrogen peroxide) is essential but can be limited by the precision of available sensors.

Overall, understanding these factors is vital for maintaining effective disinfection, especially as climate change continues to challenge water treatment systems.

In water distribution networks, higher water temperatures accelerate disinfectant decay and the formation of disinfection byproducts (DBPs) (Roccaro (2008), n.d.). Extreme weather events may increase levels of organic micropollutants, metals, and NOM (natural organic matter), causing higher DBP formation. Saline intrusion may lead to a more brominated DBP profile with toxic effects (Chang, 2020). Additionally, wildfires impact NOM levels and DBP formation (Chen et al., 2016)

2.4.2 Physical Processes

2.4.2.1 Pretreatments

Common pretreatment methods in surface water treatment plants include the use of storage basins for water homogenization and screening systems. In storage and homogenization basins, such as sedimentation tanks, rising water temperatures can reduce dissolved oxygen levels and promote algal growth, especially when mixing is insufficient.

Higher water temperatures also speed up the biodegradation and photodegradation of organic substances, leading to increased concentrations of dissolved matter. Organic matter from algal decomposition usually contains higher protein (nitrogen) levels, making it harder to remove and potentially contributing to the formation of disinfection by-products (Krasner, S.W., 2009., n.d.).

Additionally, heavy rainfall often raises the levels of both dissolved and suspended organic matter, making downstream treatment more difficult. Prolonged water retention in storage basins can further intensify biodegradation and photodegradation processes, negatively impacting water quality.

2.4.2.2 Sedimentation

Rising temperatures have multiple impacts on the sedimentation process. Warmer water in sedimentation tanks reduces fluid viscosity, which promotes sedimentation, while also speeding up

floc formation and organic matter degradation. However, these changes can introduce challenges to effective sedimentation.

According to Stoke's law, sedimentation velocity (v_p) depends on fluid properties such as density

(ρ_w) and viscosity (μ_w), as well as particle characteristics like diameter (d_p) and density (ρ_p).

$$v_p = \frac{g \times (\rho_p - \rho_w) \times d_p^2}{18 \times \mu_w}$$

Lower viscosity due to higher temperatures improves particle settling, but smaller particle sizes can significantly slow sedimentation. For instance, at 20°C, a 0.5 mm particle settles at 0.244 cm/s, but reducing the particle size to 0.1 mm dramatically decreases the settling speed. This hampers solid-liquid separation, leading to poorer clarification and increased water turbidity.

Intense rainfall further complicates sedimentation by altering water quality from surface sources. Such events can cause turbidity levels to spike from a few NTUs to several hundred or even thousand, resulting in increased sludge production and higher treatment and disposal costs.

In systems without sedimentation stages, like direct filtration plants, the challenges are particularly acute. These plants rely on coagulants to remove dissolved and suspended organic matter and are typically used for water with low turbidity and organic content. However, sudden increases in dissolved organic matter (DOM) can overwhelm these systems, as noted by (DeMont et al, 2021). For instance, higher DOM levels have been linked to an 87% rise in daily backwashing cycles in some plants (Eikebrokk, et al 2004). This increases operational demands, shortens filtration cycles, and reduces the production of drinking water.

To address these issues, one strategy is to reduce the size of filtration materials and use deeper filter beds, which enhance particle retention by increasing surface contact within the filter. Alternatively, coarser filtration media allow organic matter to penetrate deeper into the filter bed, improving retention and reducing pressure loss. However, coarser media may allow finer particles to escape, potentially raising turbidity levels (DeMont et al, 2021). Balancing filtration efficiency and water quality is therefore critical in adapting to these challenges.

2.4.2.3 Granular Filtration

Granular filtration is used to remove suspended solids that escape sedimentation, flocs that do not settle during clarification and flocculation, insoluble compounds formed during oxidation reactions, microorganisms, and serve as a barrier to protect subsequent treatment stages (including ozonation and granular activated carbon).

Plants using direct filtration do not include a clarification process capable of reducing the incoming organic load. However, they require the addition of an appropriate coagulant to remove dissolved organic matter (DOM). These systems are typically used for surface waters with low turbidity and low organic content. It is evident, therefore, that sudden increases in dissolved organic matter can have a significant impact on such systems (DeMont et al, 2021). The filtering media intercepts and retains suspended and dissolved materials, and as a result, the system must undergo backwashing more frequently. In some plants, increased DOM has led to an 87% rise in the number of daily backwashes (Eikebrokk, et al 2004)

At the same time, there is a shorter duration of filtration cycles and reduced production of potable water, as an increasing fraction of water is allocated to backwashing phases (DeMont et al, 2021). One possible strategy to extend the operation duration in a direct filtration plant is to increase the effective size of the filtering material and construct deeper filter beds. This results in a greater total surface area available to promote contact and particle interception within the filter bed, thereby increasing the overall particle removal capacity.

A coarser filtering medium allows incoming organic matter to penetrate deeper into the filter bed, leading to a greater mass of retained solids throughout the bed and a decrease in head loss. However, because the medium is coarser, the removal efficiency for finer particles may be reduced, potentially leading to an increase in turbidity (DeMont et al, 2021)

2.4.3 Physical-chemical Processes

2.4.3.1 Coagulation-Flocculation

Temperature variations significantly influence the behavior of organic matter, the kinetics of chemical reactions, and the physical characteristics of water, particularly its viscosity and the development of bacterial communities from the source. In water treatment processes, rising temperatures affect coagulation, flocculation, and sedimentation. Specifically, higher temperatures accelerate coagulation by increasing the reaction rates, especially the hydrolysis of coagulants like aluminum or iron salts. According to the Arrhenius law, a 10°C increase roughly doubles the reaction rate, although a 2°C rise results in only a modest increase (Ma et al., 2022)

While this acceleration benefits coagulation, it is offset by the deterioration of water quality due to higher temperatures, which increase dissolved organic matter (DOM) levels, including dissolved organic carbon (DOC), nitrogen (DON), and phosphorus (DOP). Elevated DOM can degrade the organoleptic qualities of water such as color, odor, taste and promote bacterial growth. Moreover, small DOM particles may carry heavy metals and surface micro-pollutants (Eikebrokk, et al 2004).

Effective removal of DOM requires optimized coagulation conditions, including coagulant type and dose, pH levels, and rapid mixing times. Considering both the positive and negative effects, the overall coagulant demand may not significantly change with temperature increases. However, in plants with advanced pre-treatments, like riverbank filtration, higher temperatures might reduce coagulant requirements

Regarding flocculation, higher temperatures lead to larger floc formation, but these flocs disaggregate more easily and struggle to reform compared to those formed at lower temperatures. Literature suggests a temperature threshold of 15°C for this phenomenon. Flocs produced with aluminum-based coagulants show greater size and strength variability with temperature changes than those formed with iron salts. In sedimentation processes, floc behavior is influenced by their size, density, and agglomeration tendencies, along with the water's viscosity. While higher temperatures can hinder floc sedimentation, this effect is partially mitigated by the reduction in water viscosity pH also plays a crucial role in coagulation, with lower (acidic) pH levels favoring the process (Delpla et al., 2009a) (Ritson et al., 2014a). The pH of surface water sources may fluctuate soon due to increased acidic DOM flows, temperature-induced changes in gas partitioning at the water-air interface, and enhanced algal activity, which can raise pH levels during the day (Ritson et al., 2014).

Furthermore, the increase in DOM is closely linked to precipitation events near surface water bodies used for drinking water. Intense rainfall promotes soil leaching, transporting organic matter into surface waters, increasing natural organic matter (NOM) levels, and degrading water quality. This results in higher turbidity, negatively impacting water treatment by necessitating increased coagulant doses to maintain turbidity control, raising operational costs (Delpla et al., 2009a)(Eikebrokk et al., 2004), and increasing sludge production, which further elevates treatment and disposal expenses (DeMont et al, 2021) Lastly, precipitation patterns influence the composition of dissolved organic matter. During droughts, DOM contains more proteins, carbohydrates, and low molecular weight amino acids, making it hydrophilic and harder to remove via coagulation (Anderson et al., 2023; (Ritson et al., 2014). Conversely, in non-drought periods, DOM is characterized by high molecular weight humic and fulvic acids, making it hydrophobic and easier to remove. However, hydrophobic DOM requires careful monitoring as it contributes to the formation of disinfection by-products (DeMont et al, 2021)

2.4.3.3 Adsorption on Granular Activated Carbon (GAC)

GAC is used to remove organic pollutants, including perfluoroalkyl and polyfluoroalkyl substances (PFASs). It is effective in removing long-chain PFASs such as PFOS and PFNA but less effective for short-chain PFASs like PFBA and PFBS. GAC's removal efficiency decreases as the carbon load increases and as the carbon chain length of PFASs shortens. Some studies suggest that linear isomers of PFASs are adsorbed more effectively on GAC than branched isomers (Kempisty et al., 2019a).

Temperature significantly affects GAC filtration efficiency, especially by affecting the interactions between water, contaminants, and the carbonaceous medium. This effect is particularly evident in relation to EBCT. EBCT (Empty Bed Contact Time) is an important parameter in granular activated carbon (GAC) filtration, defined as the ratio of the volume of the filter bed to the inlet flow rate. In other words, it is the length of time that water is in contact with the filter media under conditions where the filter bed contains no filter media. EBCT is different from effective contact time. Effective contact time is the product of EBCT and the porosity of the filter media. EBCT is an important design and operational factor in GAC filters. EBCT directly affects the efficiency of adsorption and removal of pollutants in water, the minimum EBCT is required to ensure effective adsorption (Fundneider et al., 2021)

In addition, EBCT affects the ability to remove DOC. Increasing EBCT can help remove DOC better, but after a certain value (about 20-30 minutes), further increase in EBCT does not bring significant effect. EBCT also affects the ability to remove UV absorbers. 2-methylisoborneol (MIB) and geosmin: EBCT has a significant effect on the removal of MIB and geosmin, odorous substances in water. EBCT above 15 minutes can be considered a solid threshold for the removal of these two substances (Fundneider et al., 2021)

Temperature can affect the efficiency of EBCT. At high temperatures, the efficiency of DOC removal can increase, especially at low EBCT. Conversely, at lower temperatures, increasing EBCT can help offset the negative effects of temperature. Adjusting EBCT: EBCT can be adjusted by changing the filtration velocity and the height of the filter bed

Empty Bed Contact Time (EBCT) Formula

The formula for calculating EBCT (Empty Bed Contact Time) is determined by the ratio between the volume of the filter media and the flow rate of the input stream:

$$\text{EBCT} = \text{Volume of Filter Media} / \text{Input Flow Rate}$$

Where:

- The volume of filter media refers to the volume of the media in the filter column (usually measured in units of volume such as liters or cubic meters).
- The input flow rate refers to the speed of water entering the filter column (typically measured in volume per time units, such as liters/minute or cubic meters/hour).

This formula can also be rewritten as follows:

$$\begin{aligned} \text{EBCT [minutes]} &= \text{VB [ml]} / \text{Qo [ml/min]}; \\ \text{EBCT} &= \text{Flow Rate (L/min)} / \text{Volume of Filter Bed (L)} \end{aligned}$$

Where:

- VB is the bed volume of the filter media, measured in ml.
- Qo is the input flow rate, measured in ml/min.

The EBCT was calculated using equation 3

$$\begin{aligned} EBC \text{ [min]} &= VB \text{ [ml]} \\ &lo \text{ [ml/min]} \text{ (3)} \end{aligned}$$

where *VB* is the bed volume in ml and *lo* is the flow coming out of the column in ml/min

Powdered Activated Carbon (PAC):

PAC can also be used to remove PFASs (Rahman et al., 2014)

Ion Exchange Resins:

These resins selectively remove PFASs, including short-chain compounds, from water. They often achieve rapid removal rates and can be regenerated for reuse (Riegel et al., 2023)).

Membrane Filtration Processes

High-Pressure Membranes (NF/RO):

Membrane processes such as nanofiltration (NF) and reverse osmosis (RO) are highly effective in removing PFASs, particularly long-chain compounds like perfluoropentanoic acid (PFPeA) and perfluoropentane sulfonate (PFPS).

Ultrafiltration (UF):

Ultrafiltration membranes are also used in water treatment plants to remove contaminants (Eschauzier et al., 2012)

2.4.4 Biological Processes

Biological treatment is a process used in drinking water treatment plants that utilizes indigenous bacteria to remove contaminants. This process occurs in a reactor (bioreactor) containing a filter medium and bacteria. As the water passes through the filter medium, bacteria, in combination with electron donors and nutrients, react with contaminants to produce biomass and other non-toxic by-products (US EPA (2023)., n.d.)

Biological water treatment relies on the growth of bacterial communities capable of mediating redox reactions that target specific contaminants. Heterotrophic biological processes use an organic

electron donor (e.g., acetic acid), while autotrophic biological processes use an inorganic electron donor (e.g., hydrogen) (Brown et al., 2013)

Biological drinking water treatment is effective for removing contaminants such as nitrates and perchlorates. After an initial adaptation period, bacterial populations in the water adjust to consuming target contaminants as long as favorable conditions, such as water temperature and concentrations of electron donors and nutrients, are maintained (US EPA (2023)., n.d.). Biological treatment can be used to remove natural organic matter (NOM), color, chloroform, and perchlorate, nitrate, nitrite, bromate, iron, manganese, and other compounds (Bertrand W. Dussert, 2000). However, biological processes in drinking water treatment that use indigenous and non-pathogenic bacteria are always followed by downstream processes, such as final disinfection(Q. Li et al., 2017)

Biological activated carbon (BAC) is one of the biological processes where the water purification process combines physical adsorption on granular activated carbon (GAC) with the biodegradation of organic substances through biofilm formation. BAC technology is eco-friendly and cost-effective because biodegradation helps prevent the saturation and replacement of GAC (Jin et al., 2013).

Biologically activated carbon (BAC) uses activated carbon as a support for microorganisms. Microorganisms accumulate and adhere to the surface of the activated carbon, reproduce, and form a bio-community that simultaneously performs adsorption and biodegradation functions.

Figure 2.5 illustrates temporal changes in bacterial abundance levels at the phylum and class levels in BAC. Proteobacteria are the most abundant phylum, followed by Bacteroidetes, Firmicutes, Actinobacteria, and Planctomycetes, in descending order. The relative abundances of all the listed phyla, except Bacteroidetes, differed depending on the sampling period.

The pilot-scale BAC filtration system could effectively reduce DOC (dissolved organic carbon) and AOC (assimilable organic carbon). Biomass' concentration decreased slightly with contact time but showed variability over the service period. Clone library analysis illustrated changes in microbial community structures within BAC filters as a function of contact time and service duration. Alpha proteobacteria were the most abundant bacterial group in BAC filters, contributing to DOC and AOC removal in the entire biofiltration system.

Further efforts are necessary to clarify the evolution of microbial communities in biofilters used for drinking water (T. G. Kim et al., 2014).

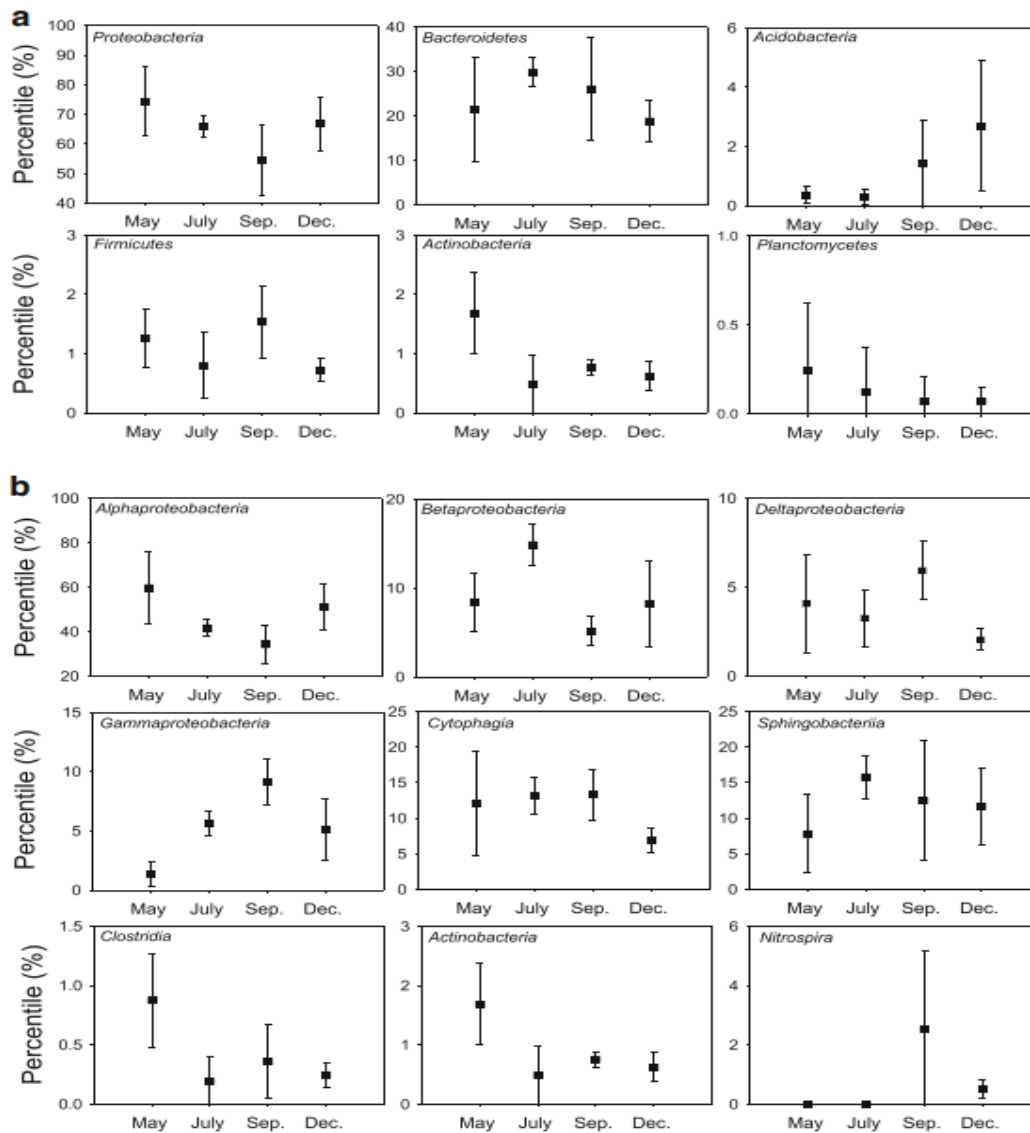


Figure 2. 5 Variation over time in the predominant bacterial taxa in BAC, showing the proportional abundances of major bacterial taxa at the phylum (a) and class (b) levels(T. G. Kim et al., 2014).

Temperature Effects on BAC

Biologically activated carbon (BAC) depends on temperature, and its efficiency is significantly reduced in cold water (below 10°C). Microbial activity in BAC does not adapt well to low water temperatures, which can affect ammonia removal capacity and nitrification/denitrification rates (Andersson et al., 2001a). Moreover, BAC requires an acclimatization period of two weeks to three months for bacterial activity to reach peak performance (Korotta-Gamage & Sathasivan, 2017). While BAC systems are highly effective at improving water quality, pathogens can persist in treated water, particularly after extreme weather events.

Rainfall and extreme weather can increase bacteria and opportunistic pathogen levels in drinking water processes, significantly impacting riverine and potable water treatment processes ($p < 0.05$). Specifically, cyanobacteria abundance increases after severe typhoons ($p < 0.05$). BAC filters have been identified as potential reservoirs for pathogenic agents and were responsible for $52 \pm 6\%$

of bacteria released downstream, according to Bayesian analysis(Wei Tang 1 et al., n.d.) These results highlight the challenges of maintaining water quality during extreme meteorological conditions.

Advantages and Challenges of BAC

BAC systems offer several advantages for water treatment, including the removal of hydrophilic fractions and many toxic and endocrine-disrupting compounds that traditional coagulation processes cannot eliminate. BAC systems reduce bacterial regrowth and the formation of disinfection by-products while efficiently removing organic carbon and turbidity from high-organic-content effluents (Korotta-Gamage & Sathasivan, 2017). However, BAC can have limitations in water treatment. It may release microbial products, such as soluble microbial products (SMPs) and extracellular polymeric substances, especially in older BAC systems, potentially leading to biological safety concerns (Cuthbertson et al., 2020). Difficult-to-biodegrade materials may not be effectively removed with BAC alone, reducing its overall efficiency ((Bertrand W. Dussert, 2000)

BAC filters can provide a suitable environment for microorganisms and aquatic organisms, potentially creating a biological chain involving microorganisms, protozoa, and macroinvertebrates. Particles that host bacteria, particularly opportunistic pathogens such as *Legionella* and *Chromobacterium*, may penetrate the BAC filter bed and reduce treatment efficiency, influencing drinking water quality (K. Yang et al., 2019)

This can be a disadvantage when rapid treatment is required. However, once bioactivity reaches maximum efficiency, BAC offers significant benefits by removing hydrophilic fractions and many toxic and endocrine-disrupting compounds that cannot be eliminated by traditional coagulation processes. BAC can also help mitigate bacterial regrowth and disinfection by-product formation.

2.5 Effects of Climate Change on Drinking Water Distribution Systems

This chapter analyzes the possible effects of climate change on drinking water distribution systems. The distribution network represents the final component of a potable water supply system, located immediately upstream of the final point of use. Therefore, it is crucial to assess the risks of water quality alterations that may arise due to climate variations. Among the most relevant factors are:

- Temperature variation.
- Biofilm formation.
- Formation of disinfection by-products.
- Presence of possible micropollutants in water.

2.5.1 Temperature Variations in the Network

Temperature is an important factor affecting water quality as it influences physical, chemical, and biological processes, including the dissolution of chemical substances, chlorine decay, and microbial competition. Temperature impacts the kinetics of many chemical reactions and the survival and growth of microorganisms, including their dynamics, favoring the role of biofilms as reservoirs for opportunistic pathogens.

The temperature of potable water can significantly increase or decrease during its distribution from the source to the consumer. This variation is strongly influenced by meteorological conditions, the depth of installation of transport and distribution pipes, soil type, groundwater levels, the presence

of anthropogenic heat sources, and hydraulic residence times. Water temperatures at the source have a limited impact on water temperature at the tap.

Some studies have shown that the temperature at the customer's tap is primarily determined by the external air temperature along the distribution network route, regardless of the type of water source and distribution network characteristics.

The temperature gradient between the soil surrounding the pipes and the water inside the pipes determines the temperature variation of water in the network. The temperature of shallow underground soil, where potable water pipes are often installed, shows seasonal variations depending on local climatic conditions (Agudelo-Vera et al., 2020). For example, a case study in the Netherlands, where pipes are shallowly buried, demonstrated that during a hot summer with a heatwave, soil temperatures at 1.0 m depth reached as high as 27°C. This posed a significant problem, as the local regulation imposes a 25°C maximum water temperature at the point of use. In contrast, in many Nordic countries, such as Finland, a minimum installation depth for potable water pipes is maintained to avoid freezing of water in pipes or subsequent ruptures.

Soil temperature is influenced by atmospheric conditions (air temperature, solar radiation), the environment (rural or urban), ground cover (artificial or natural), soil type and conditions (sand or clay and moisture content). The temperature of potable water is strongly influenced by ambient air temperature. In Figure 2.6, the correlation between water temperature and air temperature is almost linear (Lai & Dzombak, 2021). This strong correlation provides a basis for evaluating the effects of climate change on water temperature and its quality parameters in the distribution network.

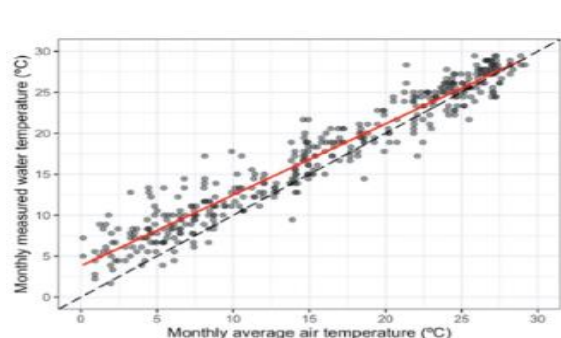


Figure 2. 6 Correlation between water temperature in a distribution network and air temperature (Lai & Dzombak, 2021)

One study identified and evaluated a water temperature estimation model and assessed water quality parameters (Blokke & Pieterse-Quirijns, 2013).

Preliminary estimates were developed for variations in water temperature and two parameters related to temperature (chlorine decay rate and bacterial activity rate) using observed data and projections of local air temperature (Lai & Dzombak, 2021)). Variations in water temperature in the distribution network generally correspond to variations in air temperature on an annual average basis, suggesting possible intense future changes with a greater increase in water temperature compared to air temperature.

Water temperature estimates indicate an increase of approximately 1.2°C from 1951–1968 to 2001–2018 and of 3.1°C from 2001–2018 to 2051–2068 in terms of annual averages. Relating to the periods indicated, as shown in Figure 2.7, there is a significant increase in bacterial activity in water during the warmer months (June–September), which corresponds to a risk of biofilm regrowth within the network, leading to a degradation in water quality.

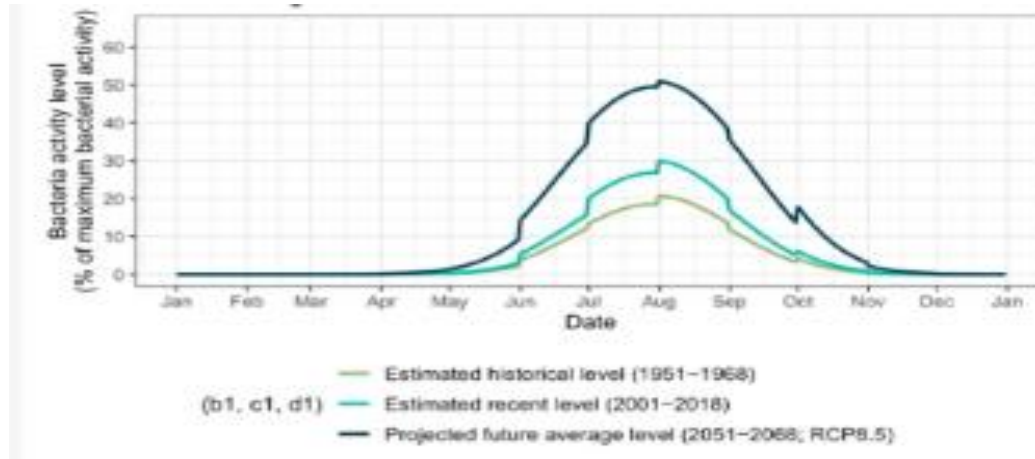


Figure 2. 7 Correlation between bacterial activity and seasons in three different periods (Lai & Dzombak, 2021)

The main concern regarding the impact of rising water temperatures is the potential proliferation of pathogenic agents, such as *Legionella* spp. Water is the main natural reservoir for *Legionella*, and temperature control is an effective measure to prevent its proliferation. LISS asserts that water temperature in cold distribution systems must not exceed 20°C unless specific risk control measures are implemented (ISTISAN Reports 22/32).

Water temperature changes can also be influenced by other factors.

The increasing use of technologies for water savings, such as rainwater harvesting and the recycling of greywater, can influence the temperature of water at various points of the distribution network. Greywater presents a greater risk than potable water as it originates from sources heated inside homes, with a significantly higher temperature compared to potable water (Nel & Jacobs, 2019). Moreover, greater use of greywater can reduce the demand for potable water, thereby increasing the residence times of water in distribution systems, which may amplify the heating effects during summer months due to the surrounding air and soil temperatures (Agudelo-Vera et al., 2020).

Temperature is also a key factor in determining chlorine decay in potable water distribution systems. The rate of chlorine decay in mass is influenced by various water quality parameters, including temperature, the initial chlorine concentration, and total organic carbon (TOC). An increase in water temperature can accelerate both chlorine decay and bacterial activity, leading to a potential increase in the required chlorine dosage. If the chlorine dosage remains unchanged, bacterial activity may further promote decay rates under higher temperatures. Additionally, an increase in water age can amplify the effects of higher temperatures (García-Ávila et al., 2020).

Water temperature can also influence the rate of various natural and chemical processes (such as ammonification, nitrification, and reactions with metals like Fe^{2+} and Mn^{2+}), as well as the

formation of disinfection by-products (DBPs) like trihalomethanes (THMs) and haloacetic acids (HAAs).

Temperature increases in distribution systems can also impact parameters such as ozone solubility or corrosion. For example, a rise in water temperature may reduce ozone solubility, consequently increasing the required ozone dosage (Stang et al., 2018). The corrosion of pipes is another consequence of temperature changes. The relationship between water temperature and corrosion rates depends on other factors, although studies suggest that rising water temperatures can lead to discoloration and reduced aesthetic quality. (Novakova & Rucka, 2019)

In addition to air temperature, research on the impact of climate change on pipe failures in water distribution systems (DWDS) has been conducted using data from the Dutch national database, which recorded 10,325 pipe failures between 2009 and 2012. Weather data from the Royal Netherlands Meteorological Institute (KNMI) was also utilized, including current weather parameters and future climate scenarios for 2050 and 2100. Statistical analysis revealed that temperature is the primary factor influencing the frequency of pipe failures. The study found that asbestos cement (AC) pipes are more prone to failure at high temperatures, while PVC pipes and gray cast iron (GCI) pipes are more susceptible at low temperatures. Climate change is projected to increase the frequency of failures in AC pipes due to higher temperatures but may reduce the frequency of failures in PVC and GCI pipes due to a decrease in extreme low temperatures.

However, the study also emphasized that in the short term, pipe lifespan and replacement strategies play a more critical role than the impact of climate change. Replacing AC pipes with PVC pipes is considered an optimal solution for building a more sustainable water distribution system and mitigating the effects of climate change. By combining predictive modeling based on temperature distribution and failure frequency with replacement strategies based on pipe lifespan, the study provides a scientific foundation for managing and improving water distribution systems in the face of increasingly complex climate change challenges (Fant et al., 2017)

2.5.2 Biofilm Development

Biofilm represents a significant problem for the potable water industry, as it is a potential source of bacterial colonization and, in many cases, causes alterations in taste, odor, and promotes corrosion.

Biofilm formation (or biocorrosion) is a significant economic problem for aqueduct networks. In the initial formation phase, the biofilm adheres to the surface of pipe materials and forms a non-permanent bond. Over time, an irreversible bond develops, leading to the growth of microcolonies of organisms. Ultimately, the structural formation of the biofilm evolves, resulting in a complex ecosystem composed of an extracellular polymeric substance (EPS) matrix. This matrix ensures the biofilm's structural integrity and cohesion among the cells within it. Biofilm can host bacteria, protozoa, fungi, viruses, and other microorganisms.

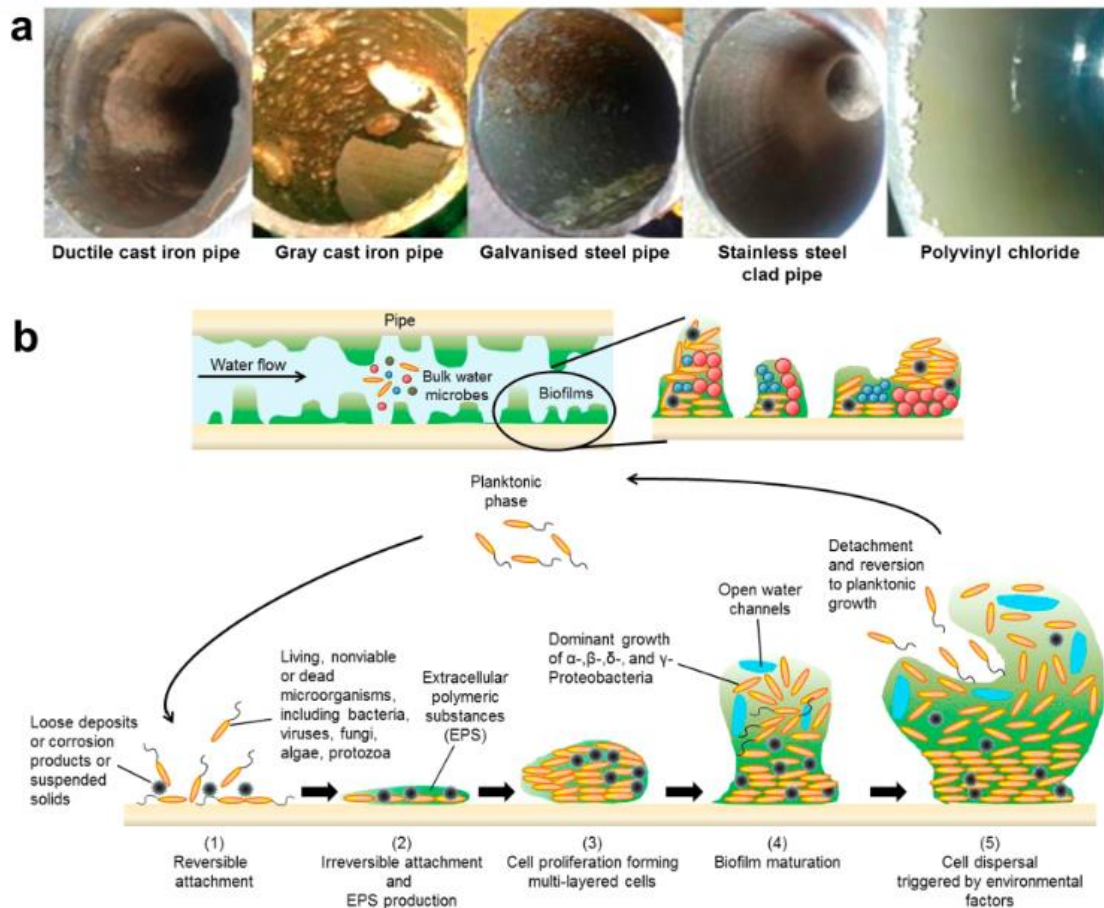


Figure 2. 8 (a) Biofilm growth on different pipe materials (b) Biofilm life cycle in DWDS(Guo et al., 2024)

Temperature is a critical factor influencing the formation and development of biofilm in drinking water distribution systems (DWDS). Research has shown that temperature variations can affect multiple aspects, including the initial adhesion of bacteria to surfaces, the growth rate of biofilm, and the species composition within biofilm communities. At higher temperatures, the hydrophobicity of bacterial cell surfaces increases, facilitating adhesion to hydrophobic surfaces, whereas at lower temperatures, bacterial cell surfaces tend to become more hydrophilic. For example, *L. monocytogenes* produces extracellular polymeric substances (EPS) to form biofilm at 21°C but does not produce EPS at 10°C or 35°C, indicating that non-optimal temperatures can inhibit biofilm formation (S. Liu et al., 2016)

Temperature also affects the growth rate of biofilm, with extended lag phases and reduced growth rates at lower temperatures. For instance, *L. monocytogenes* forms three-dimensional biofilm structures at 37°C and 20°C but only forms a monolayer at 8°C. Different bacteria respond differently to temperature; ammonia-oxidizing bacteria (AOB) form less biofilm at 12°C compared to 22°C, whereas *Vibrio cholerae* develops better biofilm at lower temperatures (15–25°C) due to increased intracellular c-di-GMP levels.

Furthermore, temperature alters the composition and structure of biofilm. Higher temperatures can promote the growth of cyanobacteria, increasing their competitiveness in freshwater biofilm. At the same time, changes in cell membrane lipids under varying temperature conditions affect bacterial

hydrophobicity and adhesion capacity. In the biofilm ecosystem, warmer temperatures can increase the prevalence of cyanobacteria and nematodes while potentially reducing the abundance of crustaceans and insects.

Temperature also interacts with other factors, such as disinfection demand and biodegradable organic matter (BOM). High temperatures accelerate the degradation of disinfectants, requiring higher doses to control biofilm. When degradable BOM is present, temperature becomes more critical under low shear force conditions, while in BOM-limited environments, shear force plays a dominant role. The combination of temperature, nutrients, and other environmental factors shapes the biodiversity and ecological functions of biofilm (Ndiongue et al., 2005)

It has been demonstrated that the presence of suspended microbes and biofilms degrades the quality of distributed water. Variations in turbidity, total organic carbon (TOC) concentrations, and nutrient concentrations (nitrogen and phosphorus) can lead to network changes with significant microbial growth consequences. High bacterial activity and biofilm accumulation on pipes can shape microbial communities and cause serious water quality issues, including the persistence of opportunistic pathogens, accelerated corrosion of pipes, and changes in taste and odor ((S. Liu et al., 2016) (Chowdhury, 2024). Biofilm formation, because of water quality changes, is further influenced by inorganic nutrients like phosphorus and nitrogen, in addition to the high content of organic matter (Kolb et al., 2017)

The presence of biofilms, along with certain pathogenic organisms (e.g., *Aeromonas* spp., *Mycobacterium* spp., and *Legionella* spp.), is common in disinfected water distribution systems (LeChevallier et al., 2024) Among the species found in these systems are protozoa like *Giardia* and *Cryptosporidium* in the form of oocysts. These oocysts are extremely resistant to disinfectants like chlorine. *Giardia* oocysts are more resistant than enteric bacteria to disinfectants like chlorine, but they are less resistant than *Cryptosporidium* oocysts. To achieve 90% inactivation with a free chlorine residual of 1 mg/L, a contact time of approximately 25–30 minutes is required (WHO, 2022).

The primary factors influencing biofilm formation and composition variability include temperature, though not all bacterial species are equally affected. For example, bacterial taxa such as *Burkholderiaceae*, *Methylobacterium*, or *Methylobacterium* decrease in biofilm formation at temperatures above 24°C. In contrast, *Pseudomonas* populations increase in biofilms at around 24°C (Calero Preciado et al., 2022) . *Pseudomonas* bacteria are among the primary contributors to the early stages of biofilm development, as they secrete significant amounts of EPS that promote biofilm growth (L. Yang et al., 2011)

Water temperature, pH, and heavy metal content further contribute to biofilm growth.

The development of biofilm, particularly at temperatures between 25°C and 42°C and pH levels between 6 and 8, represents optimal conditions for the growth and persistence of *Legionella pneumophila*. Biofilm therefore becomes a critical issue for drinking water systems but can be controlled in various ways. For many years, the application of chlorine has been the main method to limit its formation, with the chlorine application dosage proving effective in acting on biofilm formation during all phases of its development.

Other methods for biofilm control include strategies to reduce the levels of assimilable organic carbon (AOC) and the concentration of microbes suspended in drinking water before entering the distribution system. Techniques such as biofiltration or membrane filtration, oxidizing treatments

(ozonation), and UV disinfection are additional technologies that can be used to reduce microorganisms in suspension before water enters the distribution system and to minimize the potential for biofilm growth. These treatments reduce chlorine demand and pipe corrosion in distribution systems, which translates into limiting biofilm growth. Corroded pipe surfaces are more conducive to microbial colonization than smooth pipe surfaces (Ibekwe & Murinda, 2019)

Recently researchers found climate change leads to an increase in water temperature, affecting the effectiveness of biofilm control methods using shock chlorination combined with flushing (Calero Preciado et al., 2022). Recent research utilizing pilot-scale systems has shown that increasing water temperature from 16°C to 24°C enhances water discoloration potential and alters biofilm community structure. Flushing alone or in combination with high-concentration chlorine reduces discoloration potential and lowers bacterial density within the biofilm (Calero Preciado et al., 2022). However, shock chlorination does not appear to provide significant benefits in controlling biofilm (Calero Preciado et al., 2022).

2.5.3 Disinfectant Consumption and DBP Formation

The quality of drinking water depends not only on the source but also on disinfection treatment and the distribution system. To ensure good standards of water quality at the point of use, many countries maintain residual disinfectants in treated water during distribution to prevent contamination and microbial growth. However, the negative aspects of disinfectants include the formation of disinfection by-products (DBPs) and changes in taste and odor. Furthermore, the reaction of disinfectants with certain organic substances produces biodegradable compounds that may favor microbial growth in biofilm parts of the distribution network where residual disinfectants are less present.

Several countries, including Germany, Switzerland, and Austria, avoid maintaining disinfectant residuals in their respective networks. Instead, they rely on basin protection measures and appropriate treatment choices, including design, operation, and maintenance practices in distribution systems (Agudelo-Vera et al., 2020). The types of disinfection, pH, water temperature, and the nature of organic matter have a significant influence on DBP formation.

Regarding disinfection, disinfectants like chlorine have the primary objective of deactivating microorganisms to prevent water contamination. However, chlorine reacts with natural organic matter (NOM) present in raw water, forming disinfection by-products (DBPs) that can pose potential health risks. The concentration of DBPs is directly proportional to the concentration of NOM, which is higher in surface waters and lower in groundwater, and to the concentration of free residual chlorine. It also depends on the conditions of the distribution network, such as the presence of biofilms, water age, and potential malfunctions (IWA, 2022).

The use of chlorine for disinfection generates dangerous by-products like trihalomethanes (THMs) and haloacetic acids (HAAs). To avoid their formation, chlorine dioxide is often used as a disinfectant. However, chlorine dioxide can cause the formation of other compounds like chlorite and chlorate from reactions with residual oxidants and chlorine. It can thus be stated that the effective management of DBPs is not possible without controlling NOM in treated water, which is often characterized through fluorescence spectroscopy.

Another factor that can effectively increase THM levels in water is the presence of biofilm. Biofilm can act as a dynamic reservoir for various organic materials present in water, subsequently

using them as a primary nutrient source for bacterial growth. While biofilm eradication is possible with the use of disinfectants like chlorine or monochloramine, it requires very high disinfectant residues, leading to an increase in DBP concentrations (Z. Wang et al., 2021)

The formation of DBPs is also influenced by water temperature. General trends indicate that rising temperatures favor DBP formation rates. For example, the formation of chloroform in water following disinfection with monochloramine increases proportionally with temperature rise (Waters et al., 2021).

In terms of water quality, it has also been found that the fulvic and humic components of organic matter are significant precursors of THMs. Some laboratory and field studies have shown that higher concentrations of these parameters lead to higher levels of THMs formed (Delpla et al., 2009a)

DBP formation is also favored by high temperatures and drought conditions, which can lead to higher concentrations of DOM (dissolved organic matter) in soil and, consequently, in water, resulting in increased DBP formation after heavy precipitation events (Chang et al., 2020). Prolonged droughts can trigger a series of cascading effects from corrective actions taken to maintain water supply. For instance, reduced water availability at the source can increase water residence times in the network, leading to higher water age and increased DBP formation.

In distribution systems, the loss of disinfectant residues, along with increased concentrations of disinfection by-products or the development of nitrification in chloraminated systems, can lead to challenges. With longer water residence times in the network and increased contact with natural organic matter, chlorine can enter more reactions, thus increasing the formation of DBPs. Longer water residence times can also lead to significant DBP increases at the point of use. For example, in the southeastern United States, an intensive monitoring plan was adopted in some hydropotable systems to assess water quality issues. Furthermore, pipe cleaning and intensified flushing protocols for storage tank outlets were implemented to remove TOC from water effectively, achieving a 43% reduction in DBP formation and a 36% decrease in DBP concentrations after adopting these measures (EPA, 2022).

Even wildfire events can generate similar corrective actions. Significant impacts generally occur following wildfires, especially in areas experiencing intense rainfall afterward (Bixby et al., 2015). Rain transports large quantities of sediments, ash, and soluble nutrients from burned areas, causing problems in potable water supplies. Organic carbon leached from ash may have different DBP formation potentials compared to unburned forest debris. For example, it has been reported that organic material released from wildfire ashes results in reduced organic matter content in water but elevated trihalomethane and haloacetic acid formation after chlorination, as well as N-nitrosodimethylamine and haloacetonitrile formation after chloramination (Z. Wang et al., 2021)

Disinfectants such as chlorine, chloramines, ozone, and chlorine dioxide are commonly used in water treatment, each with unique advantages and drawbacks related to the formation of disinfection by-products (DBPs). Chlorine, the most widely used disinfectant, reacts with natural organic matter (NOM) to produce trihalomethanes (THMs) and haloacetic acids (HAAs). While chloramines produce fewer THMs, they can lead to more toxic DBPs, such as haloacetonitriles (HANs) and halonitromethanes (HNMs) (Agus, Voutchkov, and Sedlak 2009). Ozone, though a strong oxidizer of organic matter, can form bromate (BrO_3^-) in bromide-containing water. Bromate, a harmful DBP classified as a Group 2B carcinogen, has a stringent drinking water standard of 10 $\mu\text{g/L}$

(Mao et al., 2018) Chlorine dioxide (ClO_2) reacts less with organic matter than chlorine, avoiding THMs and other halo-organic DBPs. However, when bromide is present, ClO_2 may produce brominated by-products, particularly when combined with chloramines, potentially increasing brominated THMs and cyanogen bromide (CNBr). Additionally, ClO_2 forms distinct DBPs, such as aldehydes and ketones, which are precursors to DBPs like haloacetonitriles (Agus et al., 2009)

Temperature significantly influences DBP formation during and after disinfection. Higher temperatures accelerate chemical reactions between disinfectants and DBP precursors, especially NOM, resulting in faster and higher DBP production (X. Zhang et al., 2013). Studies show that elevated temperatures strongly promote THM and HAA formation. For example, TriChloromethane/chloroform (TCM) concentrations increase from 28.0 $\mu\text{g/L}$ at 4°C to 304 $\mu\text{g/L}$ at 50°C, with similar trends for bromodichloromethane (BDCM), dibromochloromethane (DBCM), and tribromomethane (TBM). HAA formation also rises with temperature. Dichloroacetic acid (DCAA) forms at 108 $\mu\text{g/L}$ at 50°C but not at 4°C, while trichloroacetic acid (TCAA) concentrations similarly increase with temperature. Some DBPs, like haloacetonitriles (HANs), decrease with rising temperatures due to hydrolysis, though certain HANs, such as dichloroacetonitrile (DCAN), may increase. Other DBPs, including trichloronitromethane (TCNM) and chloral hydrate (CH), also rise significantly at higher temperatures. For instance, TCNM increases from 0.8 $\mu\text{g/L}$ at 4°C to 6.0 $\mu\text{g/L}$ at 50°C, while CH rises from 13.8 $\mu\text{g/L}$ to 62.2 $\mu\text{g/L}$. Haloketones (HKs), such as 1,1-dichloropropanone (1,1-DCP) and 1,1,1-trichloropropanone (1,1,1-TCP), also exhibit temperature-dependent changes.(De Vera et al., 2016)

Under chloramine treatment, prolonged exposure to high temperatures may increase DBPs like iodinated DBPs, HNMs, and HANs. However, higher temperatures not only accelerate reaction rates but can also reduce disinfection efficiency if disinfectant concentrations are not optimized, leading to the accumulation of more toxic DBPs and increased health risks.

Apart from temperature, factors such as pH, NOM concentration, bromide levels, and contact time also affect DBP formation. At elevated temperatures, bromate (BrO_3^-) formation in bromide-containing water treated with ozone is particularly concerning. Kinetic models based on the Arrhenius equation have been developed to simulate the relationship between temperature and DBP formation rates, providing tools to predict and optimize water treatment processes.

To minimize DBP formation at high temperatures, several measures are recommended: removing NOM precursors through coagulation, adsorption, or biological filtration; optimizing disinfectant doses and contact times; using alternative disinfectants such as ozone, chloramines, or chlorine dioxide; and controlling environmental factors like pH and bromide.

In summary, high temperatures are a critical factor driving DBP formation, particularly THMs, HAAs, HANs, and HNMs, after disinfection. Therefore, temperature control combined with advanced treatment strategies is essential to mitigate DBP risks and protect public health.

Impact of Pipe Materials on DBP Formation in Water Distribution Systems (DWDS)

The material of water distribution pipes significantly affects DBP formation and degradation. Iron from various pipe materials, such as Fe(II), Fe(III), magnetite, goethite, and zero-valent iron (ZVI), can participate in chemical reactions that influence the formation of common DBPs like THMs, HAAs, haloacetamides (HAcAms), and HANs.

Global DBP Regulations

Table 2. 1 Shows varying DBP concentration limits across countries

DBPs	Italy (Legislative Decree No. 18/2023)	China	Japan	Singapore	US EPA	WHO	Vietnam (QCVN 01- 1:2018/BYT)
Total THMs	0.3 mg/L	1.0	0.1	-	0.08	1.0	0.1 mg/L
Chloroform	0.07 mg/L	0.06	0.06	0.3	0.07	0.3	0.3 mg/L
Dibromochloromethane	0.06 mg/L	0.1	-	0.1	0.06	0.1	0.06 mg/L
Bromoform	0.1 mg/L	0.1	0.09	0.1	0.0	0.1	0.1 mg/L
Chloroacetic acid	0.02 mg/L	-	0.02	0.02	0.07	0.02	0.02 mg/L
Trichloroacetic acid	0.2 mg/L	0.1	0.2	0.3	0.2	0.2	0.2 mg/L
Bromate	0.01 mg/L	0.01	0.01	0.01	0.01	0.01	0.01 mg/L
Chlorite	0.7 mg/L	0.7	0.6	0.7	1.0	0.7	-
N-nitrosodimethylamine	0.0001 mg/L	0.0001	-	0.0001	-	0.0001	-

Regions with stringent regulations, like the U.S. and the EU, closely monitor THMs and HAAs, while developing countries often lack clear guidelines. For instance, Vietnam does not specifically regulate chlorite and N-nitrosodimethylamine (NDMA), unlike nations such as Italy and China, which enforce strict limits. This presents challenges for managing DBPs in aging or substandard pipe systems.

Iron in pipes has a dual role in DBP formation, both promoting and catalyzing reactions. Iron types like Fe (II), Fe(III), magnetite, and Zero-valent iron (ZVI) contribute to DBP production through oxidation or reactions with disinfectants and NOM, increasing risks from unregulated or highly toxic DBPs (Guo et al., 2024). Corrosion in iron-containing pipes exacerbates DBP precursors and complex chemical reactions, complicating water quality control.

The “Guidelines for selecting mitigation measures for DBP control under EU Directive 2020/2184 in WTPs” in table 4.1 annex 4 is designed to assist Water Treatment Plants (WTPs) in selecting strategies to reduce disinfection by-products (DBPs) and comply with EU Directive 2020/2184 on drinking water quality. This table helps treatment plants identify and implement effective control measures to limit the formation of common DBPs such as trihalomethanes (THMs), haloacetic acids (HAAs), chlorites, chlorates and bromates, which have the potential to pose a health risk to consumers.

Through the “Guidelines for selecting mitigation options for DBP control under EU Directive 2020/2184 in WTPs” designed to assist Water Treatment Plants (WTPs) in selecting strategies to reduce disinfection by-products (DBPs) and comply with this EU Directive 2020/2184 on drinking water quality, water treatment facilities can evaluate mitigation options based on factors such as DBP removal efficiency, operating costs, impacts on water quality (including taste, odor and color) and technical feasibility. Potential options include pre-treatment to reduce dissolved organic matter (DOM/NOM) prior to disinfection, modifying the disinfection method using alternatives such as chlorine dioxide, ozone or UV to minimize DBP formation, or modifying the treatment process by modifying the Empty Bed Contact Time (EBCT), dosing, and/or disinfection. disinfectant level or pH level. The guidelines help treatment plants identify and implement effective control measures to limit the formation of common DBPs such as trihalomethanes (THMs), haloacetic acids (HAAs), chlorites,

chlorates and bromates, which have the potential to pose a health risk to consumers. The guidelines not only help ensure public health protection by minimizing harmful disinfection by-products, but also support compliance with EU regulatory standards, helping plants avoid fines and maintain their reputation. Furthermore, selecting appropriate mitigation strategies helps optimize operating and maintenance costs while ensuring that treated water meets regulatory standards. The guidelines serve as a useful tool for managers and engineers in making informed decisions to ensure efficient and sustainable water treatment operations.

To address these issues, measures include replacing or upgrading pipes with materials like PVC or stainless steel, controlling corrosion, removing NOM precursors before disinfection, and optimizing the use of alternative disinfectants like chloramines or chlorine dioxide. These steps ensure drinking water quality and compliance with global DBP standards.

2.5.4 Presence of Micropollutants

Micropollutants are compounds detected in the environment at trace concentrations, usually in the range of nanograms per liter. These include various substances such as pesticides, pharmaceuticals, food additives, cosmetics, fragrances, waterproof agents, plasticizers, and foam stabilizers (M.-K. Kim & Zoh, 2016)

The concentration of micropollutants in the distribution network is directly influenced by the concentration in the water source, as treatment barriers are often not entirely effective at ensuring complete removal.

For example, some studies have highlighted findings from monitoring micropollutant concentrations in rivers, particularly in relation to treatment plant effectiveness.

Reference is made to the presence of pharmaceutical compounds. Some authors (Sjerps et al., 2017) observed a close correlation between the concentration of pharmaceutical compounds discharged through wastewater treatment plant effluents, and river flow rates. As shown in Figure 2.9, this correlation refers to carbamazepine concentrations in the Rhine and Meuse rivers during the drought period of 2010–2011.

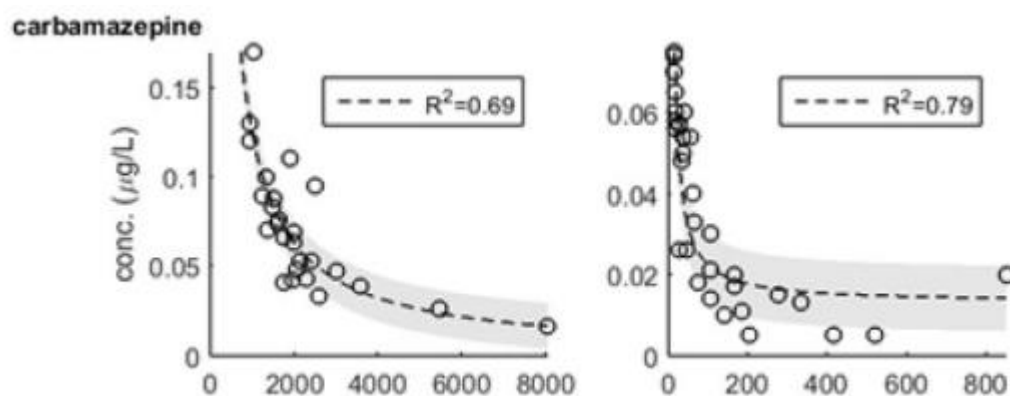


Figure 2. 9 Relationship between river flow rates and carbamazepine (b) concentrations in the Rhine and Meuse rivers (Sjerps et al., 2017)

Similarly, in lake water bodies, climate variations can significantly impact the presence of micropollutants. Increases in temperature and nutrient concentrations drive massive algal blooms.

Particularly intense heatwaves lead to cyanobacterial growth, production of cyanotoxins, reduced vertical mixing in lake water columns, and increased cellular growth rates (Jöhnk et al., 2008)

Authors (Lennartz & Louchart, 2007) studied the alteration of pesticide retention and release mechanisms in agricultural soils following drought-rainfall cycles. They observed that, under simulated heavy precipitation conditions (10–20 mm/day), certain herbicides like isoproturon and bifenthrin could pose a greater risk of contaminating water bodies and increasing ecotoxicity (Probst et al., 2005)

Regarding climate-related changes, possible alterations in inorganic micropollutant concentrations in water bodies, especially rivers and lakes, have been identified. These changes are due to potential sources of anthropogenic pollution (wastewater effluents) and natural inputs (release of metals from rocks and soils) (Delpla et al., 2009).

The presence of micropollutants in water can also alter biofilm formation and control mechanisms in distribution networks. For instance, caffeine, estrogens, and other pharmaceutical active compounds (PhACs) in water may negatively impact biofilm dynamics.

Some authors (H. Wang et al., 2019) have highlighted that the exposure of biofilm present in distribution systems to sulfadiazine and ciprofloxacin (two types of antibiotics) increases enzymatic activity and extracellular polymeric substance (EPS) production, which in turn promotes bacterial adhesion to pipe surfaces. (Y. Zhang et al., 2021) found that tetracycline promotes bacterial growth in biofilm, while exposure to tetracycline, sulfadiazine, and chloramphenicol increases bacterial resistance to chlorine and antibiotics, fostering the diversity of bacterial communities within the biofilm.

Micropollutants can be removed through conventional and non-conventional treatment processes. Conventional potabilization processes, such as coagulation, sedimentation, oxidation, and adsorption using activated carbon, can remove traces of micropollutants. It has been observed that the adsorption phase is generally the most effective barrier for micropollutants, although its efficiency can sometimes be limited by the nature of the pollutant itself or by the presence of other interfering substances that hinder removal rates. Since conventional processes cannot always completely remove micropollutants, they may persist in distribution networks, leading to human exposure and bioaccumulation of hazardous compounds.

In addition to conventional processes, advanced drinking water treatment technologies exist, such as membrane processes using nanofiltration and reverse osmosis, which have proven effective in removing micropollutants. Beyond these methods, other techniques can be used to remove micropollutants from water, including ozonation, chlorination, and combined processes like UV radiation with Cl_2 or O_3 . However, degradation often occurs very slowly and proves ineffective for certain resistant micropollutants.

In conclusion, this highlights that even at water sources and in conventional treatment systems, the issue of micropollutants persists, often resulting in a decline in water quality within distribution systems.

2.6 Control Measures for Drinking Water Supply Systems

2.6.1 Monitoring of Water Resources

Monitoring water quality and quantity is essential for ensuring that environmental regulations are met, and potential risks are managed effectively. Groundwater, surface water, and other water bodies must be assessed using specific standards prescribed by directives such as Directive 2006/118/EC and Directive 2008/105/EC. Articles 7 and 8 of Directive 2000/60/EC lay the foundation for this process, defining parameters for the quality and safety of water intended for human consumption. These parameters are not only meant to safeguard health but also to comply with periodic reviews that adapt to emerging risks and regional characteristics.

In addition to chemical and biological parameters, water resource managers are obligated to identify specific activities or events that may pose threats to water quality. River basins and extraction points are particularly sensitive to pollution, requiring coordinated efforts from stakeholders to implement preventive and mitigative measures. This includes collaboration among regulatory bodies, water service managers, and local authorities. For example, drinking water services are encouraged to adopt Water Safety Plans (WSPs), which align with the broader goals of risk management to enhance resilience against contamination.

2.6.2 Addressing Climate Change Risks

Climate change introduces a multifaceted set of risks to water resources, profoundly affecting both quality and quantity. Rising temperatures, extended heatwaves, prolonged droughts, and extreme rainfall events are among the most pressing concerns. These phenomena create cascading effects, such as shifts in water chemistry, increased evaporation rates, and ecological imbalances in aquatic ecosystems. For example, prolonged heatwaves and rising temperatures exacerbate algal blooms, particularly in reservoirs and artificial lakes, which degrade water quality and pose challenges for treatment processes.

Water quantity is equally affected. Decreased river flows, lower recharge rates for aquifers, and intensified evaporation during droughts threaten water availability. Seasonal variations further complicate the situation, as peak demands during summer months often coincide with diminished supply. This is particularly critical in regions with high agricultural and tourism demands, where water scarcity becomes both an economic and social issue.

To mitigate these impacts, strategic measures are required. Coastal regions, for instance, can benefit from desalination technologies that transform seawater into potable water. Although these methods offer a virtually unlimited supply, they come with challenges, including high energy costs and environmental concerns related to brine disposal. Similarly, constructing artificial reservoirs provides a dual advantage of water storage and flood control, enhancing resilience against extreme weather events. Such solutions underscore the importance of innovation and forward-looking policies in securing reliable water supplies.

2.6.3. Real-Time Monitoring and Early Warning Systems/Technical

The integration of real-time monitoring systems has transformed the management of water resources, providing critical tools for immediate risk assessment and response. Operational monitoring, as outlined in D.Lgs. 18/2023, focuses on evaluating the functionality of risk control measures. Unlike traditional analytical monitoring, which assesses water quality over time,

operational monitoring aims to ensure continuous compliance with safety standards. This requires frequent data collection and validation to detect anomalies and maintain the effectiveness of control measures.

Early warning systems (EWS) are a significant advancement in this field. By continuously monitoring key parameters such as pH, conductivity, and turbidity, EWS can quickly identify unexpected changes in water systems. For example, a sudden increase in turbidity may indicate contamination or structural issues in pipelines, prompting immediate intervention. These systems not only enhance responsiveness but also reduce the complexity of long-term monitoring programs by focusing on critical indicators. Furthermore, EWS can be integrated with automated controls, such as valves or discharge systems, to mitigate risks in real time.

However, the success of such systems depends on robust data management and interpretation. Statistical methods must be applied to process raw data into actionable insights, ensuring that trends and anomalies are accurately identified. The creation of comprehensive databases and control charts facilitates informed decision-making, further strengthening the reliability of water supply systems.

2.6.4. Protecting Critical Infrastructure

Water infrastructure is increasingly recognized as critical to societal well-being and economic stability. The interconnected nature of water systems makes them particularly vulnerable to disruptions, whether from natural disasters, technical failures, or malicious actions. D.Lgs. 18/2023 and EU Directive 2022/2557 emphasize the importance of protecting these infrastructures, classifying them as "critical" due to their essential role in providing safe water for human consumption.

Risk assessments for water infrastructure must account for both qualitative and quantitative threats. For instance, prolonged droughts and extreme rainfall events can lead to structural damage, service interruptions, and even complete network failures. Blackouts caused by high energy demands during heatwaves further exacerbate these risks, highlighting the need for integrated energy-water management solutions.

The directives also stress the importance of delineating responsibilities among stakeholders, fostering collaboration across sectors. Effective communication and data sharing are vital for managing risks that extend beyond the immediate scope of water utilities. For example, aligning water resource management with emergency planning can mitigate the impact of floods, droughts, and other climate-related events.

2.6.5. Toward Resilient and Sustainable Water Management

The integration of WSPs into water resource management represents a proactive approach to addressing both current and emerging challenges. By aligning with legislative frameworks, such as Directive 2000/60/EC and D.Lgs. 18/2023, water managers can develop comprehensive strategies that prioritize sustainability and resilience. These strategies must balance short-term interventions with long-term planning, ensuring that water resources remain accessible and safe for future generations.

Central to this vision is the concept of sustainability. Measures such as water reuse, efficient irrigation practices, and circular water economies offer pathways to reduce stress on freshwater resources. By treating and reusing wastewater, communities can close the loop on water consumption, minimizing environmental impacts while meeting growing demands.

Climate adaptation must also be prioritized. This includes investing in robust infrastructure, adopting advanced monitoring technologies, and promoting public awareness of water conservation. The development of policies that integrate water, energy, and environmental goals will be critical in building resilience against the multifaceted threats posed by climate change.

WSPs serve as a critical framework for managing the complex dynamics of water resources. From monitoring and real-time assessments to addressing climate-induced risks and safeguarding infrastructure, these tools provide a comprehensive approach to ensuring water security. However, achieving sustainable water management requires a collaborative effort that bridges regulatory, technical, and community-based initiatives. By adopting innovative practices and aligning with forward-looking policies, society can effectively navigate the challenges of water resource management in an increasingly uncertain world.

2.7 Research gaps, research questions and objectives

2.7.1 Research gaps

Despite the growing body of research on climate change and its implications for water systems, several gaps persist in current knowledge and practice: lack of operational responses of water utilities to extreme events, limited integration of real-time monitoring, especially in diverse geographical and regulatory contexts like Italy and Vietnam, disconnect between policy and practice, and insufficient microbial monitoring innovations. Most existing studies emphasize theoretical models or simulations, while fewer explore the real-world, operational impacts of extreme weather events on water supply systems. Although real-time data is increasingly available, its use in adaptation planning and early warning systems remains underutilized. Furthermore, most studies are concentrated in high-income countries, with limited comparative research involving both developed (e.g., Italy) and developing (e.g., Vietnam) contexts. While policies such as the EU Directive 2020/2184 and national laws promote climate-resilient water safety planning, actual implementation is often inconsistent. Additionally, traditional microbial detection methods are often too slow for early intervention, and the integration of faster methods like IDEXX Colilert remains underexplored.

2.7.2 Research Questions

Based on the identified gaps, the thesis aims to answer the following research questions:

- (1) How does climate change affect the quality and availability of drinking water in water supply systems, especially during extreme weather events?
- (2) What differences exist in climate adaptation strategies between water utilities in Italy and Vietnam?
- (3) How can real-time monitoring technologies and microbiological innovations improve the resilience of drinking water systems?
- (4) Are current regulations and policies sufficient to drive effective adaptation to climate-induced water quality risks?

2.7.3 Research Objectives

This research aims to assess the operational impacts of climate change on drinking water quality through literature review, surveys, and real-time data; evaluate the adaptive capacity and responses of water utilities in Italy and Vietnam; analyze the effectiveness of real-time monitoring systems and propose improvements; explore the potential of new microbiological detection tools to accelerate response time; and propose a set of strategic recommendations for policy and practice to enhance the resilience of drinking water systems.

2.7.4 Novelty and Contribution of the Research

This thesis presents a novel contribution by combining real-time monitoring data, microbial analysis, and climate-event correlations in an operational context (Mompiano case study); offering one of the first cross-country comparisons (Italy and Vietnam) focused specifically on climate change adaptation in the water sector; highlighting the importance of integrating early warning systems with policy frameworks and real-time response mechanisms; and suggesting practical improvements in microbial monitoring that can complement climate-resilient strategies in water governance. The findings are expected to inform both academia and practice, supporting future efforts in climate-resilient water supply planning, especially in regions vulnerable to climate variability.

2.7.5 Research Approach and Methodology Overview

Comprehensively address the research questions, this study adopts a multi-layered, mixed-method research approach that moves progressively from a broad exploration to an in-depth case-specific analysis. The methodology unfolds in the following phases:

1. Macro-level understanding through literature and surveys:

The study begins by reviewing existing scientific literature on the impacts of climate change on drinking water systems globally and in the context of Italy and Vietnam. This phase identifies knowledge gaps and sets the foundation for assessing real-world challenges. To complement this, structured surveys and interviews with water utility managers in both countries are conducted. These gather first-hand insights into adaptation strategies, institutional challenges, and regulatory responses, enabling a comparative analysis between a developed (Italy) and a developing (Vietnam) context.

2. Medium (meso)-level analysis of operational impacts at Italian water utilities:

The research then narrows its focus to the operational level, analyzing real-time water quality data and documented anomalies from Italian utilities particularly in relation to extreme weather events. This phase investigates how climate variability manifests in the daily operation of water treatment systems, including shifts in physicochemical and microbiological parameters.

3. Micro-level investigation through an in-depth case study:

At the most detailed level, the study focuses on the Mompiano Drinking Water Treatment Plant (DWTP) in Brescia, Italy. Here, high-frequency data from online sensors (e.g., turbidity, conductivity, temperature) and microbiological detection tools (notably IDEXX Colilert) are analyzed in conjunction with climate records to explore potential correlations between climate

anomalies and water quality fluctuations. Site visits further contextualize the findings, allowing for validation of sensor data and understanding operational constraints.

4. Policy and governance analysis:

To evaluate whether regulatory frameworks support climate-resilient water management, a comparative policy analysis is conducted. Key policies examined include the EU Drinking Water Directive (2020/2184), Italy's Legislative Decree 18/2023, and Vietnam's QCVN standards. Survey responses from utility operators are used to assess the implementation gap between policy and practice.

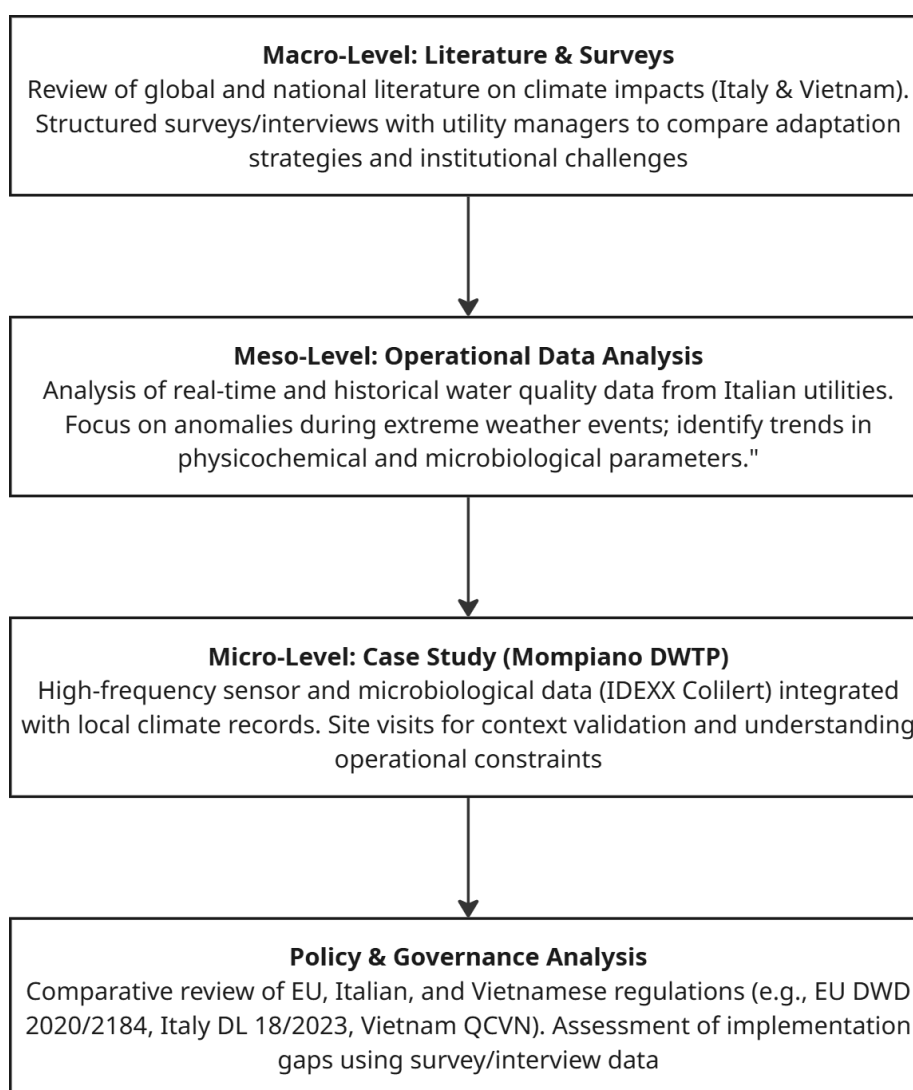


Figure 2. 10: Multi-Layered Methodology for impacts of extreme weather on the variability of critical parameters in drinking water supply systems: insights from operational experience

This tiered methodology not only enables a comprehensive understanding of climate change impacts across scales but also helps bridge the gap between scientific knowledge, operational practices, and policy frameworks. By combining qualitative insights with quantitative analysis and case-specific data, the study aligns with its goal to connect broad climate challenges with specific, actionable solutions in drinking water management.

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CHAPTER 3: IMPACTS OF EXTREME WEATHER ON THE VARIABILITY OF CRITICAL PARAMETERS IN DRINKING WATER SUPPLY SYSTEMS: INSIGHTS FROM OPERATIONAL EXPERIENCE

3.1 Methodology

3.1.1 Data collection and source

This study is unique in its full chain approach to analyzing climate change impacts on water treatment processes, covering each operational phase rather than just focusing on raw water intake. Furthermore, the research utilized a mixed-methods approach, primarily focusing on surveys to gather comprehensive information from key individuals involved in the management of water utilities. This study was conducted by Prof Sabriana Sorlini at the University of Brescia in Italy the questionnaire developed aimed to address critical aspects of water management, including drinking water sources, treatment technologies, and distribution systems, with a specific emphasis on treatment processes and the impacts of climate change.

The questionnaire was distributed to water supply companies across Italy and Vietnam, resulting in responses from 19 companies representing 23 provincial utilities in Vietnam and 40 utilities in national survey in Italy.

This approach is intended to bridge the gap between perception and action regarding climate change adaptation and mitigation, ensuring clean and stable water supply, environmental protection, and sustainable development. The research followed these steps:

1. Identify the Number of Water Treatment Plants: Document the number of plants managed, the population served, and the urban areas covered by each water supply system (refer to Annex 2: table 2.2 DWTPs list).

2. List Water Sources: Compile a list of water sources and specify the extent of usage as a percentage of the total processed water, Plant Descriptions: Provide descriptions of each water treatment plant, detailing the water treatment methods employed, the purification process, and their relationship with designated water sources.

3. Climate Change Effects: Inquire about the effects of climate change phenomena on the water supply system, including changes in temperature, precipitation patterns, sea levels, and other related factors.

4. Impact on Treatment Processes: Explore the effects of climate change-induced variations in water source parameters on different stages of the water treatment process, such as pre-oxidation, coagulation-flocculation, filtration (granular and activated carbon), and final disinfection.

6. Distribution Network Impact: Investigate the impacts of water source parameter variations on the distribution network downstream of the treatment plant, including biofilm growth, bio-corrosion, and disinfection by-product formation.

7. Control measure mitigation actions: Identify the actions taken by the respondent's organization or WSTP to mitigate or address problems related to climate change impacts.

This methodology aims to understand the significant climate-related challenges faced by these treatment plants and their corresponding responses. Additionally, it sought to synthesize existing adaptation measures and explore the impact of climate change on water sources, treatment processes, distribution networks, and regulatory compliance. By comparing contingency plans and operational experiences among various utilities, the study aimed to highlight the best practices and evaluate the effectiveness of monitoring systems and climate-informed data for strategic planning. Insights from utility managers were expected to provide valuable perspectives on climate-induced changes in raw water quality and treatment requirements, identifying critical vulnerabilities within Italy and Vietnam's water supply chain and informing targeted adaptation strategies.

3.1.2 Survey Design and analysis

To deepen the understanding of climate change's impacts on drinking water resources, a nationwide survey was administered targeting facilities involved in water treatment and distribution. The survey aimed to highlight the challenges identified by utility managers and the steps they have taken to address these challenges. The investigation focused on identifying the root causes of climate-related issues, examining the various climate phenomena contributing to alterations in managed water systems, and evaluating the effects on treatment processes leading to distribution.

The survey was distributed to water supply utilities in Italy and Vietnam in Excel format, accompanied by a questionnaire designed to gather detailed data. Its purpose was to capture comprehensive insights on the effectiveness of water service management as observed by the operators.

The questionnaire included both open-ended and multiple-choice questions, allowing respondents to provide additional details or specifications as needed. A full version of the questionnaire, as presented to water utility managers, is provided in Annex I. The questionnaire consisted of three main sections:

- Section I: General Overview - This section provided an overview of the drinking water supply system, covering general information about each utility, including supply area, the number of operational water treatment plants, population served, and sources of raw water utilized.
- Section II: Effects of Climate Change - This section examined the specific impacts of climate change on both the quality and quantity of raw water, as well as the resulting effects on water treatment technologies and drinking water distribution networks.
- Section III: Control Measures - This section focused on the actions implemented by water utilities to reduce the adverse effects of climate change on water supply systems.

3.1.3 Data Analysis

Survey results were analyzed using tables and graphs generated from the responses and further analyzed using Excel. In specific cases, managers were contacted directly to obtain more detailed information, clarify responses, or gain a deeper understanding of significant issues and assess the approaches used to address related concerns.

3.2 Results from survey results from Italian water utilities

(This section detailed description in the specified journal, with Italian survey in the servizi a rete ISSN 2499-6688 Number 4 July – august 2024 page 131-133 on the website: www.serviziarete.it)

In Italy, water resources are distributed unevenly, with 53% located in the northern regions, 19% in the central areas, and 28% in the south and islands. This disparity poses significant challenges, especially for the southern regions, which are more susceptible to water scarcity.

In recent years, the situation has been exacerbated by climate change, leading to prolonged droughts and increased temperatures. For instance, in 2024, Sicily faced one of its most severe water crises, with towns like Troina experiencing near-dry reservoirs and implementing water rationing measures. Residents protested water distribution decisions, highlighting the dire circumstances. (Guardian, 2024)

Managing these resources aligns with the European Union's Water Framework Directive, which establishes policies for water management across the EU (WFD,2000, n.d.) Climate change, however, has started to impact Italy's water resources, particularly in the north. In the Alps, rising temperatures have led to a dramatic reduction in glacier volume-over 50% since 1900 as Marmolada Glacier, the largest glacier in the Dolomites, Marmolada has experienced rapid melting. In July 2022, a massive collapse occurred, resulting in an avalanche that tragically killed seven people and left 13 missing. Experts have warned that if current trends continue, the glacier could disappear entirely by 2040 and the other Forni Glacier in Lombardy, Forni is one of Italy's largest valley glaciers. Over the past century, it has retreated approximately 2 kilometers, with 800 meters of that retreat occurring in the last 30 years. This significant reduction is attributed to rising temperatures and decreased snowfall.

Projections indicate that if global temperatures rise by 2–4°C, Italy could lose 50–90% of its mountain glacier mass by the end of the century (Miller & Belton, 2014).

The Intergovernmental Panel on Climate Change's (IPCC)2024 Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) provides detailed projections on glacier mass loss under various global temperature scenarios: Low-Emission Scenario (RCP2.6): Projected glacier mass reductions between 2015 and 2100 are likely to be between 22% and 44%. High-Emission Scenario (RCP8.5): Projected glacier mass reductions between 2015 and 2100 are likely to be between 37% and 57%.

These projections indicate that even with ambitious mitigation efforts, significant glacier mass loss is anticipated by the end of the century. The extent of this loss will largely depend on the effectiveness of global efforts to reduce greenhouse gas emissions.

Italy also has one of the highest rates of drinking water consumption in Europe, with daily per capita use between 150 and 240 liters ((Niccolucci et al., 2011)

Drought is a growing issue, especially in southern Italy, due to extended periods of high temperatures and low precipitation. The Mediterranean climate intensifies these conditions, leaving many areas in the south with critically low water resources. Prolonged heat waves and low rainfall affect water availability, posing significant challenges for agriculture, households, and various other sectors dependent on water. The European Commission's Joint Research Centre (2024) recently noted that such conditions have strained Italy's water supply infrastructure.

Italy has endured several major droughts in its history, including severe episodes in 1590, 1669-1670, 1763-1764, 1929-1935, and 2017-2018 (Fotia, 2023). These droughts have typically resulted from decreased rainfall, rising temperatures, and inadequate water management (Nadotti, 2023). Their impacts are far-reaching, affecting agriculture, water access, and the broader economy, often leading to food shortages, social disruption, and damage to aqueducts. In addition, the

accumulation of sediment in dams and reservoirs has reduced their capacity by up to 30% (Manuela Perrone, 2024)

Flooding also presents challenges. In 2023, Emilia-Romagna was struck by catastrophic floods, with 23 rivers overflowing, over 290 landslides, and more than 500 road closures. The region has the highest flood-risk population in Italy, with 428,000 residents in high-risk zones and 2.3 million in medium-risk areas (Cronaca, 2023)

Climate change has had a notable effect on water treatment processes across Italy, challenging the systems that purify drinking water. For instance, increased temperatures and pollution raise turbidity, requiring higher doses of coagulants in treatment. Additionally, more contaminants are passing through granular filtration, straining the process and demanding greater filtration efficiency. Elevated pollution levels also mean that activated carbon filters must handle higher contaminant loads, while final disinfection faces increased microbial loads and disinfectant demand (Centers for Disease Control and Prevention, 2022; Safe Drinking Water Foundation, 2024). Globally, the United Nations' World Meteorological Organization highlights that climate change worsens water-related hazards like floods and droughts, impacting drinking water supplies worldwide.

Rising sea levels bring the additional risk of saltwater intrusion into coastal groundwater, which could degrade water quality and damage underground infrastructure (Ketabchi et al., 2016). Research has shown that climate change can raise stream temperatures and nitrogen levels in rivers, threatening water quality (Bartlett & Dedekorkut-Howes, 2023). Studies suggest that enhanced treatment technologies may be required to maintain resilience in water systems, as current methods may not withstand the impacts of extreme weather events (Nijhawan & Howard, 2022). For example, recommendations to prevent anoxic conditions include artificial aeration and increased chemical dosages to counteract water quality degradation (Magee et al., 2019) (

Additionally, drinking water utilities-known for their reliability face new challenges due to climate change, which affects their ability to deliver water consistently. These utilities must adapt to gradual weather changes and more extreme events by updating infrastructure and emergency protocols. However, research indicates that utility managers may lack comprehensive knowledge of climate risks to their systems, despite available resources for climate resilience planning (Water Utility Climate Alliance, n.d.)

In examining Italy's water management strategies, this study explores the impacts of climate change on water resources, treatment, and distribution networks. By analyzing the measures taken by Italian water managers, the research aims to provide a deeper understanding of how climate change is shaping the water sector and the strategies being implemented to ensure a resilient and sustainable water supply.

Results of Section I:

General characteristics of supply systems

In the first section of the survey, it was asked to show a general overview of the plants managed, indicating their number and capacity in terms of inhabitants and municipalities served.

Within the group of 40 managers surveyed, it's become evident that many oversee a small number of purification plants. Notably, two operators, G8 and G9 ("G" is shorthand for Gestione, referring to the management or operation of facilities like DWTPs (Drinking Water Treatment Plants), focus solely on distribution without managing any plants. Additionally, four managers are responsible

for just one purification plant each. Among them, the manager of G17 mentioned that theirs is inactive. Under the survey, the distribution of water purification facilities is based on the number of managed drinking water plants, allowing for a better understanding of how resources and workloads are allocated among different managers. The survey suggests that there are a greater number of companies managing a smaller number of plants (<10) compared to those managing a larger number of plants (>100).

The following figures present a comparison of companies' capacities in serving total inhabitants, arranged in ascending order. These figures were sourced from data from the Regulation Authority for Energy, Networks, and the Environment (Arera) for the year 2021. Continued with surveys, it reveals a notable variation in service capacity among different companies, with the smallest providers, such as G23, G9, and G19, catering to relatively few inhabitants, likely numbering in their tens of thousands. In contrast, the larger companies, particularly G5 and G29, serve significantly larger populations, with G29 reaching nearly 3,000,000 inhabitants. Most of the companies operate with a capacity of fewer than 500,000 inhabitants, while only a small number can accommodate between 1,000,000 to 3,000,000 inhabitants. G29 distinctly stands out as the leader in terms of service capacity, serving far more inhabitants than the second-largest provider, G5. Other noteworthy companies with substantial service capabilities include G5, G21, and G1, each serving between 1,500,000 to 2,000,000 inhabitants.

3.2.1 Type of water sources used.

Out of 40 managers surveyed, 97% (38 out of 39) utilize underground aquifers, with 9 relying solely on this source.

Additionally, 28 companies use spring water alongside groundwater. Rivers are also used, although to a lesser extent. One manager, G5, extracts 61% of water from rivers. Other sources like natural lakes and artificial basins are utilized, mainly by companies near such reservoirs, e.g., G12 with Lake Como. None extract water directly from the sea; instead, interconnections with other operators or purchasing from third parties are common, as reported by G18 and G28, respectively.

Phenomenon related to climate change:

The questionnaire's main inquiry is: "Have climate change-related events caused alterations in the drinking water supply systems you manage?" All operators responded, with 33 managers most noting changes in their plants due to climate-related phenomena affecting water sources. This widespread impact, regardless of plant location or capacity, highlights the significant influence of climate change.

Out of the 33 managers who responded affirmatively, most reported increased drought periods. Nearly half (15 out of 33) attributed supply source phenomena to rising temperatures and intensified rainfall. Only manager G31 mentioned an increase in precipitation frequency as an option. Additionally, one-third of the companies cited flooding phenomena as altering their water sources.

Table 3.1 summarizes the key climate change phenomena that have altered water supply sources, as reported by managers. These phenomena highlight the increasing challenges faced in maintaining water quality and supply reliability.

Table 3. 1 Phenomenon related to climate change: Alterations to the supply sources

Phenomenon	Percentage
Increase in precipitation intensity	45%
Increase in drought periods	88%
Increase in precipitation frequency	3%
Flood phenomenon	33%

Table 3.1 highlights how climate change phenomena are altering water sources, with drought periods emerging as the most significant concern. A striking 88% of managers reported prolonged droughts, underscoring the growing challenge of maintaining consistent water supplies. Meanwhile, both temperature increases, and heightened precipitation intensity were reported by 45% of managers, suggesting that water systems must now address both extreme dryness and potential overflows. Interestingly, only a small fraction (3%) noted changes in precipitation frequency, indicating that while rainfall patterns may not be shifting significantly in timing, their intensity is becoming more problematic. Flooding remains a critical concern for a third of respondents, particularly in regions prone to extreme weather events. These findings emphasize the need for adaptive strategies to address the diverse impacts of climate change on water resource management.

Results section II:

3.2.3 Effects deriving from climate change on sources of supply.

The second part addresses the impacts of climate change observed on the drinking water supply systems of participating operators. Initially, it compares the effects of climatic variations on water sources, as depicted in the following graph.

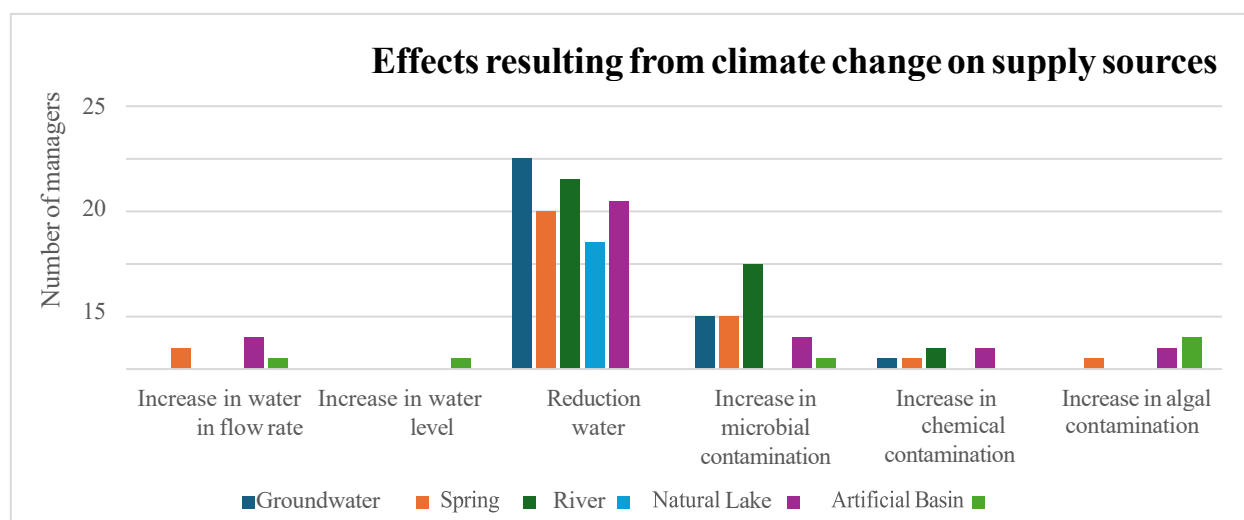


Figure 3. 1 Effects resulting from climate change on supply sources

The predominant effect noted is the decrease in water levels across various source types, particularly in aquifers and springs, followed by rivers and artificial reservoirs. There is also an increase in microbial contamination, notably in springs and to a lesser extent in rivers, aquifers, and

artificial reservoirs. Algal contamination primarily affects artificial reservoirs. Chemical contamination was reported by few and impacted on all source types equally. Few opted to increase water flow rates and levels.

3.2.4 Effects on individual treatment compartments:

The study then examined the conventional treatment components individually, starting with the pre-oxidation phase. Many operators utilize chlorine, oxygen, ozone (O₃), potassium permanganate (KMnO₄), chlorine dioxide (ClO₂), and sodium hypochlorite (NaClO) for this phase. These substances are employed to oxidize various compounds, including inorganic substances like iron, manganese, and ammonia, as well as organic pollutants such as chlorinated solvents and pesticides.

In the pre-oxidation phase, out of the 11 managers noting climate change effects, 10 observed increased oxidant demand. Some also reported a slight rise in disinfection by-products (DBPs) and alterations in hydraulic residence time. One operator, G39, noted a specific plant near the river Po experiencing increased chloride concentration, posing challenges for existing treatment systems. The percentages in Figure 3.2 represent the proportion of surveyed water treatment managers who reported experiencing each effect during the pre-oxidation phase.”

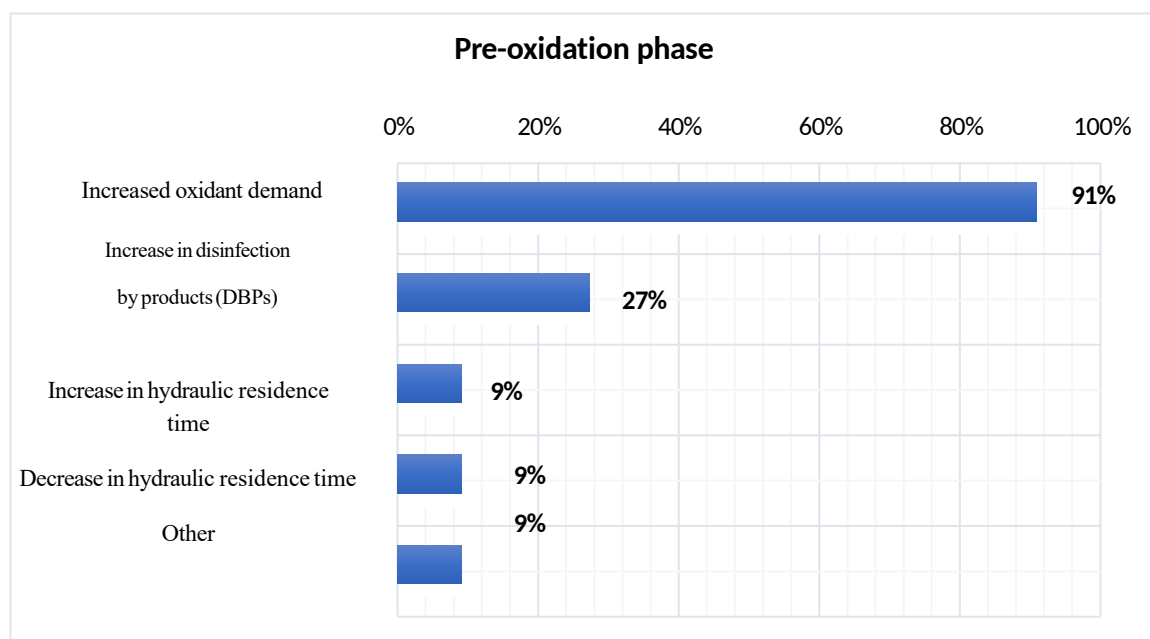


Figure 3. 2 Effects on the chemical pre-oxidation phase

Moving forward, the coagulation-flocculation phase was examined, particularly common among managers treating surface water sources like rivers, lakes, and artificial basins.

In the coagulation-flocculation phase in figure 3.3, 14 managers observed climate change effects, making it one of the most impacted sections. Most reported increased water turbidity and higher demand for coagulants and flocculant (such as ferrous chloride, ferric chloride, aluminum polychloride, and/or ferrous sulphate). Changes in hydraulic residence time, noted earlier in the pre-oxidation phase, were attributed to incoming flow variations.

G12, treating lake water, noted increased turbidity due to algal contamination. G26 observed decreased coagulant demand due to lower turbidity in springs following reduced precipitation during a dry spell. G4 highlighted the need to reduce water flow rates during significant deteriorations in treated water quality to ensure compatibility with drinking water standards. This reduction prolongs hydraulic residence times in the coagulation-flocculation compartment due to reduced flow rates.

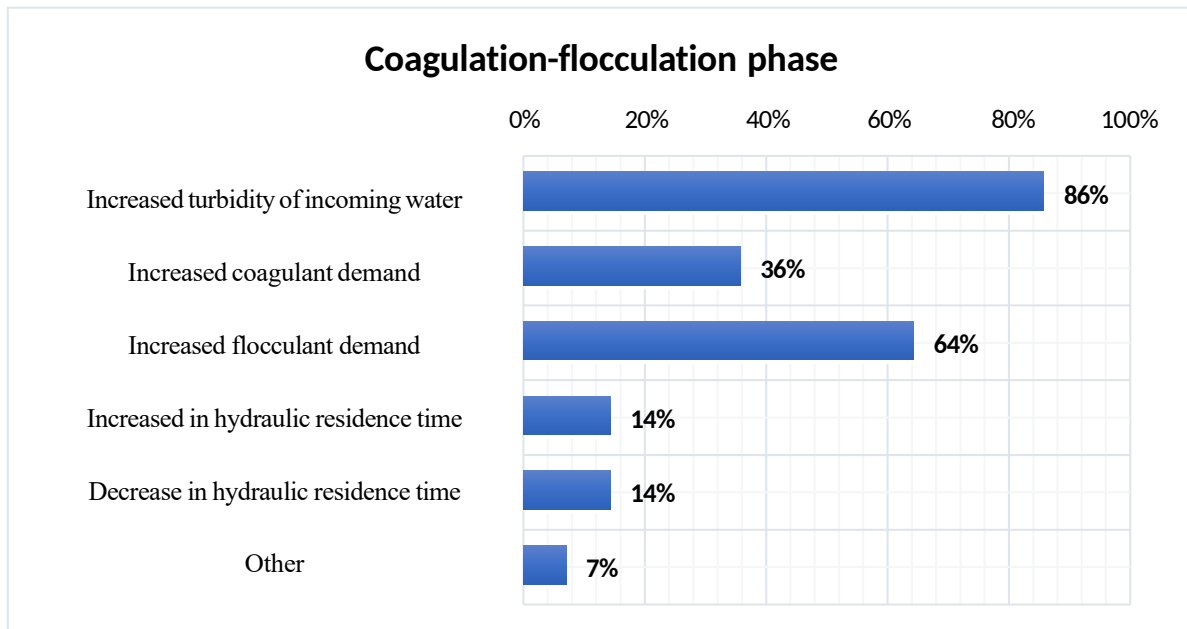


Figure 3. 3 Effects on the coagulation-flocculation phase

In the analysis of granular filtration in figure 3.4, primarily quartz sand filtration, only a few managers utilize advanced treatments such as microfiltration and ultrafiltration. The primary effect observed was an increase in suspended solids entering the filter, reported by 12 out of 13 respondents. Additionally, variations in filtration speed were noted, with some reporting decreased speed likely due to increased inlet load specifically, a higher concentration of suspended solids clogging the filter media, which slowed down the filtration process. G12 increased suspended solids in water entering the granular filtration system, linked to algal contamination from lake water extraction. Similarly, G4 found that reducing water flow rates distributed in the network decreased filtration speed in granular filtration despite using the same number of filters and filtering surface area.

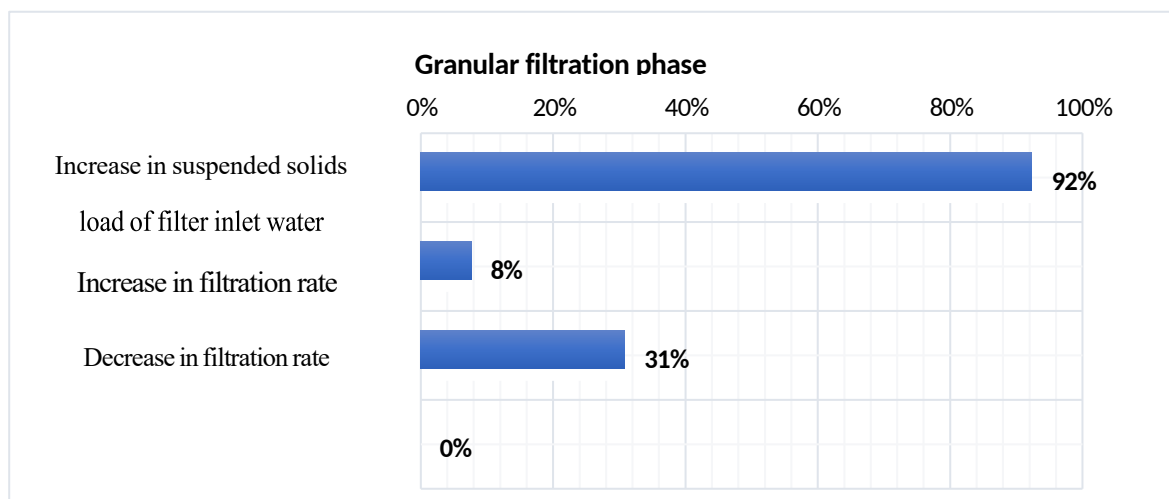


Figure 3. 4 Effects on the granular filtration phase

In the filtration phase using activated carbon figure 3.5, commonly found in the water purification plants in question, granular activated carbon (GAC) filtration is predominant, with some cases utilizing powdered activated carbon (PAC). Seven managers reported an increase in suspended solids load in incoming water at this stage. Additionally, two plants noted an increase in dissolved pollutants. Dissolved pollutants refer to soluble contaminants like natural organic matter (NOM), disinfection by-products (DBPs), and volatile organic compounds (VOCs) that can pass through initial treatment stages and require removal during GAC filtration. Entering the GAC filter, another two reported a decrease in water-GAC contact time (EBCT), typically associated with increased water flow.

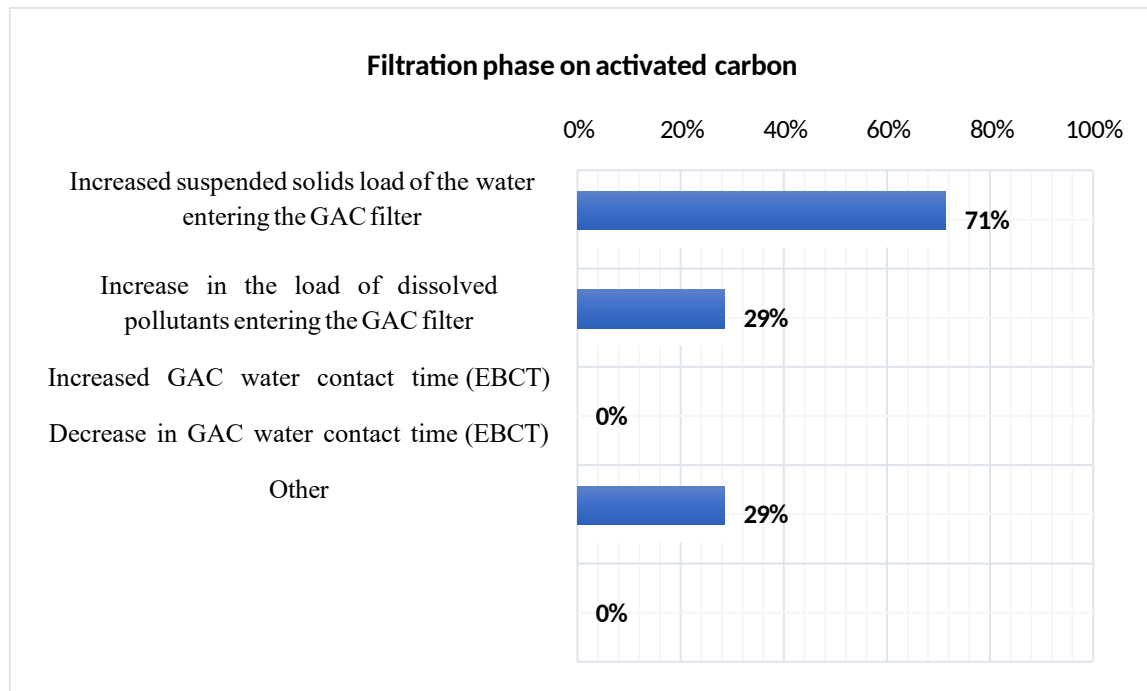


Figure 3. 5 Effects on the filtration phase on activated carbon

The final disinfection phase, which is the essential stage used for treatment, received the most responses regarding effects attributed to climate change. Companies primarily employ sodium hypochlorite (NaClO), chlorine dioxide (ClO_2), and, in some instances, ultraviolet (UV) radiation as disinfectants. (*) The precursors refer to substances like dissolved organic carbon (DOC), total organic carbon (TOC), and bromide ions that react with disinfectants to form DBPs.

In Figure 3.6 below, responses from 18 managers are shown, with over half reporting an increased demand for disinfectants and around a third noting heightened microbiological contamination in incoming water. Another observed parameter was the increase in disinfection by-product (DBP) formation and their inlet concentration. Additionally, there were reports of a lesser extent of increased hydraulic residence time.

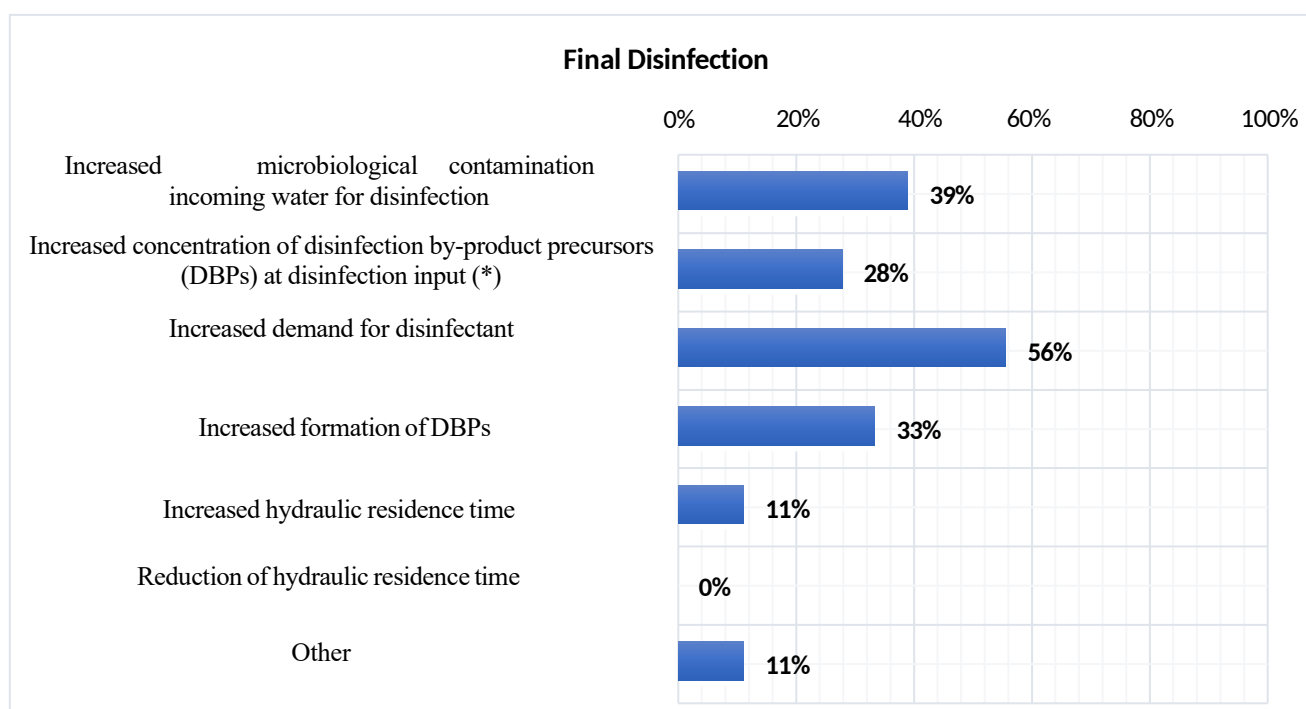


Figure 3. 6 Effects on the final disinfection phase

3.2.5 Effects on distribution system:

After examining the treatment phases in table 3.7, the effects of climate change on drinking water distribution systems were considered. These networks are utilized by both companies with treatment plants and aqueduct companies (e.g., G9) that deliver water directly to the point of use.

The primary effect observed was an increase in water temperature, reported by 15 out of 23 managers who responded to the question. About a third noted changes in microbiological quality and increased disinfectant consumption. Some managers also reported biofilm growth, chemical quality changes, and increased formation of disinfection by-products (DBPs)

Certain effects, such as increased DBP formation, are direct consequences of alterations occurring during treatment phases. Similarly, higher disinfectant consumption is linked to increased demand during earlier disinfection phases. Additionally, three managers reported issues with biocorrosion of pipes.

G7 highlighted temperature increases in the distribution network near corrosion-resistant metal cartridge filters used for fine particle removal. G17 noted biofilm growth and temperature increases in the network, with increased levels of indicator organisms (e.g., *E. coli*, total coliforms) detected at sensitive sampling points. They also mentioned biocorrosion issues in managing terminal sections composed of metallic pipes. While 13% of respondents reported issues such as biocorrosion of pipes and attributed these to climate change, the specific methods used to determine this causal link were not uniformly detailed. In many cases, such correlations were based on observed temporal patterns such as increased corrosion episodes coinciding with rising summer temperatures or prolonged droughts rather than controlled scientific verification. As such, while the survey reflects managerial perceptions, further in-depth technical assessments (e.g., corrosion rate analysis under

varying temperature and flow regimes) would be needed to isolate the precise contribution of climate-related factors versus other causes like water chemistry or infrastructure aging

Furthermore, G23 experienced numerous breakages due to night closures caused by water shortages in the distribution network. G26 reported temporary service interruptions due to drought conditions.

Table 3. 2 Effects on the distribution network

Effects in the distribution network	Percentage (%)
Biofilm growth	22%
Biocorrosion of pipes*	13%
Increased formation of DBPs	22%
Temperature increase	65%
Change in chemical quality	22%
Variation of microbiological quality	35%
Increased consumption of disinfectant	35%
Other	9%

Episodes of non-compliance in the distribution system:

The effects observed in distribution systems have led to problematic situations, necessitating compliance with organoleptic, microbiological, and chemical parameters to ensure safe drinking water. In Italy, compliance is regulated by Legislative Decree 31/2001. Managers were questioned about non-compliance episodes under these regulations: "Have there been any episodes of non-compliance of the water distributed resulting from climate change with Legislative Decree 31/2001?" While 12 managers reported non-compliance episodes (The term "some instances" refers to the non-compliance episodes reported by the 12 managers. When 16 managers reported no non-compliance episodes, it indicates that their water systems were fully compliant with Legislative Decree 31/2001., some instances were noted.

G9 reported non-compliance episodes concerning total coliforms, *Escherichia coli*, Enterococci, and pH (with observed decreases at specific sampling points). G15 also noted exceedances of the total coliform limit. G38 recorded excess residual aluminum due to rising water temperatures, which affected coagulation efficiency and increased aluminum solubility in the treated water. G40 identified values exceeding thresholds for chlorides and conductivity in areas served by wells near the coast.

3.2.6 Control measures

In response to the problems generated by climate change on treatment and distribution systems, companies have implemented various control measures. These range from general

evaluations of the issue to the use of existing procedures and the introduction of new systems tailored to address these challenges.

Many managers are conducting intensive studies and monitoring to better understand the problem's implications. Some have introduced new management procedures, including water safety plans (WSP), to assess risks and mitigate impacts. Others have implemented new technologies to manage climate-related problems.

For example, G1 is studying groundwater levels and flow rates and is considering installing online probes to monitor source turbidity. G5, despite not directly detecting climate change effects, has undertaken interconnection activities between aqueduct systems to ensure water service reliability during shortages.

G6 addressed ammonia alterations with a biological BAC refinement system and implemented measures to manage bromide increase. G14 introduced new procedures for proactive inspections and maintenance of turbidity meters and network systems to prevent potential failures during weather alerts. G15 activated water distribution with tankers due to drought and implemented tank cleaning procedures.

G17 is intensively studying and monitoring biofilm growth in the distribution network, increasing sampling and laboratory analyses, and conducting local hydrogeological studies, and conducting local hydrogeological studies. G18 is studying new deep aquifer sources and considering the use of reverse osmosis filters. G21 built a bypass to ensure water supply from alternative plants during droughts.

G23 enhanced monitoring networks with electronic meters and IoT systems, reducing losses and enabling better management during summer. G28 rented a mobile reverse osmosis unit to combat the rising layer of denser seawater intruding into the Po River due to saltwater intrusion threatening freshwater quality. G32 upgraded purifiers with inert filters and increased hydraulic connections between networks to ensure supply during crises.

Furthermore, G35 installed a bypass between critical sources and released potable water at another plant to serve utilities. Overall, these measures aim to ensure the continued supply of safe drinking water in the face of climate change challenges.

In table 3.8 The table highlights various control measures implemented to address water quality issues. Intensive monitoring of the problem stands out as the most frequently applied measure, with 73% implementation. This indicates a strong emphasis on regular and continuous monitoring to promptly detect issues and adjust responses accordingly. Problem study phase and the introduction of new management procedures both account for 39%, suggesting that while there is considerable effort to understand the underlying causes and update management strategies, there may be hesitation or limited resources to implement changes more broadly.

Similarly, risk assessment with water safety plans (PSA) is also applied in 39% of cases, reflecting a balanced focus on preventive measures alongside problem analysis. However, the introduction of new technologies (such as new collection systems and membrane filters) is notably lower at 27%, indicating potential barriers such as high costs or a lack of technical knowledge. Interestingly, another category labeled “introduction of new technologies” appears with only 15% implementation. This could either reflect a data entry error or an unclear distinction between types of

technologies being introduced. If not, it highlights a general reluctance or challenge in adopting technological innovations.

Overall, the data suggest that monitoring and risk assessment are prioritized over technological advancements, potentially limiting long-term effectiveness. Clarification of overlapping categories is recommended to ensure accurate data interpretation. Furthermore, increased investment in modern technologies could enhance long-term problem-solving, while integrating monitoring with new management procedures would create a more comprehensive control system.

Table 3. 3 Control Measure

Control Measure	Percentage (%)
Problem study phase	39%
Intensive monitoring of the problem	73%
Introduction of new management procedures	39%
Risk assessment with water safety plans (PSA)	39%
Introduction of new technologies (e.g., new collection systems, membrane filters)	27%
Introduction of new technologies	15%

Conclusion:

The impacts of climate change on drinking water supply systems in Italy are widespread and multifaceted, as evidenced by the experiences reported by 40 water managers surveyed in this study. Nearly all respondents (97%) have observed climate-related effects, with increased drought periods being the most prevalent phenomenon. Decreased water levels across sources like aquifers, springs, rivers, and reservoirs are the primary consequence, accompanied by heightened microbial and algal contamination.

Within treatment plants, various unit processes are affected, with increased oxidant demand in pre-oxidation, higher coagulant needs and turbidity in coagulation-flocculation, more suspended solids in granular filtration, higher contaminant loads in activated carbon filtration, and elevated disinfectant requirements and microbial loads in the final disinfection phase. Distribution networks also face challenges like increased water temperatures, deteriorated microbiological quality, higher disinfectant consumption, and disinfection by-product formation.

To mitigate these impacts and ensure a reliable and safe water supply, Italian water utilities have implemented a range of adaptive measures. These include enhanced monitoring, risk assessment procedures like Water Safety Plans, and the adoption of new treatment technologies such as membrane filtration. Strategies like interconnections between systems, mobile treatment units, and network upgrades have also been employed to maintain service during crises.

Overall, this nationwide study highlights the significant vulnerability of Italy's drinking water sector to climate change impacts. It underscores the need for continued research, innovation, and proactive measures to bolster the resilience of water supply systems against the evolving challenges posed by a changing climate. Collaborative efforts among utilities, policymakers, and stakeholders

will be crucial in safeguarding access to safe and sustainable drinking water resources for Italy's population.

3.3 Results from survey results from Vietnam water utilities

Vietnam is highly vulnerable to the impacts of climate change on its water resources, facing heightened risks from rising temperatures, shifting rainfall, and sea-level rise. These changes contribute to severe challenges, including flooding, drought, and saltwater intrusion, particularly in coastal areas with high population densities (World Bank, 2022) (D. T. Nguyen, 2023). According to Vietnam's Ministry of Natural Resources and Environment (MONRE), under the RCP4.5 climate scenario, annual river discharge is expected to rise by 2-18% across most basins. However, this increase will mainly occur in the wet season, while discharge tends to decrease during the dry season, leading to frequent flooding in rainy months and severe water shortages and saltwater intrusion in the dry months (Monre, 2022). This uneven water distribution impacts both flood-prone and drought-prone areas, creating challenges for maintaining clean and accessible water sources.

Flooding, particularly in central Vietnam, has led to numerous fatalities and displacements, with annual rains causing widespread damage (Pham et al., 2023). Floodwater often contains contaminants from sewage, industrial waste, and chemicals, which spread disease-causing organisms and increase turbidity levels, making water treatment more challenging. Private drinking water sources, such as wells, are especially vulnerable to contamination during floods (Pieper et al., 2021). In addition, climate change intensifies droughts, depleting natural water reserves and concentrating contaminants, which affects the availability and quality of drinking water (Sahisna Suwal, n.d.) (Michel Jarraud WMO, 2015). Sea-level rise compounds this issue by pushing saltwater into groundwater aquifers, damaging infrastructure and reducing water quality (Ketabchi et al., 2016) (Earman & Dettinger, 2011)

Climate change also affects water treatment processes. Higher temperatures, increased pollution, and nitrogen in rivers pose challenges to water quality, requiring improvements in treatment technologies to ensure resilience (Bartlett & Dedekorkut-Howes, 2023); (Nijhawan & Howard, 2022). However, technological advancements in Vietnam's water treatment plants are mostly short-term measures, with recommendations for upgrades to existing processes rather than revolutionary solutions (Garnier & Holman, 2019b). One suggested method is dynamic withdrawal from reservoirs to mitigate issues related to thermal stratification, but this is unlikely to counteract the full impact of climate change (Feldbauer et al., 2020)

Vietnam's rapid urbanization and industrialization further complicate water quality management. Many urban areas and industrial zones lack proper wastewater treatment facilities, leading to untreated waste being discharged into rivers. Only 46% of urban households have drainage systems, and just 12.5% of municipal wastewater undergoes treatment before release. Agricultural runoff also contributes to pollution, introducing pesticides and fertilizers into water sources, while livestock production adds harmful nutrients and pathogens. This pollution disrupts ecosystems, endangers public health, and affects industries like aquaculture, where harmful algal blooms are becoming more common (World Bank, 2022)

Contaminants from industrial and hospital waste, including harmful chemicals and heavy metals like arsenic, cadmium, lead, and manganese, are detected in rivers and pose additional

challenges to water treatment facilities. These contaminants exacerbate the difficulties of providing safe drinking water as rapid urban growth intensifies the strain on treatment systems.

This study examines how water treatment plant managers in Vietnam perceive and respond to climate-related challenges. Insights from these managers highlight real-time adaptations, operational challenges, and short-term solutions employed to combat issues such as droughts and floods. While these managers' reports on practical coping strategies, the research underscores the need for more comprehensive, long-term planning to ensure resilient water supply systems.

Significant research gaps persist in understanding climate change's full impact on Vietnam's water supply chain, from source management to treatment and distribution. Although there has been considerable research on the impacts of climate change on Vietnam's water resources, significant knowledge gaps remain in understanding the full extent of climate change effects on the entire water supply chain, from source management to treatment and distribution. In particular, there is a lack of research on how water treatment plants are adapting to these challenges and the development of long-term strategies to ensure sustainable water supply systems.

A national survey conducted in 2023 involving 19 water supply treatment plants (WSTPs), aimed to address this need. Managers from these plants shared valuable information on the effects of climate change, such as temperature increases, changes in rainfall intensity and frequency, and their impact on water quality. This survey provided insights into current strategies in Vietnam to maintain a safe and reliable water supply amidst shifting climate conditions.

This study sets out three main objectives. The first is to assess the impact of climate change on the quality and quantity of water resources in Vietnam, focusing on factors such as rising temperatures, changes in rainfall patterns, and saltwater intrusion. However, this objective has not yet been fully addressed, as the study has primarily concentrated on the second objective: investigating the current response measures implemented by water treatment plants to address climate-related challenges. Through surveys with water treatment plant managers, the study gathers insights into practical strategies and solutions being used to cope with droughts, floods, and water pollution. The third objective is to propose future research directions and long-term technological solutions to enhance the resilience of the water supply system, emphasizing the need for advanced treatment technologies and sustainable management strategies to mitigate the long-term impacts of climate change.

The findings from this study not only highlight the current challenges but also lay the groundwork for future research aimed at fully assessing the impacts of climate change on water resources and developing more effective adaptation strategies for Vietnam's water sector.

And Vietnam survey part I detail in the book: *Impatti dei cambiamenti climatici sull'approvvigionamento di acqua potabile sicura* – Maggioli editore ISBN 8891667519 page 224-sottotitolo qualità, soluzioni tecnologiche, Esperienze gestionali Collana Ambiente territorio edilizia urbanistica

3.3.1 Impact of Climate Change on Different Water Sources

A recent survey aimed to understand how climate change affects Vietnam's drinking water supply systems. Nearly all (95.8%) of the water companies surveyed reported experiencing some impacts of climate change on their operations. Although Vietnam's annual per capita water availability is relatively high at 9,560 m³ above the international average of 7,400 m³ over 60% of its water

resources flow in from other countries. This external dependency means that, domestically, the annual per capita water supply was only 4,000 m³ in 2012, a figure projected to drop to 3,100 m³ by 2025, which highlights Vietnam's reliance on cooperation with upstream countries to ensure a stable water supply (Pham et al., 2023)

Vietnam's primary water sources are rivers, underground water, and, to a lesser extent, coastal and sea water. The Red River and the Mekong River (also called the Cuu Long River) are Vietnam's two largest river systems, providing substantial surface water. However, underground water sources are increasingly crucial, especially in water-scarce regions like northern Vietnam, the central highlands, and the Mekong Delta during dry months. Coastal and marine areas also contribute, particularly to industries like fishing, mangrove preservation, and maritime transport, while limited snowfall occasionally supplements water in northern mountainous regions.

In the scope of this research, focus on source of water supply influent into near 19 WSTPs. Surveyed Water Supply Treatment Plants (WSTPs) largely rely on river water (83.3%), with the remainder using a mix of sources including springs, lakes, and groundwater, each of which presents unique challenges due to seasonal and climate-driven variations.

- **River Water:** The most common water source, river water has a large flow and is easy to extract, with relatively low hardness and iron content. However, it faces high sediment levels, microbial contamination, and substantial seasonal changes in turbidity, flow, and temperature, leading to elevated treatment costs (Pham et al., 2023).

- **Spring Water:** Only 4.2% of WSTPs use spring water, as it is scarce during the dry season and becomes turbid with high sand and silt levels during the rainy season, resulting in significant water level fluctuations.

- **Lake Water:** This source can exhibit high colorization due to aquatic life and algae, and without proper protection, lakes are prone to contamination.

- **Groundwater:** Used by 37.5% of WSTPs, groundwater has low sediment and microbial contamination, making it relatively easy and affordable to treat. It can be safely distributed through smaller pipes, though issues arise in coastal areas where saltwater intrusion and high iron content complicate treatment.

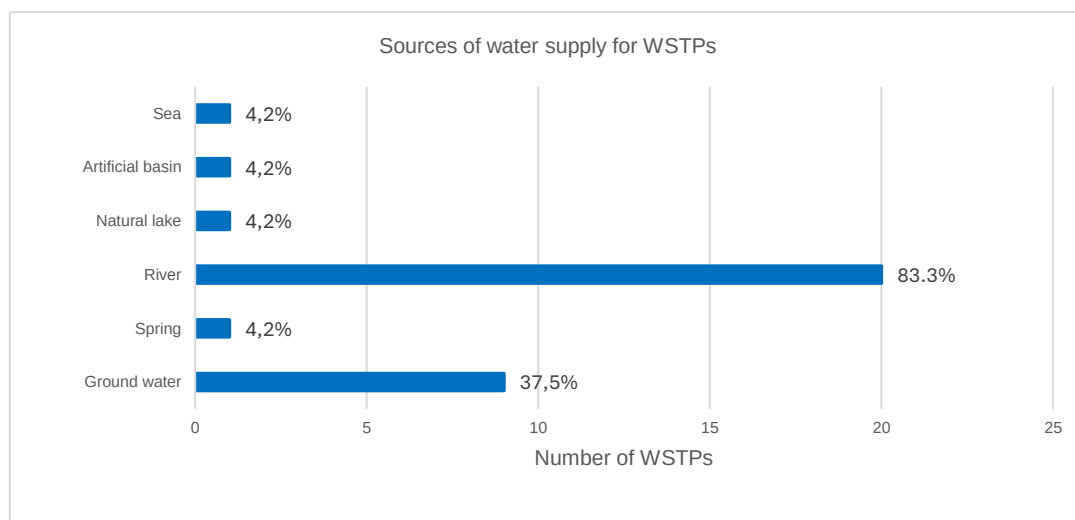


Figure 3. 7 The breakdown of sources water type used by surveyed WSTPs

3.3.2. Climate change impact on quantity of water intake at WSTPs

The questionnaire results revealed several key climate change impacts across different raw water sources used by supply water treatment plants in Vietnam. As shown in Figure 3 the most commonly reported in the survey effect across source types was decreasing water levels, as noted by managers for rivers, lakes, reservoirs, and groundwater sources. Increased water flows were also reported for multiple source types including rivers, springs, and reservoirs.

River, lake, and reservoir water sources saw the greatest increases in microbial and chemical pollution, as reported by managers. A few utilities using reservoir water also noted increased algal contamination. The variety of climate impacts underscores the need for source-specific evaluations and protections.

Beyond the commonly reported impacts, some utilities shared additional climate-related effects on their sources. The Luong Yen WSTP using groundwater described issues like increased nitrates and micropollutants being washed out from soils during intense rains. Coastal utilities like Hai Phong WSTP reported saline intrusion increasing during droughts due to reduced river flows.

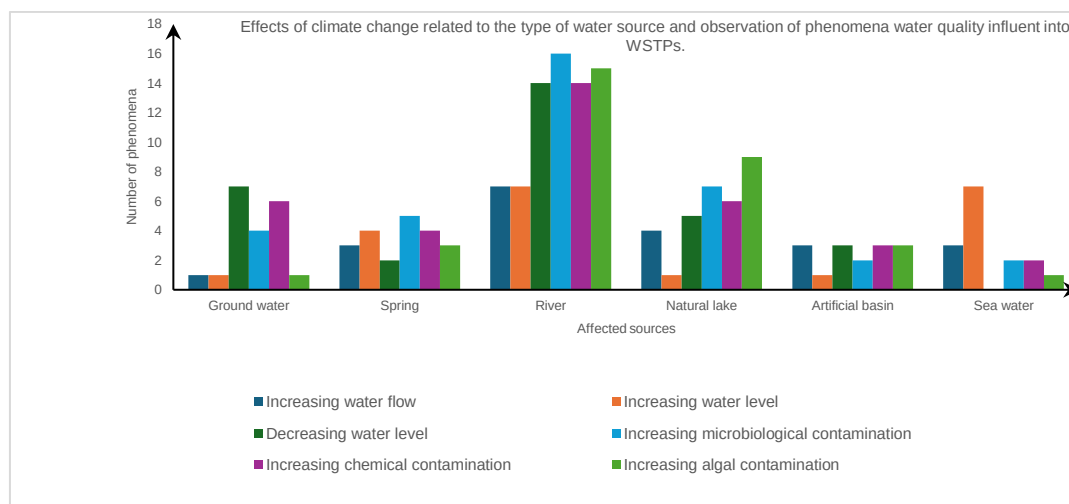


Figure 3. 8 Effects of climate change related to the type of water source and observation of phenomena water quantity influence into WSTPs.

3.3.3. Climate change impact on quality of water intake at WSTPs

The specific climate change impacts experienced by the water companies, such as increased drought frequency, intense precipitation, rising temperatures, and deteriorating water quality. Figure 3.9, the most reported impact, experienced by 34.7% of utilities, was increased frequency and intensity of drought periods. Other major issues included more intense precipitation, rising temperatures, and increased water demand compared to previous years, reported by around half of the respondents. About 13% of utilities also noted increased flooding and deteriorating water quality as key climate change impacts.

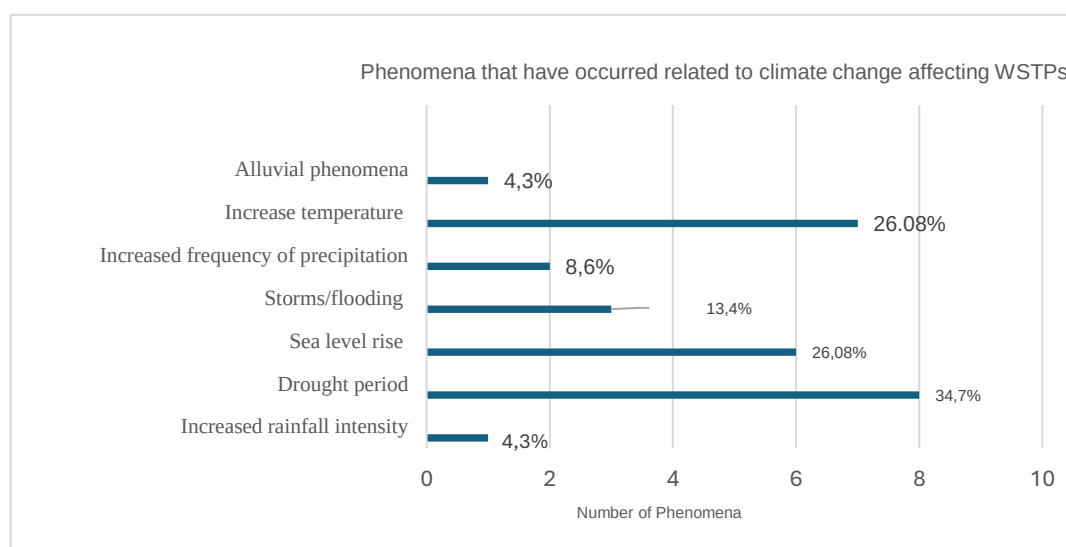


Figure 3. 9 Category of Phenomena Related to Climate Change Impacting Water Supply Treatment Plants

While the specific climate change effects on raw water sources differed between locations, the majority of participating drinking water treatment plants in the survey confirmed that shifts in long-term weather patterns were negatively impacting the observed impacts align with climate projections of increasing temperature, shifts in precipitation patterns, and more heavy rain and drought events in Vietnam. While further study is needed, the questionnaire provides early evidence that accelerating climate change is negatively impacting the quality and reliability of key water sources for drinking water treatment plants across multiple regions of Vietnam.

Impact of the variations of parameters of the supply sources on the water distribution network and system.

The most prevalent problem, reported by approximately 63.2% of respondents was bio corrosion pipe. Biofilm buildup can corrode pipes, reduce water quality, and pose health risks. In figure 5 approximately 15% of the companies also reported an increase in disinfection by-products (DBPs) in treated water, probably due to higher levels of DBP precursors in degraded source water. Additionally, some utilities noted heightened bio-corrosion of distribution system components when microorganisms grew and produced corrosive metabolic byproducts. They noted that as water body temperatures rise, reaction rates accelerate which can increase the formation of disinfection by-products when chlorine is used. Higher temperatures also speed up bacterial growth and biofilm production in distribution systems.

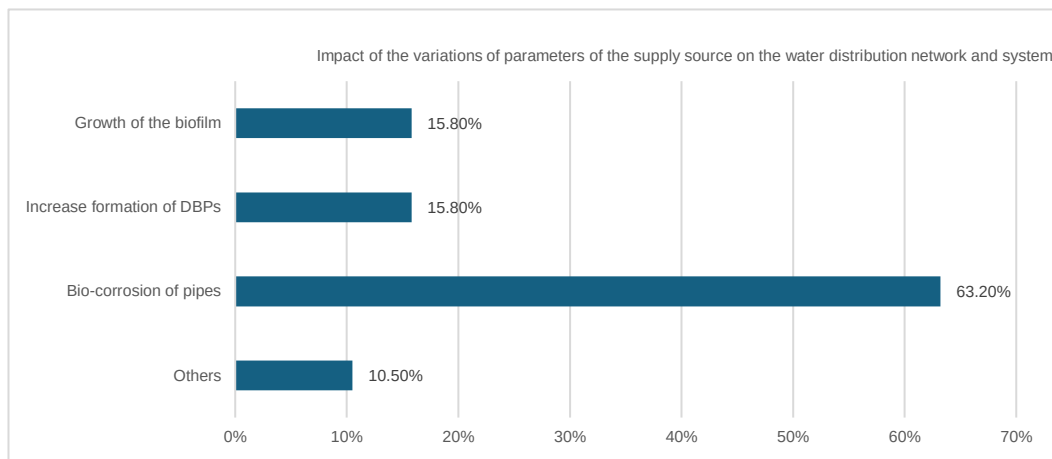


Figure 3. 10 Impact of the variations of parameters of the supply source on the water distribution network and system

3.3.4. Effects of climate change on treatment technologies of drinking water supply system

Through a survey of 19 treatment plants, conventional treatment technologies were predominantly used (Annex1). The study discusses the specific technologies and processes used by the surveyed plants. The aim is to highlight commonalities in challenges and responses rather than providing a one-to-one map of each plant's design. The diagram summarizes the conventional surface water treatment process, which is predominantly utilized in the surveyed treatment plants. The process involves several key steps: oxidation (using potassium permanganate or chlorine), coagulation/flocculation (using poly aluminum chloride or PAC), sedimentation, second oxidation (additional chlorine), rapid gravity filtration, and disinfection (using chlorine or sodium hypochlorite). The overall process flow includes pumping raw water from the river to the treatment plant, blending coagulants in mixing basins, allowing floc formation in reaction basins, settling out flocs in sedimentation basins, removing remaining particles through filters, storing the finished water in clear well storage tanks, and distributing treated water using high-service pumps.

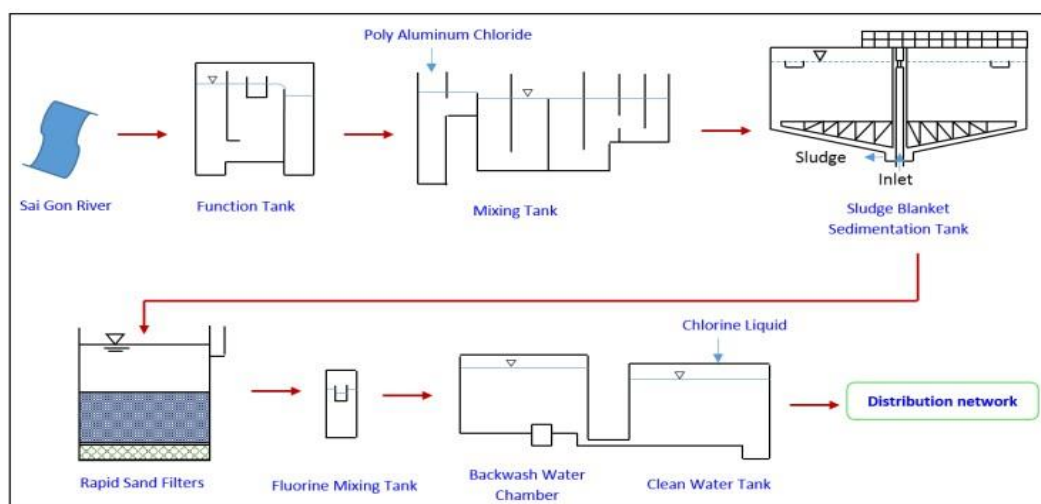


Figure 3. 11 Diagram depicting the convention treatment process at Tan Hiep WSTP (Southern)

Treatment plants act as a barrier between water sources and distribution systems, minimizing the effects of degraded quality on drinking water. Therefore, understanding how climate factors influence treatment processes is critical. The questionnaire addressed technologies in detail given the vital intermediary role of plants. Specific questions remain about which stages are most affected, like pre-oxidation, coagulation, flocculation, granular activated carbon filtration, or disinfection. Typical treatment begins by removing suspended solids and dissolved substances, often using aluminum sulfate coagulants. Gentle mixing allows particle aggregation and sedimentation. However, smaller particles, chemicals, and bacteria may remain after this stage. Filtration through sand beds provides additional clarity, but bacteria may persist. Disinfection using chlorine compounds is the final step, which kills bacteria but also reacts with organics, forming potentially harmful by-products. Chlorine residuals in finished water continue to prevent recontamination. Overall, climate factors could influence multiple phases of water supply system treatment. (Ma et al., 2022),(Leveque et al., 2021).

3.3.4 Current responses and measures in DW treatment processes

3.3.4.1 Chemical pre-oxidation

In the chemical pre-oxidation phase, frequent activities often involve adjustments to cope with higher organic loads and algal-derived compounds promoted by warmer temperatures. The most reported impact (40.9%) in figure 7 is an increased hydraulic residence time (HRT) in the pre-oxidation processes. This could be due to factors like higher influent water temperatures or changes in water quality that require longer oxidant contact times. 41% of utilities reported an increased demand for oxidants (e.g., chlorine, ozone) during the pre-oxidation stage, likely related to higher organic matter loads or other water quality changes resulting from climate effects. 13.6% of utilities experienced an increase in disinfection by-products (DBPs) formation during pre-oxidation, which can occur with higher oxidant doses and certain water quality conditions. 13.6% of utilities reported a reduction in hydraulic residence time (HRT) for the pre-oxidation processes.

The data indicates that climate change is impacting pre-oxidation treatment at many utilities, with the most significant effects being the need for longer contact times and higher oxidant doses to address deteriorating raw water quality issues. These operational adjustments can increase treatment costs and the risk of DBP formation.

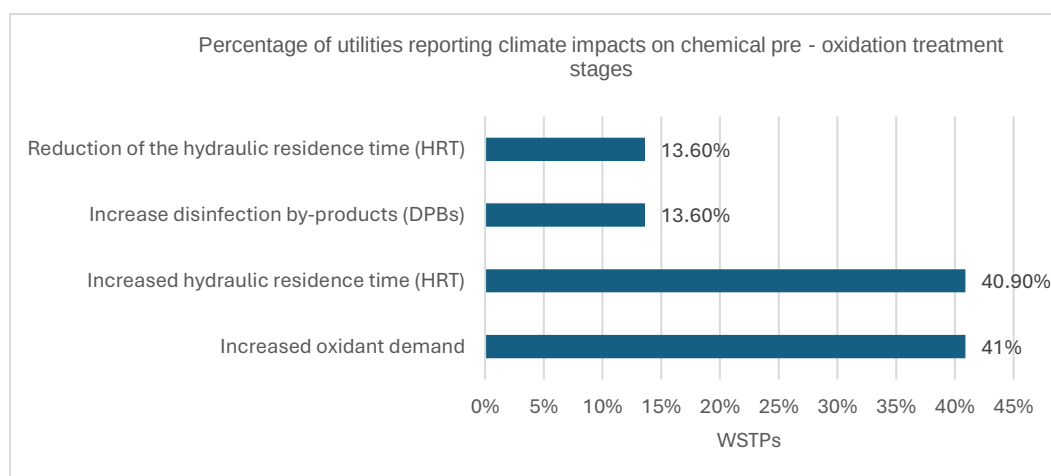


Figure 3. 12 Percentage of utilities reporting climate impacts on Chemical pre - oxidation treatment stages

Overall, the results underscore the importance of optimizing pre-oxidation processes and potentially implementing treatment modifications to maintain efficacy under changing source water conditions driven by climate change.

3.3.4.2. Coagulation-Flocculation

For the coagulation-flocculation stage 44% of utilities reported in figure 6 an increased demand for both coagulant and flocculant chemicals. Higher coagulant/flocculant dosages may be required due to changes in raw water quality caused by climate effects. 16% of utilities experienced an increase in the turbidity of the influent water entering this treatment stage, likely resulting from factors like increased runoff or algal blooms. 12% of utilities reported an increased hydraulic residence time (HRT) in their coagulation-flocculation processes, which could be due to higher solids loading or the need for longer reaction times. 24% of utilities reported "other" unspecified climate change impacts on these treatment stages. The data highlights how climate change is impacting the coagulation-flocculation processes at a significant number of utilities, primarily through effects on raw water quality and the resulting need for operational adjustments in chemical usage and process controls.

During the coagulants-flocculation phase, 11 plants documented climate change impacts, making it one of the most affected stages. Most of them showed an increase in influent water turbidity, leading to a greater demand for coagulants and flocculants (in the examined cases, iron FeCl_2 , FeCl_3 , poly aluminum chloride (PAC) and FeSO_4). Variations in hydraulic retention time, also detected during pre-oxidation, are due to fluctuating incoming flow rates. Plant C4, which treats lake water (from Lake Quao), noted increased turbidity of influent water due to increased algal contamination. When Plant C4 experienced a significant decrease in treated water's physical-chemical and microbiological characteristics, they reduced the flow rate to ensure compatibility with drinking water standards before distribution. This reduced flow rate increased the hydraulic residence time in the flocculation-flocculation tank (with the same accumulated volume, a lower flow rate increases retention time).

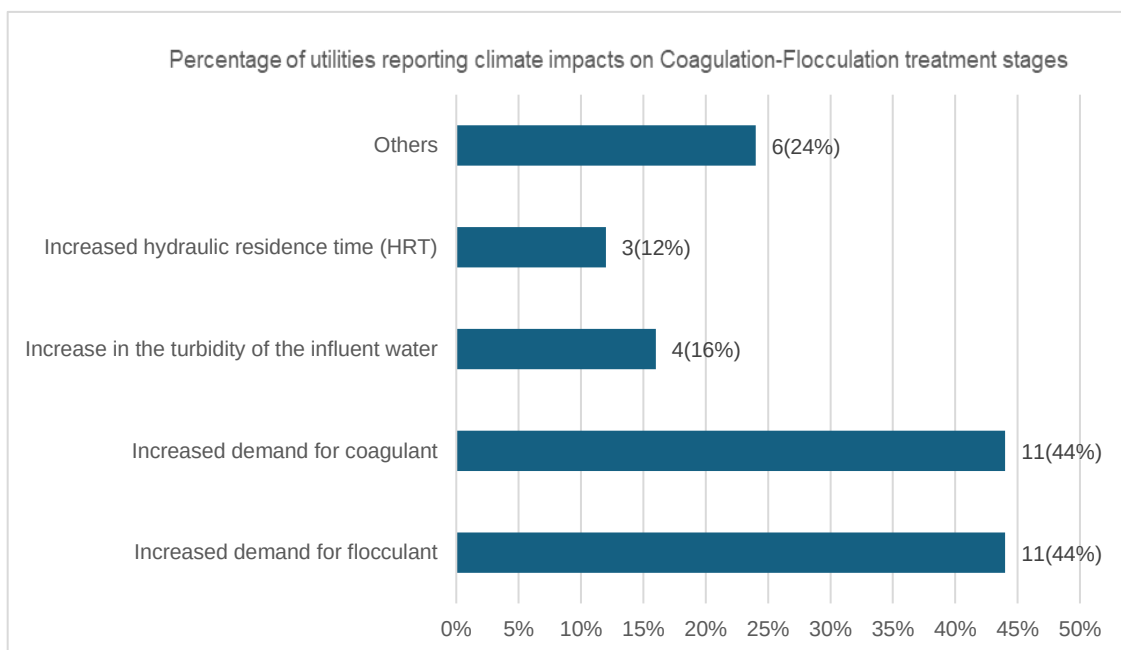


Figure 3. 13 Percentage of utilities reporting climate change impact on Coagulation - flocculation

3.3.4.3. Sand filtration

Over half of the utilities, in figure 9 at 52.4%, have observed a rise in the rate of sand filtration, possibly as a result of heightened water temperatures or fluctuations in water purity that influence the effectiveness of the filters. Nearly one-fifth of utilities, or 19%, have detected a heavier presence of suspended solids in the water approaching the filters, presenting operational difficulties and potentially shortening the length of filter operation. A proportion of 14.3% of utilities have seen a slowdown in their filtration rates, which may be attributed to increased amounts of suspended solids or alterations in the water quality. The same number, 14.3% of utilities, have noted various other unspecified effects of climate change on their granular filtration systems. The data highlights how climate change can affect granular filtration performance in opposing ways both increasing and decreasing filtration speeds for different utilities likely due to site-specific water quality and temperature impacts.

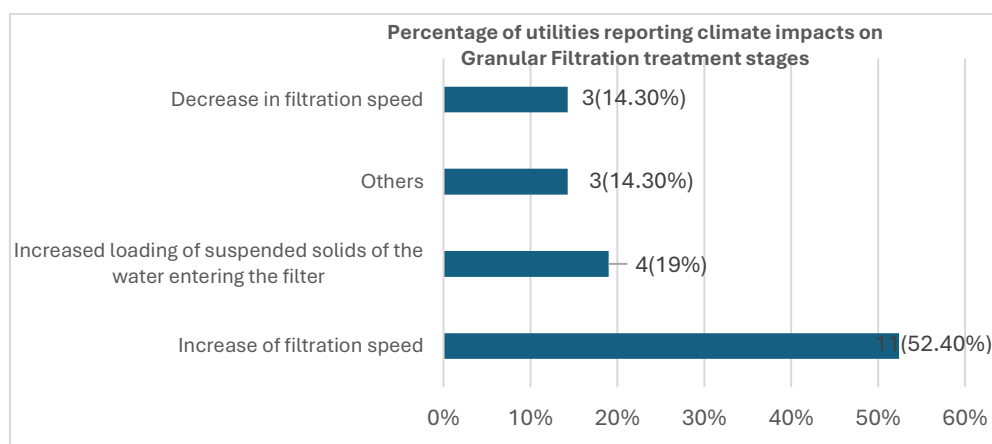


Figure 3. 14 Percentage of utilities reporting climate impacts on Sand Filtration treatment stages

3.3.4.4. Granular Activated Carbon (GAC)

In the figure 3.15 filtration phase using activated carbon, commonly found in the water purification plants in question, granular activated carbon (GAC) filtration is predominant, with some cases utilizing powdered activated carbon (PAC). Seven managers reported an increase in suspended solids load in incoming water at this stage. Additionally, two plants noted an increase in dissolved pollutants entering the GAC filter, while another two reported a decrease in water-GAC contact time (EBCT), typically associated with increased water flow.

3.3.4.5. Final disinfection

According to surveys on geographical location, in figure 3.16 water source, and water treatment systems, as well as based on time and environmental conditions, all water treatment plants reported that the quality of their input water is not guaranteed. Managers reported the highest reported impact 42.9% is an increase in microbiological contamination of the water entering the disinfection process. 23.8% of utilities reported an increased demand for disinfectant. 14.3% reported an increase in the concentration of disinfection byproduct (DBP) precursors at the entrance to disinfection, as well as an increase in the formation of DBPs themselves. 9.5% reported an increased hydraulic residence time (HRT). 28.6% of utilities reported no opinions or did not observe any climate change impacts on their disinfection processes.

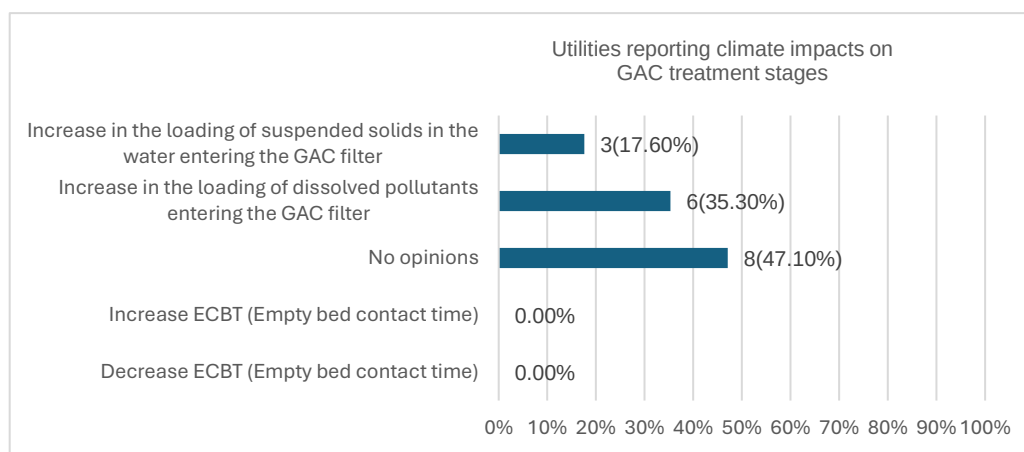


Figure 3. 15 Utilities reporting climate impacts on GAC treatment stages

Highlights how climate change can adversely affect water quality and treatment processes, with microbiological contamination and changes in disinfectant demand/byproduct formation being among the most commonly reported issues by these utilities

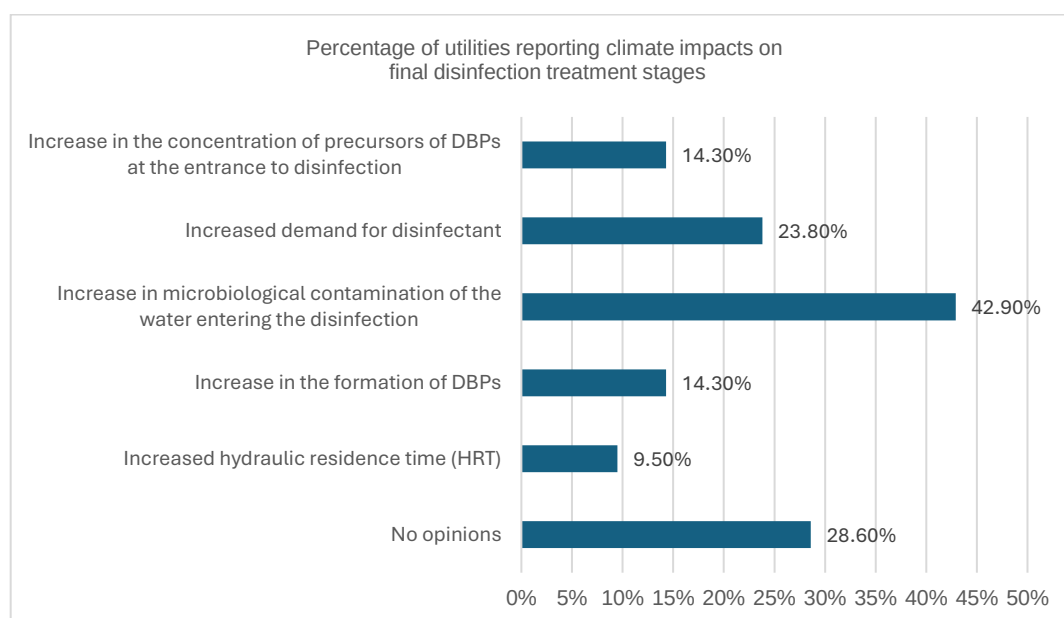


Figure 3. 16 Utilities reporting climate impacts on the final disinfection treatment process

3.4.4.6 Best practices of adaption to Climate change Impact in water supply system Vietnam

Hai Phong Supply Water Treatment Plant (WSTP), pretreatment processes are employed for raw water with high organic pollution levels. Methods such as coagulation or oxidation are utilized to remove some organic matter and other contaminants before water undergoes the main treatment process. Additionally, biological filtration processes are employed, utilizing microorganisms to address organic pollution in water. These processes, implemented through biological filters or sand filters, aim to enhance the biodegradation of organic matter and produce cleaner water. Furthermore, activated carbon filtration processes are applied using active materials like activated carbon or zeolite to absorb organic contaminants in water, thereby improving water quality. Chemical treatment methods, such as oxidants or disinfectants, are also utilized to treat water with high levels of organic pollution, oxidizing and disinfecting organic matter to reduce pollution levels. In some cases, a combination of multiple treatment methods, including coagulation, biological filtration, activated

carbon filtration, and chemical treatment, may be necessary to effectively eliminate organic pollutants from water.

Hai Phong WSTPs collaborated with Hanoi National University of Civil Engineering to research the production and use of nanofiltrations (NF) to treat water contaminated with organic, ammonium, manganese, etc. While Hai Phong stated these seasonal fluctuations have occurred in the past, climate change may exacerbate such temperature-related effects. However, the utility indicated they have not yet experienced any major climate-linked phenomena in their supply network. Any anomalies observed so far cannot be attributed to climate change over typical seasonal variations. Overall, Hai Phong's comments highlight the potential for higher temperatures to impact drinking water quality and infrastructure. However further data is needed to quantify how projected temperature increases from climate change may specifically alter their treatment processes and distribution network. Long-term monitoring paired with climate modeling would help this and other utilities better understand future temperature-related risks.

Furthermore, to address salinity issues, the best utility mentioned appears to be Tan Hiep Clean Water Treatment Plant (THWTP), which collaborates with the source river by releasing water to push back seawater. However, if the salinity level exceeds 250 mg Cl/L, THWTP has several options:

- Ceasing the use of raw water.
- Adjusting the operation mode of the reservoirs and clean water pumping stations to store clean water and reduce pumping capacity.
- Modifying the water distribution network and increasing the capacity of other plants to provide support.
- Being ready to implement emergency water supply measures such as tanker trucks and drilled wells.

Additionally, during the dry season, THWTP takes measures to prevent sludge from rising and clogging the filter bed. These measures include sludge disposal, cleaning of sedimentation tanks, per chlorination to eliminate algae in the raw water pumping station, and chlorine soaking in sand filter beds.

Furthermore, it mentions the importance of applying new treatment technologies capable of efficiently treating and controlling unwanted by-products like Disinfection By-Products (DBPs). Although THWTP currently does not employ specific technologies to address DBP issues, it's crucial for them to consider implementing methods to control DBP formation, such as technical measures during the preliminary treatment of raw water and replacing chlorine with alternative oxidants/disinfectants that produce fewer or no undesirable DBPs.

In summary, the Tan Hiep Clean Water Treatment Plant demonstrates proactive measures to address water quality issues and adapt to changing conditions, making it the best utility highlighted in the text.

Challenges and appropriate strategies at WSTP for adaptation and strengthen water facilities to climate change.

Figure 3.17 proposed control measures by water safety plan providers (WSTPs) to address challenges related to climate change adaptation and strengthening water facilities. The measures with the highest percentages are risk assessment with water safety plans (52.2%) and intensive monitoring

of the problem (34.8%). Problem identification (30.4%) and introduction of new technologies like membrane filters and abstraction water systems (30.4%) are also commonly proposed measures. Introduction of new management procedures (21.7%) and none (4.3%) make up the remaining responses from WSTPs on control measures to improve resilience against climate change impacts on water infrastructure and operations.

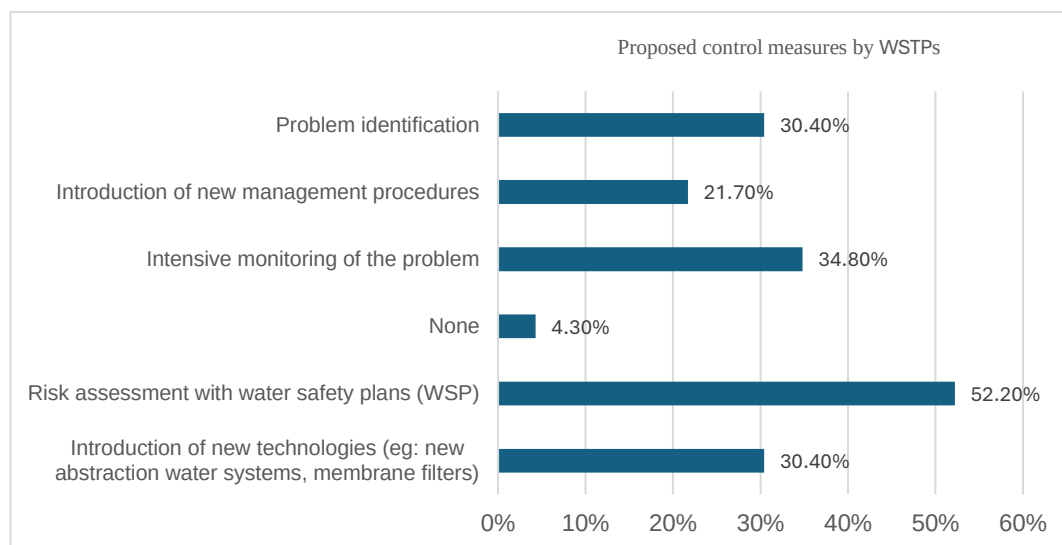


Figure 3. 17 Proposed control measures by WSTPs

In detail with plant Binh Thuan WSTP with suggestion method of preliminary treatment by oxidation with liquid chlorine at the source at the raw water pumping station, increasing PAC during the treatment process to support flocculation, add activated carbon to the filter to enhance treatment. Kanyo private WSTP mentions regular monitoring of the number of chemicals used, daily testing and evaluation, reserve land to supplement technology in the case of pollution detection (especially in rivers), having a reservoir to stabilize river water, and increasing retention time Tan Hiep WSTP Reducing the filtration rate can indeed have significant effects on the performance of water treatment processes, particularly when using technologies like Reverse Osmosis (RO) and Ultrafiltration (UF) for treating saltwater and seawater. Developing climate-sensitive water safety plans to identify and mitigate vulnerabilities in the water supply chain. Conducting localized climate risk assessments for drinking water infrastructure. Improving water quality monitoring to better understand and adapt to changing water conditions. Prioritizing resilient infrastructure upgrades and redundancy to deal with intensifying climate variability. Capacity building and training for water utilities on climate-smart drinking water management. Organic matter in raw water to reduce the risk of Disinfection Byproducts DBP formation through a combination of organic matter and chlorine (or other oxidants/disinfectants) (Tan Hiep WSTP).

Conclusions

Vietnam remains vulnerable to the impacts of climate change on its water resources. The country is already experiencing the effects of rising temperatures, erratic precipitation patterns, sea-level rise, and extreme weather events such as droughts, floods, and saltwater intrusion. These climate-induced hazards are adversely affecting raw water sources like rivers, lakes, and groundwater, leading to reduced water quantity and deteriorating water quality. Water treatment plants across Vietnam are facing mounting challenges due to increased turbidity, organic matter, ammonia, manganese, and microbial contamination in raw water sources. To effectively treat this poorer quality

raw water across various stages like pre-oxidation, coagulation-flocculation, and disinfection, higher doses of coagulants, flocculants, oxidants, and disinfectants are required. Consequently, there is an increased risk of disinfection by-product formation due to higher oxidant use and the presence of organic precursors. Filtration processes are also impacted, with faster filter clogging, reduced filtration speeds, and more frequent backwashing needed due to high solids and organic loading. Furthermore, factors like higher temperatures and stagnation times are contributing to biofilm growth, bio-corrosion, and deteriorating water quality in distribution systems. To mitigate these risks and strengthen resilience, water treatment plants (WTPs) in Vietnam have taken various measures. These include adjusting treatment processes by increasing chemical doses, modifying hydraulic retention times, and employing additional oxidation/filtration steps. WTPs are also adopting new treatment technologies like membranes, activated carbon, and advanced oxidation to improve treatment efficacy.

Furthermore, utilities are enhancing monitoring of water quality, chemical usage, and treatment performance indicators. Risk assessments and climate-informed water safety plans are being developed to identify and manage vulnerabilities systematically. Efforts are underway to explore alternative water sources or implement supply/demand management strategies during droughts and floods. Additionally, collaborations with research institutions are being pursued to develop solutions like nanofiltrations for removing specific contaminants.

Key strategies recommended for the water supply sector in Vietnam involve conducting localized climate risk assessments and developing water safety plans for drinking water infrastructure. Upgrading treatment processes and implementing resilient technologies to handle degraded source water quality are also crucial. Improving water quality monitoring to detect changes and inform adaptive management is essential.

Prioritizing infrastructure upgrades, redundancy, and supply/demand management for climate variability is imperative. Building technical capacity through training on climate adaptation for water management is vital for utilities. Enhancing research collaborations can accelerate the development and adoption of climate-resilient solutions.

Overall, a multi-pronged approach involving infrastructure investments, operational adjustments, climate risk planning, and knowledge-building is needed to bolster the resilience of Vietnam's water supply systems against the intensifying impacts of climate change. By proactively addressing these challenges, Vietnam can ensure the provision of safe and reliable drinking water for its citizens, while safeguarding public health and promoting sustainable development.

3.4 Comparative Analysis of Water Management Strategies in Italy and Vietnam: Addressing Technological, Economic, and Environmental Challenges for Sustainable Development

In this item 3.2, all content found and synthesis from 2 surveys implemented in Italy and Viet Nam in 2023, focus on collect challenges identified by utility managers and the steps they have taken to address these challenges in both countries Italy and Vietnam. This comparative study will offer valuable perspectives on managing and treating water resources across different economic contexts, contributing to a broader understanding of sustainable practices in water treatment worldwide. The purpose of this multinational study aligns with goals of global development and sustainability by exploring how diverse approaches to water management can improve water quality not only within each country but also contribute to international advancements in sustainable water treatment.

The first objective is to gain a deeper understanding of the contrasting methods and strategies employed by developed and developing countries. This comparison provides insights into policy strategies and technological practices that could be adapted internationally to enhance water management systems, thereby contributing to the achievement of the UN Sustainable Development Goals (SDG), specifically Goal 6, which focuses on ensuring clean water and sanitation for all.

Secondly, the study focuses on identifying factors that influence water treatment processes, such as pre-oxidation. Despite the differing resources and management capacities in Italy and Vietnam, certain climate-induced issues-like increased oxidation demand and the production of disinfection by-products-can affect both countries. By comparing these factors, I hope to clarify which challenges are common to both and which are unique to each country.

The third aspect of this study is to examine how different management and operational systems impact water treatment and distribution processes. By evaluating these processes in both countries, we can identify areas for improvement, adjust operational approaches, and optimize treatment methods. Sometimes, complex systems in developed nations can benefit from the simplicity of methods used in developing nations and vice versa.

Fourth, the study considers social, economic, and environmental factors. We can confirm that Italy, with a stronger financial foundation, can invest more in advanced treatment technologies like membrane filtration and UV disinfection, whereas Vietnam often relies on more basic treatment methods due to budget constraints.

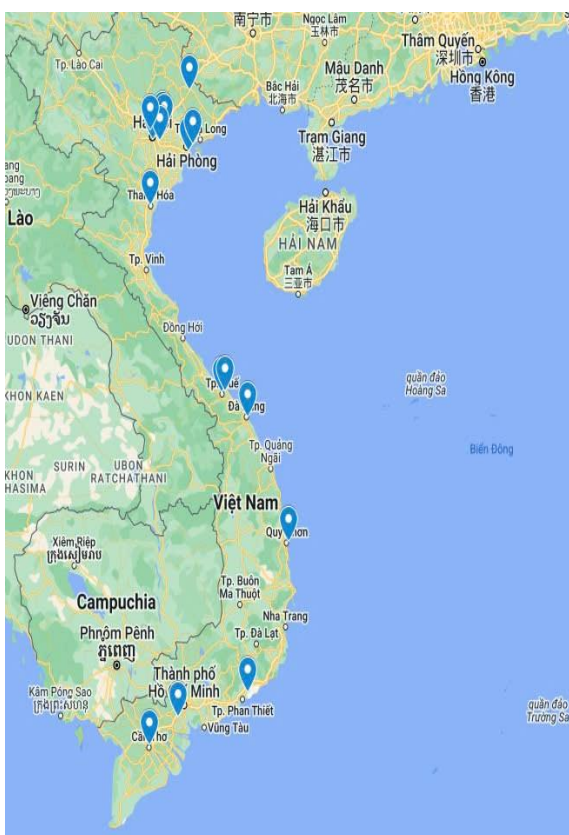


Figure 3. 18 Vietnam 331,212 km² with coastlines 3,260 km

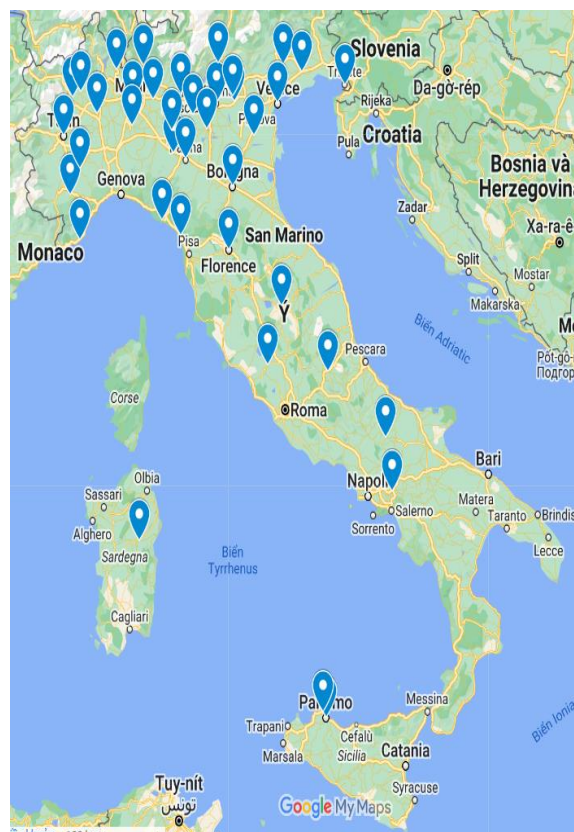


Figure 3. 19 Italy 301,340 km² with coastlines

Additionally, cultural and behavioral aspects around water usage vary. Italians may have greater awareness of water conservation, while water consumption patterns differ across regions in

Vietnam, shaped by local habits and awareness levels. Technical differences also emerge: Italy has access to advanced technologies, such as membrane filtration, Ozone, UV which are not widely available in Vietnam due to higher costs. Italy's sophisticated water quality monitoring systems, which use real-time sensors to monitor pH, turbidity, and redox, conductivity, oxidation levels..., contrast with Vietnam's reliance on manual or less frequent monitoring due to regulatory limitations.

Environmental and climate factors also play a role. IPCC scenario A1 water availability by 2050, compared to the baseline average from 1961 to 1990, based state that water stress in both of country

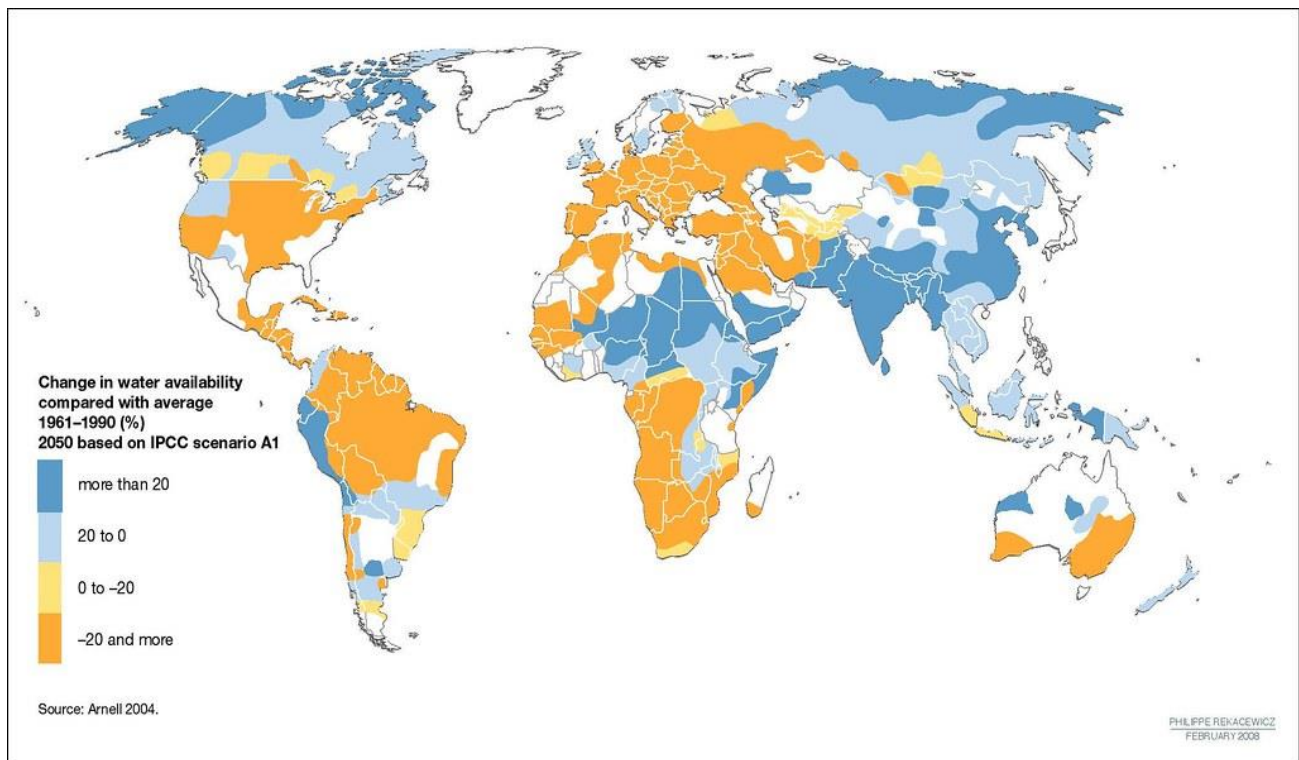


Figure 3. 20 Map 1: Change in water availability compared with average 1961-1990(%) 2050 based on IPCC scenario A1

Although both countries share similar areas more Vietnam's tropical climate heightens the demand for disinfection to control microbial growth, whereas Italy faces different challenges, such as water treatment needs in colder regions. Furthermore, Italy's input water sources may be better protected and monitored, whereas Vietnam's raw water sources may face industrial or agricultural pollution challenges.

Finally, regulatory standards and governance are critical. Italy's stringent regulations ensure high public health protection, for example Turbidity in the raw water in groundwater source under 1 NTU (95% sample<0.3 NTU or no sample>1 NTU) while Vietnam's standards may be less strict or less rigorously enforced. For instance, in Vietnam, water supplied to households meets basic standards for general use but may not yet fully meet drinking water quality standards.

3.4.1 Type of Raw Water Sources Used

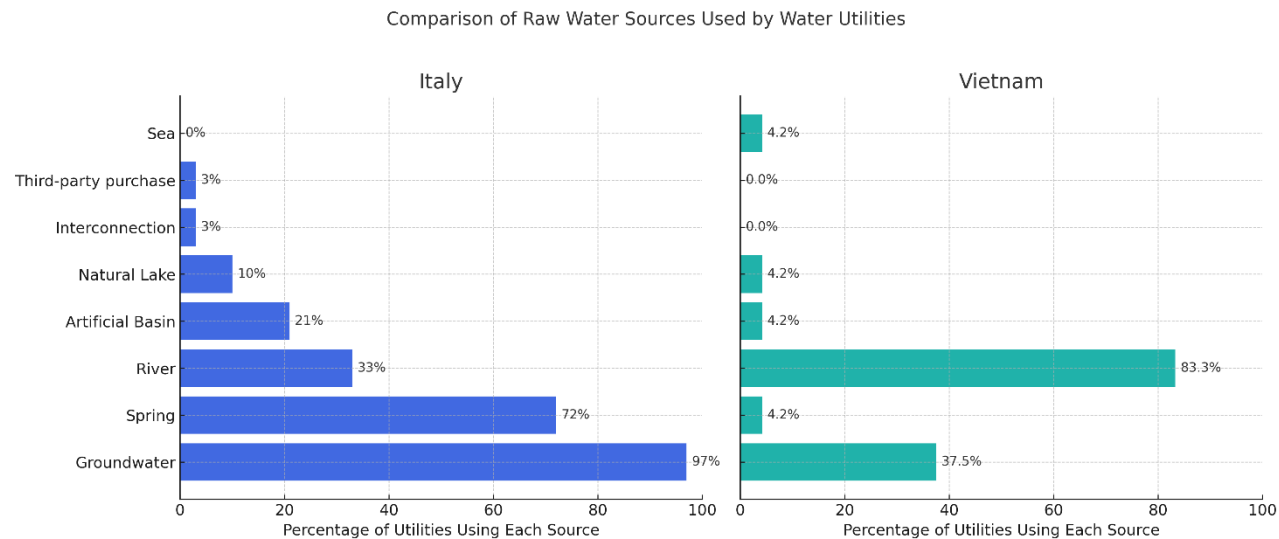


Figure 3. 21 Comparison of raw water source usage by Utilities in Vietnam and Italy

Italy: Italian water utilities primarily rely on groundwater and spring water, with some regions also using rivers and artificial reservoirs. Northern Italy, in particular, benefits from groundwater fed by glacial melt, while central and southern Italy are more reliant on reservoirs and rivers.

Vietnam: Vietnamese utilities predominantly use surface water sources like rivers (especially the Red River and Mekong River), alongside groundwater in certain regions, especially where surface water access is limited. Groundwater is crucial in dry season water-scarce areas, such as mountainous regions and the Central Highlands.

Comparison: Italy’s reliance on springs and groundwater differs from Vietnam’s heavier use of rivers, highlighting geographic and climate differences that influence water sourcing.

a. Rivers:

Vietnam: The primary sources of water for many water treatment plants (WTPs) in Vietnam are major rivers like the Red River and Mekong River, which supply about 83.3% of water. River water is abundant and relatively easy to extract but often has high sedimentation and microbial contamination. Seasonal changes significantly impact water quality, increasing turbidity during heavy rains (Pham et al., 2023)

Italy: Italy uses rivers as one of its raw water sources, though less extensively compared to other sources like aquifers. One manager, G5, extracts 61% of water from rivers. .(list Utilities in annex 2)

b. Groundwater and Aquifers:

Vietnam: Groundwater is crucial, especially in regions with water scarcity during the dry season, covering 37.5% of WTPs. It covers about 37.5% of water sources for utilities, especially where rivers are not accessible. However, saline intrusion in coastal areas challenges groundwater quality.

Italy: Groundwater is the most extensively used source, with 97% of surveyed managers relying on aquifers. This preference is due to groundwater’s lower contamination levels and

consistency, though Italy faces significant depletion and contamination risks from climate-induced droughts. (Maurizio Barbieri et al., 2021)

c. Springs:

Vietnam: Spring water is utilized by a smaller percentage (4.2%) of utilities, typically in rural and mountainous regions. Springs are vulnerable to seasonal variability, with low flow in dry seasons impacting their reliability as a water source.

Italy: Springs are a common supplementary source alongside aquifers, used by 28 companies. These sources also experience seasonal variability, especially increased microbial contamination following heavy rainfall events. (Besmer et al., 2017)

d. Lakes and Artificial Reservoirs:

Vietnam: Lakes are minor yet valuable sources, primarily supporting utilities in northern Vietnam. Contaminants such as organic material and algae, exacerbated by rain-induced runoff, often increase treatment complexity.

Italy: Reservoirs, G12 like Lake Como, provide strategic reserves for Italian utilities, offering resilience during dry periods. Italian utilities face challenges with sediment accumulation in reservoirs, which reduces storage capacity, and with algal contamination during warmer seasons.

e. Sea and Coastal Areas (for desalination):

Vietnam: Coastal sources are not widely utilized for drinking water but are critical for other applications like aquaculture. However, some coastal areas face challenges with saline intrusion, impacting groundwater sources.

Italy: Italy does not use seawater directly for drinking water; instead, certain utilities connect with other systems or third-party sources to supplement supplies, especially in coastal regions facing salinity issues. (Ministry for the Environment, Land and Sea., 2022)

3.4.2. Effect of Climate Change on Water Sources

Italy: Italian utilities report reduced water levels across groundwater, rivers, and reservoirs, largely due to prolonged droughts, particularly in the southern and central regions. Increased microbial and algal contamination from warmer temperatures and reduced water flow is also common.

Vietnam: Climate change effects include droughts and extreme rainfall that cause seasonal fluctuations in water availability. Increased turbidity and contamination with organic pollutants, ammonia, and heavy metals are seen, especially during the rainy season when flooding exacerbates pollution.

Comparison: Both countries experience water shortages due to drought, but Italy's issues are more consistent across the year, while Vietnam faces seasonal extremes that vary between the dry and wet seasons.

3.4.2.1. Phenomena on water source in Italy and Vietnam

Italy, while geographically different from Vietnam, also grapples with climate-induced changes that affect its water sources, particularly in the context of droughts, floods, and contamination challenges. The country's varied climate zones, from the Alps to the Mediterranean coast, create diverse climate impacts on water resources. Key Observations based on Figure 3.1 and Figure 3.9 Temperature Increase and Increase in Precipitation Intensity:

Both phenomena show significantly higher values in the Italy data (45%) compared to the Vietnam data (26.08% and 4.3%, respectively), indicating a perceived increase in their impact.

Increase in Drought Periods:

Drought periods are shown to have the highest impact in the Italy data at 88%, compared to 34.7% in the Vietnam data, emphasizing how crucial this factor is for WSTP operations.

Flood Phenomenon:

The Italy data highlights a greater impact of floods (33%) compared to the Vietnam data where storms/flooding were at 13.4%, suggesting a heightened concern for flood events.

Differences in Reporting for Other Phenomena:

Several phenomena (such as alluvial events and sea level rise) are not represented in the additional dataset, indicating either a different focus in data collection or perceived relevance. This chart allows for a clear comparison, highlighting which climate phenomena are gaining more attention or are considered more impactful in different datasets.

Climate-Related Phenomena Impact Levels on Water Resources in Vietnam

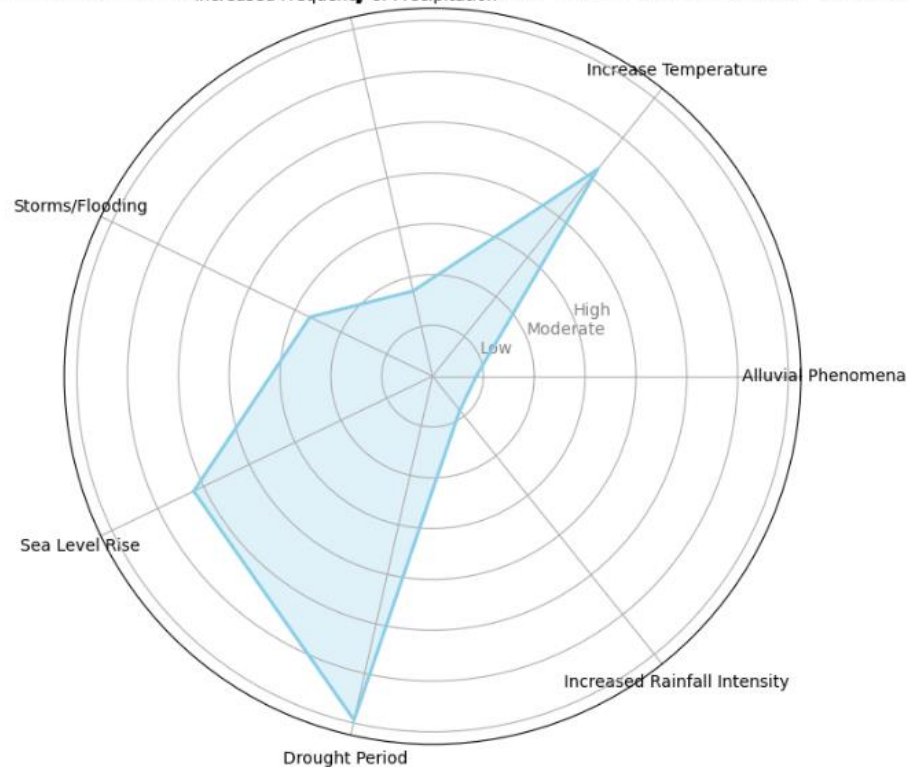


Figure 3. 22 Radar chart Impact level of climate - related phenomena on water source in Vietnam by Utilities

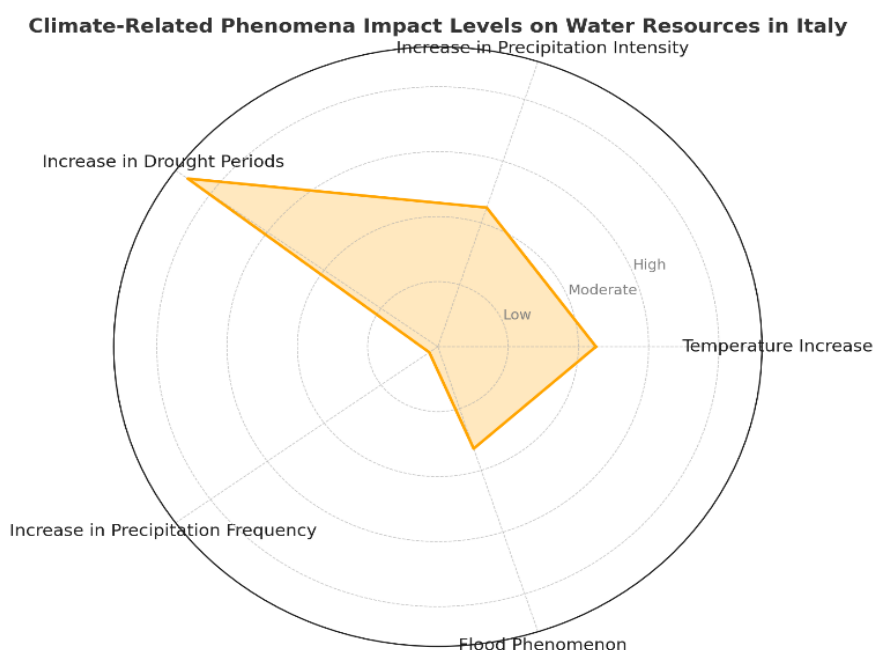


Figure 3. 23 Radar chart Impact level of climate - related phenomena on water source in Italy by Utilities

3.4.3 Effects on Individual Treatment Processes

This research focuses on identifying the root causes of the problem, i.e. the factors that influence pre-oxidation in the water treatment system. Although the conditions and management capabilities in the two countries are different, many of the phenomena that affect water quality (such as increased oxygen demand or increased disinfection by-products) can occur in both countries. Therefore, the comparison helps clarify which factors are common and which factors are unique to each country.

Beside identifying system factors and impacts in the water treatment chain, this comparison also helps the study better understand how system factors and management processes affect water quality in the treatment and distribution chain. By looking at two different systems, the study can show the differences in management practices, thereby identifying factors that can be improved or adjusted to optimize water treatment in both systems. Sometimes, more developed or complex systems can learn from simpler systems and vice versa.

3.4.3.1. Pre-oxidation

Table 3. 4 Investigate Percentage of Utilities Impact Climate change on Pre oxidation stage

Impact on Pre-Oxidation Stage	Percentage - Italy	Percentage - Vietnam
Increased Oxidant Demand	91%	41%
Increased Hydraulic Residence Time (HRT)	9%	40.9%
Increase in Disinfection By-Products (DBPs)	27%	13.6%
Reduction in Hydraulic Residence Time (HRT)	9%	13.6%
Other	9%	

Climate change has significantly impacted pre-oxidation processes in table 3.3 in both Italy and Vietnam, leading to notable shifts in water treatment practices. In Italy, 91% of utilities (36 out of 40) reported a substantial increase in oxidant demand, such as chlorine and ozone. This surge is

primarily driven by higher levels of organic pollutants, algal growth, and contaminants associated with warmer temperatures and increased organic loads. Similarly, in Vietnam, 41% of utilities (8 out of 20) experienced a rise in oxidant demand due to the challenges of treating elevated organic matter and managing algal by-products.

Hydraulic Residence Time (HRT) has also been affected. In Italy, 9% of utilities reported an increase in HRT to accommodate higher organic content and warmer influent water, which requires more contact time for effective oxidation. Conversely, another 9% of utilities reduced HRT, likely due to lower water levels or throughput demands. In Vietnam, 40.9% of utilities increased HRT in response to deteriorating water quality, necessitating extended contact time for effective pre-oxidation.

Disinfection By-Products (DBPs) have become a growing concern. In Italy, 27% of utilities observed an increase in DBP formation, a consequence of higher oxidant doses and specific water conditions that promote their development. This not only poses health risks but also complicates subsequent treatment stages. In Vietnam, 13.6% of utilities reported DBP formation during pre-oxidation, likely due to increased organic matter and higher oxidant doses.

Interestingly, a reduction in HRT was also reported in both countries, with 9% of Italian utilities and 13.6% of Vietnamese utilities shortening residence times. This is possibly driven by the need for faster processing due to reduced water flows or pressures to maintain efficiency despite changing water quality conditions.

In summary, the data highlight three major trends influenced by climate change: higher oxidant demand due to increased organic loads and algal growth; variable HRT adjustments, reflecting the need to balance treatment efficiency with resource availability; and increased DBP formation, requiring careful monitoring to mitigate health risks. These climate-induced changes are driving significant adjustments in pre-oxidation stages, compelling water utilities in both Italy and Vietnam to adapt chemical dosing and processing times. This not only elevates treatment costs but also introduces potential health concerns. To mitigate these impacts and ensure a safe, reliable water supply, investments in adaptive treatment technologies and consistent monitoring are essential.

3.4.3.2 Coagulation/Flocculation

Total Italy utilities responses to climate impacts on the coagulation-flocculation treatment stage:

- Increased demand for coagulants and flocculant: Both received the highest responses, with 11 utilities (31.4%) reporting impacts in these areas.
- Increase in turbidity of influent water: Reported by 4 utilities (11.4%).
- Increased hydraulic residence time (HRT): Reported by 3 utilities (8.6%).
- Others: Reported by 6 utilities (17.1%).

This visualization highlights which impacts are most commonly reported across utilities, with the increased demand for treatment of chemicals (coagulants and flocculants) being the most significant.

Vietnam

Most of them showed an increase in influent water turbidity, leading to a greater demand for coagulants and flocculants (in the examined cases, iron FeCl_2 , FeCl_3 , poly aluminum chloride (PAC))

and FeSO_4). Variations in hydraulic retention time, also detected during pre-oxidation, are due to fluctuating incoming flow rates. Plant C4, which treats lake water (from Lake Quao), noted increased turbidity of influent water due to increased algal contamination. When Plant C4 experienced a significant decrease in treated water's physical-chemical and microbiological characteristics, they reduced the flow rate to ensure compatibility with drinking water standards before distribution. This reduced flow rate increased the hydraulic residence time in the flocculation-flocculation tank (with the same accumulated volume, a lower flow rate increases retention time).

Italy: In the coagulation-flocculation phase, 14 managers observed climate change effects, making it one of the most impacted sections. Most reported increased water turbidity and higher demand for coagulant and flocculant (such as ferrous chloride, ferric chloride, aluminum polychloride, and/or ferrous sulphate). Changes in hydraulic residence time, noted earlier in the pre-oxidation phase, were attributed to incoming flow variations.

G12, treating lake water, noted increased turbidity due to algal contamination. G26 observed decreased coagulant demand due to lower turbidity in springs following reduced precipitation during a dry spell. G4 highlighted the need to reduce water flow rates during significant deteriorations in treated water quality to ensure compatibility with drinking water standards. This reduction prolongs hydraulic residence times in the coagulation-flocculation

3.4.3.3 GAC filtration

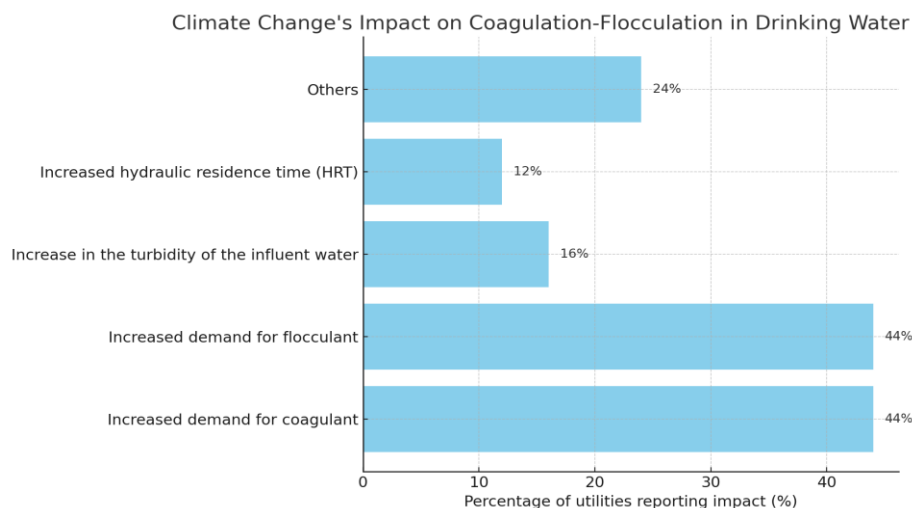


Figure 3. 24 Climate change Impact on Coagulation – Flocculation in Drinking water treatment plants

Italy: Italian utilities report increased loads of suspended solids, reducing filtration efficiency and necessitating frequent maintenance.

In the table 3.5, in the filtration phase using activated carbon, commonly found in the water purification plants in question, granular activated carbon (GAC) filtration is predominant, with some cases utilizing powdered activated carbon (PAC). Seven managers reported an increase in suspended solids load in incoming water at this stage. Additionally, two plants noted an increase in dissolved pollutants entering the GAC filter, while another two reported a decrease in water-GAC contact time (EBCT), typically associated with increased water flow.

Vietnam: Filtration processes are impacted by fluctuating turbidity levels, requiring additional backwashing and adjustments in filtration speed to maintain water quality standards. Seven managers reported an increase in suspended solids load in incoming water at this stage. Additionally, two plants

noted an increase in dissolved pollutants entering the GAC filter, while another two reported a decrease in water-GAC contact time (EBCT), typically associated with increased water flow.

Table 3. 5 Climate change Impact on filtration phase on GAC treatment in Drinking water treatment plants

Filter Parameter	Percentage (19 Utilities in Vietnam)	Percentage (40 utilities in Italy)
Increase in loading of suspended solids entering the GAC filter	10%	70%
Increase in loading of dissolved pollutants entering the GAC filter	30%	10% (4 Utilities)
Increase in Empty Bed Contact Time (EBCT)	0%	20%
Decrease in Empty Bed Contact Time (EBCT)	10% (2 Utilities)	0%

3.4.3.4 Disinfection

Italy: The final disinfection phase I figure 3.25 which is the most used treatment, received the most responses regarding effects attributed to climate change. Companies primarily employ sodium hypochlorite (NaClO), chlorine dioxide (ClO₂), and, in some instances, ultraviolet (UV) radiation as disinfectants.

Responses from 18 managers are depicted, with over half reporting an increased demand for disinfectants and around a third noting heightened microbiological contamination in incoming water. Another observed parameter was the increase in disinfection by-product (DBP) formation and their inlet concentration. Additionally, there were reports of a lesser extent of increased hydraulic residence time.

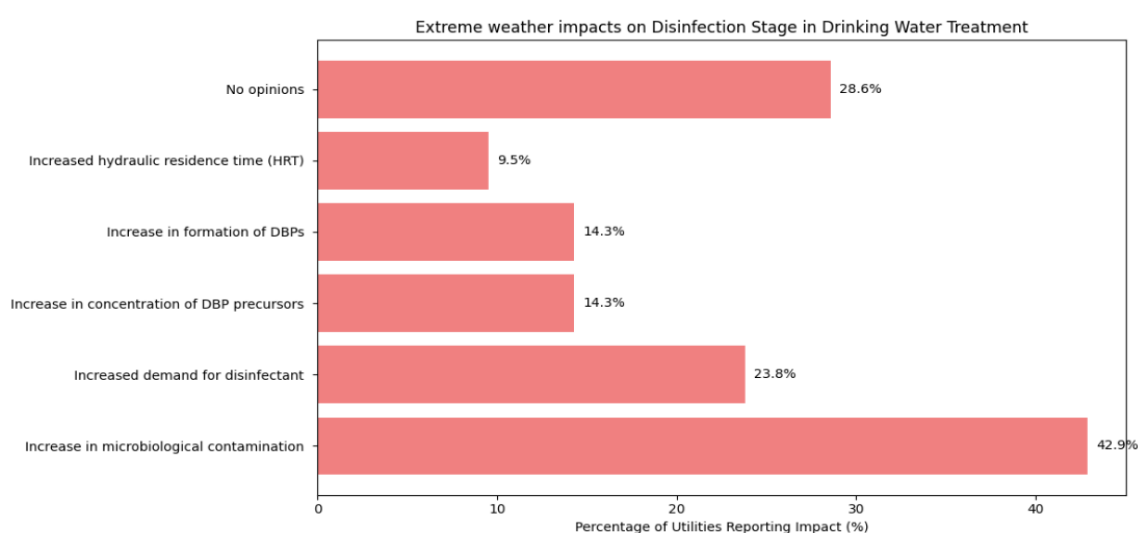


Figure 3. 25 Extreme weather impact on filtration phase on disinfection stage in Drinking water treatment plants

3.4.3.5 Effects on Distribution System

Temperature increases, reported by 65% of utilities, represent the most significant impact on water distribution systems, likely contributing to related issues such as biofilm growth and heightened microbial activity. Both the increased consumption of disinfectants and variations in microbiological water quality stand at 35%, underscoring concerns about microbial contamination and the need for intensified chemical treatments. Bio-corrosion of pipes, affecting 38.1% of systems, reflects the combined effects of biofilm accumulation and corrosive conditions, leading to potential infrastructure degradation. Meanwhile, the increased formation of disinfection by-products (DBPs) and biofilm growth each have moderate impacts, reported by 18.9% of utilities. Changes in chemical water quality are noted by 22%, while other miscellaneous impacts account for 9.8%. This data provides a comprehensive overview of how climate change and source water variations affect distribution systems, emphasizing critical areas that require monitoring and adaptation to maintain water quality and infrastructure integrity.

In Italy, utilities report rising water temperatures within distribution networks, leading to increased biofilm formation, bio-corrosion, and higher disinfectant consumption. These changes occasionally result in non-compliance with microbial standards. In Vietnam, distribution systems face similar challenges with biofilm growth and bio-corrosion, driven by warmer temperatures and fluctuating water chemistry, particularly after droughts that concentrate contaminants. Disinfectant residuals in Vietnam vary significantly, causing inconsistent water quality.

When comparing the two countries, both face biofilm and corrosion issues in their distribution systems due to climate change. However, Italian utilities report more consistent temperature-driven changes, while Vietnamese utilities experience greater seasonal variability, particularly influenced by extreme weather events like droughts.

3.4.3.6 Control Measures

Italy

In response to the problems generated by climate change on treatment and distribution systems, companies have implemented various control measures. These range from general evaluations of the issue to the use of existing procedures and the introduction of new systems tailored to address these challenges.

Many managers are conducting intensive studies and monitoring to better understand the problem's implications. Some have introduced new management procedures, including water safety plans (WSP), to assess risks and mitigate impacts. Others have implemented new technologies to manage climate-related problems.

For example, G1 is studying groundwater levels and flow rates and is considering installing online probes to monitor source turbidity (real time sensor). G5, despite not directly detecting climate change effects, has undertaken interconnection activities between aqueduct systems to ensure water service reliability during shortages.

G6 addressed ammonia alterations with a biological BAC refinement system and implemented measures to manage bromide increase. G14 introduced new procedures for preventive visits to turbidity meters and extraordinary network sampling during weather alerts. G15 activated water distribution with tankers due to drought phenomena and implemented tank cleaning procedures.

G17 is intensively studying and monitoring the issue, increasing sampling and laboratory analysis, and conducting local hydrogeological studies. G18 is studying new deep aquifer sources and considering the use of reverse osmosis filters. G21 built a bypass to ensure water supply from alternative plants during droughts.

G23 enhanced monitoring networks with electronic meters and IoT systems, reducing losses and enabling better management during summer. G28 rented a mobile reverse osmosis unit to combat rising salt wedges in the Po river. G32 upgraded purifiers with inert filters and increased hydraulic connections between networks to ensure supply during crises.

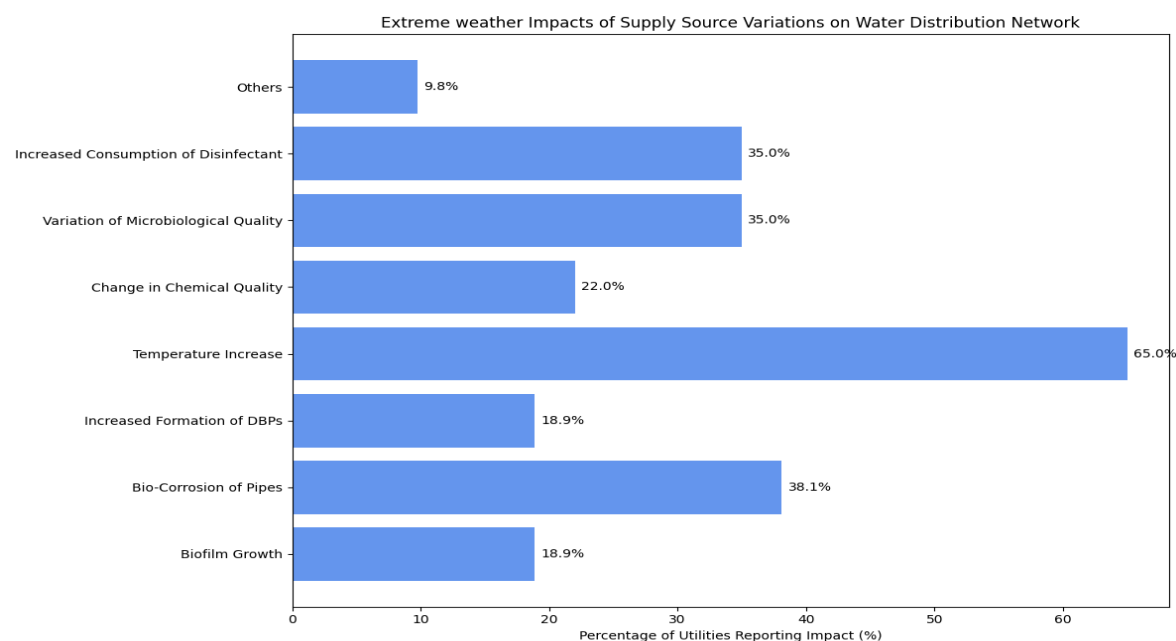


Figure 3. 26 Exteme wether impacts of supply source variation on water distribution network

Furthermore, G35 installed a bypass between critical sources and released potable water at another plant to serve utilities. Overall, these measures aim to ensure the continued supply of safe drinking water in the face of climate change challenges.

Vietnam

Vietnam: Vietnamese utilities focus on enhancing monitoring, improving treatment technologies (e.g., activated carbon filtration), and collaborating with research institutions to develop adaptive technologies like nanofiltration for specific pollutants. Water Safety Plans and localized climate risk assessments are also being developed to strengthen resilience.

Our paper is well-structured, providing a detailed comparative analysis of the challenges and climate impacts on water utilities in Italy and Vietnam. Here are some observations and suggestions for enhancing its clarity and engagement:

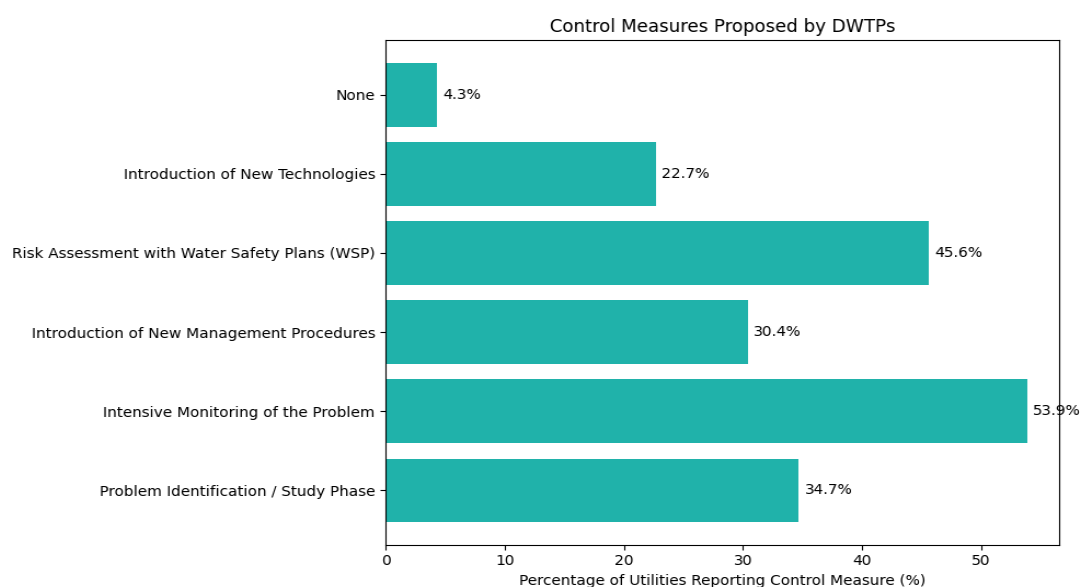


Figure 3. 27 Control measure proposed by DWTPs

This comparative study provided valuable insights into the diverse approaches to water management employed by utilities in Italy and Vietnam. The analysis underscores that while both countries face significant climate-related impacts on their water supply and treatment processes, the specific challenges they encounter differ due to geographic and economic contexts.

Italy Utilities in this survey predominantly relies on groundwater and spring water, while Vietnam depends more heavily on surface water from major rivers like the Red River and Mekong. Both countries confront issues related to droughts, floods, and water quality deterioration. However, Vietnam's tropical climate leads to more extreme seasonal fluctuations, creating unique challenges for water availability and quality during the wet and dry seasons. In response, utilities in both Italy and Vietnam have implemented control measures such as enhanced monitoring, the development of alternative water sources, and upgrades to treatment processes to protect water supply and quality.

A critical takeaway is the need to adapt treatment processes to handle climate-induced changes. Utilities in both countries have reported increased oxidant demands, variability in hydraulic residence times, and a rise in disinfection by-products during key stages like pre-oxidation, coagulation-flocculation, and final disinfection. To address these challenges, both Italian and Vietnamese utilities are increasingly turning to advanced technologies, optimizing treatment conditions, and enhancing monitoring systems.

The study also highlights the differences in resource availability and regulatory frameworks between the two countries. Italian utilities, benefiting from a stronger economic base, are able to implement more sophisticated treatment technologies and infrastructure. In contrast, Vietnam, working within tighter budget constraints, often relies on more cost-effective and basic treatment solutions. These contrasts provide important insights into how water management practices can be adapted to suit local resources and conditions while still supporting global sustainability goals.

In conclusion, this study emphasizes the need for water utilities around the world to proactively assess climate risks, build adaptive capacity, and adopt innovative yet locally appropriate strategies to ensure the resilience of water resources and treatment systems. The experiences of Italy and Vietnam offer valuable lessons that can inspire water management practices globally, as

communities work toward achieving the UN Sustainable Development Goal of ensuring universal access to clean water and sanitation.

3.5 Conclusion

Chapter 3 explores the effects of climate change on drinking water supply systems (DWSS) in Italy and Vietnam, with a focus on managerial adaptation strategies. Using a mixed-methods approach, primarily through surveys, the study gathers insights from 40 Italian and 19 Vietnamese water utilities. It examines how climate change influences raw water sources, treatment processes, and distribution networks while evaluating the control measures implemented in response.

The study adopts a full-chain approach, analyzing climate impacts across all stages of water treatment rather than just raw water intake. Surveys were distributed to utility managers in both countries, collecting data on water sources, supply capacity, climate change effects on water quantity and quality, impacts on treatment and distribution systems, and adaptation measures taken by utilities. The findings highlight significant climate-related challenges in both nations, with common issues such as droughts, flooding, rising temperatures, and water quality deterioration. In Italy, climate change has reduced water availability, increased microbial contamination, and led to a higher demand for water treatment chemicals. Prolonged droughts and altered precipitation patterns have affected aquifers and reservoirs, while rising sea levels threaten coastal groundwater sources. Meanwhile, in Vietnam, particularly in the Mekong Delta and other coastal regions, flooding, salinity intrusion, and declining water quality have become major concerns. Water treatment plants must contend with rising turbidity, organic matter, and microbial contaminants resulting from extreme weather events.

Climate change affects all major stages of water treatment, requiring utilities to adjust their processes. In pre-oxidation, increasing organic loads have raised oxidant demand, particularly for chlorine and ozone. In coagulation/flocculation, turbidity levels have risen, necessitating a higher usage of coagulants and flocculants. Filtration efficiency has declined due to increased suspended solids and microbial contaminants, while disinfection processes now require more disinfectants, increasing the risk of disinfection by-product (DBP) formation. Additionally, in distribution networks, rising temperatures accelerate chlorine decay, promote biofilm growth, and increase pipe corrosion, creating further challenges for water utilities.

To mitigate these issues, utilities in both countries have implemented various control measures and adaptation strategies. Enhanced monitoring through real-time tracking of turbidity, microbial contaminants, and disinfectant residuals allows for quicker responses to climate-induced changes. Upgrading treatment systems with advanced filtration technologies (such as membrane filtration and activated carbon) helps address emerging water quality challenges. Strengthening infrastructure resilience, including reinforcing pipelines, increasing reservoir capacity, and interconnecting water systems, is another critical adaptation strategy. Additionally, utilities are focusing on regulatory compliance, updating water safety plans (WSPs), and adjusting treatment strategies to meet evolving climate and water quality regulations.

Despite differences in economic development and technological capacity, in this research scope Italy and Vietnam face similar climate-related water management challenges. Italy primarily relies on groundwater and spring sources, whereas Vietnam depends more on rivers. While Vietnam experiences extreme weather fluctuations, Italy faces prolonged droughts and snowmelt variability. Italy benefits from advanced treatment technologies, while Vietnam focuses on cost-effective

solutions due to financial and technological constraints. Furthermore, Italy enforces stricter water quality regulations, whereas Vietnam struggles with policy implementation challenges due to rapid urbanization and resource limitations.

In conclusion, the study highlights the urgent need for climate adaptation in DWSS. Without proactive measures, climate change will lead to water shortages, degraded water quality, and increased stress on treatment infrastructure. Future research should focus on integrating climate risk assessments, real-time monitoring technologies, and adaptive treatment processes to enhance the resilience of drinking water systems in both developed and developing nations.

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CHAPTER 4: SUB CHAPTER OF NATIONAL SURVEY AND PRESENTATION OF CASE STUDIES

This chapter presents phase two of a national survey conducted to evaluate the effects of climate change on drinking water supply systems. The survey is part of the activities of the research subgroup 'Water intended for human consumption' under the Working Group 'Management of purification plants' of the University of Brescia. The overall aim was to identify technological and managerial solutions to ensure high standards of water safety under climate risks.

The survey was structured in two phases: phase one consisted of a multiple-choice questionnaire, while phase two involved online interviews, document collection, and, where possible, technical visits. Phase one findings were previously reported in a thesis by Matteo Donghi, with contributions from the present candidate. In this thesis, the candidate contributed by analyzing the full dataset collected during phase one, identifying relevant utilities for case studies, and synthesizing their reported anomalies and mitigation strategies into comparative case profiles. The candidate also collaborated in reviewing technical documents, cross-checking data from utility reports and annexes, and organizing the material into structured narratives. All technical data presented in the tables (e.g., raw water quality parameters, treatment plant performance) were provided by the water utilities during phase two of the survey in 2023, either through follow-up interviews or via internal reports. This chapter presents a synthesis of the most representative cases, including: The survey engaged approximately 40 companies, with most participants concentrated in Northern Italy. Of these, 33 managers identified anomalies linked to climate change, such as decreases in water levels and increases in chemical and microbiological contamination of springs and groundwater. Flooding led to increased turbidity and a corresponding rise in reagent demands within treatment processes. Other issues included elevated temperatures, biofilm growth in distribution systems, and occasional regulatory non-compliance, particularly concerning Legislative Decree No. 31/2001. Solutions ranged from intensive monitoring to adopting advanced technologies and implementing Water Safety Plans (WSPs), as encouraged by recent regulations such as Legislative Decree no. 18/2023 and Law no. 68 of 13 June 2023. These findings underscored the need for in-depth case studies.

The data collected during phase one was used to create Google data to facilitate phase two. This database enabled cross-comparisons of information provided by integrated water service managers. From these analyses, 23 managers were identified as key subjects for further investigation, leading to the creation of a Detailed Database.

In this sub chapter, my involvement extended to phase one activities conducted in Vietnam, where I surveyed and collected responses relevant to local drinking water supply systems. However, due to limited scope under PON program and time constraints, I was unable to conduct on-site visits or further work during phase two in Vietnam. Instead, I focused on contributing to discussions and analysis of the data collected.

My contributions during the second phase were complemented with Erick, a master's student, we participated in technical visits to selected facilities. These visits were instrumental in validating the data collected in phase one and allowed for direct observation of the practical challenges faced by water treatment operators. Together, Erick and I analyzed specific cases of anomalies observed in

various facilities, discussing potential technological and procedural solutions with operators. This hands-on collaboration enriched the research by integrating field observations with database analyses.

The selection of case studies for phase two was based on cross-referencing the managers' responses, related attachments, and publicly available company information. This targeted approach ensured the representation of diverse supply sources and the most significant cases. The findings, along with accompanying images and diagrams from the technical visits, are included in the annex to provide a comprehensive understanding of the methodologies and results. Additionally, this chapter offers readers insights into various design techniques, enabling informed decision-making in addressing the impacts of climate change on water supply systems across different regions. These collaborative efforts reflect the integrated approach required to address the complex challenges posed by climate change in drinking water supply systems.

- Acque Venete S.p.A.
- Municipalized Water Company of Palermo (AMAP) S.p.A.
- Hera Group S.p.A.
- Padania Acque S.p.A.
- Metropolitan Water Company of Turin (SMAT) S.p.A.

4.1 Acque Venete S.P.A. (Rovigo)

This subchapter presents the case study of Acque Venete, which ensures the integrated water service for the area identified by the ATO (Optimal Territorial Area) Polesine (covers areas in Rovigo, Veneto) and the southwestern portion of ATO Bacchiglione (covers parts of Padua and Vicenza). The operator guarantees the drinking water needs of 108 municipalities located in the provinces of Padua, Rovigo, Verona, Vicenza, Venice, serving a user base of 520,000 inhabitants for a territorial extension of 3200 km². The area served includes many medium-small sized towns, including the largest, the municipality of Rovigo with approximately 50,000 inhabitants. The morphology of the territory is varied: there are plain areas, belonging to the hydrographic basins of the Po, Adige and Bacchiglione, hilly areas and coastal areas of the province of Rovigo, including the mouths of the Po and Adige rivers. In the presentation of this case study, we will focus on the Boara Polesine Water treatment Plant whose supply source is the Adige River, and the Ponte Molo Power Plant whose supply source is the Po River.



Figure 4. 1 Territorial framework of Acque Venete S.P.A. Source: Google Maps & Google Earth

4.1.1 Supply System Accque Venete

The supply sources from which Acque Venete captures water are multiple: direct withdrawal of river water (Adige and Po), extraction from the underground aquifer by means of wells, interception from springs located in hilly and piedmont areas and external supplies from other managers (purchase). In particular, 18.7 million m³ of water are extracted from the underground aquifer (26%), 32 million m³ of water come from surface water (45%), 10.3 million m³ come from springs (15%) and 10 million m³ of water are purchased from other operators (the remaining 14%). Surface water, by its nature, requires complex treatment chains. The operator in question manages 6 water purification plants whose source of supply is the Adige, 3 water purification plants whose source of supply is the Po.

In 2022, due to an exceptionally dry winter with minimal snowfall, there was a continuous decline in hydrometric levels and river flows throughout and leading up to the irrigation season. This resulted in both qualitative and quantitative impacts on the water extracted from the river. At the Boara Polesine and Ponte Molo water treatment plants, critical issues were identified concerning the changes in both the quality and quantity of water from the affected rivers.

4.1.2 Quality of Raw Water Accque Venete

Then, the quality of raw water is analyzed in relation to the supply sources from which the respective power plants draw water for drinking purposes, both located in the province of Rovigo.

4.1.2.1 Boara Polesine Water treatment Plant - Rovigo

The Adige River, situated in northeastern Italy, spans approximately 410 km with a drainage basin of

12,200 km². It originates near Lake Resia in Trentino-Alto Adige, flows through Merano, Bolzano, and Trento, longitudinal axis of Lake Garda, passes through Verona, traverses the Po Valley, Adriatic Sea near the By Delta Park. The river has an average flow rate of 235 m³/s at its mouth.

In general, water management authorities report good raw water quality, except for hydrogen ion concentration (pH). In the case study of the Polesine Water Treatment Plant, the primary concern is the anomalous variations in the pH parameter, indicating potential water quality fluctuations.

4.1.2.2 Ponte Molo Water treatment Plant - Po Cutting

The Po River, located in northern Italy, stretches 652 km drainage basin of 71,000 km². It originates from Monviso in Piedmont and flows across northern Italy, steps Lombardy and Emilia-Romagna, before reaching Veneto and emptying into the Adriatic Sea near the Po Delta Park (like the Adige River) maximum flow rate of 13,000 m³/s, an average flow rate of 1,540 m³/s, and an absolute minimum flow rate of 270 m³/s.

Regarding water quality, the Po River presents greater critical issues compared to the previously mentioned water source. In addition to a slightly elevated hydrogen ion concentration (pH), the chloride and conductivity levels significantly exceed the limits established by current regulations. Since conductivity represents the total ion concentration in water, high levels of chlorides, nitrates, and nitrites naturally correspond to elevated conductivity values.

The high chloride concentration is primarily attributed to the intrusion of the salt wedge, a phenomenon that will be explored in detail in the following sections.

4.1.3 Description of the plant Accque Venete

The detailed characteristics of the plants that are the object of the case study in question are reported below: the Boara Polesine water treatment plant and the Ponte Molo water treatment plant.

4.1.3.1 Boara polesine water treatment plant - Rovigo

The Boara Polesine Water Treatment Plant, located north-east of the Municipality of Rovigo, serves a user base of 70,000 inhabitants (PE). The inlet flow rate to the plant, which occurs through direct drawing from the Adige River by means of submersible pumps, is 292 l/s. The plant produces drinking water with an average flow rate of 285 l/s according to a pushed treatment reported as follows.

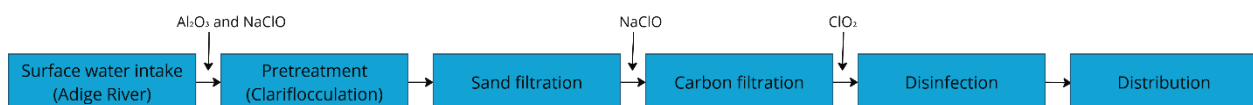


Figure 4. 2 Representation, by means of a block diagram, of the drinking water treatment chain – Fonte Acque Venete S.p.A.

As previously mentioned, the intake work from the Adige River consists of direct withdrawal by means of submersible pumps.

The subsequent treatment consists of two parallel tanks: a longitudinal decanter and a clariflocculator with three concentric circular stages. The clariflocculator operates as follows:

1. First Stage (Inner Crown - Coagulation): Chemical reagents are mixed with the water using a propeller turbine to initiate coagulation.

2. Second Stage (Middle Crown - Flocculation): Flocculation occurs, where particles aggregate into larger flakes.

3. Third Stage (Outer Crown - Sedimentation): Sedimentation takes place, allowing the flakes formed in the previous stages to settle undisturbed.

This operational setup, chosen based on practical experience, has proven more effective than clariflocculators with three in-line stages. During this treatment phase, sodium hypochlorite (15% solution) is used as an oxidizing agent, and alumina or aluminum polychloride (18% solution) is added as a flocculating agent.

Next, the water undergoes filtration through a granular medium, specifically sand. Following this, it is subjected to pressurized filtration using Biological Activated Carbon (BAC). Between these filtration systems, sodium hypochlorite is added again for further oxidation. Although the use of sodium hypochlorite before BAC filtration is generally discouraged due to its potential to disrupt the bacterial flora in the filters, the manager applies a very low dosage (1-2 µg/L) to achieve partial disinfection while maintaining effective filtration performance. Both filters undergo periodic backwashing, typically every 20 days.

After filtration, the water is disinfected with chlorine dioxide and stored temporarily in a storage tank before being distributed into the network. Parallel to the main water treatment process, a waste treatment line handles sludge, using a static thickener and mechanical dehydration via belt pressing.

4.1.3.2 Ponte molo water treatment plant – Taglio di po

The Ponte Molo Water Treatment Plant, located in the homonymous hamlet of the municipality of Taglio di Po, near the mouth of the Po, serves a user base of 25,000 inhabitants (AE). The inlet flow rate to the plant, which occurs through direct drawing from the river by means of submersible pumps, is 89 l/s. The plant produces drinking water with an average flow rate of 86 l/s according to a pushed treatment reported as follows.

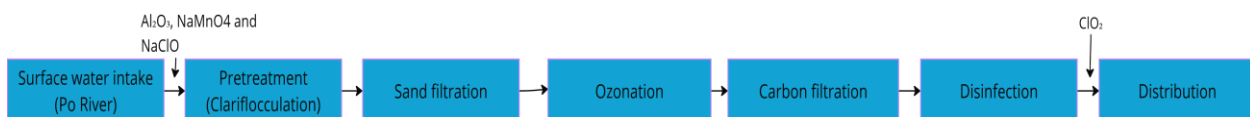


Figure 4. 3 Representation, by means of a block diagram, of the drinking water treatment chain – Fonte Acque Venete S.p.A

Finding a configuration very similar to that of the previous plant, we limit ourselves to highlighting the presence of any plant implementations. The intake work by means of direct withdrawal takes place on the Po River.

The subsequent treatment consists of a single clariflocculator with the same operating principle as the one present in Boara Polesine. In this phase of the treatment, in addition to the addition of sodium hypochlorite in a 15% solution (NaClO), as an oxidizing agent, and alumina or aluminum polychloride in a 18% solution (Al₂O₃), as a flocculating agent, sodium permanganate in a 20% solution (NaMnO₄) is added, implementing the already present oxidizing agent.

The same management aspect is found for the two filtration units, on granular support and on active biological support.

The further oxidation planned between the two filtering systems is different, carried out by means ozone (ozonation treatment).

The disinfection treatment, the presence of the storage tank, as well as the treatment of the waste products (sludge) in the specific parallel line, are based on the same technical-managerial and plant criteria described in the previous paragraph.

4.1.4 Anomalies detected and strategies implemented in Accque Venete

The operator finds phenomena related to climate change with consequent alterations to the drinking water supply systems; in particular, it observes an increase in dry periods, an increase in temperatures, and, in the case of meteoric precipitation phenomena, an increase in intensity and unpredictability. The anomalies found concern rivers, where it is usual to find a reduction in the water level and an increase in microbial contamination, and the sea, where the level and consequently the flow rate have increased (rising of the sea from the mouth of the river, resulting in chemical pollution in the river used by the operator as a source of supply). An increase in turbidity is reported, however, to date, this parameter is not representative of the main anomalies recorded in the plant. For example, in Adige, turbidity values of around 90/100 NTU at most have been found despite intense meteorological events. This phenomenon may be connected to the fact that, before the intense meteorological events, the Alpine basins were half filled. Therefore, before the downstream flow, the Alpine basins filled. The intense phenomenon was thus attenuated by this “benefit”. As regards the plants, the operator observed an increase in the demand for oxidant, coagulant and flocculant, an increase in turbidity at the inlet to the clariflocculators, a decrease in the filtration speed and an increase in the formation of disinfection by-products (DBPs). In the network, these anomalies manifested themselves through biofilm growth and changes in microbiological quality. The operator promptly adopted management procedures to deal with some anomalies, explained in detail in the following paragraphs.

4.1.4.1 Boara Polesine Water treatment Plant - Rovigo

At the supply source, the Adige River, sudden changes in pH were found. These variations are correlated both with the hydrometric levels measured by ARPAV (Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto), near the intake structure, and with the water temperature recorded directly in the water treatment plant. In particular, the manager finds an inversely proportional correlation between pH and the parameters mentioned above. The manager interprets this relationship by referring to the flow rate of the water inside the river. In fact, low hydrometric levels generally correspond to low flow rates and consequently low flow rates passing through the section of the riverbed. In these circumstances, the water temperature tends to increase and with it also the organic matter present.

In the plant, these variations have affected the clariflocculation treatment and subsequently the filtration treatment. Coagulation, flocculation and sedimentation are significantly influenced by pH and temperature, in addition to reaction time, quantity and order of dosing of reagents and mixing speed. The pH influences the treatment by establishing the quality of the formation of the flocs, the temperature influences the treatment by causing convective motions inside the tank, motions that can induce the flocs to remain on the surface. According to the Fair and Meins model, the optimal pH is approximately 6.8. Such a low pH can cause problems within the water purification chain; therefore, to obtain maximum yields in the clariflocculation treatment, it is conventionally expected to have a

pH value between 7.5 and 7.8. During normal operation of the plant, the manager has detected conditions in which this range has been exceeded several times. To deal with pH alterations, the operator has implemented a management procedure that consists of acidifying the water upstream of the dosage of existing reagents. The dosage of acidifier, as well as hydrochloric acid, is 5-8 ml HCl/m³ of water to be treated for pH between 7.5 and 8.2; for pH higher than 8.2 the acid dosage is 15-20 ml HCl/m³ of water to be treated. The management solution was implemented through a careful study conducted on the "Water Quality & Treatment-American Water Works Association" manual.

The malfunction of the clariflocculation unit, manifested by partial sedimentation of the sludge flakes, caused anomalies in the filtration systems. The operator has taken countermeasures, in this sense, by installing turbidimeters at a depth of two meters from the free surface of the clariflocculator (thereby measuring the turbidity of the water exiting the clariflocculator). Up to a turbidity value of five NTU, the plant is able to function correctly. Above five NTU, alarms are triggered that force, in addition to the normal routine procedures, the backwashing of the filters and the discharge of the sludge from the clariflocculators.

4.1.4.2 Ponte Molo Water treatment Plant – Taglio Di Po

At the supply source, the Po River, sudden variations in conductivity were found, a symptomatic parameter of the rise of the salt wedge. This event was the natural consequence of the progressive decrease in the passing flows; flows for which were never previously found were recorded. The ordinary low flow rate is 650 m³/s. The threshold, such as the rise of the salt wedge in the Po River occurs, is 450 m³/s. In the summer of 2022, a flow rate of 80 m³/s was detected at the Pontelagoscuro monitoring station in Ferrara. The conductivity parameter, as it is critical, was measured using portable instruments by Acque Venete staff. The measurements were conducted 3 km from the mouth at Polesine Camerini, 5 km from the mouth at Oca Marina, 10 km from the mouth at Tolle Centro.

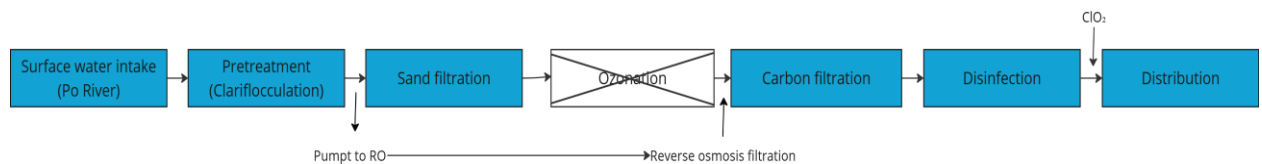


Figure 4. 4 Mitigation action undertaken in Ponte Molo during the emergency period – Fonte Acque Venete S.p.A

4.1.5 Summary of the case study in Acque Venete

The year 2022 was a critical time for the availability of drinking water. Based on utility reports and follow-up interviews, the candidate analyzed the anomalies observed at Boara Polesine and Ponte Molo plants, and structured the key findings into this case profile. 2022 was a very critical year for the availability of water resources to be used for drinking purposes. The drought period that has passed is a direct consequence of the ongoing climate changes; similar situations cannot be considered exceptional but can be found again in the coming years.

4.1.5.1 Boara Polesine Water treatment Plant - Rovigo

At the Adige River, the manager detected an alteration of the pH parameter with direct consequences in the plant on the treatment yields of the clariflocculation process. The problem was addressed by introducing an acidifier upstream of the reagent dosage. The new management procedure has achieved excellent results and, to date, remains the only solution undertaken by the manager.

4.1.5.2 Ponte Molo Water treatment Plant – Taglio Di Po

At Po River, the operator detected the alteration of the conductivity parameter, representative of the rise of the salt wedge. The value of the parameter found exceeds the limits imposed by current legislation. The operator implemented the supply chain with a reverse osmosis treatment section. The mobile unit guaranteed the drinking water supply during the emergency period. However, the desalination plant cannot be considered the only solution, since it is very expensive to manage, complex in terms of management and procedural aspects. It is an excellent technology to adapt to emergency periods, but not futuristic. The other management procedures adopted show how the introduction of Water Safety Plans can represent a valid tool capable of dealing with emergency conditions in full awareness.

4.2 Palermo Municipal Water Supply Company - Amap S.P.A. (Palermo)

In this subchapter, the case study of AMAP is presented, which ensures a water service for drinking water needs, collection, purification and reuse of water for 47 municipalities of the Metropolitan City of Palermo, serving a user base of over 1 million inhabitants (923,605 AE residents, 212,540 AE floating).

AMAP manages five water purification plants in a province characterized by surface waters not suitable for human consumption. In this sense, the priority objective of AMAP is to extend its consolidated experience to the other municipalities that are part of the Optimal Territorial Area 1 Palermo.



Figure 4. 5 Territorial framework AMAP S.P.A. – Palermo. Source: Google Maps & Google Earth

4.2.1 Supply system of Amap S.P.A.

The supply sources from which AMAP collects water are multiple:

Direct withdrawal from surface water resources (23%), from underground aquifers (21%), from springs (23%) and from rivers (2%).

4.2.2 Quality of raw water of Amap S.P.A.

Then, the quality of raw water is analyzed in relation to the supply sources from which the respective water treatment plants collect water for drinking purposes, both located in the Jato valley.

4.2.2.1 Risalaimi Water treatment Plant – Palermo

Initially, the Risalaimi water treatment plant's sources of supply consisted of water withdrawals: from an artificial reservoir, "Scanzano", from the "Eleuterio" river and from the springs bordering the area where the "Sorgenti di Risalaimi" plant was located.

Between 1980 and the early 2000s, in line with the construction of new hydraulic works aimed at expanding the supply system, water withdrawn from the "Piana degli Albanesi" reservoir and water from the "Rosamarina" reservoir were brought into the plant.

The quality parameters of the raw water are good except for the aluminum parameter, which was repeatedly found to be above the limit of the legislation in force at national level.

4.2.2.2 Jato Water treatment Plant – Palermo

The main source of supply for the plant is Lake Poma (90%); the residual water is collected from a stretch of the "Jato" river near the "Madonna del Ponte" hamlet.

Around the 1970s, the "Jato" river, which extends for 33 km, was dammed about 10 km from its mouth, thus allowing the formation of the artificial "Lago di Poma" reservoir. The lake, located at about 200 m above sea level, has a surface area of 1.6 km² and a capacity of 72.5 million m³ of water. Currently, one of the largest reservoirs in Sicily, it allows the irrigation of the territory of the Partinico plain and the drinking water supply for the City of Palermo as well as some towns on the coastal strip.

Below, in Table 4.1, the values of the qualitative parameters of the raw water are reported in reference to the artificial reservoir "Lago di Poma".

Table 4. 1 Raw water quality parameters – ND: not declared – Source AMAP S.p.A Data provided by utility during phase two of the survey (2023), referring to measurements from 2020–2022.

Parameter	Unit	MIN	AVERAGE	MAX	L. D.Lgs 31/2001	L. D.Lgs 18/2023
pH	---	7.43	7.88	8.46	6.5 - 9.5	6.5 - 9.5
Electrical Conductivity at 20°C	µs/Cm	534	694	810	2500	2500
Turbidity	NTU	1.3	9.3	47.6	ND	ND
Temperature	°C	10	15.6	21.5	ND	ND
TOC	mg/L	3.41	3.81	4.13	ND	ND
Total Nitrogen	mg/L	0	1.22	1.6	---	---
Ammonium NH ₄	mg/L	0	0.03	0.55	0.5	0.5
Nitrite NO ₂	mg/L	0	0	0	0.5	0.5
Nitrate NO ₃	mg/L	6	6.6	12.7	50	50
Iron	µg/L	0	4	41	200	200

Chloride	mg/L	49	64.6	74.3	250	250
Manganese	µg/L	5.4	141	548	50	50
Calcium	mg/L	56.5	83.1	110.7	ND	ND
Magnesium	mg/L	14.2	21.4	27.3	ND	ND
Sulfates	mg/L	44	11.4	142.5	250	250
Nickel	µg/L	0	4.1	8.1	20	20
Copper	µg/L	15	15	15	1000	2000
Escherichia coli	n/100 mL	1	1	1	0	0
Fecal Coliforms	n/100 mL	0	57.7	520	0	0
Total Coliforms	n/100 mL	12	653	3800	0	0

4.2.3 Description of Plant Amap S.P.A.

The detailed characteristics of the plants in the case study are reported below: the Risalaimi water treatment plant, the Jato water treatment plant.

4.2.3.1 Risalaimi Plant – Palermo

The Risalaimi water treatment plant, built around 1960, guarantees approximately 50-60% of the operator's entire water production. The annual flow rate entering the plant is approximately 29 million m³ of water, providing drinking water for over 350,000 inhabitants (PE). The plant's capacity is 1800 l/s. As can be seen from the figure below, Figure 4.6, the water purifier is divided into 5 sections.

- 1) Reagent reception and mixing section
- 2) Clariflocculation section
- 3) Sand filtration section
- 4) Disinfection section
- 5) Sludge treatment section

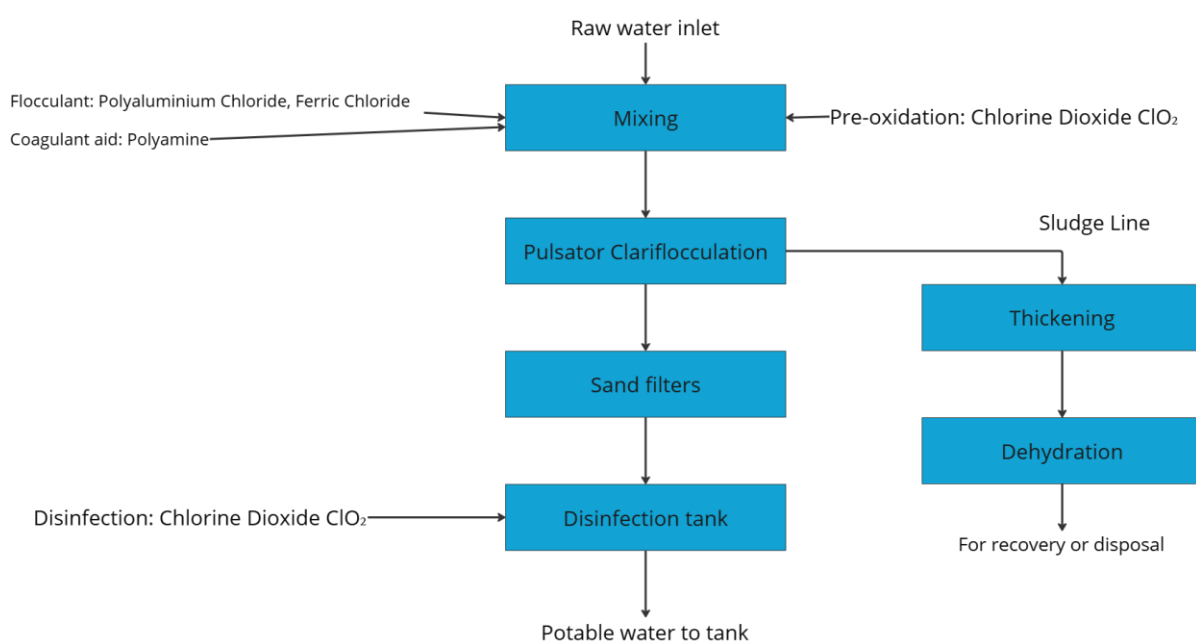


Figure 4. 6 Block diagram representation of the drinking water treatment chain – Source AMAP S.p.A

REAGENTS RECEIVING AND MIXING SECTION

The first section consists of a pre-treatment aimed at introducing reagents in preparation for clariflocculation and introducing reagents to promote pre-oxidation. The oxidizing reagent is chlorine dioxide, while the reagents used for clariflocculation are highly basic aluminum polychloride (PAC) or alternatively ferric chloride and, as an adjuvant, polyamine. The water is conducted to the next section by means of a channel.

CLARIFLOCCULATION SECTION

This section is composed of three rectangular clariflocculators, “Pulsator” model, placed in parallel. Here the flocculation phase and the sedimentation of the flakes that have formed in the previous section are completed. Each basin has a capacity of 2500 m³ and uses a pulsating system, hence the name of the model.

The system is composed of:

- a tower housing a vacuum pump, an automatic valve and the level gauge.
- a depression bell.
- a system of distribution pipes.
- sludge and clarified water outlet channels.
- calming deflectors.

The system operates in two phases, with the intensity and frequency managed by the operator. In the first phase, the automatic valve closes, and the vacuum pump creates a vacuum inside the depression bell. This causes the water level in the depression bell to rise while the water level in the main tank remains unchanged. This phase continues until the level gauge detects that the maximum level has been reached. During this process, mud particles gradually settle at the bottom of the depression bell. In the second phase, the automatic valve opens, allowing air to enter the depression chamber. The incoming air compresses the fluid due to atmospheric pressure, pushing the water into distribution tubes located at the bottom of the tank. The water then flows through calming deflectors and rises to the surface, where it is discharged through exit channels. Meanwhile, mud particles pass through the deflectors and accumulate at the bottom of the tank. As the mud builds up over time, it is eventually removed using hoppers once it reaches a certain level. This two-phase process ensures efficient water circulation and effective mud removal from the system.

SAND FILTRATION SECTION

The water, once extracted from the clariflocculators, is transferred to nine rectangular filters. In this treatment, the flakes that escaped the sedimentation of the clariflocculator are retained by the water.

DISINFECTION SECTION

Disinfection occurs by dosing chlorine dioxide at the water inlet in the 2700 m³ volume tank. This tank has the function of storing water before it leaves the plant to be transferred to the city tanks; among these, with a capacity of 90,000 m³, there is also the tank that supplies water to the City of Palermo.

4.2.3.2 Jato Water treatment Plant – Palermo

The Jato water purification plant, built around 1970, serves a user base of 270,000 inhabitants with a treatment capacity of approximately 2000 l/s. As anticipated, the plant draws water mainly from the artificial reservoir “Lago di Poma”. In any case, the supply source is characterized by surface water; therefore, the configuration of the treatment system is composed of: pre-oxidation, clariflocculation, filtration and disinfection. Below, in Figure 4.7, the treatment system at the Jato water purification plant is visible in detail.

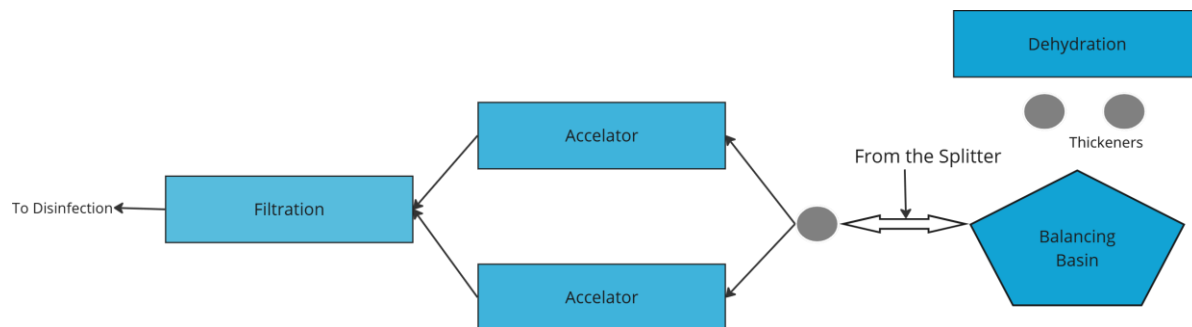


Figure 4. 7 Representation, by means of a block diagram, of the drinking water treatment chain – Source AMAP S.p.A

Specifically, the purification process begins with a hexagonal lamination basin with a capacity of approximately 50,000 m³. The basin, suitably waterproofed on the bottom, has the function of normalizing the treatment flow rates, avoiding external fluctuations.

The water is conducted to two clarification-flocculation tanks by means of a divider. In the divider, the pre-oxidizing and flocculant agents are dosed; in this specific case, the flocculant reagent used is highly basic polyaluminum chloride (PAC) with an alumina content (Al₂O₃) of 9%. The clarification-flocculation tanks, “Accelerator” model, have a circular section, a diameter of 38 meters, a depth of 6 meters, for a capacity, each, of 7,200 m³ of water.

The water, once clarified, is transferred to a filtration unit composed of 12 rapid gravity filters with an automated system for cleaning and backwashing.

The water is then collected in the disinfection tank; generally, the disinfectant reagent is chlorine dioxide. Finally, the water is fed into the aqueduct network to supply the city of Palermo and surrounding municipalities.

4.2.4 Anomalies detected and strategies implemented in Amap S.P.A.

4.2.4.1 Risalaimi Water treatment Plant – Palermo

At the Risalaimi water treatment plant, changes in the quality of drinking water were detected due to the presence of aluminum. Although aluminum is one of the most abundant elements in the Earth's crust and naturally exists in insoluble, non-toxic forms, it can become mobile through soil erosion and participate in biogeochemical processes. Additionally, humus and clay, which contain negatively charged colloidal particles, can attract and hold positively charged aluminum ions. This suggests that the aluminum found in the plant's water likely originated from surrounding soil minerals. Specifically, high aluminum concentrations were recorded in Lake Rosamarina (1,000 µg/L) and Lake Scanzano (5,000 µg/L), which supply water to the plant. A smaller portion of the aluminum also came from the use of aluminum-based chemical treatments, such as polyaluminum chloride.

Given that the aluminum contamination was mainly natural, the plant focused on evaluating the

efficiency of its treatment systems, especially the clariflocculators responsible for sludge sedimentation. The plant used a "Pulsator" reactor with a rectangular tank, but this design had flaws -dead zones in the tank's corners allowed sludge to build up. During the colder months, temperature differences within the tank created upward currents that caused aluminum sludge flakes to rise, bypassing sedimentation and reaching the filtration systems. As a result, aluminum entered the water distribution network, violating water quality regulations.

Attempts to adjust the "Pulsator" reactor's operation led to little improvement in aluminum removal. Therefore, the plant introduced a combination of three chemicals: aluminum polychloride, ferric chloride, and a cationic polyamine coagulant. Proper dosing of these reagents successfully reduced water turbidity to around 0.2 NTU at the plant's output. However, during the period when aluminum levels exceeded safety limits, the local mayor issued a non-potability order to protect public health.

4.2.4.2 Jato Water treatment Plant – Palermo

The Jato water purification plant faces several challenges and has been the subject of past studies evaluating surface water contamination by Salmonella and red algae. More recently, turbidity has emerged as a particularly critical parameter.

Turbidity Issues and Causes

The problem of turbidity is a common concern for all surface water sources, with artificial basins being particularly affected. In previous years, these basins were relatively unaffected due to the long water retention times, allowing biogeochemical cycles to naturally improve water quality. However, this natural equilibrium is no longer maintained.

- Extreme weather events, particularly those concentrated over short timeframes, have resulted in sudden and excessive turbidity levels.
- Flooding from the Jato River and its tributaries have continuously transported inorganic materials into Lake Poma, accelerating a silting process.
- A bathymetric study of the lake revealed a progressive decrease in its average depth, further exacerbating sediment accumulation.

Impact on Water Treatment

Given these factors, turbidity levels can reach extremely high values, sometimes up to 10,000 NTU, compared to an average of around 25 NTU. Such extreme turbidity far exceeds regulatory limits, including:

- WHO guidelines: <1 NTU
- Legislative Decree No. 18/2023: <0.3 NTU

At these levels, the water becomes untreatable, causing temporary shutdowns of the plant and disruptions in drinking water supply.

To mitigate these challenges, the plant manager conducted a study analyzing 10 years of historical data. The findings showed a direct correlation between climate change (specifically, rainfall intensity) and turbidity.

- Instead of focusing on annual or seasonal rainfall averages, the study highlighted the critical role of extreme, localized storm events that have devastating effects on water quality.

- Following a severe turbidity event in 2019, where levels exceeded 10,000 NTU, the manager implemented new management procedures and advanced technologies to reduce the impact of turbidity spikes and enhance water treatment resilience.

- Initially, a turbidimeter was installed at the entrance and exit of the POMA reservoir in order to have at least a pre-alarm and an alarm on the increase in turbidity, even in the case of sudden phenomena.

- Secondly, after 40 years of operation, the plant has been updated to recent needs.

Today, the plant is able to treat water with turbidity up to 250 NTU; after which the risk of service interruption is concrete. Despite this, the plant is equipped with a compensation tank that allows 200 l/s to be treated for a duration of 13/14 hours in order to minimize emergencies.

The revamping of the plant was carried out with a view to respecting the minimum environmental criteria, paying attention to the carbon footprint but, above all, making the plant resilient and able to resist water modified by physical, chemical and biological factors that are not always easy to control. The revamping of the plant consists of guaranteeing at least 400 l/s of treated water, compared to raw water with a turbidity of 1000 NTU. The new plant will be composed of: flotation tank, introduction of a pre-oxidation tank with ozone layers, implementation of a third clariflocculator, bringing the potentially treatable flow rate to 2000 l/s, adoption of biological activated carbon filters (BAC) to remove ammonia more efficiently, maintenance of sand filters, disinfection with a UV system.

As regards management procedures, the operator has limited himself to standardizing the cleaning and backwashing procedures of the sand filters, replacing and completely restoring the filter medium.

4.2.5 Summary of the case study in Amap S.P.A.

4.2.5.1 *Risalaimi Water treatment Plant – Palermo*

Following the mitigation actions undertaken by the operator, the benefits obtained concern the reduction of the residual aluminum content in the water supplied by the water purifier, the improvement of the coagulation and flocculation process, the improvement of the filtration treatment with a reduction in the washing frequency of the sand filters, and the reduction of the drying time of the muddy water extracted from the “Pulsators”.

Net of these improvements, at the point of distribution the following are found on average: 148 µg/L of Aluminum (against the 219 µg/L observed in previous years), 0.5 NTU of Turbidity and an average temperature of 20.2 °C.

4.2.5.2 *Jato Water treatment Plant – Palermo*

As regards the revamping, the procedures are well underway; the executive design works will start soon, the start of the on-site works is scheduled for November 2023. As regards the filtration system, with the new standardized procedure, excellent turbidity reduction yields have been found (up to 0.1 NTU contrary to the previous 0.6 NTU).

4.3 Gruppo Hera S.P.A. (Bologna)

This subchapter presents the case study of Gruppo Hera, a company that operates in the northern part of Italy, with a greater focus on the Romagna area. Gruppo Hera ensures a water service for drinking water needs, collection, purification and reuse of water for 175 municipalities, a user base of approximately 3 million inhabitants (3 million PE) through 24 plants equipped with remote-controlled multi-line treatment. In Emilia-Romagna, Gruppo Hera serves the municipalities of the provinces of Bologna, Ferrara, Forlì-Cesena, Imola-Faenza, Modena, Ravenna and Rimini. The case studies reported below concern Pontelagoscuro, located in the municipality of Ferrara, and Suviana respectively located in the province of Bologna.

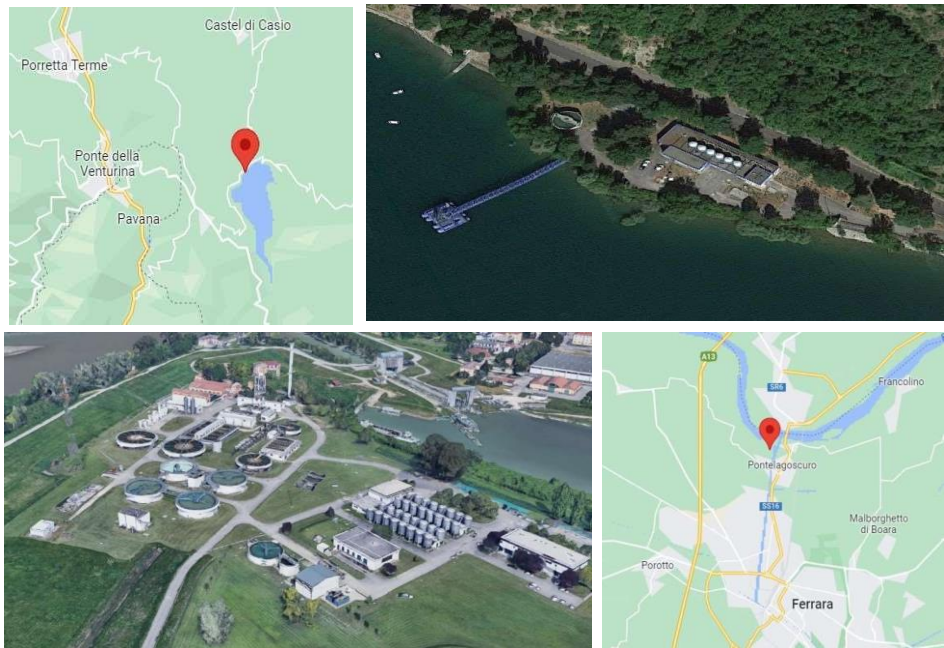


Figure 4. 8 GRUPPO HERA S.P.A. Source: Google Maps & Google Earth

4.3.1 Supply system of Gruppo Hera S.P.A. (Bologna)

The Hera Group draws water from multiple supply sources, direct withdrawal from surface water resources, from underground aquifers and to a residual extent from springs and minor sources. Specifically, 135 million m³ of water is drawn from the underground aquifer (approximately 50%), 152 million m³ of water from surface sources represented by rivers and artificial reservoirs (approximately 44%), 18 million m³ from springs and minor sources (residual 6%). The Hera Group manages the aqueduct service through 389 purification plants, 24 of which are subject to complex treatments: physical (sedimentation and filtration), physical-chemical (clarification-reflocculation) and chemical (oxidation and disinfection). Through a distribution network of over 27,000 km, the operator is able to supply over 300 million m³ of water in a year.

4.3.2 Raw water quality Gruppo Hera S.P.A. (Bologna)

The paragraphs below report the two case studies analyzed for the operator Gruppo Hera. Only the case study of the Suviana plant is complete; the case study of the Pontelagoscuro plant, in the absence of many details, offers only some general information from which it will be possible to proceed with more in-depth analyses in the future.

4.3.2.1 Suviana Plant – Bologna

The supply source from which the treatment plant captures water is Lake Suviana, an artificial basin located in the Bologna Apennines at 470 meters above sea level with an extension of approximately 1.5 km². The intake structure is located approximately 50 meters from the lake shore and consists of electric pumps housed on a floating platform that collect water at a depth of approximately 2 meters. The qualitative characteristics of raw water are good overall: low content of organic substances, absence of micropollutants of anthropogenic origin. Usually, the qualitative characteristics of the water are determined by laboratory analysis, with the exception of parameters such as pH and turbidity which are continuously detected by remote sensing systems. However, both parameters have never shown anomalous trends; sporadic cases of turbidity with peaks of up to 20 NTU have occurred, but the parameter soon returned to the average trend.

4.3.2.2 Pontelagoscuro Water treatment Plant – Ferrara

The purification process arises from the collection of water from a surface source, specifically from the Po River, near the municipality of Ferrara. Unlike the Suviana Water treatment Plant, there is no data on the quality of raw water for the plant in question. The only information we have concerns the persistent presence of algae with very high values. high; in exceptional cases, the condition occurred where over 10 million algae elements were found (algal bloom phenomenon).

4.3.3 Description of the plant of Gruppo Hera S.P.A

4.3.3.1 Suviana Water treatment Plant – Bologna

The Suviana water treatment plant was built around the 1980s to ensure the supply of drinking water to the municipalities bordering the lake of the same name located in the Bologna Apennines. With a maximum flow rate of 95 l/s, it supplies drinking water to approximately 25,000 inhabitants.

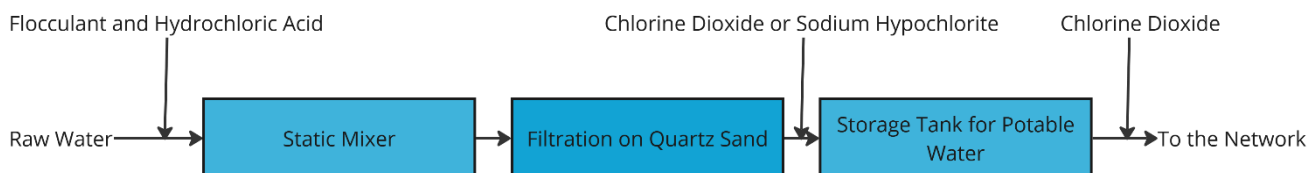


Figure 4. 9 Representation, using a block diagram, of the drinking water treatment chain – Source Gruppo Hera S.p.A

The average flow rate pumped from the artificial basin by the electric pumps is approximately 67 l/s.

DOSAGE OF REAGENTS

Following the lifting, the reagents are dosed into the water; in particular flocculant and hydrochloric acid. The dosage of hydrochloric acid is aimed at restoring the correct pH value; the dosage of flocculant, polyaluminium chloride (PAC), is aimed at removing turbidity. The dosage of flocculant is variable, depending on the incoming organic load that can be assessed by the turbidity parameter: from 0 to 10 NTU, 4.5 g PAC/m³ of treated water is dosed, above 10 NTU, 6 g PAC/m³ is dosed respectively.

FILTRATION ON QUARTZ GRITS

Following the dosage of reagents, the water passes through a static mixer in which a homogeneous mixing condition is created. The water is then subjected to filtration for the appropriate

removal of suspended solids and colloidal substances typical of surface water. Filtration occurs by means of 6 filters, each with a diameter of 3 m and a height of the filter medium, quartz sand, of 2.5 m. The filter crossing speed (hydraulic load) is approximately 9 m/h. The size of the granules of the filter medium varies in a range of 0.7 – 1.2 mm.

The filters require regular backwashing operations. The backwashing operations consist of lowering the level with exclusion of the filter from the die, backwashing of the filter with air flow, backwashing of the filter with a mixed flow of air and water, sanitization of the filter medium by dosing sodium hypochlorite with a contact time of five minutes, backwashing of water only for rinsing, filling of the tank and restoring the normal flow direction. These operations occur automatically based on the turbidity detected by the probes, on average every 1000/2000 minutes of operation. Since it depends on the turbidity, this time can be anticipated or postponed.

DISINFECTION

After filtration, the reagent, chlorine dioxide (in emergencies only sodium hypochlorite), is dosed to destroy the residual microbiological load. The water is then transferred to a storage tank with a capacity of 445 m³ and, by means of a lift, transferred to a network tank of approximately 500 m³. At this stage, it is possible to dose additional chlorine dioxide to ensure network coverage.

The entire treatment process is continuously monitored through qualitative and quantitative measurement systems: total flow rate, flow rate on each filter, storage tank level, reagent dosage, temperature, pH, turbidity and residual disinfectant in the network.

4.3.3.2 Pontelagoscuro Water treatment Plant – Ferrara

Located north of Ferrara, the Pontelagoscuro water treatment plant mainly treats surface water taken from the Po River and, to a lesser extent, water taken from the floodplain of the same river through a system of wells. It guarantees a drinking water supply for approximately 240,000 inhabitants with an average flow rate delivered to the network of approximately 1,400 l/s.

In the absence of detailed information on the operation of the plant, a brief general summary and its outline are provided below.

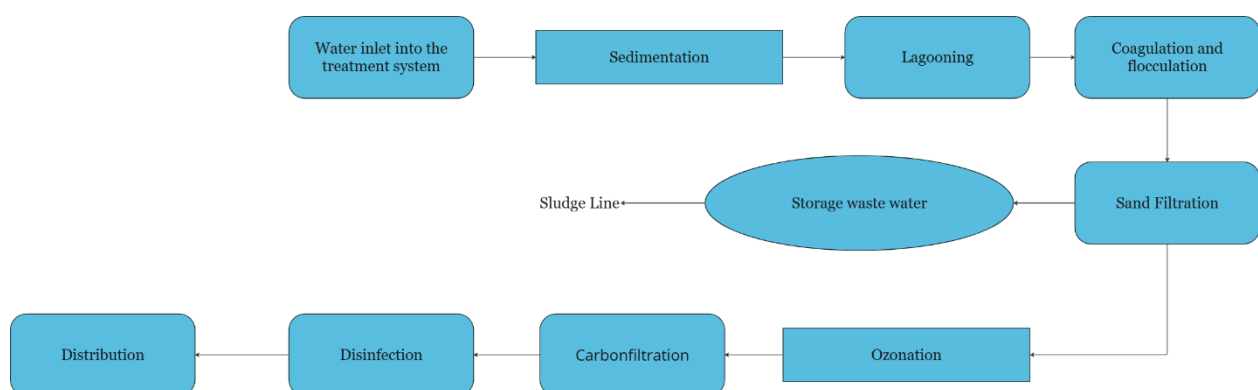


Figure 4. 10 Block diagram representation of the drinking water treatment chain – Source Gruppo Hera S.p.A

The first treatment that the water undergoes is pre-sedimentation. Subsequently, the water is conducted to three lagoon basins, with a capacity of 250,000 m³ of water and a depth of approximately 4-5 meters, where it remains for approximately three days. During this time, physical sedimentation processes and natural biological purification reactions occur.

To eliminate colloidal substances still present in the water, the next treatment is clariflocculation, where chemical reagents destabilize the structure and electrical charge of the colloidal particles, favoring their aggregation at first and precipitation at a later time.

After clariflocculation, the water is filtered through a one-meter-thick filter medium composed of millimeter-sized sand (sand filtration).

Through ozonation, the water is sanitized, enriched with oxygen, and the molecules of the organic substances dissolved in it are destroyed.

The water then undergoes a further filtration process, activating carbon filtration. Filtration is carried out by granular activated carbon, whose purpose is to trap microscopic pollutants inside the pores.

The last treatment consists of final disinfection with chlorine dioxide, ClO_2 , and storage in tanks before being released into the distribution network.

4.3.4 Anomalies detected and strategies implemented

4.3.4.1 Suviana Water treatment Plant – Bologna

Starting in 2017, the first changes in the quality of the raw water of the reservoir began to be highlighted, linked to low rainfall, winters with less cloud cover (consequent greater solar radiation of the surface), a greater number of algae present, and an episode of algal bloom. This led to two main management difficulties in the treatment chain: retaining the large quantity of highly mobile algae (such as diatoms) in the filtration treatment, possible formation of cyanotoxins (plant not equipped with a specific removal treatment).

About the first problem, the manager implemented two mitigation actions:

1) The filter backwash system was implemented with a dosage of sodium hypochlorite in order to obtain complete sanitization of the filter (contact time five minutes);

2) A new flocculant product based on polyamine and aluminum polychloride was tested, which is more efficient than aluminum polychloride alone, for the specific treatment of algae. Through appropriate jar-tests, the right component of aluminum and cationic polymers was determined. As reported in the previous chapter, in the bibliography, the cationic component is very efficient in making microalgae less mobile (American Water Works Association). In the laboratory, the by-products deriving from the use of the new flocculant were also checked: aluminum and epichlorohydrin (resulted lower than the detection limit of 50 nanograms/liter). The choice of a mixed product, with a high hydrolysis speed and consequent formation of flakes, allowed obtaining an algal reduction of over 98%.

Regarding the second problem, the manager implemented an analytical plan for determining the number of algae present in the raw water (identification by optical microscope). In case cyanobacteria are found, the analysis of microcystin-LR is implemented. In addition, another reagent was used for its removal. As reported in the previous chapter, in the bibliography, chlorine dioxide is not a very efficient reagent for the intra and extracellular removal of microcystin-LR (AWWA – “Algae Source to Treatment” - M.57, 2010); consequently, as suggested by the literature, the dosage of sodium hypochlorite is introduced, a chemical reagent with more powerful oxidizing properties.

3.3.4.2 Pontelagoscuro Water treatment Plant – Ferrara

In the lagoon basin of the Pontelagoscuro Water treatment Plant, a strong growth of algae has been observed in recent years. We can speak of a substantial increase in algal bloom, with up to 10 million algal elements/L being found. This phenomenon is essentially due to sudden temperature variations. However, despite the algal growth, unlike the Suviana Water treatment Plant, no toxicity phenomena have occurred (absence of cyanobacteria).

Despite the absence of toxicity, the operator has implemented measures to contain algal growth, implemented its monitoring system with the introduction of ultrasonic probes. This choice is motivated because counteracting algal growth means saving on the use of reagents or avoiding implementing further advanced chemical processes. The system continuously monitors the following parameters at the entrance and exit of the lagoon basins: chlorophyll, phycocyanin (the main characteristic molecule of cyanobacteria), pH, turbidity and dissolved oxygen. It is composed of a fluorescence probe which, depending on the values of the parameters it detects, implements an ultrasound system which, by changing the frequency and power of emission, can contain algal growth. The operation of this technology is based on a physical principle that consists of sinking the algae 1/1.5 meters below the free surface of the basin, preventing them from being hindered from receiving light and nutrients for photosynthesis. The probe placed in the basins around April 2023 began to work at full capacity from the beginning of May. To date, this system, of an experimental nature, represents a pilot technology in Italy.

4.3.5 Summary of the case study of Gruppo Hera S.P.A

4.3.5.1 Suviana Water treatment Plant – Bologna

This plant has not yet been subject to risk assessment with the development of the related Water Safety Plan; it is scheduled for 2026. However, given the experience of the operator in developing the Water Safety Plans and the approach in managing this case study, it can be deduced that the problems encountered have been addressed with a risk-based approach, just as the WSP suggests. The management changes and the tests carried out have given results of efficiency in the removal of algae and natural substances present. In the summer of 2022, to counteract a possible lowering of the basin level and to make further improvement, the suction pipe of the electric pumps housed on the floating dock was lowered by one meter, so as to collect water with less radiation and a lower number of algae/liter.

4.3.5.2 Pontelagoscuro Water treatment Plant – Ferrara

To date, the operator has not provided any feedback on the strategies implemented; as anticipated, the probe was installed recently, therefore there is no data on which conclusions can be drawn. Furthermore, the operator is still in contact with the University of Bologna to further investigate this case study.

PADANIA ACQUE S.P.A. (CREMONA)

This subchapter presents the case study of Padania Acque, which provides a water service for drinking water needs, collection, purification and reuse of water for 113 municipalities, serving a user base of over 350,000 inhabitants (300,000 PE). Padania Acque manages over 70 drinking water treatment plants, in a province characterized by surface water not suitable for human consumption.



Figure 4. 11 Territorial framework of Padania Acque S.P.A. - Cremona. Source: Google Maps
Google Earth

4.4 Cremona Supply system

Due to the surface water of dubious quality, the intake structure is composed of a system of wells that pump water from the underground aquifer using immersion pumps. The province of Cremona can be defined as uniform from a hydrogeological point of view; however, it is possible to distinguish three areas with different water qualities:

Casalasca area: in this area the water is characterized by the presence of substances such as ammonia, iron, manganese, hydrogen sulfide, methane, chlorides and arsenic.

Cremasca area: in this area the wells, of modest depth (between 50 and 100 meters deep), extract water from the aquifers with good quality characteristics. The presence of manganese, traces of iron, and, if present, a low ammonia content are found.

Cremonese area: in this area the wells, of greater depth (between 100 and 150 meters deep), extract water rich in substances such as: ammonia, iron, manganese, arsenic and traces of dissolved gases such as hydrogen sulfide, carbon dioxide and methane.

4.4.1 Raw water quality

4.4.1.1 Cremona Water treatment Plant – Cremona

Of the three areas, the plant under study is located in the Cremona area. In particular, the aqueduct supply system is composed of two well heads: 9 located to the west (Cambonino area) and 10 located to the east (Via Postumia area). The wells extract a flow rate of approximately 30-70 l/s (each well) up to a depth of 230 meters. The qualitative characteristics of the raw water taken from the wells are reported in Table 4.2 below.

Table 4. 2 Qualitative parameters of raw water – Source Padania Acque S.p.A

Data provided by utility during phase two of the survey (2023), referring to measurements from 2020–2022.

Parameters	UDM	MEDIO	MAX	L. D.Lgs 31/2001	L. D.Lgs 18/2023
NH ₄	mg/L	1.5	2.4	0.5	0.5
Fe	µg/L	55	350	200	200
Mn	µg/L	41	60	50	50
As	µg/L	17	24	10	10
Oxidation index	mg/L	1.8	2.5	5	5

Numerous considerations can be made from the table. Undoubtedly, the water taken from the wells has a high content of ammonium and arsenic; in fact, the average value is above the limit value imposed by current legislation. For the oxidation index and iron there are no problems of exceeding the legal limit. The manganese parameter is a critical parameter as it is close to exceeding the legal limit, furthermore there are cases in which this limit has been exceeded. As anticipated, and verified by the qualitative parameters reported above, the quality of the water pumped is not entirely compatible with the current regulations. Specific treatments are therefore necessary in order to return within the values imposed by the legislation.

4.4.2 Description of the plant

4.4.2.1 Cremona Water treatment Plant – Cremona

The plant under study, located near the intersection between the SP27 and Viale Concordia di Cremona, serves 76,000 PE with a daily flow rate of 31,000 m³/d (potential of 450 l/s). As anticipated in the previous subchapter, the main substances removed during the treatments are: Arsenic (As), Iron (Fe), Manganese (Mn), Ammonia (NH₃) and Hydrogen Sulphide (H₂S). Below, in Figure 4.12, the scheme of the treatment chain is shown with a focus on the individual compartments.



Figure 4. 12 Block diagram representation of the drinking water treatment chain – Fonte Padania Acque S.p.A

AREATION

Following pumping, the first treatment phase that the water undergoes is aeration. The water passes through progressive weirs, thus forming a stepped waterfall, obtaining a double benefit. Natural self-oxygenation through oxygen captured in the air and stripping of gases, such as Methane (CH₄) and Hydrogen Sulphide (H₂S), contained in dissolved form in the pumped water.

BIOLOGICAL FILTRATION

The biological filtration implemented at this plant is aerobic filtration, therefore it uses non-pathogenic bacteria. The support material used is biolite, and the plant technology adopted is the BIOFOR system.

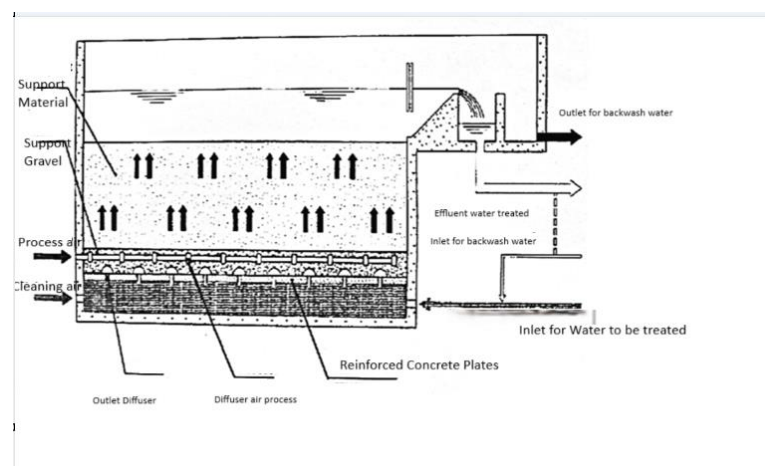


Figure 4. 13 Simplified operation of the biological water treatment -BIOFOR system – Fonte Padania Acque S.p.A

Biofiltration allows the retention of suspended solids by means of the filtering material, and the removal of the nitrogenous component by means of the biological development of bacterial flora with consequent formation of biomass. Obviously, the system requires backwashing operations aimed at removing excess biomass and restoring the initial filtering capacity of the filtering material. Thanks to the action of the bacteria, in this phase the oxidation of ammonia and other substances such as iron, manganese and arsenic is obtained. The nitrate obtained from the oxidation of ammonia is in concentrations considerably lower than the legal limits prescribed by current regulations (5 mg/L compared to the 50 mg/L of law).

MIXING

After biological filtration, the water is conveyed into a single tank, where, thanks to the presence of an agitator (rapid mixing), the dosing of reagents such as potassium permanganate (KMnO_4) and ferric chloride (FeCl_3) takes place. In this tank the coagulation and flocculation process are triggered.

FILTRATION ON SANDY SUPPORT

The second filtration stage has the purpose of removing arsenic and manganese; the water passes through a support composed of silica sand that retains the suspended solids consisting of precipitated arsenic, iron and manganese. The filters are periodically washed by backwashing operations.

DISINFECTION

The last treatment of the chain is disinfection. The reagent used in this phase is chlorine dioxide (ClO_2) or sodium hypochlorite (NaClO), to obtain the reduction of the bacterial load developed during the treatment processes, but above all, to protect the distribution network from any bacterial proliferation.

SLUDGE LINE

Equipped with biological filters and sand filters, in order to guarantee continuity of service and excellent performance in removing harmful substances, periodic backwashing of the filters is carried out on the system. The water destined for the sludge line contains: suspended solids contained in the raw water, biomass detached from the washing of the biofilters and suspended and settleable solids retained in the sand filters. The treated flow rate is approximately $3,600 \text{ m}^3/\text{d}$.

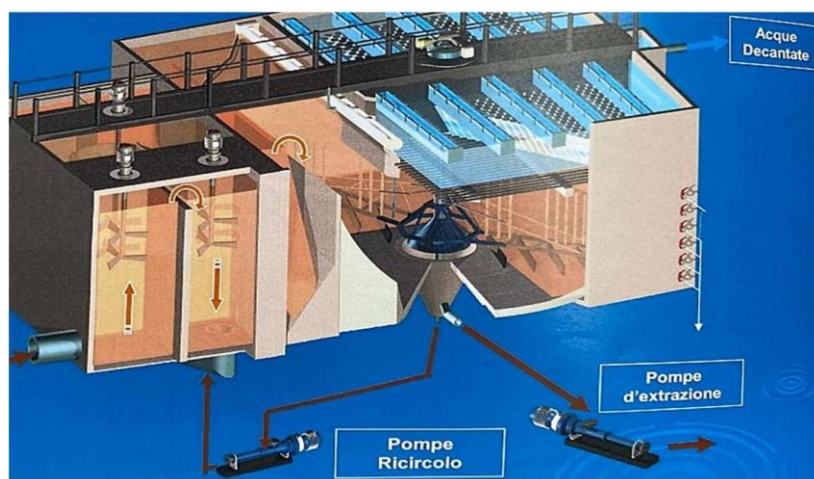


Figure 4. 14 Flocculation, sedimentation and thickening treatment. Source – Padania Acque S.p.A

The treatment consists of a preliminary flocculation phase and a second sedimentation/thickening phase. The flocculation phase occurs by dosing an anionic polyelectrolyte at a dosage of 4.2 mg/L for a hydraulic retention time (HRT) of 10 minutes. The sedimentation and thickening phase consist of a tank in which a support of lamellar packs coexists with a scraper on the bottom from which the thickened sludge is extracted. The settled waters that pass through the lamellar pack sedimentation tanks are released into a surface water body. The sludge extracted from the thickener, taken to a centrifuge, undergoes the dehydration process and is subsequently disposed of in a landfill as special waste.

4.4.3 Anomalies detected and strategies implemented

4.4.3.1 Cremona Water treatment Plant – Cremona

The operator does not report any particular anomalies. The only anomalies detected consist of the increase in temperature and the reduction of the water level in the aquifer. The reduction in the water level did not cause any problems for the treatment plants and distribution networks; the same goes for the temperature variation, a parameter that generated unwanted effects in the distribution network. In fact, multiple problems were found: biofilm growth and variation in microbiological quality that required greater consumption of disinfectant. The control measures aimed at mitigating the effects of climate change were: analysis, study and intensive monitoring of the problem. Having established that it was impossible to intervene on the water temperature, the solution fell on increasing the disinfectant in the network.

4.4.4 Case study summary

4.4.4.1 Cremona Water treatment Plant – Cremona

With the increase of disinfectant in the network, the problem of biofilm growth and microbiological quality variation is solved. In addition, the operator has adopted a monitoring and remote sensing system to control the quality of the water supplied: monitoring of piezometers located near the wells, optimization of reagent dosages, surveillance of the systems, use of continuous analyzers that perform chemical and biological analysis of the wells, treated water and the distribution network.

4.5 Società Metropolitana Acque Torino - Smat S.P.A. (Torino)

This subchapter presents the case study of SMAT, a company located in Turin that provides a water service for drinking water needs, collection, purification and reuse of water for 290 municipalities, a user base of over 2 million inhabitants (2 million PE) through 94 plants.

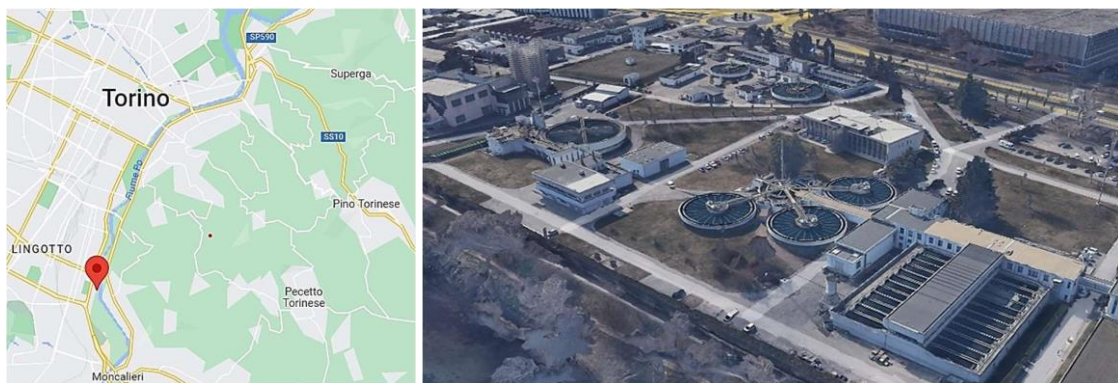


Figure 4. 15 Territorial framework of SMAT S.P.A. – Turin. Source: Google Maps & Google Earth

4.5.1 Supply system

The supply sources from which SMAT collects water are multiple, direct withdrawal from surface water resources, from the springs of Pian della Mussa and Sangano, and from wells located throughout the territory. Specifically, the collection is distributed as follows: underground aquifer for 67%, spring for approximately 14% and river for the remaining 19%. The reported case study concerns the water purification plant whose water supply point is the Po River. The complex is composed of 3 plants: Po 1 and Po 2, built around the 1960s, with a production capacity of 86,400 m³/d, and Po3, more recent with a capacity of about 130,000 m³/d. The plants supply 20% of the water distributed by SMAT with an average daily flow rate of 2,500 l/s.

4.5.2 Raw water quality

4.5.2.1 Po 3 Water treatment Plant – Turin

The water purification process begins with a river intake structure and a lagoon structure located about 10 km upstream of the plants. The lagoon technique is widely described in the previous chapter; we proceed with an in-depth analysis of the traditional river intake.

The collection takes place through submerged intakes, protected by automatic gates and grate cleaners. The water is then passed through metal mesh belt filters. The primary treatment is aimed at removing the coarsest impurities; the belt filter is periodically washed with washing water, appropriately disposed of in the company's purification plant. The riverbed is connected to the first lifting station by tunnels; from here, the water is uniquely conducted to the Po1, Po2, and Po3 plants.

Through a computerized supervision and control system, it is possible to continuously monitor the quality of the water entering and leaving the plant; it is also possible to adopt corrective operations aimed at improving the efficiency of the plant and the potabilization yields. Below, in Table 4.3, are reported the values of the parameters observed for the raw water (Source: Technical Notebook, SMAT).

Table 4. 3 Raw water quality parameters – ND: not declared – Source SMAT S.p.A. Data provided by utility during phase two of the survey (2023), referring to measurements from 2020–2022.

Parameter	Unit	MIN	AVERAGE	MAX	L. D.Lgs 31/2001	L. D.Lgs 18/2023
pH	---	6.9	7.7	8.1	6.5 - 9.5	6.5 - 9.5
Electrical Conductivity at 20°C	µs/Cm	230	420	500	2500	2500
Turbidity	NTU	2	10	2000	ND	ND
Temperature	°C	4	10	24	ND	ND
TOC	mg/L	0.8	2	10	ND	ND
Dissolved Oxygen	mg/L	7.5	9.5	11.4	ND	ND
Ammonium NH ₄	mg/L	0.08	0.4	2	0.5	0.5

Nitrite NO ₂	mg/L	0.1	0.16	0.4	0.5	0.5
Nitrate NO ₃	mg/L	6	13	22	50	50
Iron	µg/L	40	90	400	200	200
Aluminum	µg/L	---	---	20	200	200
Chloride	mg/L	9	16	22	250	250
Phosphorus	µg/L	---	300	1150	ND	ND
Manganese	µg/L	---	60	100	50	50
Hardness	°F	16	23	27	ND	ND
Alkalinity	°F	16	18	20	ND	ND
Calcium	mg/L	48	76	87	ND	ND
Magnesium	mg/L	8	12	16	ND	ND
Sulfates	mg/L	42	55	83	250	250
Silica	mg/L	6	9	11	ND	ND
Nickel	µg/L	2	3	5	20	20
Copper	µg/L	1	3	8	1000	2000

From the table it is possible to analyze a pH value within the norm although slightly basic, an acceptable value for all other parameters, a marked deviation in the turbidity values and the microbiological load. This deviation is motivated by the intense meteorological events that cause the river to become turbid. The average turbidity value observed at the river intake is ten NTU. However, this value is not significant of the turbidity at the inlet to the treatment plant, generally around 1-2 NTU, since the water taken from the river is appropriately mixed with the water taken from the lagoon system, thus drastically decreasing the turbidity value. As regards microbiological load, in line with the regulatory limits, in the plant, specific disinfection treatments are planned for complete reduction (see for example the Ozonation treatment).

4.5.3 Plant description

4.5.3.1 Po 3 Water treatment Plant – Turin

Of the three plants, only the Po3 plant is described in detail, as it is more efficient and has a greater water production capacity.

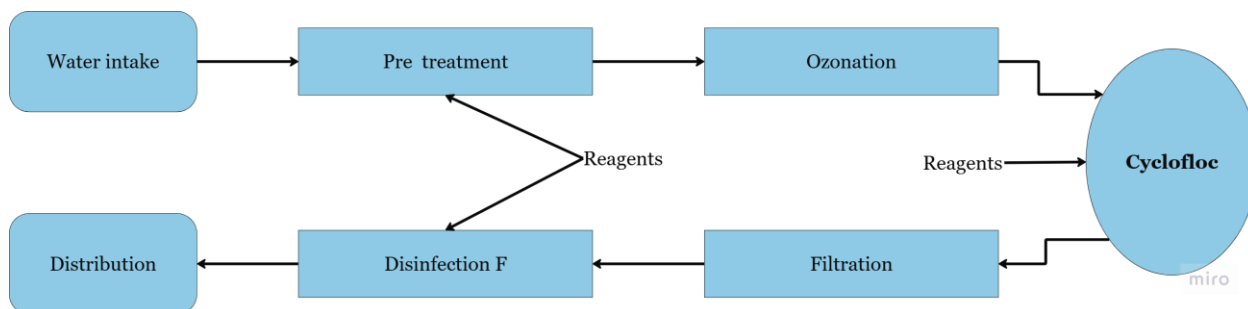


Figure 4. 16 Cyclofloc diagram representation of the drinking water treatment chain – Source SMAT S.p.A

- The water treatment process begins with the Water Intake (Opera di Presa), where water is drawn from natural sources such as rivers, reservoirs, or lakes into the treatment system. Next, the water passes through the Pre-settler (Predecantatore) stage, where sedimentation occurs to remove suspended solids and larger particles. Chemical reagents may be added to improve the sedimentation process. Following this, water undergoes Ozonation (Ozonizzazione), where ozone is used to disinfect the water, oxidize organic compounds, and eliminate contaminants like pesticides and other micropollutants. The water then moves to the Cyclofloc unit, a specialized system for coagulation and flocculation. Here, chemicals are introduced to bind fine particles into larger flocs, making them easier to remove. Afterward, the water is processed through the Filtration (Filtrazione) stage, where it passes through filters made of sand, gravel, or other materials to eliminate remaining impurities. To ensure complete safety, the water undergoes Final Disinfection (Disinfezione F.), typically with chlorine or other disinfectants, before being sent to the Distribution Network (Rete di Distr.), where it is delivered to consumers for use.

PRE-DECANTATION TANK

The pre-decanter, 33 m in diameter, has a flow rate of 2 m³/s. On the bottom of the tank, a rotating scraper removes the sludge which, once extracted, is sent to the company's purification plant. Upstream of the pre-decanter



Figure 4. 17 Horizontal static pre-decanter – Source SMAT S.p.A

There is a mixing tank in which it is possible to add chemical reagents. It is thus possible to dose sodium chlorite (NaClO_2) and hydrochloric acid (HCl) to produce chlorine dioxide (ClO_2) to be used as pre-oxidation. Alternatively, it is possible to dose coagulant or flocculant reagents based on iron or aluminum salts, or powdered activated carbon (PAC) to help reduce organic micropollutants.

OZONIZATION

After the pre-decanter there is the ozonization phase. Ozone is an effective disinfectant against bacteria and viruses and also leads to oxidation and consequent removal of iron and manganese. It is also able to destroy many micropollutants such as pesticides and phenols. One of the main defects of using this reagent is the production process: complex, energy-intensive and not very economical. Furthermore, it is not free from the formation of disinfection by-products (DBPs) such as bromate ion, aldehydes, ketones and NDMA-N-nitrosodimethylamine acids. Ultimately, it has a short residence time in the network, therefore, due to this aspect, its use as a final disinfectant is not recommended. As anticipated, the ozonation process is not immediate and arises from the production of ozone through the use of dry air. The pre-treatment thus consists of: air suction, compression with consequent increase in temperature up to 90-100°C, cooling of the air up to about 35°C through a system of tube bundles, air refrigeration up to 4-6°C, and finally, removal of humidity from the treated air through dryers. The dry air is then inserted into an ozone generator. The air, enriched with ozone (20 mg of Ozone/ m^3 of air), is introduced into the water to be treated through a system of porous ceramic diffusers, placed on the bottom of the ozonation tank. To obtain an efficient disinfection system, ozone must be used in a dose of 1-2 mg/L with a contact time of 5-10 min. The tank has specific characteristics: high, to facilitate the ozone released by the diffusers to dissolve with excellent yield; closed, to prevent undissolved ozone from dispersing into the atmosphere; equipped with an ozone destructor in case, at the top of the tank, ozone in the gaseous phase should accumulate

CLARIFICATION BASINS – CYCLOFLOC

After ozonation, the water flows into three Cyclofloc type clarification basins, respectively with a flow rate of about 700 litres/s and a diameter of 24 m. Upstream of each Cyclofloc there is a mixing chamber for dosing aluminium polychloride and, if necessary, oxidant. The Cyclofloc system is based on the addition of micro-sand which, by weighing down the aluminium hydroxide flakes, facilitates the precipitation of sludge on the bottom of the basin equipped with rotating metal scrapers. From the bottom, the sludge mixed with the micro-sand is removed by electric pumps in devices called Hydrocyclones, where, due to the centrifugal force, the lighter clayey part is separated from the micro-sand that precipitates on the bottom where it is recovered and put back into the cycle. During the clariflocculation, a further oxidation treatment using sodium hypochlorite (NaClO) allows the elimination of ammonia and derived nitrogen compounds. The Cyclofloc system allows a high efficiency of the clarification process with clear and constant quality water.

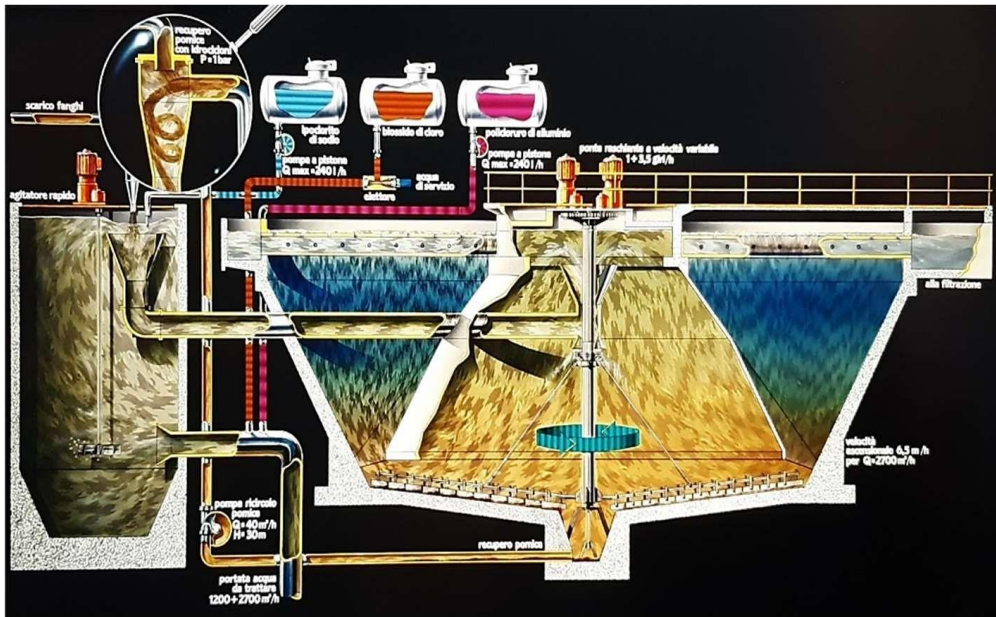


Figure 4. 18 Cyclofloc system used – Source SMAT S.p.A.

FILTRATION UNIT

The water filtration process takes place on two filter batteries of six units. The filters are multi-stage (with overlapping beds): the first layer, 100 cm high, is composed of sand; the second layer, 80 cm high, is composed of granular activated carbon. The total surface area of the filter beds is 88 m² with a hydraulic load (CI) of 6 m/h. This procedural phase is aimed at refining the quality of the water, eliminating unpleasant tastes and odors as well as removing micro-polluting organic substances and reducing residual coloration.



Figure 4. 19 Filtration tanks – Source SMAT S.p.A

The filters are washed with air and water in countercurrent, using specific backwashing operations daily for the granular activated carbon layer and every six days for the sand layer.

DISINFECTION

After filtration, the water passes into a first tank with a capacity of approximately 3,500 m³ and then into a second tank with a capacity of approximately 11,000 m³. The final disinfection phase takes place in the second tank using chlorine dioxide as a chemical reagent. The reagent is added in quantities that ensure a residual content of active chlorine (0.2-0.3 mg/l) in the distribution network, thus avoiding the proliferation of bacterial colonies.

Through a distribution network of 12,483 km, SMAT supplies, for drinking water needs, an average daily flow rate of 6,137 liters/day on the day of maximum consumption.

4.5.4 Anomalies detected and strategies implemented

4.5.4.1 Po 3 Water treatment Plant – Turin

The manager reported no significant issues at the plant or the water supply source, except for fluctuations in river levels during dry periods or floods caused by extreme weather events. For this type of water source, it is common to experience spikes in organic matter, indicated by higher levels of Total Organic Carbon (TOC), turbidity, or microbial content. Additionally, dry periods often lead to severe water shortages. A study by the University of Turin, Arpa Piemonte, and the SMAT Research Centre revealed that, based on the region's size and rainfall, 21 billion cubic meters of water are available. Of this, 6 billion cubic meters are used for irrigation and 1 billion for drinking or industrial purposes, leaving two-thirds of the water unused. This highlights the need for infrastructure to better manage and conserve water resources.

To address droughts and water shortages, SMAT has developed an Industrial Investment Plan with several future strategies. These include prioritizing the use of stored Alpine waters, implementing innovative technologies to reduce water loss in distribution networks, identifying areas for creating surface water storage basins, establishing municipal interconnections to optimize water supply, and strengthening existing infrastructure and treatment plants.

With support from the SMAT Research Centre, the manager has initiated research projects to assess the impact of climate change on groundwater resources, apply a bottom-up approach to manage water scarcity risks, and develop early warning systems to provide advance notice of potential water crises.

4.5.5 Summary of the case study

4.5.5.1 Po 3 Water treatment Plant – Turin

About fifteen years ago, the SMAT operator built the La Loggia lagoon basin, a water reserve with a current capacity of 2 million cubic meters. Water is collected approximately 10 km upstream from the treatment plant and stored in the basin for 7 to 50 days. This management strategy offers several benefits. First, the basin naturally allows for partial primary sedimentation, helping to control spikes in organic and microbiological loads, even during severe weather events. Second, the basin serves as a water reserve that can be used during droughts, floods, or river pollution, ensuring a stable water supply during emergencies.



Figure 4. 20 La Loggia artificial basin prepared for lagooning – Source SMAT S.p.

The system has proven effective in addressing these challenges, and the drinking water treatment plant has not been significantly impacted by climate change-related issues. To further strengthen the system, there are plans to expand the La Loggia basin by constructing a second reservoir with a capacity of 5 million cubic meters, increasing the total storage to 7 million cubic meters.

A summary in Table 4.4 outlines the supply sources used, the detected anomalies throughout the water supply chain, and the measures taken to resolve these issues. Many of the identified problems are linked to climate change. Rising temperatures have caused algal blooms and biofilm growth, while extreme weather events have led to spikes in turbidity and aluminum levels entering the plant. Additionally, pH fluctuations and higher chloride concentrations (due to the rising salt wedge) are connected to reduced river flow, which results from decreased rainfall, increased evapotranspiration, and land use changes driven by human activity.

Table 4. 4 Summary of the case studies examined in depth

Manager	Source	Detected Anomalies	Actions Taken
Acque Venete S.p.A. (RO)	Adige River	• Sudden pH variations.	• Acidification with hydrochloric acid (HCl).
	Po River	• Increase in chloride concentration.	• Rented a mobile unit for 'Reverse Osmosis'.
AMAP S.p.A. (PA)	Scanzano Reservoir	• Increase in aluminum concentration; • Aluminum in plant output.	• Simultaneous use of polyaluminum chloride (PAC), ferric chloride, and cationic coagulant polydadmec.
	Poma Reservoir	• Excessive increase in turbidity.	• Technical and managerial revamping of the plant.
Gruppo Hera S.p.A. (BO)	Suviana Reservoir	Algal blooms with cyanotoxin development.	• Simultaneous use of polyaluminum chloride (PAC), ferric chloride, and cationic coagulant

			polydadmec; • New disinfectant: sodium hypochlorite (NaClO).
	Po River	• Algal bloom without cyanotoxin development.	• Use of ultrasonic probes to control algal growth.
Padania Acque S.p.A. (CR)	Groundwater	• Increase in water temperature and biofilm growth in distribution pipes.	• Increased concentration of disinfectant.
SMAT S.p.A. (TO)	Po River	• Peaks in turbidity and pollutant concentration.	• Implementation of intake works: lagooning.

This chapter highlights technical investigations aimed at understanding the specific challenges faced by water service managers and the solutions they have implemented to address these issues. The study examines eight case studies from Acque Venete S.p.A., AMAP S.p.A., Gruppo Hera S.p.A., Padania Acque S.p.A., and SMAT S.p.A., along with a detailed analysis of A2A S.p.A.

The findings reveal several key challenges and solutions. For rivers used as water sources, common problems include sudden pH fluctuations, significant increases in chloride levels due to saltwater intrusion, and turbidity spikes during severe weather. To address these issues, managers have applied hydrochloric acid to stabilize pH, deployed mobile reverse osmosis units to manage chloride spikes, and used lagooning techniques to reduce turbidity and enhance natural self-purification.

In the case of lakes and artificial reservoirs, rising temperatures have led to algal blooms that may produce harmful cyanotoxins, while heavy rainfall has caused aluminum spikes from soil runoff and turbidity increases due to the movement of organic matter. To combat these problems, water managers have used coagulant and flocculant reagents (such as aluminum polychloride, ferric chloride, and cationic polyamine) to improve water clarification and filtration. Additionally, ultrasonic probes have been installed to control algal growth, and oxidizing agents are used to eliminate cyanotoxins like microcystin-LR.

When comparing surface water and groundwater sources, surface waters are more vulnerable to climate-related anomalies and environmental changes, whereas groundwater sources, such as wells, generally maintain stable water quality with fewer variations.

In conclusion, water service managers have proactively responded to these challenges by adopting advanced technologies and management strategies in line with Water Safety Plans. These efforts aim to strengthen the resilience and safety of water supply systems, ensuring consistent water quality despite the growing impacts of climate change and environmental pressures.

4.6 Conclusion

Chapter 4 presents the results of a national survey and detailed case studies investigating the effects of climate change on drinking water supply systems in Italy. The study highlights the increasing challenges water utilities face due to climate-induced anomalies in raw water quality, treatment processes, and distribution networks. The findings, drawn from surveys, technical visits, and interviews with water service managers, demonstrate the urgent need for adaptation strategies to maintain water safety and compliance with regulatory standards.

The survey engaged approximately 40 water utilities, with most participants from Northern Italy. Among them, 33 managers reported significant climate-related issues, including declining water levels, increased chemical and microbiological contamination in springs and groundwater, and rising

turbidity due to flooding. These challenges have intensified the demand for treatment of chemicals, increased energy consumption, and, in some cases, led to regulatory non-compliance.

The case studies analyzed water utilities in different regions, including Acque Venete (Rovigo), AMAP (Palermo), Hera Group (Bologna), Padania Acque (Cremona), and SMAT (Turin). These companies have implemented various adaptation measures to counteract the effects of climate change. Strategies include intensified monitoring, the use of advanced treatment technologies, adjustments to disinfection processes, and infrastructure upgrades to enhance resilience. For instance, utilities have deployed real-time turbidity sensors, optimized reagent dosing, and introduced innovative treatment solutions such as biological filtration, reverse osmosis, and ultrasonic control.

One of the most pressing issues identified is the impact of extreme weather events on water treatment processes. High turbidity events following intense rainfall have challenged conventional treatment systems, leading to the need for process modifications such as enhanced coagulation, flocculation, and filtration upgrades. Additionally, increasing temperatures have accelerated microbial regrowth in distribution networks, necessitating stronger disinfection measures.

The study underscores that while utilities have taken proactive steps, long-term sustainability requires integrated climate adaptation strategies, improved regulatory frameworks, and investments in resilient infrastructure. Strengthening water safety plans (WSPs) and leveraging digital monitoring technologies will be crucial in mitigating climate-related risks. Moving forward, further research should focus on predictive climate models, smart water management systems, and cross-sector collaboration to enhance the adaptability of drinking water supply systems in the face of climate change.

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CHAPTER 5: THE CASE STUDY OF MOMPIANO

This chapter introduces a novel case study of the Mompiano source that integrates continuous online monitoring data (e.g., turbidity, conductivity, redox potential) with meteorological trends to evaluate how climate variability affects a groundwater-based system. Unlike previous studies, this research applies early warning concepts to a karstic groundwater source, offering new insights into its vulnerabilities and real-time response strategies.

This chapter provides a comprehensive analysis of the Mompiano water source, emphasizing its historical significance and its current critical role in supplying water to the city of Brescia. It begins by exploring the development and contributions of this vital source. From November 2022 to March 2023, I collaborated with Simone and Marika to study the history and origins of the Mompiano water source, leveraging data from the hydrology department of the supplying company.

Building on this foundation, analysis incorporates advanced methodologies using Python for data analysis and extends the scope with additional datasets from 2023 and 2024. In this chapter, the descriptive and historical sections were primarily developed by Simone, while I focused on applying new analytical techniques and distribution network data. These efforts included integrating data collected in 2023 and utilizing IDEXX tool. The system is a tool that allows the identification of certain bacteria using an improved technique that allows obtaining results with shorter incubation times than classical methods. to gather microbial data for 2024.

To strengthen the analysis, this chapter examines the potential impact of climate change, particularly extreme temperature variations, on fountain water temperatures and chlorine concentrations at the wells within the distribution network. Additionally, fieldwork was conducted in collaboration with colleagues from the company at various sampling sites, where water samples from the fountain and distribution points were analyzed to assess water quality trends. Notably, this work marks the first application of automated microbial measurement probes in the system, providing a cutting-edge perspective on water quality dynamics. Through this multi-faceted approach, the chapter combines historical context with innovative tools and methodologies to address present and future challenges in the management of the Mompiano water source.

The chapter then explores the hydrology of the source, identifying its primary and secondary water sources through tracer tests and geological studies, while emphasizing the balance between these sources and their impact on the system's reliability. To protect the source from potential pollution, protection zones established by the resource manager are discussed, which are still in force and integrated into Brescia's territorial management plans. Additionally, the chapter explains the operation of the chromium removal treatment plant, emphasizing its role in ensuring water quality.

Furthermore, the water supply system is described in detail, including an assessment of risks and concerns beyond what appears in the system description based on Real-time Data Analytics. This involves analyzing hazardous events and associated risks, evaluating the materials used in the construction of pipelines and storage facilities, and reviewing historical water quality data along the drinking water supply chain. Finally, it provides an overview of the remote monitoring and control system, supported by detailed flowcharts and plant schematics, showcasing the advanced measures in place to manage and safeguard this essential resource.

This comprehensive analysis underscores the strategic significance of Mompiano as a sustainable and resilient water source for Brescia.

This chapter consists of:

- Describe the Water Supply System
- Method to Identify Hazards and Risks of extreme weather events on the variability of critical parameters in drinking water quality systems
- Results and control measures by overview of the remote monitoring and control system

5.1 Describe the water supply system

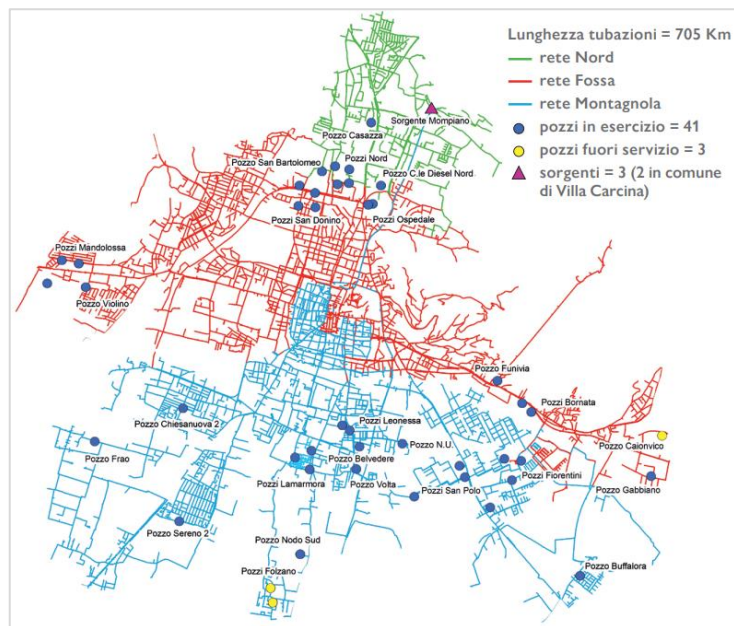
5.1.1 Description of the intake system and historical overview

The Mompiano water source, located at an altitude of 172 meters at the foot of the southern slope of Saint Joseph Hill in the Monte Maddalena complex, has played a critical role in Brescia's water supply for centuries. The hill is composed of fractured limestone formations and alluvial deposits, which create a natural threshold that saturates the rock and triggers the emergence of the spring through localized fractures. Since ancient times, this source has been a vital natural water reserve for Brescia. Initially, the water flowed nearly 5 kilometers to the city through an open-air channel, later covered with stone slabs along the Cidneo Hill to reach the city center.

Over time, the system was adapted to meet growing demands, including significant renovation in 770 AD during the Lombard era. By the late 19th century, the Mompiano waters supplied 73 public fountains and over 2,500 municipal and private taps, earning Brescia the nickname "the city of a thousand fountains." At the source, water is collected in a large reservoir with a capacity of 500 m³ and features for periodic maintenance, such as drains and overflows.

In the early 20th century, as Brescia's population and industries grew, a new water network was established in 1902, extending the system with a 3,480-meter reinforced concrete pipe to a reservoir on the northern slope of the Cidneo Hill. This expansion, along with the discovery of additional springs, improved the system's capacity and protected the water source from contamination. By 1914, a new reservoir with a capacity of 7,100 m³ was added, drawing water from the Cogozzo source wells to meet increasing demand. The Mompiano source, despite its reduced contribution over the years, remains a strategic element in Brescia's water management, now providing 14% of the city's water supply alongside the Cogozzo source.

Currently, Brescia's water network spans approximately 705 kilometers, including multiple storage tanks with a total volume of 29,000 m³. The system is powered by 41 wells tapping into deep aquifers, along with the natural sources of Mompiano and Cogozzo. The network is divided into three interconnected sub-networks: the North Network, supplying the northern city areas with 400 l/s from 7 wells and the Cogozzo source; the RoSSa Network, covering the east, west, and northern city districts with 760 l/s from 16 wells; and the Montagnola Network, which serves the historic center and southern areas with 600 l/s from the Mompiano source and 18 wells. Together, these systems ensure a reliable and efficient supply of drinking water for the city.



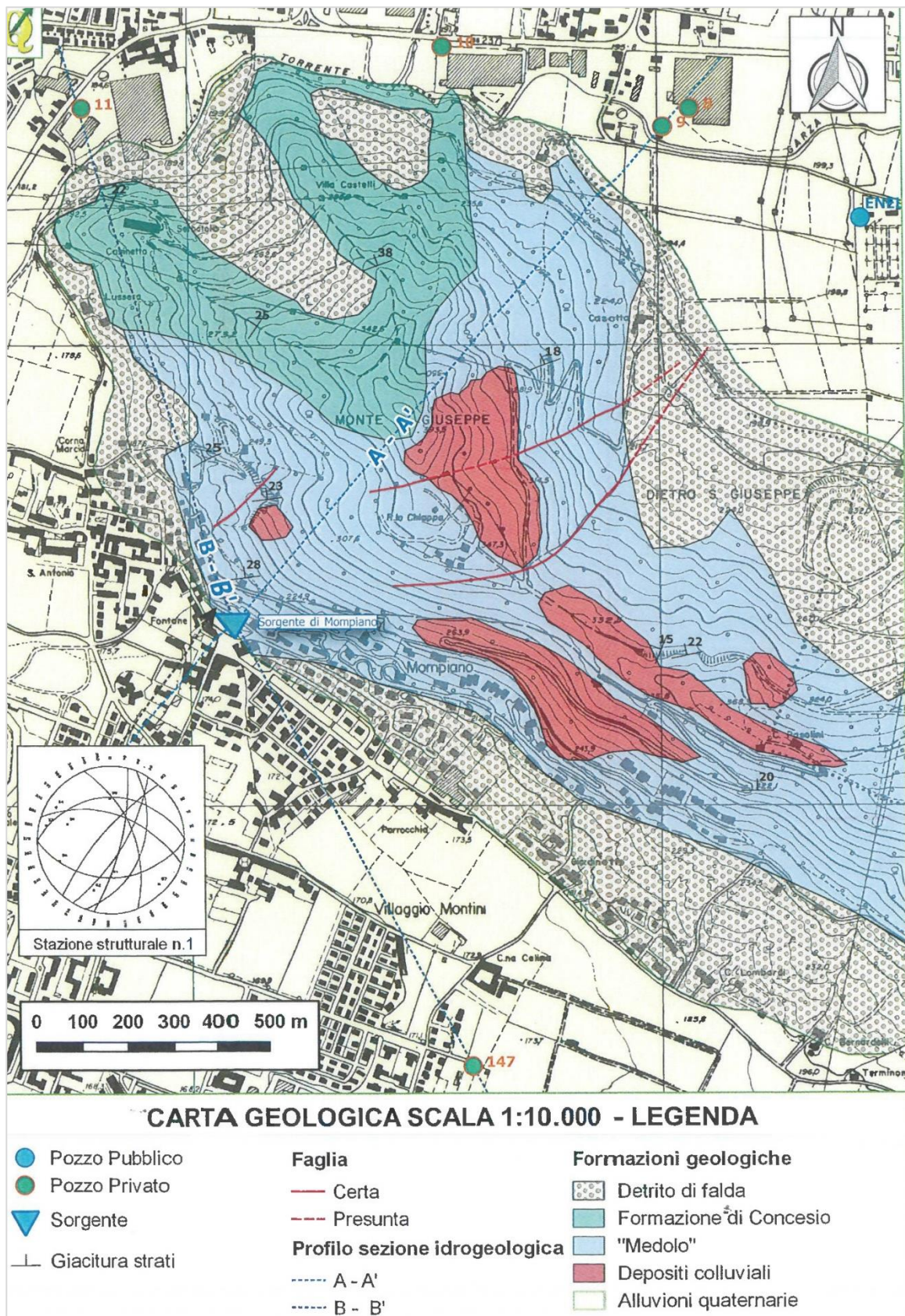


Figure 5. 2 A geological map showing the recharge area that supplies water to the Mompiano source.

Source: internal Document A2A (Francani V. et al., 1991).

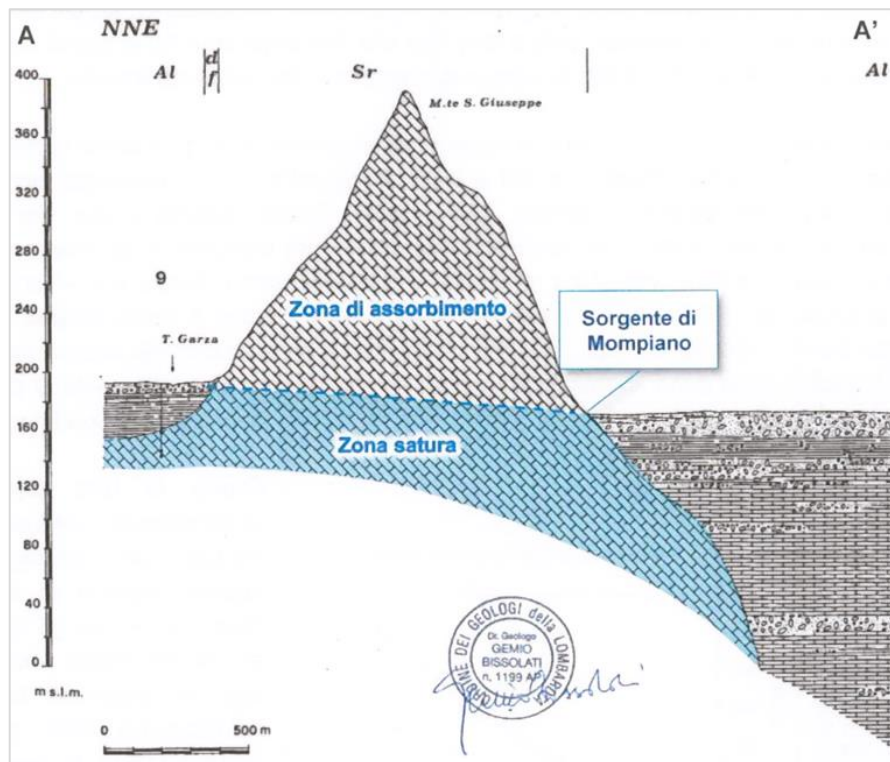


Figure 5. 3 Profile section hydrogeological A-A' in the direction NE-sw

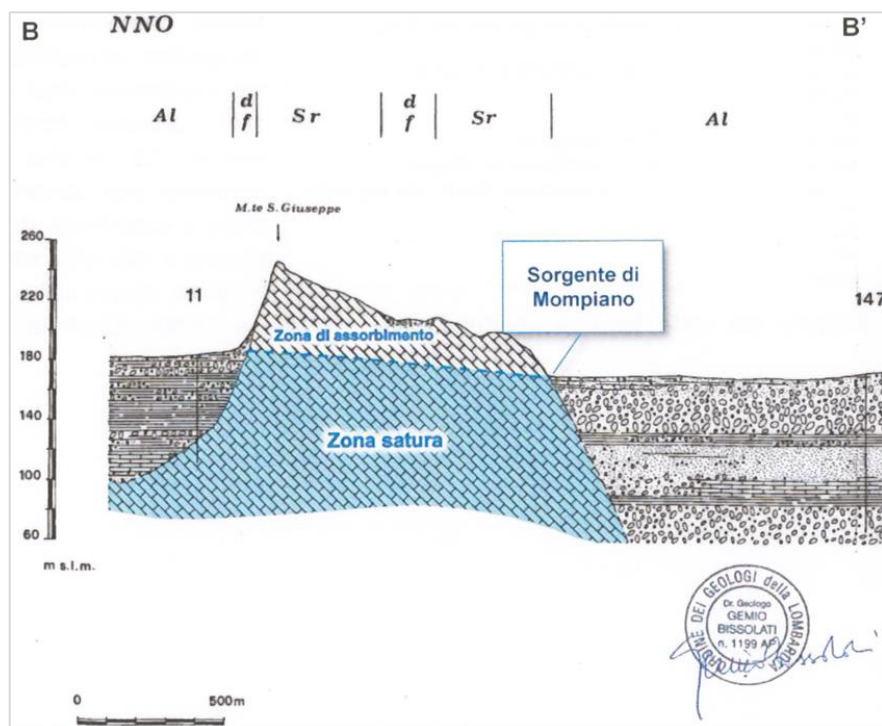


Figure 5. 4 Profile section hydrogeological B-B' in the direction of NNW-SSE.

The study involved a rapid field analysis using portable UV lamps, followed by laboratory verification through fluorometric spectrum analysis. This investigation focused on tracking the movement of groundwater from its recharge area to its emergence at various sources, including Zugna, Mompiano, and Fontanone di Paitone. The findings helped establish groundwater flow times and transfer speeds between the absorption zone and the source points.

The most responsive source during the tests was Zugna, where the tracer reappeared in high concentrations in less than 18 hours. This quick response indicated a direct connection between the cave system (Omber en band to the büs zel) and the source. The flow velocity was estimated at approximately 2 meters per minute. Additionally, the variability in flow rates at Zugna (ranging from 15-20 l/s during dry periods to over 300 l/s during peak flow) confirmed it as the sole outlet of the karst system in question.

In contrast, other sources around the plateau showed less definitive results, likely due to longer and more complex flow paths or interference with surface-fed aquifers, such as those connected to the Garza torrent. This led to the conclusion that the Mompiano source is not directly fed by water from the Plateau of Cariadeghe. However, historical studies, including Canovetti (1894), identified a connection between losses in the Garza torrent bed and some of the water feeding the Mompiano source.

Interestingly, while it was expected that part of the tracer from Zugna would eventually appear at Mompiano after a delayed period, this was not observed, even after 40 days of monitoring. The likely explanation is that a flood in the Garza torrent, occurring two days after the tracer's introduction, rapidly carried it downstream, preventing infiltration into the Zugna and, subsequently, its arrival at Mompiano.

The hydrogeological map of the southern Prealps (Figure 5.5) illustrates these findings, highlighting the established groundwater routes tracked with Tinopal CBS-X. The map particularly emphasizes the connection from the Zugna to the southern slope of St. Joseph Hill, where the Mompiano source emerges.

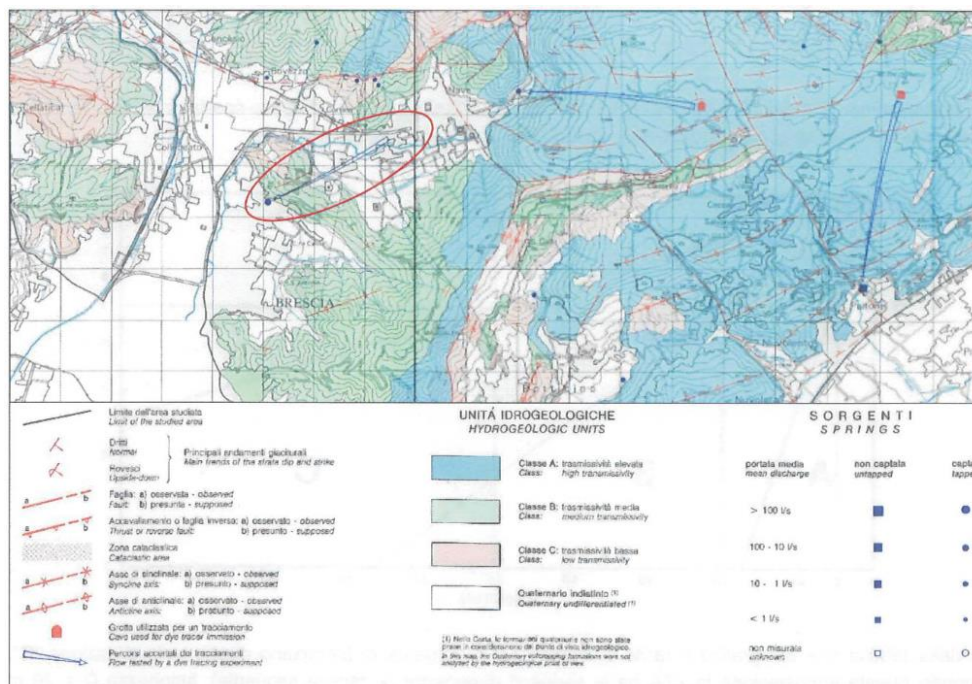


Figure 5. 5 Hydrogeological map of the southern part of the prealps

Source: Avanzini et al., Brescia, 1991.

During the tracer testing campaign, a genetic-evolutionary model was developed to understand the deep karst topography of the Cariadeghe Plateau. According to this model, before the Holocene sedimentation, water infiltrating the karst plateau flowed directly to the lowest source in the valley

(referred to as the paleo-source) through natural conduits carved into the rock, without feeding other springs. However, after the sedimentation and subsequent flooding, the overall rise in groundwater levels caused new springs, such as those at Zugna and Mompiano, to emerge and flow continuously. This change reduced the amount of water reaching the paleo-source downstream, as illustrated in Figure 5.6.

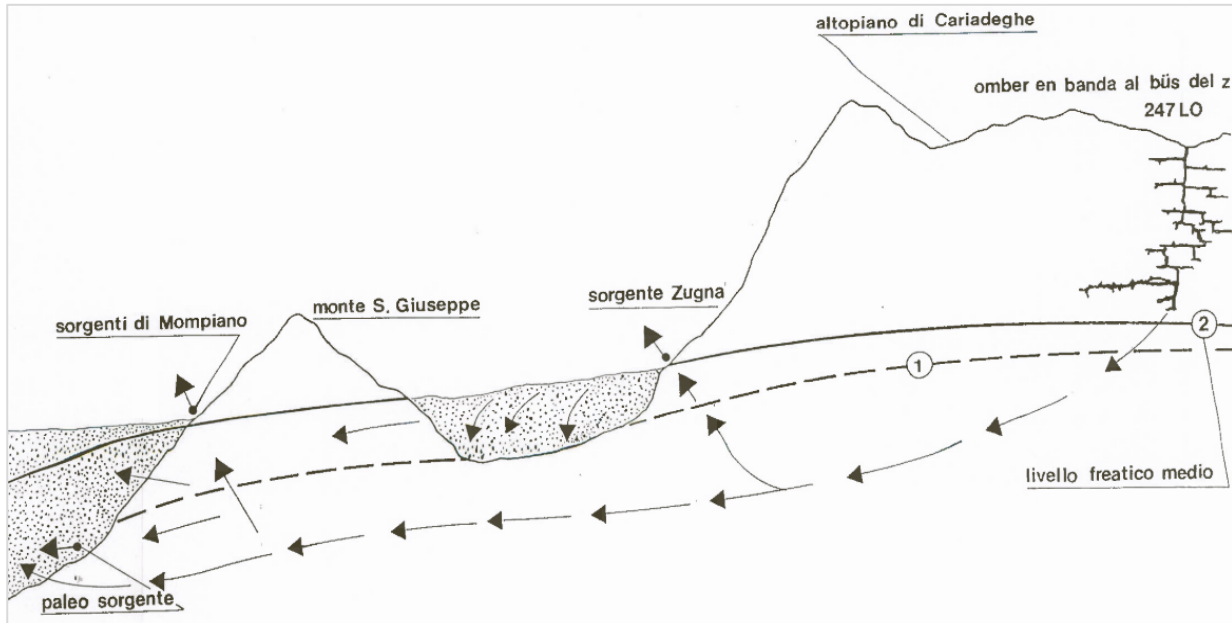


Figure 5. 6 The movement of water within the aquifer that supplies the Mompiano source after the Holocene flooding

Source: the Strong and the Marquis, 1993

The base level of the springs around the karst plateau is significantly higher than the lowest level ever reached during the evolution of the karst system, which remains buried beneath Holocene flood deposits. Researchers have noted a "reverse evolution" in the karst plateau during its final evolutionary stage. This term describes the upward movement of infiltrated water, which flows in the opposite direction to gravity, creating ascending conduits near spring emergence points.

In the 1970s, the installation of multiple wells in the Plain of the Ship and the Brescia area (Figure 5.7) became widespread. These wells, combined with intense industrialization in the region, caused a significant lowering of the groundwater table and accelerated the depletion of karst and alluvial conduits that transport water to the floodplain.

These combined factors have further reduced the flow to the Mompiano source, whose recharge was already characterized by a relatively slow hydrodynamic process.

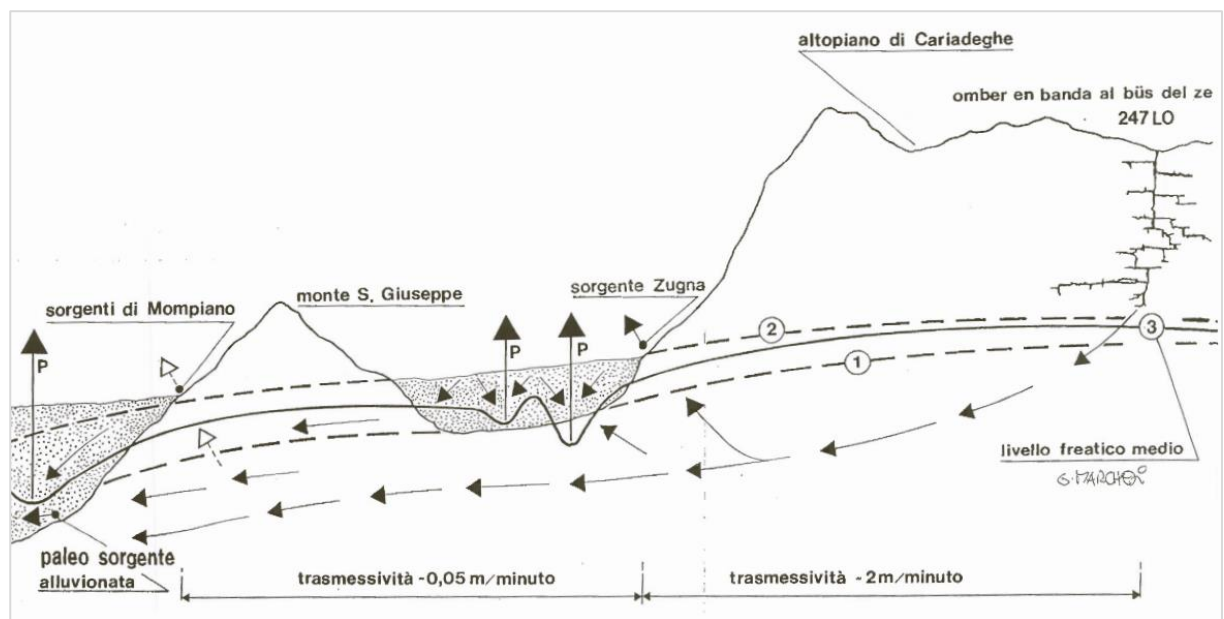


Figure 5. 7 The movement of water in the aquifer supplying the Mompiano source changed significantly after the installation of wells in the Plan of Zugna (2P) and the Brescia plain. These wells caused a drop in groundwater levels, altering the natural flow patterns

Source: the Strong and the Marquis, 1993

To verify the reliability of the assumptions made about the recharge of the Mompiano source during the study by Francani et al. (1991), the authors analyzed hydrological data provided by the Brescia municipal water service company (ASM, now A2A Water Cycle).

Francani team compared rainfall data (from August 1990 to March 1991) with flow data from the source (August 1990 to January 1991). During periods when the land was already saturated, even small and sporadic rainfall events (a few millimeters) quickly impacted flow rates at the source within 2–3 days. However, during drier conditions, the delay between rainfall and flow changes was significantly longer. This indicated that the flow at the source throughout the year is strongly influenced by precipitation in the recharge basin and is predominantly driven by deep karstic water circulation.

They also compared rainfall with fluctuations in the groundwater table, as recorded by two piezometers in Brescia's water distribution network, to assess potential links between the groundwater in the Plain of the Ship (2P) and the Mompiano source. The analysis revealed strong correlations: rainfall and source flow had a correlation coefficient of $R^2 = 0.89$, while rainfall and groundwater table fluctuations had a coefficient of $R^2 = 0.64$. These findings support the assumption that the recharge of the Mompiano source is influenced both by the degree of rock fracturing in the mountain and by the groundwater in the Plain of the Ship (2P)

Further evidence of these connections emerged in April-May 2009, when the Mompiano source experienced episodes of sudden and severe turbidity, leading to inefficiencies in the water system. Investigations revealed that these events were caused by geothermal drilling in the San Giuseppe area, which intercepted a saturated karstic conduit feeding the source and disturbed the water quality.

5.1.2 Definition of areas of protection for the source

In the early 1990s, discussions began about potential residential expansion near the Mompiano source in Brescia. The Municipal Services Company of Brescia (ASM, now A2A), responsible for managing the water supply from the source, expressed concerns about the potential impact of urban and industrial development on water quality. They emphasized the need for enhanced protection of the water resource to mitigate risks arising from increased urbanization, which can alter natural flow conditions and the distribution of surface and groundwater. Improperly planned or executed interventions in such areas could have unpredictable and harmful consequences for water quality.

To address these concerns, hydrogeological studies were conducted, leading to the establishment of protection zones around the Mompiano source. These zones were defined according to regulations in force at the time (D.P.R. n. 236, 1988, later updated by D. Lgs. 152/2006) using the methodology proposed by Civita (1988). The process involved analyzing flow data from the source, measured continuously between September 1991 and May 1992. The protection area was divided into three zones:

Absolute Protection Zone (HAZ): This area, closest to the source, is fenced and managed exclusively by authorized personnel. It includes activities such as water capture, treatment, and distribution.

Respect Zone (ZR): Encompasses the HAZ and provides an additional buffer.

Protection Zone (ZP): Covers the recharge area of the aquifer supplying the source and includes the HAZ and ZR.

During the study, structural surveys identified fractures in the rock mass near the source. These fractures, combined with calcareous layers and deformations, create a dense network of discontinuities that facilitate deep water circulation from the Plain of the Ship to the Mompiano source. The surveys also revealed that the rock's fracturing decreases with depth, allowing for significant surface seepage. Discontinuities arranged almost vertically promote rapid surface water infiltration, which, in the presence of pollutants, could lead to contamination of the source within 1 to 10 days, depending on the distance from the entry point.

Figures 5.8 and 5.9 illustrate the boundaries of the protection zones defined during the study and their inclusion in Brescia's Territorial Government Plan. These boundaries have been maintained over time to safeguard the source and its surrounding area. Additionally, a hydrological analysis compared flow rates at the source with rainfall data from Brescia's meteorological station (ITAS G. Giuseppe Pastori) during the same study period. Although limited, the data showed a clear relationship: rainfall events led to increased flow at the source within approximately two days, confirming that local infiltration contributes significantly to the source's recharge.



Figure 5. 8 Areas of protection of the groundwater resources carried out in 1993 (according to D. P. R. 236/88) in source of Mompiano

Source: “the Delineation of areas of protection of the groundwater resources (D. P. R. 24.05.88 n° 236) Sorgente of Mompiano Brescia”.

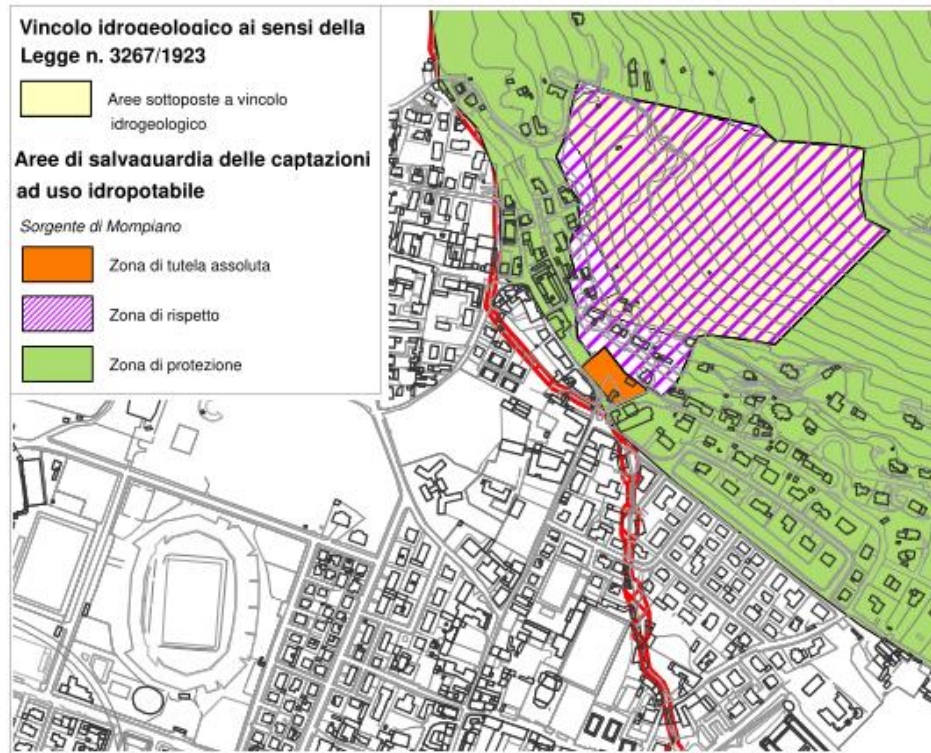


Figure 5. 9 Land Protection Plan highlighting soil conservation measures. (V - PR06)

Source: PGT of the Town of Brescia (2020).

5.1.3 Water Treatment of Mompiano

As mentioned earlier, in Mompiano, the water is collected through a structure that includes a large reservoir integrated with a sedimentation tank, with a capacity of approximately 500 m³. This structure forms the origin of the source. The reservoir is equipped with bottom drains and overflow systems to facilitate regular maintenance. As shown in Figure 5.10, the base of the reservoir consists of exposed rock partially covered with a layer of gravel.



Figure 5. 10 The source of Mompiano

At the beginning of the 20th century, as part of the expansion of the water network, a new reinforced concrete pipeline was constructed. This pipeline, measuring 1,000 mm in diameter, 3,480 meters in length, and with a slope of 1‰, was designed to transport water from Mompiano to the Hill Tank (Figure 5.11), located on the northern slope of Cidneo Hill. The Hill Tank has a storage capacity of 6,400 m³ and serves as the starting point for the aqueduct network that supplies the southern areas of the city.

The average flow rate of water utilized by the aqueduct, calculated over the past 25 years, is approximately 100 liters per second. This represents about 80% of the total production capacity of the Mompiano source. However, due to the absence of an upstream filtration system, the water can only be used when it is clear and free of turbidity. If turbidity exceeds 1 NTU, the water is diverted directly to the sewer system instead of being distributed.



Figure 5. 11 Structure of access to the water tank Hill

5.1.3.1 System for the removal of chromium



Figure 5. 12 System of filtration with granular activated carbon (GAC) of Mompiano

Based on information collected before this study about the water quality at the Mompiano source, sampling conducted by the operator (up to 2015) at the point before disinfection (raw water) shows that the incoming water is of good quality from a chemical and physical perspective. It meets the standards of the then-current legislation (D. Lgs. 31/2001). In the past, increased turbidity were observed during significant meteorological events, but in such cases, the water was excluded from the aqueduct network. As a result, the Mompiano source is not equipped with a full-scale drinking water treatment plant.

In 1988, a treatment plant with activated carbon was installed to prevent service disruptions caused by sudden pollution events from industrial or agricultural sources (e.g., chlorinated solvents, chromium, atrazine). This setup ensures the continued provision of safe water in such scenarios (Figure 5.12).

The system is primarily composed of the following components:

- 4 Granular Activated Carbon (GAC) Filters: Designed to handle a total flow of up to 400 m³/h.
- 4 Ferrous Sulfate Tanks: Each with a capacity of 1,000 liters, arranged in parallel.
- 2 Ferrous Sulfate Injection Pumps: For dosing the chemical into the water.
- PLC (Programmable Logic Controller): Manages the entire treatment process.
- Uninterruptible Power Supply (UPS): Ensures uninterrupted operation of the PLC.
- Filter Equipment Kit: Includes solenoid valves, pneumatic valves, compressors, air tanks, compressed air dryer, blower, and backwash pump.

The system features two transfer pumps capable of drawing approximately 110 l/s from the source and delivering it to the filters. These pumps are equipped with inverters and are manually controlled on-site using a PLC, allowing operators to start, stop, and adjust flow rates as needed. A pressure relief valve at the treatment outlet ensures filtration pressure is maintained at an optimal range of 1.3-1.5 bar. Designed as a precautionary measure, the system is equipped to handle potential contamination and prevent interruptions in the water supply.

In 2014, the system was upgraded to address high chromium concentrations in Brescia's groundwater. Ferrous sulfate (FeSO₄) is injected into the raw water pipes, where it reacts with chromium. to form red-colored. The oxidation of iron results in the formation of red scales, which contain chromium which is reduced to chromium VI. This residue is then retained with activated carbon.. The ferrous sulfate tanks and dosing lines are equipped with heating elements that adjust to environmental temperatures, ensuring proper functionality under varying conditions.

To maintain efficiency, filters are routinely backwashed to remove retained iron and chromium particles. This process, fully automated by the PLC, utilizes water from two sources: a dedicated outlet in the northern network and filtered process water. Additionally, the system monitors water turbidity through a Lange instrument. If turbidity exceeds 12 NTU, a "High Turbidity" alarm is triggered by the PLC. If the high turbidity persists for few minutes, the transfer pumps automatically shut down. The system remains inactive until turbidity falls below 1NTU for at least 15 minutes, at which point normal operations resume.

According to the managing entity, the system has been activated only once for a short period and has not been required since, demonstrating its reliability and robustness in safeguarding water quality.

5.1.3.2 Remote control system: remote sensing

During normal operations, water transport and distribution systems can occasionally experience issues that disrupt their functionality, such as excavation damage, equipment faults, maintenance activities, or power outages. To address this, the water services management agency has equipped all facilities and supply points with remote monitoring systems. These systems enable the timely detection of any malfunction, allowing for rapid intervention.

The remote-control system operates 24/7, year-round, and is staffed by a dedicated team. It collects data from various monitoring systems, records and processes it, and determines the best operational configurations to ensure the safety and continuity of the water service. Additionally, the system allows for remote management, including starting and stopping pumps and partially or fully opening and closing motorized valves.

Figures 5.13, 5.14, and 5.15 illustrate the remote-control interface for Brescia's aqueduct network. The interface displays all key interception points, the city's three interconnected networks, and the storage tanks, including those specifically for the Mompiano source and the Hill Tank. This system ensures reliable and efficient water supply management.

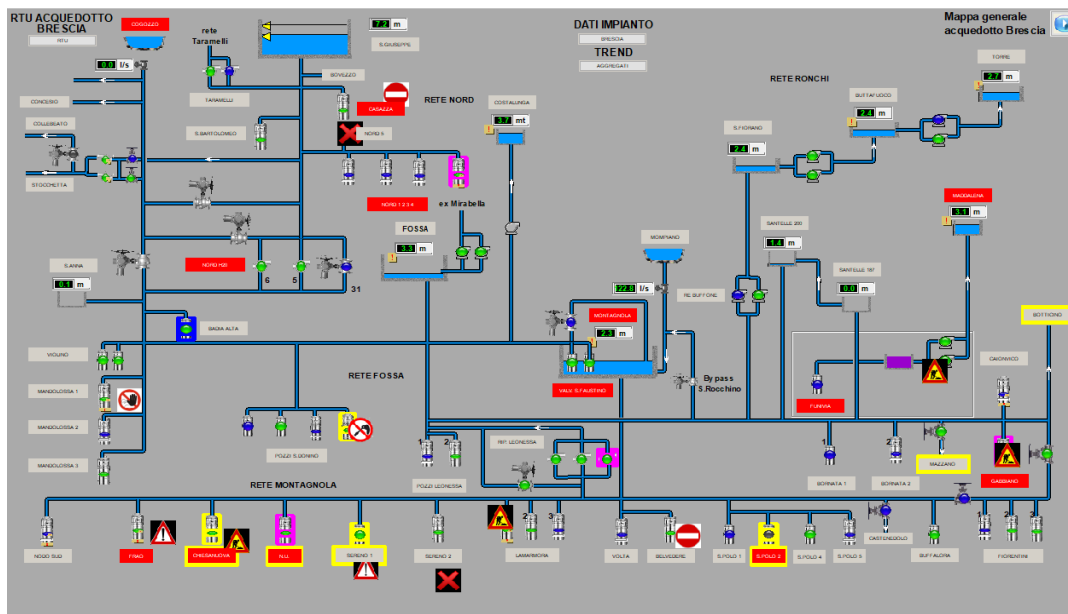


Figure 5. 13 Diagram of the remote control relative to the entire aqueduct network of Brescia

Source: A2A Water Cycle Brescia (2023)

Figure 5.14, the treatment plant layout with activated carbon filters, the FeSO_4 dosing tanks, and various pumping systems can be clearly seen on the right side. On the left side, real-time data from sensors installed at the source is displayed. These sensors continuously monitor the incoming water. One sensor, the HACH probe, measures turbidity, pH, conductivity, and redox potential. The other, a multiparametric Isoil probe, measures turbidity, nitrate levels, and provides a spectrum analysis.

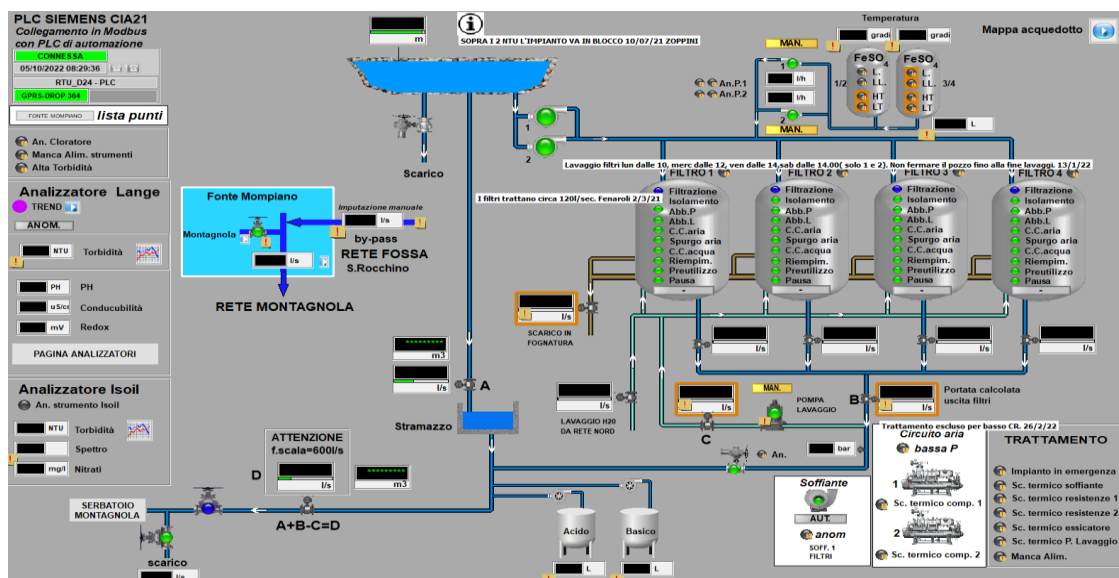


Figure 5. 14 Diagram of the remote control corresponding to the source of Mompiano

Source: A2A Water Cycle Brescia (2023)

Before being distributed, water from the Mompiano source is disinfected with chlorine dioxide (ClO_2). This disinfectant is prepared in a compact reactor by mixing a basic substance (sodium chlorite, NaClO_2) with an acid (hydrochloric acid, HCl), and the solution is introduced into the pipeline.

The water is then transported to the Hill Reservoir (Figure 5.15), where it mixes with water from nearby wells before being distributed to users in the southern zone of the city. At the entry point of the Montagnola Reservoir, within the "control room," continuous monitoring is carried out using aHACHanalyzer. This device measures turbidity, pH, conductivity, and redox potential. Additionally, a chlorine dioxide monitor checks the residual chlorine levels to ensure effective disinfection from the Mompiano treatment process.

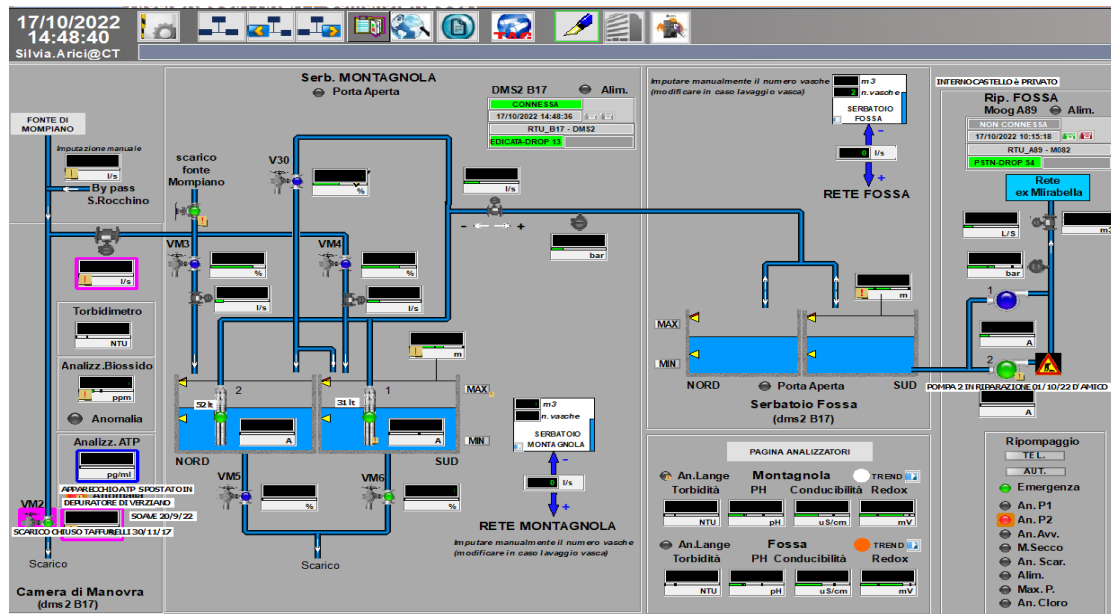


Figure 5. 15 Diagram of the remote control relative to the reservoir Hill

Source: A2A Water Cycle Brescia (2023)

This highlights the crucial role of the Mompiano source as the primary supply for the Hilllock distribution network. If the Mompiano source alone could fully meet the demands of the southern zone, the nearby wells would be shut off, and only water from Mompiano would be used in the network.

The diagram also shows the / Fossa Tank, which supports the central network of the city, stretching from east to west and fed by several wells surrounding the city. The two tanks, Fossa and Montagnola, are interconnected to provide mutual support. This setup ensures that if the Mompiano source is unavailable or insufficient, the Fossa Tank can compensate by supplying water to the Montagnola system. Similarly, Montagnola can support the Fossa network if needed, ensuring a reliable water supply for users in all scenarios.

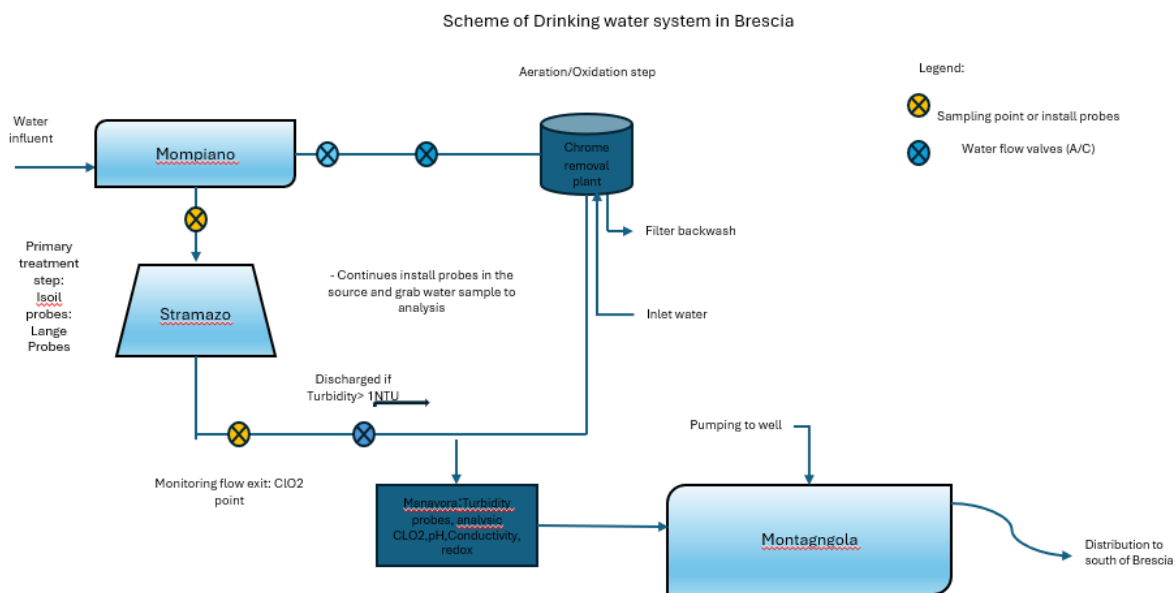


Figure 5. 16 Diagram of flow relative to the source of Mompiano

5.2 Methodology

In the first phase of the study, the team focused on collecting data related to the water supply system under investigation. Management data were obtained from A2A Water Cycle, the company responsible for water resource management, while meteorological data (precipitation and temperature) were sourced from the online database of ARPA Lombardia.

In the second phase, data were analyzed, including laboratory tests from Mompiano source samples and continuous real time data key parameter measurements. These included physicochemical parameters like pH, conductivity, turbidity, and temperature, as well as microbiological indicators such as E. coli and coliforms. The analysis was based on updated drinking water regulations (D. Lgs. n°18/2023), comparing the highest parameter concentrations against both current and previous regulatory limits (D. Lgs. 31/2001). All data were processed and analyzed using Python.

Python was used in the study for

a. Data Processing:

- Cleaning and organizing grab water sample data with pandas (pd).
- Time-series analysis (e.g., rainfall and water quality trends) using statsmodels

b. Statistical Analysis:

- Correlation analysis (Pearson, Spearman) with scipy.
- Multivariable regression (e.g., rainfall and turbidity) with statsmodels or sklearn.

c. Advanced Analysis:

- Principal Component Analysis (PCA) for dimensionality reduction using sklearn.
- Clustering (K-Means, Hierarchical) for classifying water samples by quality.
- Machine learning for prediction (Random Forest, XGBoost) and classification (Logistic Regression).

d. Data Visualization:

- Visualizing trends, correlations, and spatial maps with matplotlib,

Given the primary objective of operational monitoring, it appears appropriate that this activity is closely linked to high-frequency measurements, resulting in a large amount of data being available. The processing of this data can significantly and clearly outline the current operational framework of control measures and the context in which Early Warning Systems (EWS) are integrated. These systems rely on online monitoring, enabling continuous sampling to ensure the detection of any abnormal variations in monitored parameters and timely interventions to reduce or eliminate associated risks.

The fundamental concept of early warning systems includes simplifying the complexity of parameter sets by focusing on more specific parameters, such as physicochemical indicators (pH, conductivity, turbidity, temperature) and microbiological factors (HPC, IDEXX and indicator microorganisms). These parameters can be effectively used as indirect indicators of unwanted changes in the system under analysis. To manage critical variations in control measures in real-time accurately, it is necessary to link the measurement results to response actions capable of restoring the correct operational conditions of the control system.

The conditions for applying early warning systems include, in addition to verifying their practical utility, economic accessibility, ease of use and management, compatibility with remote control systems, and an adequate level of accuracy and reproducibility of the generated data.

5.2.1 Analysis of historical meteorological data

Meteorological data on precipitation and temperature were sourced from ARPA Lombardia's official online database, "Hydro-Nivo-Meteorological Data Store." For this study, daily average values were used to represent the conditions in the Mompiano area.

Precipitation Data

Daily average precipitation data were chosen as the most representative measure of the conditions in Mompiano. This decision was based on a comparison of data from three different sources:

ARPA Lombardia (Brescia ITAS Giuseppe Pastori Station): Data from the meteorological station at the Istituto Tecnico Agrario Statale "Giuseppe Pastori" in Brescia.

ARPA Lombardia (Multiple Stations): Data from stations in Caino, Gavardo, Odolo (Via Praes), and Brescia (Via Ziziola). The daily average precipitation was calculated as the means of the measurements from these four stations.

Weather Radar (Serle Station): Data from the meteorological station in the municipality of Serle.

By using these varied sources, the study ensured accurate and representative precipitation data for the area, forming a solid basis for understanding the impact of weather patterns on the water supply system.



Figure 5. 17 Identifying meteorological stations located near the Mompiano source

Source: Google of the Maps, (April 2023).

The three types of data were compared pairwise by analyzing their deviations and correlations (see Figure 5.18.). After processing the data, it was found that there were no significant differences between the three datasets. As a result, the ARPA data from the Brescia ITAS Giuseppe Pastori station was selected as the reference for this study. This station was deemed the most suitable due to its proximity to the Mompiano source and the availability of comprehensive data. The station's location is particularly important because, as highlighted in previous studies, local infiltration significantly impacts the quantity and quality of water at the source following weather events.

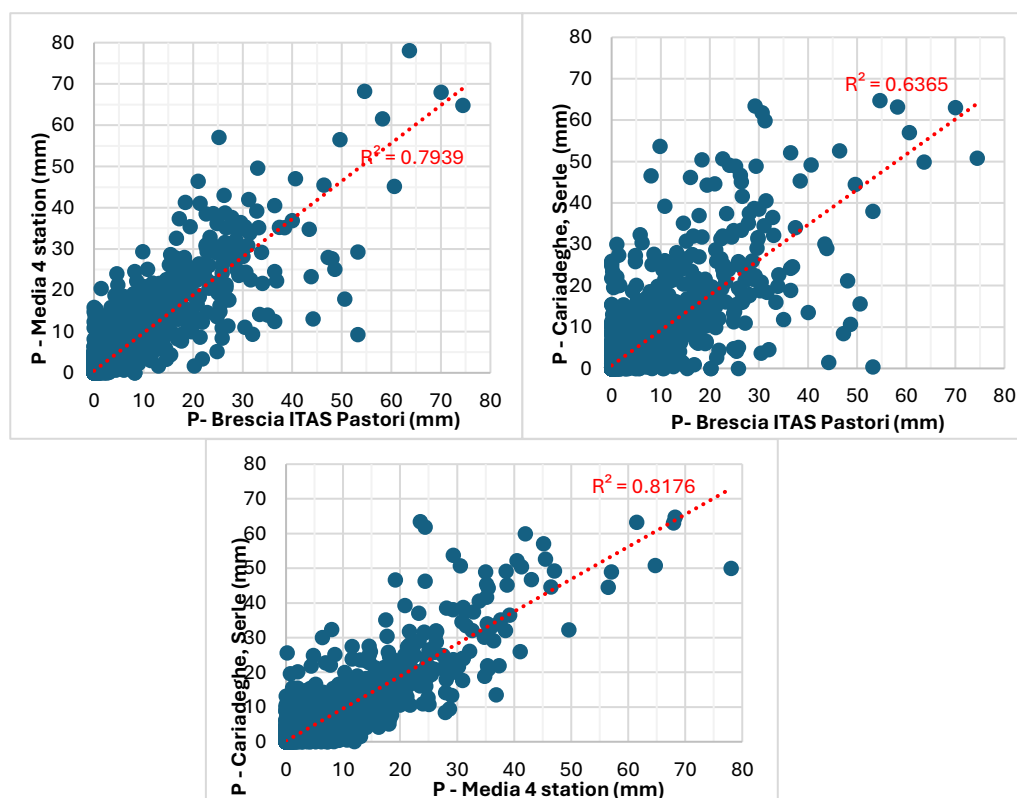


Figure 5.18 Statistical Correlation Between Different Precipitation Data

The upper-left graph illustrates the correlation between daily average precipitation recorded at the Brescia ITAS Pastori weather station and the average precipitation from four other stations: Caino, Odolo, Gavardo, and Brescia (Via Ziziola).

The upper-right graph shows the correlation between the daily average precipitation at Brescia ITAS Pastori and the daily averages recorded at the Serle station, which corresponds to the Plateau of Cariadeghe.

In the lower section, the graph compares the average precipitation from the four stations (Caino, Odolo, Gavardo, and Brescia) with the daily averages recorded at Serle, highlighting the relationship between the two datasets.

Rainfall Analysis

The graphs below depict rainfall patterns in the study area, based on precipitation data recorded at Brescia ITAS Giuseppe Pastori from January 2014 to December 2024. Graph 4.1 focuses on annual total precipitation over the period. Notably, 2024 stands out as the year with the highest number of rainy days. Additionally, the chart highlights trends of increasing and decreasing precipitation in subsequent years, offering valuable insights into changing rainfall patterns in the region.

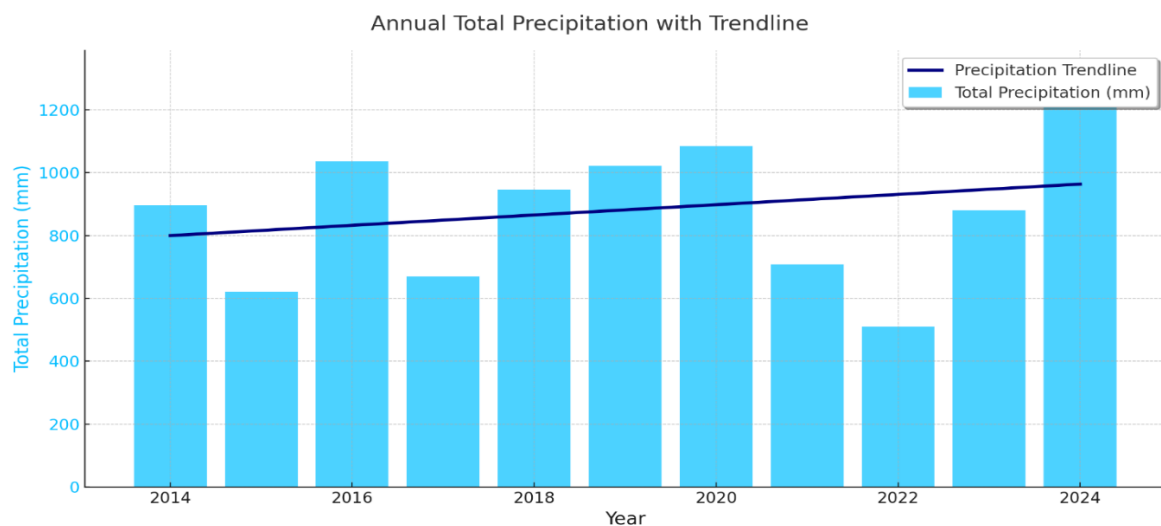


Figure 5. 19 Performance of the value of total annual precipitation in the period 2014-2024

In particular, after a sharp decline compared to the previous year, the period 2017-2020 is characterized by a progressive increase in the total annual rainfall, which culminates in the year 2020 (second year, most rainy of the series analyzed) and then begins a gradual decrease, in a manner quite abrupt, until today.

In the Figure 5.20 shows the precipitation trend during the period considered (2014-2024). You can see that there are peaks distributed rather intense over the period, a sign of a trend in the seasonal variation of rainfall. The maximum precipitation recorded, equal to 83,4 mm in 10/3/2024, was the day with extremely precipitation.

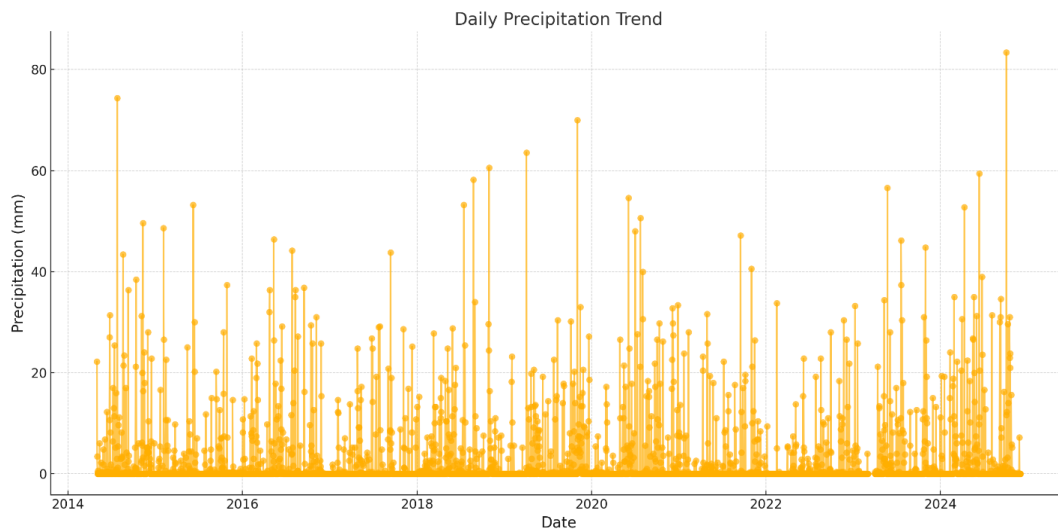


Figure 5. 20 Trend of precipitation and daily average in the period 2014-2024

Temperature

The air temperature data for the analysis was obtained from the APRA database, specifically from the Brescia ITAS Giuseppe PastoriPastori weather station. The analysis covered a longer period (2003–2024) to identify climate trends in the average air temperature over the years in the area of the Mompiano source. The entire APRA dataset was reviewed.

Figure 5.21 illustrates a steady increase in the average annual temperature since 2003. In 2024, the temperature reached the highest average temperature in the dataset is 2024, with an average temperature of 17.02°C

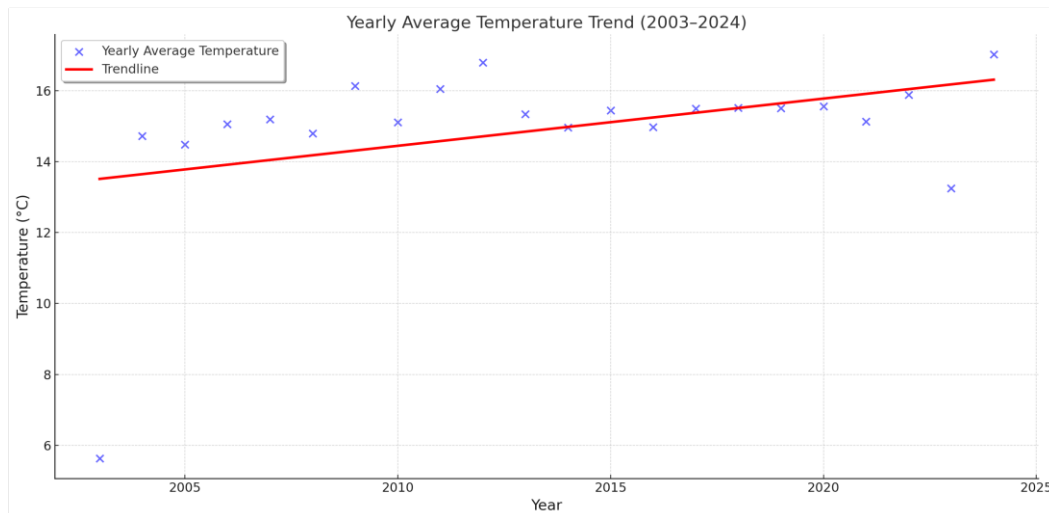


Figure 5. 21 Trend of mean annual air temperature in the period 2003-2024 (area of Mompiano)

The trend confirms that the mean annual air temperature has steadily risen since 2011. From 2018 onward, the annual average temperature consistently exceeds the overall period average of 14.91°C, except for 2023, which shows a significant decline of 1.66°C below the average. In 2021, the temperature remained 0.21°C above the period average, despite a slight decrease compared to previous years. The largest deviation occurred in 2024, where the temperature was 2.11°C higher than

the average, with an annual average temperature of 17.02°C. This progressive rise in temperature highlights the potential effects of climate change on environmental and resource quality.

5.2.2 Data analysis and management

The analysis of management data focuses on information provided by the water services agency for the Mompiano source. Two types of data were analyzed, differing in their measurement methods: the first is based on laboratory analyses of water samples collected from the source, and the second is derived from continuous measurements using instruments installed at the source.

5.2.1.1 Laboratory Analysis of Sampled Water

Periodic water sampling at the Mompiano source is conducted by the local authority. These samples are sent to a laboratory for routine analysis to ensure compliance with legal limits and detect any abnormalities. Historical data from 2003 to 2023 were analyzed, with sampling occurring roughly once a year. However, the frequency of sampling varies by parameter. Microbiological parameters, along with sulfate, chloride, nitrate, and chromium, are monitored more frequently, with chromium being the most closely observed parameter.

Chromium and nitrate are given special attention due to their historical presence at the source. During the analysis campaigns conducted between 1981 and 1987, nitrate concentrations increased from 19 mg/L to 25 mg/L, while chromium concentrations reached 18 µg/L. Additionally, chlorinated solvents were detected with a maximum concentration of 12 µg/L. Although these values were below the legal limits established by D.P.R. 236/88 at the time, they prompted the installation of an activated carbon treatment plant in 1988 to ensure water safety.

A preliminary review of the data provided a snapshot of water quality at the Mompiano source. This analysis aimed to determine whether the source water could be considered safe for human consumption without additional treatment or if natural pollutants necessitated further purification. Data from 2003 onward were evaluated primarily against the limits set by D.Lgs. 31/2001. Following the implementation of the new D.Lgs. 18/2023, which introduced additional parameters and updated some limits, the analysis also assessed whether any historical concentrations might exceed these new thresholds.

For new parameters introduced under D.Lgs. 18/2023, such as bisphenol A, uranium, and PFAS ("Sum of PFAS"), the dataset was insufficient for a comprehensive evaluation. However, in limited tests, concentrations for all three parameters were well below the new maximum limits specified by the updated legislation.

For other parameters regulated by law, the analysis distinguished between those exceeding maximum limits and those approaching the limits but remaining compliant. Critical issues primarily involved microbiological contamination. Over the years, the raw water from the Mompiano source has shown varying concentrations of *Escherichia coli*, intestinal Enterococci, coliform bacteria, bacterial colonies (at 22°C and 37°C), and *Clostridium* species, particularly *Clostridium perfringens* (including spores). These findings highlight the need for continued monitoring and potential intervention to ensure water safety.

Escherichia coli

Escherichia coli (E. coli) is one of the primary microorganisms used as a specific indicator of fecal contamination in drinking water. During routine monitoring, it is often analyzed alongside

Enterococci and total coliforms, as these microorganisms are commonly found in large quantities in the feces of humans and animals. For raw water sources, the presence of *E. coli* is typically attributed to contamination occurring prior to the water reaching the source, likely during the infiltration process through the subsoil.

According to both D.Lgs. 31/2001 and the updated D.Lgs. 18/2023, drinking water must be completely free of *E. coli*, with a maximum allowable limit of 0 CFU/100 ml. However, this regulation specifically applies to treated water intended for human consumption, not to raw (untreated) water. While there is no defined limit for *E. coli* in raw water under these decrees, its presence can negatively impact the treatment process and the quality of the final drinking water. Therefore, continuous monitoring and control of *E. coli* in raw water are essential to ensure the safety of the water supply. In this case, the condition of zero *E. coli* contamination has not been met, highlighting the need for improved monitoring and treatment measures.

As shown in Figure 5.23, between 2004 and the present, only 2 out of 31 samples complied with the regulatory limit, indicating consistent contamination in the incoming raw water. Additionally, recent sampling results show an increase in *E. coli* concentrations, suggesting that microbiological contamination of the spring water has worsened over time. This highlights the need for further measures to address the issue.

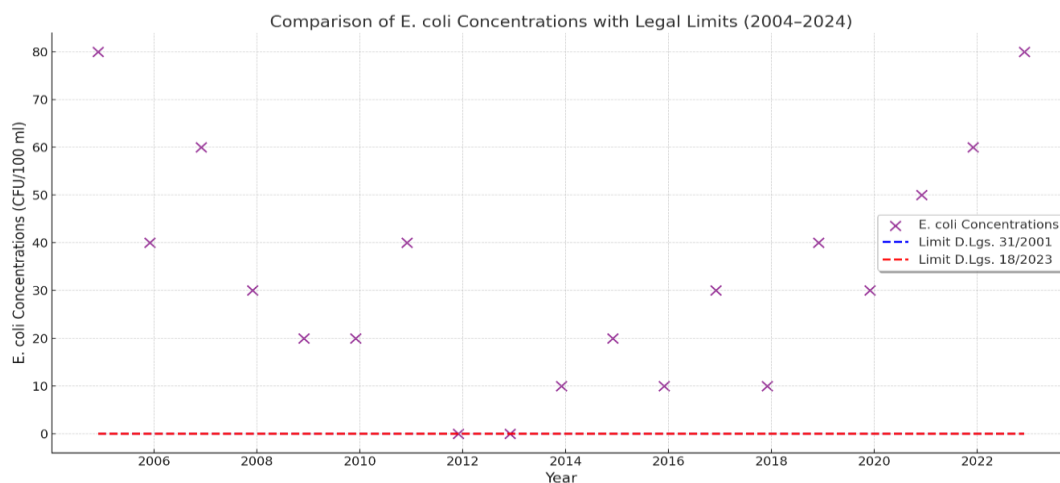


Figure 5. 22 Detected concentrations of Escherichia coli in the raw water from the Mompiano source (2004–2024)

Enterococci

Enterococci, a group of microbiological bacteria, is another key parameter used to assess potential fecal contamination. Compared to other bacterial colonies, Enterococci are present in human feces in smaller quantities. However, they exhibit higher resistance to environmental conditions, such as drying and chlorine-based disinfection, and tend to survive longer in water. For this reason, they are often used as indicators to detect the presence of fecal pathogens that may persist in raw water for extended periods.

This parameter is categorized as a microbiological parameter (Annex I, Part A) with a maximum allowable limit of 0 CFU/100 ml, as defined by D.Lgs. 31/2001 and reaffirmed by D.Lgs. 18/2023. According to Graph 5.24, out of 31 samples collected between 2004 and the present, only two complied with the regulatory limit of 0 CFU/100 ml. Furthermore, recent samples indicate an

increase in Enterococci concentrations, suggesting higher microbiological contamination during the most recent period. This trend highlights the need for enhanced monitoring and potential intervention.

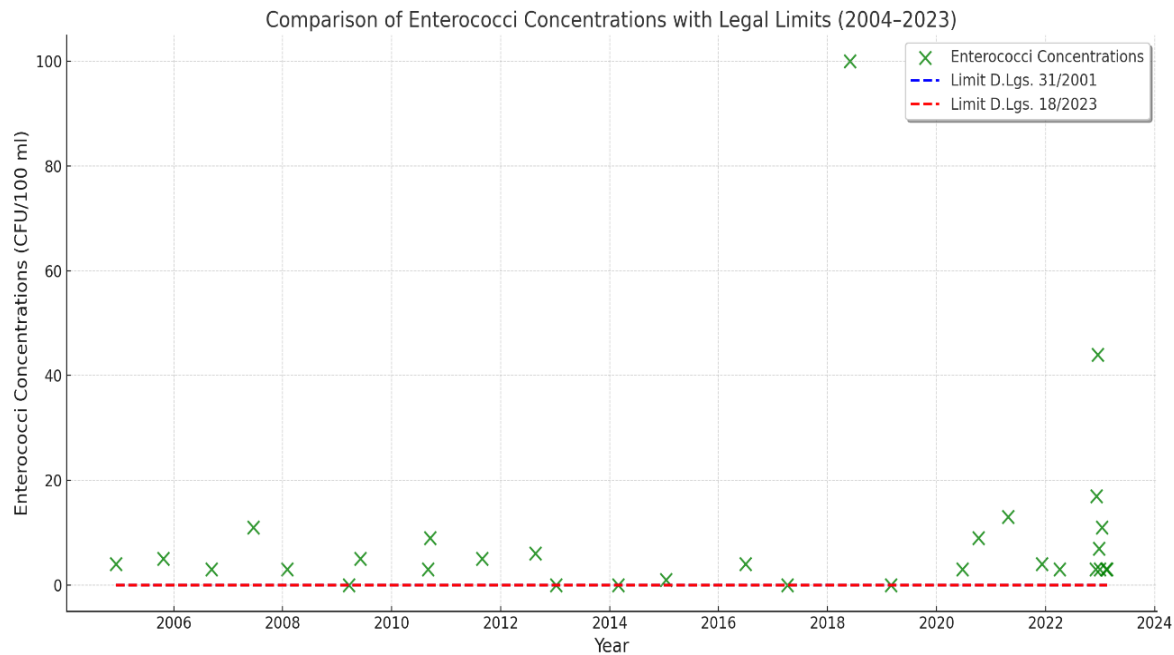


Figure 5. 23 Detected concentrations of Enterococci in the raw water from the Mompiano source (2004–2023)

Coliform bacteria

Figure 5.24: The figure shows total coliform counts in raw water over time, compared to the legal limit of 0 CFU/100 mL established by D.Lgs. 31/2001 and D.Lgs. 18/2023 for drinking water. While this limit applies strictly to treated water at the point of compliance, the data shown here refer to the raw water source prior to treatment. Nevertheless, the frequency and magnitude of coliform presence in raw water are essential indicators of source vulnerability and treatment needs.

According to D.Lgs. 18/2023, coliform bacteria are listed under Annex I, Part C as indicator parameters, meaning they do not pose a direct health risk, but reflect possible microbial contamination and changes in water quality. A Ministry of Health circular clarifies that exceeding the 0 CFU/100 mL threshold for coliforms may be tolerated if Enterococci and *E. coli* are absent, and corrective action is only required if the ASL (local health authority) considers the situation harmful to public health.

In response to requests from local authorities, the Istituto Superiore di Sanità (ISS) recommended a threshold of 10 coliforms/100 mL and issued procedural guidelines. As shown in the figure, coliform levels in the raw water exceeded this threshold in over 85% of samples. In only one instance were Enterococci and *E. coli* absent, but the coliform count was 16 CFU/100 mL, indicating potential concern even under tolerant criteria.

Notably, in 2005, the raw water source exhibited extremely high contamination, with peaks above 600 CFU/100 mL, highlighting a critical vulnerability and underlining the importance of effective treatment. Monitoring these levels over time is essential to guide adaptive water treatment strategies and protect downstream water quality and public health.

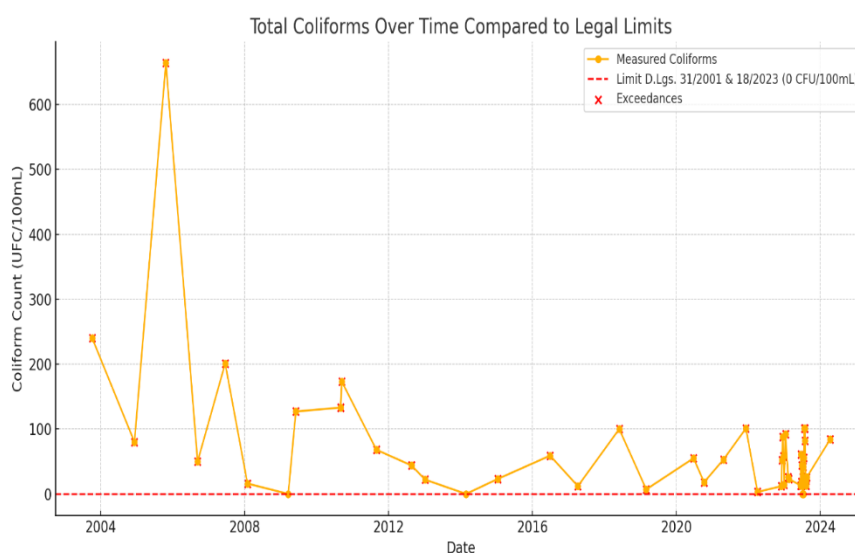


Figure 5. 24 Concentrations detected coliform Bacteria in the raw water at the source of Mompiano (2004-2024)

Total coliform concentrations in raw water over time. The dashed red line represents the regulatory limit of 0 CFU/100 mL set by D.Lgs. 31/2001 and 18/2023 for treated drinking water. However, for raw water, coliforms are considered indicator parameters, and occasional exceedances may be tolerated if *E. coli* and Enterococci are absent, as clarified by a circular from the Ministry of Health and recommendations by the ISS.

Counting of the colonies at 22°C and 37°C

Bacterial Colony Count

The bacterial colony count is another method for assessing the general microbial quality of water. This analysis identifies groups of microorganisms based on their growth characteristics in culture. The colonies are typically grown at 22°C and 37°C to distinguish between naturally occurring microbial flora in water (not related to fecal contamination) and bacteria of human or animal origin. An increase in bacterial colonies at 37°C can serve as an early warning of contamination.

For water intended for human consumption, D.Lgs. 31/2001 and D.Lgs. 18/2023 (Annex I, Part C) do not set a maximum limit for this parameter but recommend monitoring for "abnormal" variations in bacterial counts. According to ISS guidelines, comparisons should be made against historically recorded microbial concentrations for the specific water supply.

Figure 5.25 presents bacterial colony concentrations from sampling conducted between 2004 and the present. While this parameter is not directly linked to health risks, a significant presence of bacteria at 22°C suggests that the area surrounding the water source may be influenced by heterotrophic microorganisms. Bacterial counts at 37°C were monitored until October 2022, and during the initial sampling period, the concentrations at 37°C were higher than those at 22°C. This could indicate notable bacterial contamination. However, the year-long intervals between samplings make it difficult to determine whether this was a persistent issue during that time or the result of isolated events prior to sampling.

Proper treatment of raw water, such as disinfection with chlorine dioxide (as performed in this case), can effectively eliminate bacterial contamination. However, regrowth can occur due to factors

like rising temperatures, increased nutrient availability (from the water or materials in contact with it), and insufficient residual disinfectant levels after treatment.

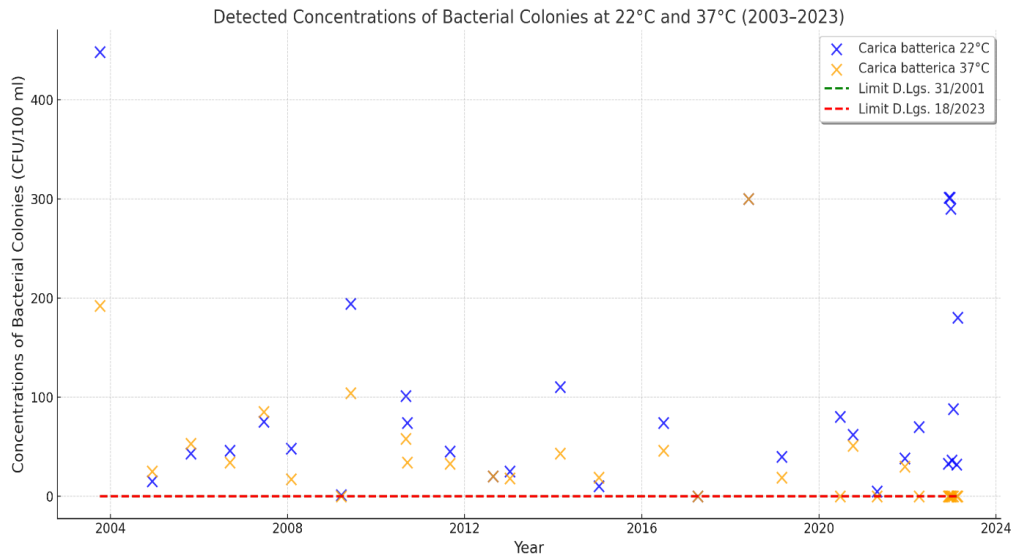


Figure 5. 25 Concentrations detected of bacterial Colonies at 22°C and 37°C in the raw water at the source of Mompiano (2003-2023)

Nitrate

Nitrate Levels at the Mompiano Source

During a sampling campaign conducted between 1981 and 1987, nitrate concentrations at the Mompiano source ranged from 19 mg/L to a maximum of 25 mg/L. Since the source is primarily fed by deep groundwater, which infiltrates from the surface and circulates underground, the presence of nitrates in raw water is likely attributed to surface runoff carrying agricultural waste (e.g., fertilizers) or leaching from natural vegetation.

Nitrate contamination is closely monitored, and there is a comprehensive historical dataset from 2004 to the present (Figure 5.26). In all recorded cases, nitrate levels remained below the legal limit specified by D.Lgs. 18/2023 (Annex I, Part B), consistent with the limits established by the previous legislation (D.Lgs. 31/2001). Nitrate concentrations have fluctuated between 15 mg/L and 30 mg/L, indicating relatively stable and compliant water quality in this regard.

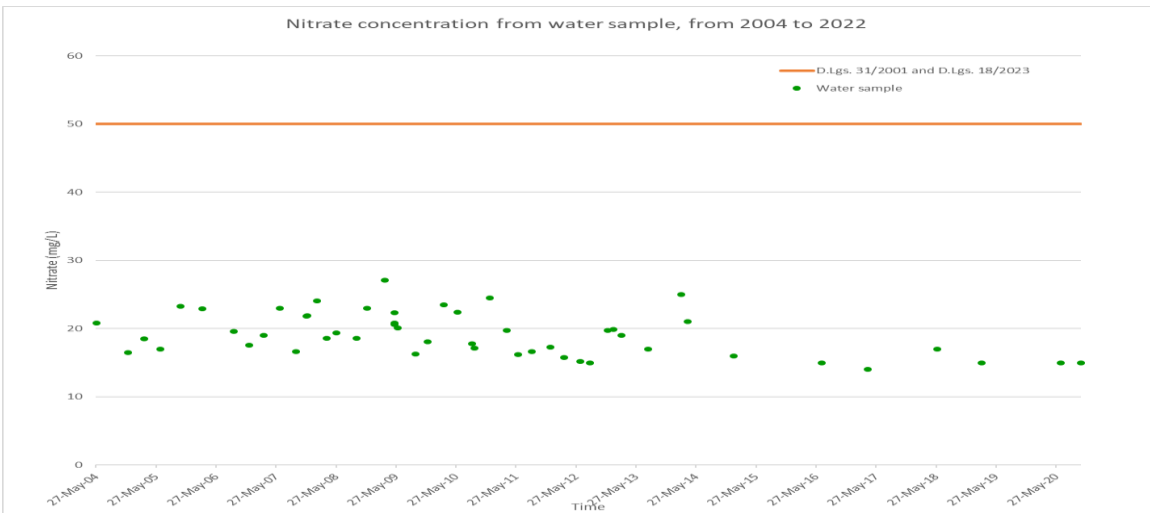


Figure 5. 26 Concentrations detected of Nitrates in raw water at the source of Mompiano (2004-2022)

In addition, considering that the water of Mompiano has some type of contamination due to the presence of nitrate, the Entity manager has been installed of the probes that perform continuous measurements directly at the source, in order to keep under control the concentration, allowing a constant monitoring of the changes.

Turbidity

Turbidity in drinking water is primarily caused by the presence of particulate matter, sediments, colloidal particles, and microorganisms. It serves as a key indicator of water quality. High turbidity levels can pose health risks by altering the microbiological quality of water and promoting bacterial growth. A significant concern arises during disinfection processes, as elevated turbidity can shield microorganisms from disinfectants, thereby increasing the demand for chemical reagents. According to the ISS, if disinfection is properly conducted, turbidity levels below 5 NTU do not negatively impact the process.

The D.Lgs. 18/2023, like its predecessor, does not specify a maximum turbidity limit for water intended for human consumption. The previous legislation only set a maximum turbidity of 1 NTU for treated drinking water from surface sources (Annex I, Part C). The new decree emphasizes consumer acceptability and the absence of abnormal changes. Additionally, operational monitoring guidelines (Annex I, D.Lgs. 18/2023) specify that turbidity must be below 0.3 NTU in 95% of samples and should not exceed 1 NTU for systems involving filtration. However, this requirement does not apply to the Mompiano source, as it does not undergo physical filtration but only chlorine dioxide disinfection before entering the distribution network.

Under normal conditions, the Mompiano source does not exhibit significant turbidity issues. As mentioned in Section 5.1.2), the managing institution has self-imposed a turbidity limit of 1 NTU. Water exceeding this limit is not distributed but discharged into the sewer system. In most analyses of samples taken at the source, turbidity values were below 1 NTU, with only four instances exceeding this threshold (Figure 5.27). In one recent isolated case, turbidity reached nearly 4 NTU.

Historical studies and investigations by the managing institution (April–May 2009) have shown that during periods of heavy precipitation, the source is particularly vulnerable to sudden turbidity spikes, which render it temporarily unsuitable for distribution. Since the sampling reflects specific conditions at the time of collection, it cannot provide a complete picture of how turbidity varies during rainfall events, emphasizing the need for further monitoring during such periods.

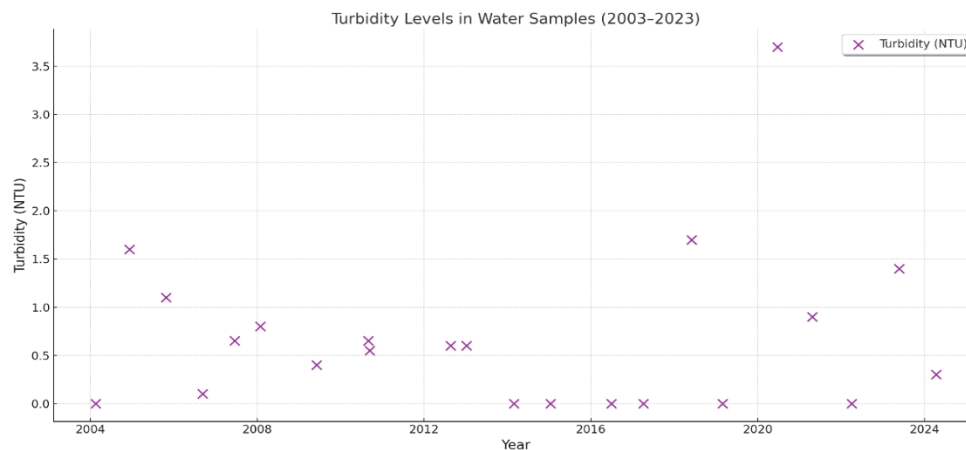


Figure 5. 27 Concentrations detected of turbidity in the raw water at the source of Mompiano (2003-2023)

Total Chromium and Hexavalent Chromium in Drinking Water

Sources and Characteristics

Chromium in drinking water can originate from two main sources: natural geogenic processes at the water's origin or anthropogenic contamination from industrial activities. The risk is particularly relevant in the absence of adequate water treatment infrastructure.

In the environment, chromium exists in two stable oxidation states:

- Trivalent chromium (Cr III): an essential micronutrient with relatively low toxicity, naturally present in soils and rocks.
- Hexavalent chromium (Cr VI): highly toxic and carcinogenic, primarily associated with industrial compounds and activities (e.g., metal plating, dyes, tanneries).

According to the Italian National Institute of Health (ISS), only Cr VI poses serious health concerns due to its mutagenic and carcinogenic properties, while Cr III is generally considered safe and even beneficial in trace amounts.

Regulatory Framework

The D. Lgs. 18/2023, in alignment with EU Directive 2020/2184, introduces a stricter maximum allowable concentration for total chromium (Cr III + Cr VI) of 25 µg/L, to become mandatory by January 2026. Until then, the previous limit of 50 µg/L, as defined by D. Lgs. 31/2001 and based on WHO guidelines, remains in force.

Separately, D. Lgs. 152/2006, which governs environmental standards, sets a limit for Cr VI in groundwater at 5 µg/L. However, no specific EU-wide limit exists yet for Cr VI in drinking water, although countries like California (USA) have adopted a maximum contaminant level (MCL) of 10 µg/L since 2014.

Chromium in Italian Drinking Water

The Italian Ministry of Health reports that most drinking water sources in Italy contain chromium well below regulatory thresholds, typically under 10 µg/L. However, some northern regions exhibit elevated chromium levels, requiring localized treatment systems to maintain water quality standards.

Case Study: Chromium at the Mompiano Source

The Mompiano spring has been under continuous chromium monitoring since 2003, with intensified surveillance from August 2012 due to emerging concerns. In 2013, a targeted research campaign began, focusing on reducing Cr VI levels at vulnerable points in the distribution network.

By August 2014, advanced treatment systems were commissioned. These interventions successfully reduced Cr VI concentrations to below 2 µg/L, surpassing even the stringent standards adopted by California.

Monitoring Results and Interpretation

Figure 5.29 illustrates the trends in chromium concentrations at Mompiano over time:

- Total chromium levels consistently remained well below both the 50 µg/L and 25 µg/L limits, rarely exceeding 5 µg/L.
- Cr VI levels displayed moderate variability prior to treatment, including a notable peak in 2011, but have remained under 5 µg/L since 2014, averaging around 2.7 µg/L.

- From July 2014 onward, the proportion of Cr VI to total chromium has stabilized at approximately 50%, highlighting the effectiveness and consistency of the treatment processes.

Despite slight fluctuations in Cr VI, all concentrations of both chromium species have remained safely within the regulatory thresholds. This confirms the microbiological and chemical stability of the Mompiano water source and the success of the management measures taken.

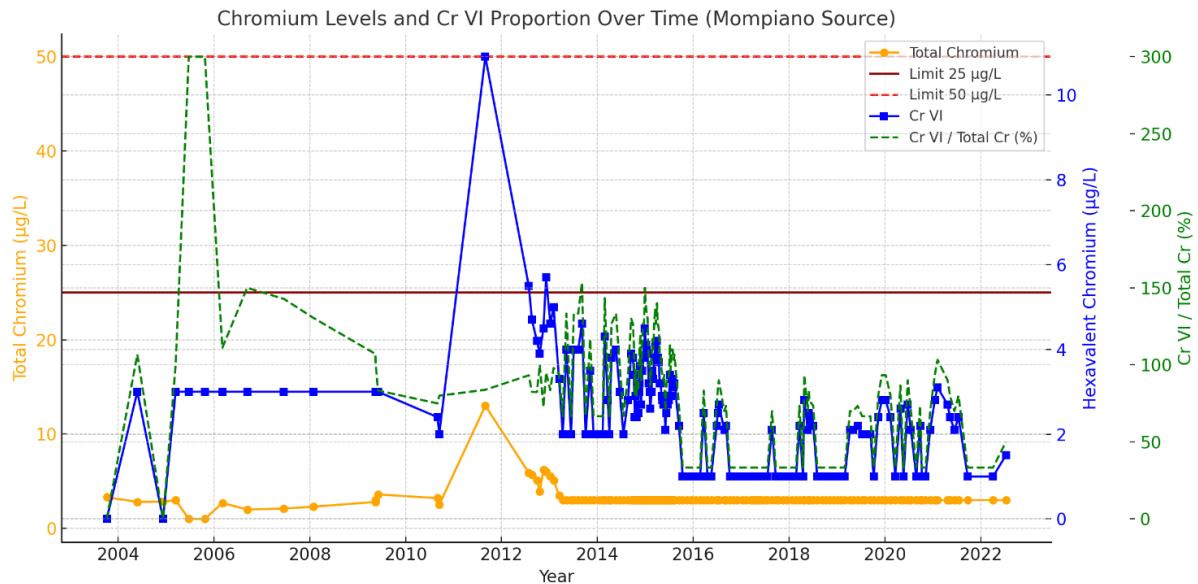


Figure 5. 28 The concentrations measured in the Total Crome and exavalent chromium over time Chromium (VI) in the raw water at the source of Mompiano (2003-2022)

Chromium concentrations (Total Cr and Cr VI) measured at the Mompiano source over time. A secondary axis shows the ratio of Cr VI to Total Cr, which has remained close to 50% on average since mid-2014, as also noted in the text. All concentrations remained below the regulatory limits set by D.Lgs. 31/2001 (50 µg/L) and D.Lgs. 18/2023 (25 µg/L).

5.2.3 Real time monitoring _Continuous Monitoring Using Probes

In the field of drinking water, **multi-parameter spectrophotometers** are commonly used to evaluate water quality. These devices can measure multiple parameters simultaneously, making them ideal for use in drinking water surveillance systems. Other tools that enhance monitoring include probes, sensors, and transmitters for chemical-physical analysis, such as pH, conductivity, dissolved oxygen, and turbidity, in addition to process analyzers.

At the **Mompiano source**, the water services agency installed two different probes directly at the source. These probes perform continuous measurements of various parameters, recording average values every 15 minutes. Additionally, a water level and flow meter is installed to monitor water output from the source.

The installed probes measure the following:

1. **First probe (Hach):**
 - Turbidity
 - pH
 - Conductivity (at 20°C)
 - Redox potential
2. **Second probe (Isoil):**

- Turbidity
- Nitrates
- UV absorbance

Both probes are connected to a control unit, which varies depending on the model and manufacturer. These control units act as compact, powerful data acquisition systems equipped with processors that interface with monitoring and supervision systems. Figure 5.29 illustrates the setup, showing the units for the two different probes.

The collected data is processed using user-friendly software, which supports sensor and station management. The software automatically filters the data to provide clean and reliable outputs. During continuous monitoring, any changes in water composition are detected. An alarm system, enhanced by learning algorithms, notifies users of anomalies or variations in water quality characteristics.

This monitoring system enables:

- Real-time detection of anomalies, including sudden changes or external factors affecting water quality.
- Proactive intervention by the water services agency, allowing for the temporary isolation of the source to perform necessary restoration or safety operations.

All data collected during the monitoring period (May 2014 to February 2023) were provided by the local authority. Based on the recommendation of the water services manager, turbidity data from the Hach probe was used for all subsequent analyses, as it was deemed more reliable and representative of the overall condition at the source compared to data from the Isoil probe.



Figure 5. 29 Monitoring system installed at the Mompiano source

The image shows the Hach probe (center), the Isoil probe (bottom right), and various points for direct water withdrawal from the source.

The automatic data collected by the two probes, Hach and Isoil, is comprehensive and detailed, and it has been incorporated into Simonre's thesis. In my analysis, I will focus on the results that

provide evidence suggesting groundwater can also be affected by climate change, as indicated by the variability and fluctuations in certain critical parameters.

5.3 Recommendation for practices

The Mompiano water source is a crucial part of Brescia's drinking water supply system, but it faces increasing challenges due to climate change and evolving regulatory requirements. This study analyzed the effects of extreme weather conditions on water quality, focusing on critical parameters such as turbidity, microbiological contamination, chromium, nitrates, and other pollutants. The findings highlight the importance of continuous monitoring and adaptive management strategies to ensure compliance with new legal standards and long-term water safety.

A key aspect of the study was comparing Mompiano's water quality parameters with the updated limits introduced by Legislative Decree No. 18/2023 (D.Lgs. 18/2023). The analysis revealed that turbidity occasionally exceeded the new regulatory limit of 0.3 NTU, necessitating enhanced filtration and real-time monitoring. Microbiological contamination, including the sporadic presence of *E. coli*, Enterococci, and total coliforms, was observed, particularly after heavy rainfall events, emphasizing the need for strengthened disinfection measures. Nitrate (NO_3^-) concentrations ranged between 15-30 mg/L, remaining within the allowable 50 mg/L limit, though seasonal variations indicate a need for further assessment of agricultural runoff impacts. Additionally, emerging contaminants such as PFAS, bisphenol A, and uranium, now subject to monitoring under the new decree, are not currently a concern, but periodic testing should be expanded for early detection.

To comply with D.Lgs. 18/2023 and enhance Mompiano's resilience, several key adaptation measures are recommended. Real-time monitoring enhancements should include automated turbidity sensors with alert systems to maintain compliance, online microbiological probes for early detection of bacterial contamination, and continuous temperature and chlorine monitoring at critical distribution points. Treatment process optimizations should focus on improving filtration and disinfection strategies, enhancing the chromium removal system to meet the 2026 deadline, and considering activated carbon or membrane filtration for PFAS control. Climate resilience strategies should incorporate an early warning system linking meteorological conditions to water quality risks, protective measures for groundwater recharge zones, and stronger interconnections between water sources to ensure supply stability. Lastly, regulatory compliance efforts should include annual water quality reviews aligned with D.Lgs. 18/2023 and increased public transparency on water safety measures.

This case study highlights the growing intersection between climate change, regulatory compliance, and drinking water safety. While Brescia's water supply currently meets legal standards, emerging risks such as extreme weather events, microbial growth, and new contaminants demand proactive adaptation strategies. By integrating real-time monitoring, advanced treatment, and predictive analytics, utilities can safeguard water quality while maintaining compliance with Italy's evolving regulatory landscape. Future research should focus on long-term climate impact modeling and adaptive infrastructure planning to ensure the sustainability and resilience of water supply systems in the face of climate change.

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CHAPTER 6: CLIMATE CHANGE EFFECT SOME CRITICAL PARAMETERS IN DRINKING WATER SUPPLY SYSTEM

This chapter presents original recommendations based on the integration of case study findings with water safety plan principles, proposing specific, actionable strategies for incorporating real-time monitoring and early warning tools into daily utility operations.

Results evident of groundwater can also be affected by climate change, as indicated by the variability and fluctuations in critical parameters

After presenting the collected data and initial calculations in this chapter, the analysis focused on how climatic factors specifically rainfall and temperature affect the quality of source water. This evaluation considered both climatic and non-climatic influences to identify which water quality parameters are most sensitive to climate change. The main goal was to explore these issues in greater depth and propose future strategies for more accurate and real-time monitoring of these critical parameters.

For the comparative analysis with climate data, the study selected parameters from the initial analysis that best reflected the quality of the raw water entering the source. This selection included results from regular water sampling and continuous measurements collected by monitoring probes. The updated grab sample data from 2023-2024.

6.1 Results from microbiological sampling

Laboratory analysis focused on water quality parameters that exceeded legal limits at least once, as these pose potential health risks. The initial tests consistently revealed microbiological issues, particularly with the presence of Enterococci, *Escherichia coli* (*E. coli*), total coliforms, and bacteria measured at 22°C and 37°C.

Figure 6.1 shows the concentrations of these microbiological indicators alongside rainfall data over the observation period. However, understanding the link between rainfall and microbial contamination is difficult because water samples are collected at specific moments, which may not capture the rapid changes in contamination levels that occur during and after rain.

Figure 6.1 presents annual sample data from 2019 to the present, highlighting major rainfall events (the top 5% of rainfall data) and their connection to spikes in microbiological contamination. The graph shows that heavy rain (marked by blue bars) often coincides with sharp increases in total coliform levels (shown as gray circles). This trend suggests that rainwater runoff carries microorganisms from domestic, agricultural, or natural sources into water bodies, increasing contamination levels.

Notably, total coliform levels tend to rise more sharply than other indicators like *E. coli*, Enterococci, or bacteria at 22°C. This pattern suggests that total coliforms are more sensitive to contamination caused by rainfall, making them a strong warning sign of water pollution during heavy rain. However, it's important to consider that there may be a delay between rainfall and the peak of coliform levels because it takes time for runoff to carry microbes into the water supply.

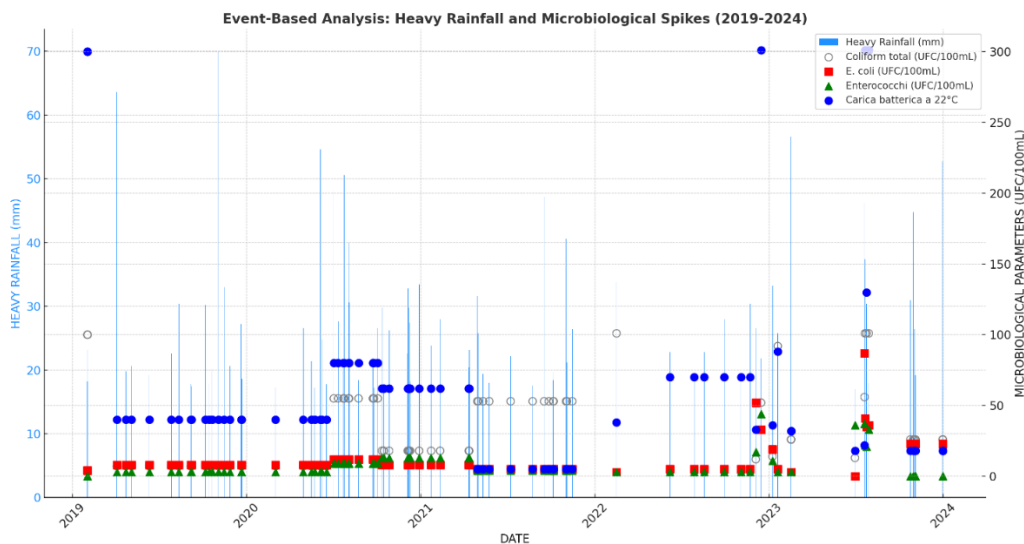


Figure 6. 1 **Event-Based Analysis:** Focus on specific periods of heavy rainfall and corresponding microbiological spikes

As illustrated in Figure 6.2, sample analyses have been conducted annually from 2019 to the present. Significant heavy rainfall events (top 5% of rainfall).

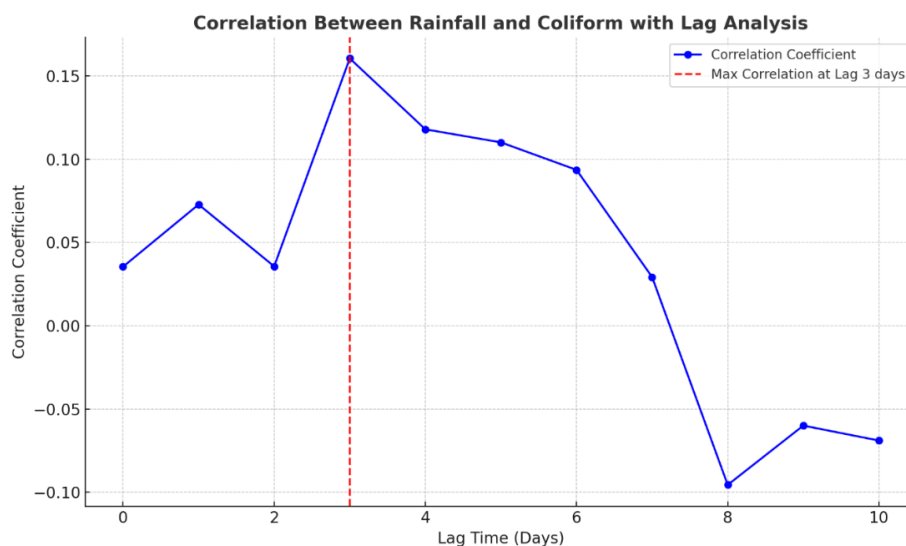


Figure 6. 2 Correlation between rainfall and coliform with Lag Analysis

The highest correlation ($r = 0.161$) was observed at a 3-day lag, suggesting that coliform contamination may peak approximately three days after heavy rainfall. However, this correlation is weak, indicating that rainfall alone does not strongly explain the changes in coliform levels.

Several factors may explain the weak or even negative correlation between rainfall and coliform levels in water systems. One significant factor is inappropriate lag time in the analysis. If the lag period studied does not align with the actual time required for microbial transport, the correlation may appear inaccurate. For instance, if contamination peaks 5–7 days after rainfall but the analysis only considers up to 3 days, the relationship might seem weaker than it truly is. Another factor is the dilution effect, where heavy rainfall increases water volume, diluting microbial concentrations and leading to lower measured levels despite higher microbial input. Additionally, natural self-purification processes, such as strong water currents after heavy rain, can flush contaminants out of the system,

reducing microbial levels. Data quality issues like outliers or data entry errors can also distort correlation results, emphasizing the need for thorough data cleaning and validation. Moreover, the influence of other environmental factors including temperature, soil type, vegetation cover, and human activities like wastewater discharge can significantly impact microbial contamination, weakening the direct relationship between rainfall and coliform levels.

Although the analysis suggests that heavy rainfall contributes to increased microbial contamination, particularly in total coliform levels, the statistical relationship remains weak. This indicates that rainfall is not the sole factor affecting water quality, and other environmental and human-related factors are likely influencing contamination levels

Additionally, within this recent period, the availability of more granular data made it possible to isolate a smaller sub-period for consecutive sampling. This enabled comparisons with daily average precipitation values, providing a more detailed understanding of the relationship between microbiological concentrations and rainfall events.

Escherichia coli Analysis

The incoming raw water source has been identified as particularly susceptible to contamination by *Escherichia coli* (E. coli). To investigate whether this contamination is influenced by significant weather events, particularly precipitation, a correlation analysis was performed. The chart illustrates the fluctuations in E.coli levels and rainfall over time. The E.coli levels show noticeable variations throughout the recorded period, with certain peaks that may be influenced by environmental or seasonal factors affecting water quality. The rainfall, represented in blue, clearly highlights its changing patterns, showing distinct dry periods followed by sudden spikes in precipitation. In some cases, increases in rainfall seem to align with rising E.coli levels, suggesting that rainfall could contribute to the spread of E.coli, possibly due to runoff or water contamination. Additionally, the data distribution over various dates reflect how both variables evolve throughout the year, with consistent dry intervals indicating dry seasons and sharp increases marking rainy periods.

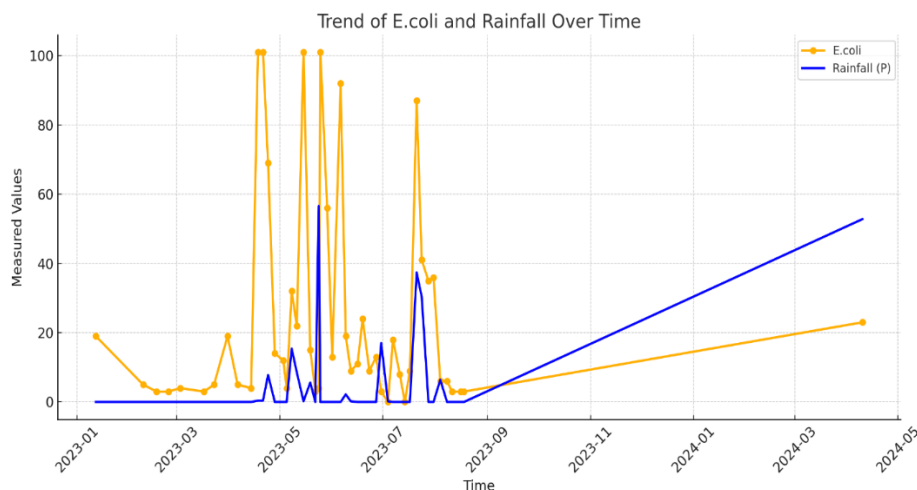


Figure 6. 3 Time series of E.coli and the precipitation measured the sampling period (01/2003-5/2024)

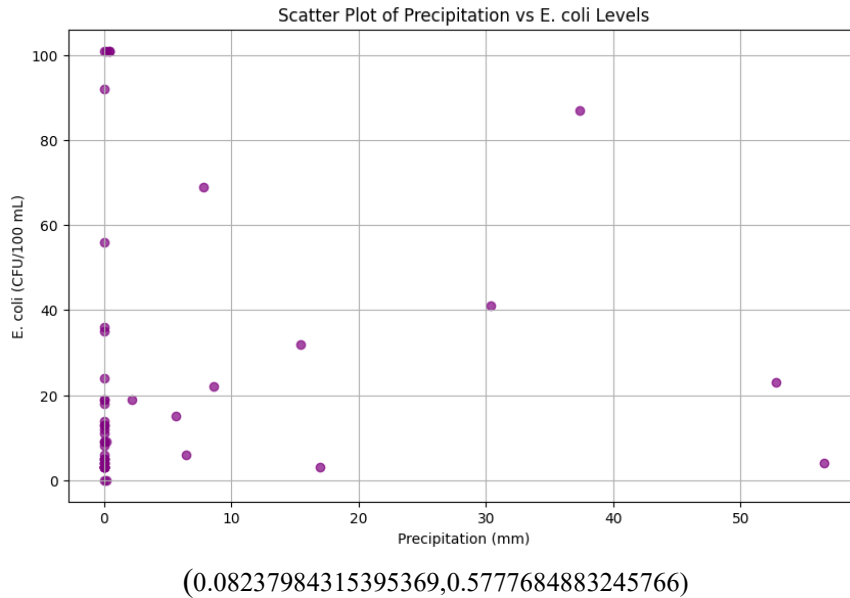


Figure 6. 4 The scatter plot shows the trend of relationship between rainfall (P) and Ecoli levels
Pearson is 0.08 and $p = 0.57$ there is no strong correlation between

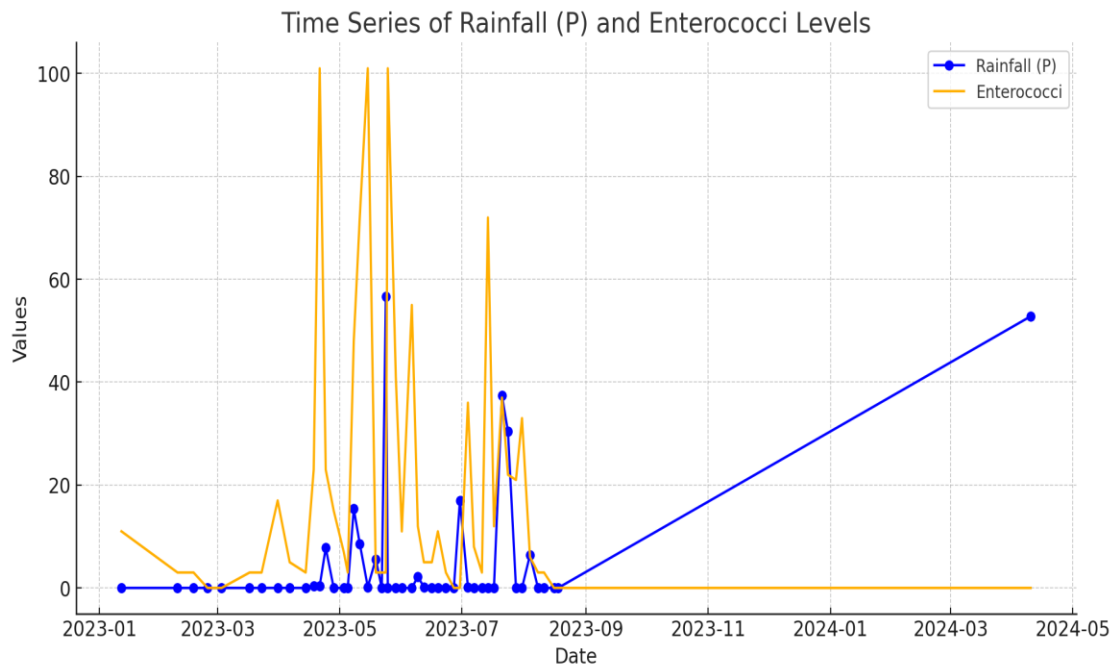
Analysis of Enterococci in Water Sources

Like the findings for *Escherichia coli*, the concentrations of Enterococci were analyzed in relation to precipitation events. The correlation between Enterococci concentrations and rainfall intensity is illustrated in Graph 6.5 and 6.6. While a general relationship between precipitation and microbiological contamination can be observed, specific exceptions warrant closer attention.

The analysis of the scatter plot reveals the relationship between rainfall (P) and Enterococci levels. The data points are widely dispersed without forming a clear pattern, suggesting a weak or negligible relationship between the two variables. Additionally, the time series plot illustrates how rainfall and Enterococci levels change over time. Both variables fluctuate independently, showing no evident synchronization or consistent pattern Figure 6.5

Statistical analysis using the Pearson correlation coefficient further supports these observations. The calculated correlation coefficient (r) is -0.051, indicating a very weak and slightly negative relationship between rainfall and Enterococci levels. Moreover, the p -value of 0.731 is significantly higher than the standard threshold of 0.05, suggesting that this correlation is not statistically significant. Therefore, there is no strong evidence to conclude that rainfall directly influences Enterococci concentrations.

These findings underscore the need for a multifactorial approach to understanding microbiological contamination in water sources. While precipitation appears to play a role, additional factors, such as land use, seasonal variations, and potential upstream contamination sources, should be investigated to provide a more comprehensive understanding of Enterococci dynamics.



(-0.05101390458877755, 0.7305886533037718)

Figure 6. 5 Time series of Enterococci and the precipitation measured the sampling period (01/2003-5/2024)

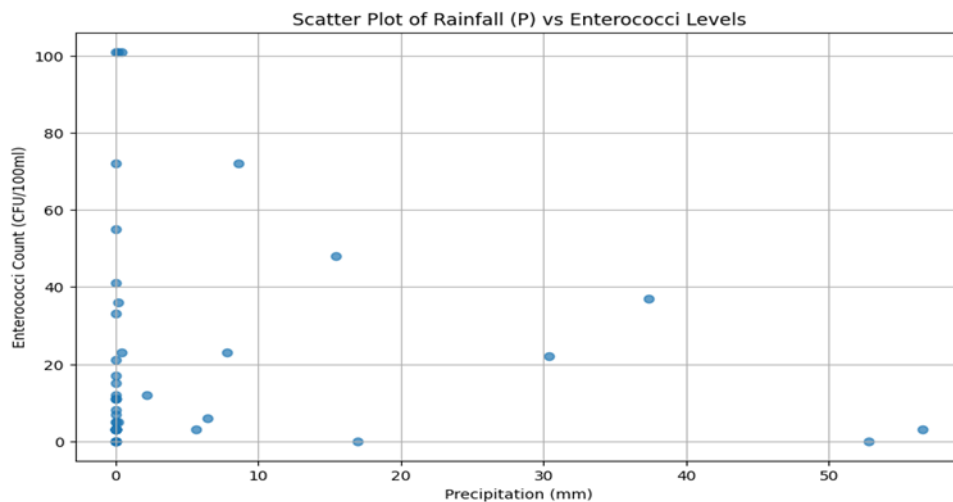


Figure 6. 6 The scatter plot shows the relationship between rainfall (P) and Enterococci levels

Coliform bacteria

Compared to the previously mentioned microbiological parameters, the concentration of coliform bacteria is higher. Similarly, patterns observed with Enterococci and *E. coli* during the third and fourth sampling periods can also be seen here. In one instance, coliform levels were extremely high despite low rainfall, while in another case, heavy rainfall was followed by much lower coliform concentrations. Following Figure 6.7

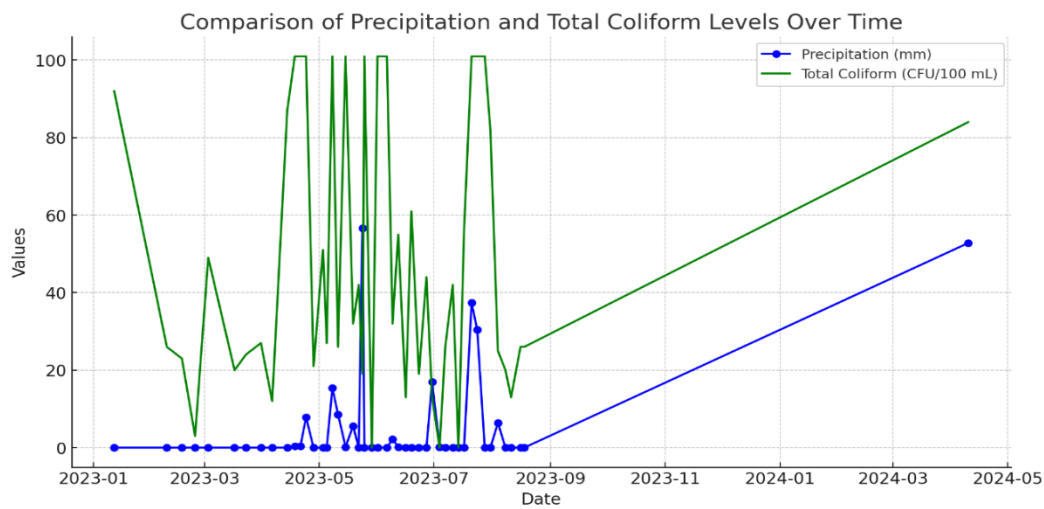
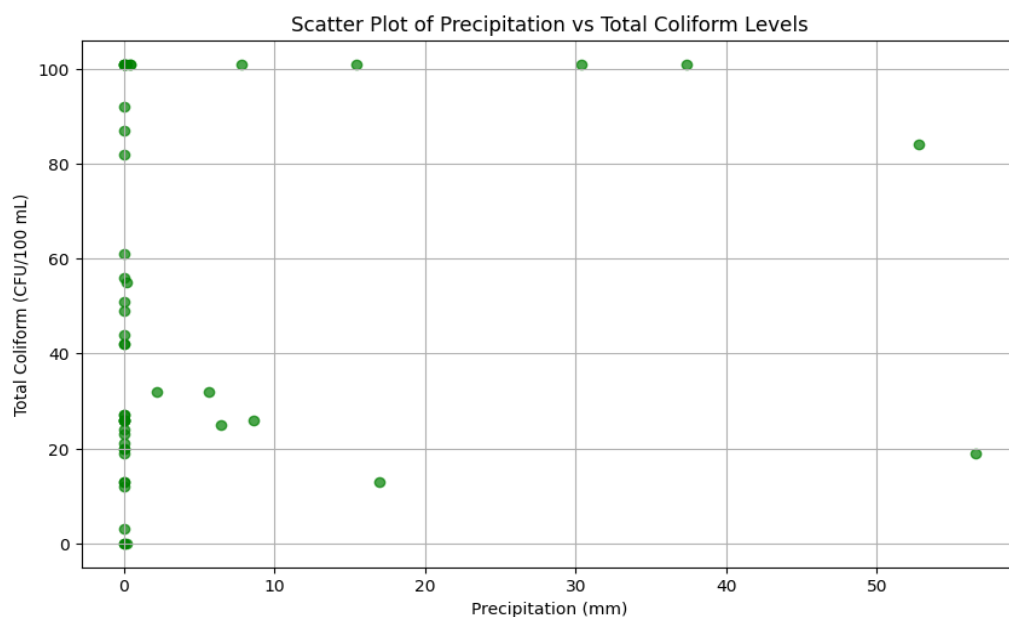


Figure 6. 7 Time series of Total Coliform and the precipitation measured the sampling period



(0.1810245590709623, 0.218203737279623)

Figure 6. 8 The scatter plot shows the relationship between rainfall (P) and Total Coliform levels

The correlation between precipitation and total coliform levels is weakly positive figure 6.8, suggesting that as rainfall increases, coliform levels tend to rise slightly. However, the p-value greater than 0.05 indicates that this relationship is not statistically significant, meaning the observed correlation could be due to random variation. The scatter plot also illustrates this, as the data points are widely dispersed, confirming the weak relationship between the two variables.

In general, the lack of significant correlation between precipitation and microbiological concentrations can be attributed to the distribution of rainfall over the 15-day period preceding the sampling. The timing and intensity of precipitation appear to play a critical role. For instance, increases in concentration may be caused by moderately intense rainfall occurring just a few days prior to sampling. Alternatively, if significant rainfall occurred further in the past, the effects may already have diminished by the time of sampling. This hypothesis is supported by the observation that the average daily precipitation over the 15-day period was consistently very low (below 10 mm, or

less than 1 mm per day), indicating that information about significant precipitation events is often not captured in the average data.

6.2 Real time data Analysis and Correlations of Parameters Measured via Continuous Online Monitoring

Continuous online monitoring provides real-time data that captures variations in specific parameters over time in response to external factors. By identifying phenomena that could lead to changes in water quality characteristics, it becomes possible to trace the concentration of specific parameters before, during, and after an event, thereby identifying potential anomalies.

The parameters continuously measured at the Mompiano source are as follows:

- Using the Lange analyzer: Turbidity, pH, electrical conductivity at 20°C, and redox potential.
- Using the Isoil multi-parametric probe: Turbidity, nitrates concentration, and UV absorbance.

Electrical Conductivity and Redox Potential

Measurements of electrical conductivity and redox potential at 20°C indicate no significant anomalies at the source. These parameters have consistently remained below regulatory limits, with only minor fluctuations, posing no immediate concern for water quality. However, during certain precipitation events, small but detectable shifts were observed. For instance, in early January 2023, a drop in redox potential coincided with a spike in turbidity. These observations suggest that both conductivity and redox potential may serve as early indicators of the infiltration of oxidizable organic matter. Their continuous monitoring can enhance the effectiveness of Early Warning Systems (EWS) and assist in defining appropriate response thresholds within Water Safety Plans (WSPs).

pH

Over the observation period (2023–2024), a correlation was observed between pH values ranging from 7.4 to 7.7 and increased *E. coli* concentrations. This trend suggests that pH fluctuations may influence or signal microbial contamination risks, warranting further investigation in future monitoring efforts.

These two parameters require particular attention due to their behavior in response to external factors:

- Turbidity has shown frequent and sudden variations, particularly during and after heavy rainfall events that impact the recharge area. In some cases, turbidity increased sharply to levels requiring temporary suspension of water extraction from the Mompiano source.

- Nitrate concentrations have remained consistently below the European regulatory threshold. Historical data dating back to the 1980s confirm that nitrate levels have generally remained stable and under 30 mg/L, indicating low variability in this parameter.

Correlations with Meteorological Events

An annual comparative analysis between continuous monitoring data and rainfall records reveals that: Turbidity demonstrates a strong and consistent correlation with precipitation, confirming its sensitivity to climatic events. pH and nitrate concentrations do not show a clear pattern in relation to rainfall, suggesting the influence of other environmental or anthropogenic factors. UV absorbance exhibits seasonal trends, the causes of which require additional targeted investigation.

The continuous monitoring system at the Mompiano source provides valuable insights into the temporal dynamics of water quality and their potential triggers. While turbidity stands out as a reliable indicator of weather-related impacts, other parameters such as pH and nitrate display more stable

behavior. These results highlight the importance of prioritizing sensitive parameters in real-time monitoring frameworks and integrating them into proactive management strategies under the Water Safety Plan approach

6.2.1 Comparison nitrate, precipitation and temperature

Figure 6.9 illustrates the relationship between precipitation (mm, orange) and nitrate concentration (mg/L, blue) from March 2021 to March 2023. Initially, nitrate levels remained relatively stable around 18–19 mg/L, with some brief fluctuations that appear loosely associated with precipitation events, likely due to dilution effects or surface runoff.

In mid-2022, a sudden and sustained increase in nitrate concentrations is observed, with values exceeding 20 mg/L for several months. However, the sharp onset and extended stability of these higher values raise questions about their origin. In natural contamination scenarios, such a constant concentration over time would be unusual. Given the absence of corroborating evidence and the fact that this is historical data, one possibility is that the change reflects a probe calibration shift or sensor anomaly, rather than a true environmental change.

Meanwhile, precipitation remained unnormal, with distinct spikes corresponding to individual rainfall events. These events may influence nitrate levels through surface runoff or infiltration, but their exact contribution during the period of elevated nitrate remains unclear.

Importantly, nitrate concentrations never exceeded the legal threshold set by D. Lgs. 18/2023. Despite some fluctuations, levels generally remained within the range of 18–20 mg/L, and no abnormal spikes were recorded. This highlights the importance of interpreting sensor data carefully, especially when evaluating long-term trends in water quality from historical monitoring records.

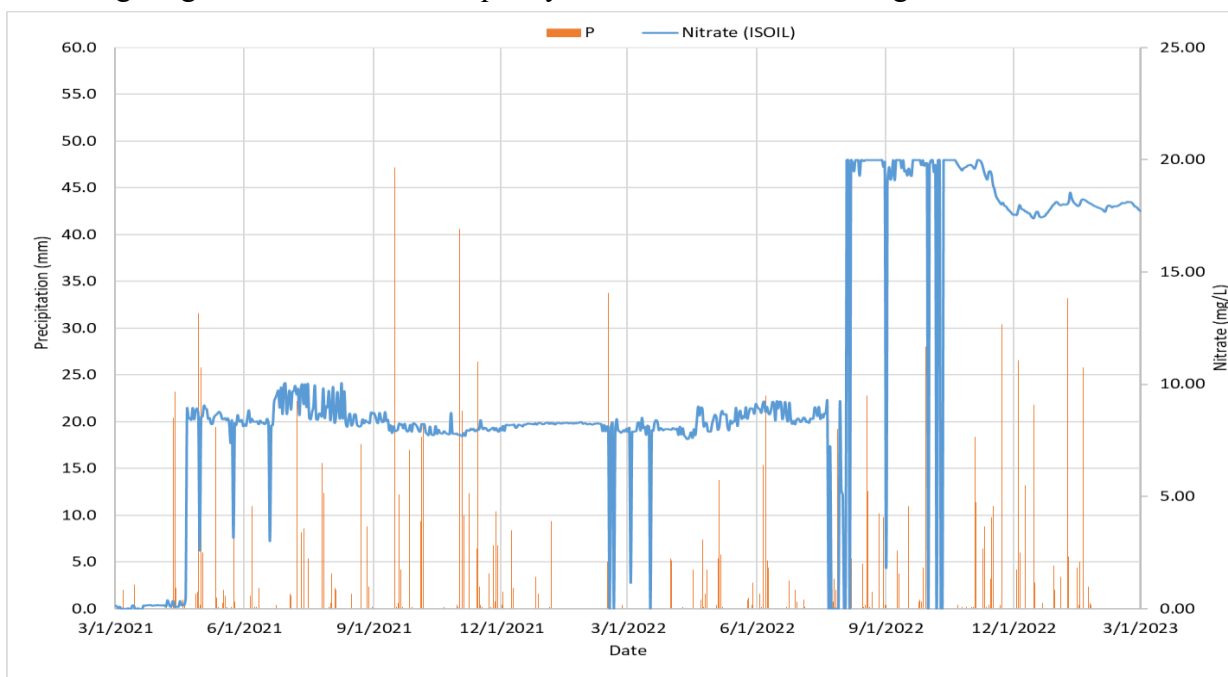


Figure 6. 9 Shows the relationship between rainfall (P) and Nitrate levels

Since turbidity is a parameter that historically represents the major problem for the source of Mompiano, mainly as a result of weather events locally rather important, before analyzing individual rainfall events, Figures 6.10 provide a long-term overview of turbidity behavior in relation to meteorological parameters. These figures offer context for selecting representative events and justify the need for focused response curve analysis to better understand the short-term dynamics of turbidity following intense precipitation, in addition to the simple comparison with the trend of the precipitation (Figure 6.10), this long-term time series highlights the strong correlation between rainfall and turbidity peaks in raw water. Recurrent turbidity spikes, often following major rainfall events, confirm the high sensitivity of the source to meteorological conditions. These trends justify further investigation through targeted response curve analysis in selected events.

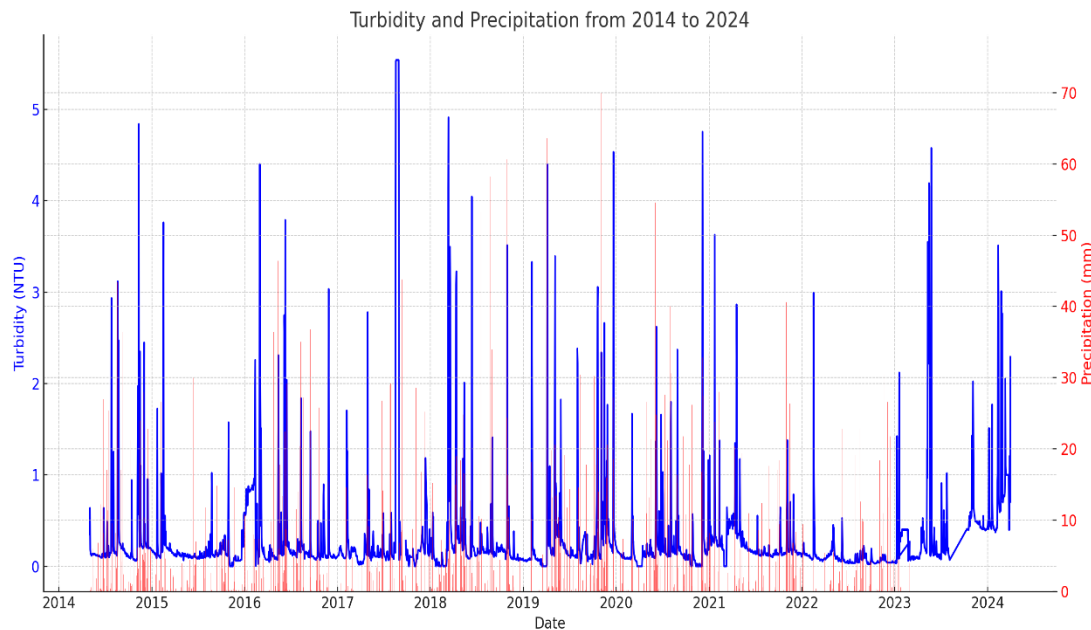


Figure 6. 10 The analysis of data from 2022 and 2024 reveals a clear relationship between precipitation and turbidity in raw water.

Peaks in turbidity consistently follow rainfall events, particularly after heavy precipitation, due to surface runoff carrying suspended solids, silt, and organic matter into the water source. This strong correlation highlights the need for robust physical pretreatment systems such as sedimentation, filtration, and coagulation-flocculation to manage high turbidity loads during and after storms. In contrast, nitrate concentrations remain relatively stable and do not exhibit a consistent response to rainfall, although slight increases may occur due to fertilizer or organic nitrogen runoff. The relationship between nitrate and turbidity is weak, as these parameters are influenced by different pollution pathways: turbidity by particulate matter and nitrate by dissolved substances.

From an operational standpoint, these findings suggest that treatment plants should adopt adaptive management strategies during rainfall events, such as adjusting coagulant dosing or activating bypass sedimentation units to handle sudden turbidity surges. Continuous online monitoring of turbidity and precipitation trends is essential to anticipate and respond quickly to changes in raw water quality. While nitrate levels currently remain below regulatory limits, periodic spikes especially in agricultural regions should still be monitored to prevent long-term accumulation. Ultimately, a climate-resilient pretreatment approach, integrating real-time data and flexible

operation, will be critical to ensuring consistent drinking water quality under increasing hydrological variability driven by climate change analysis in selected events.

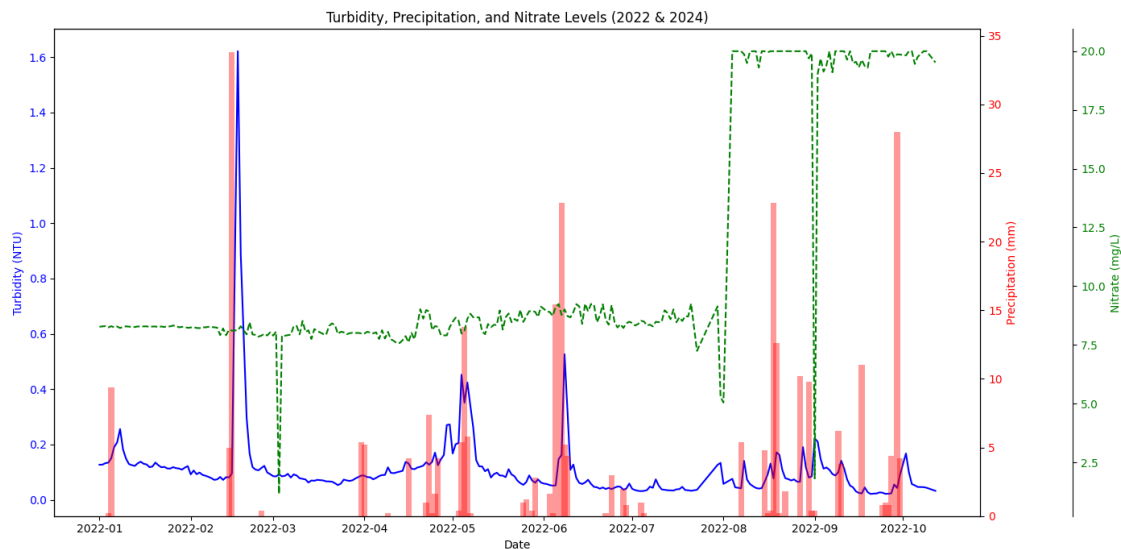


Figure 6. 11 Time Series of Turbidity and Precipitation, Nitrate at Mompiano Source (2022 - 2024)

6.2.2 Analysis of Turbidity Response to Significant Rainfall Events at the Mompiano Source

Turbidity has historically been a major issue for the Mompiano source, primarily due to significant local weather events. Beyond simply comparing turbidity trends with rainfall patterns a turbidity response curve was created to analyze how the source reacts to significant precipitation events.

For this analysis, specific days of intense rainfall were selected, along with data from the three days prior and the ten days following each event. This approach allowed for observation of how and when heavy rainfall affected the source's turbidity. Additionally, continuous pH measurements were included in the analysis due to a known tendency for acidification in the source water. This helped determine whether acidification was caused by acidic rain or was an inherent characteristic of the raw water entering the source.

The response curves of turbidity in the event significant proposals for four special situations considered quite significant to confirm what has been said so far. The days taken as a reference, in the period from may 2014 to march 2023

- July 26, 2014 (max daily rainfall of 74.4 mm)
- November 10, 2014 (peak within a sequence of moderate rainfall events)
- April 4, 2019 (isolated intense rainfall event)
- January 8, 2023 (two back-to-back rainfall events during an otherwise dry period)

Case Study: July 26, 2014, Rain Event

During this period, only one significant rainfall event occurred, providing a clear scenario for evaluating turbidity response. Data from continuous monitoring revealed a sharp increase in turbidity, shifting from near-zero levels before the event to much higher values on the day of rainfall and the following day. This immediate response indicates the source was directly impacted by the rain.

In the days after the event, turbidity levels quickly returned to very low values and remained stable, even during two additional rainy days that had minimal impact. A smaller, isolated rainfall event later in the period caused a slight increase in turbidity, though less severe than the initial spike.

Throughout this period of extreme weather, pH levels remained stable, suggesting that rain did not influence the pH in the same way it affected turbidity.

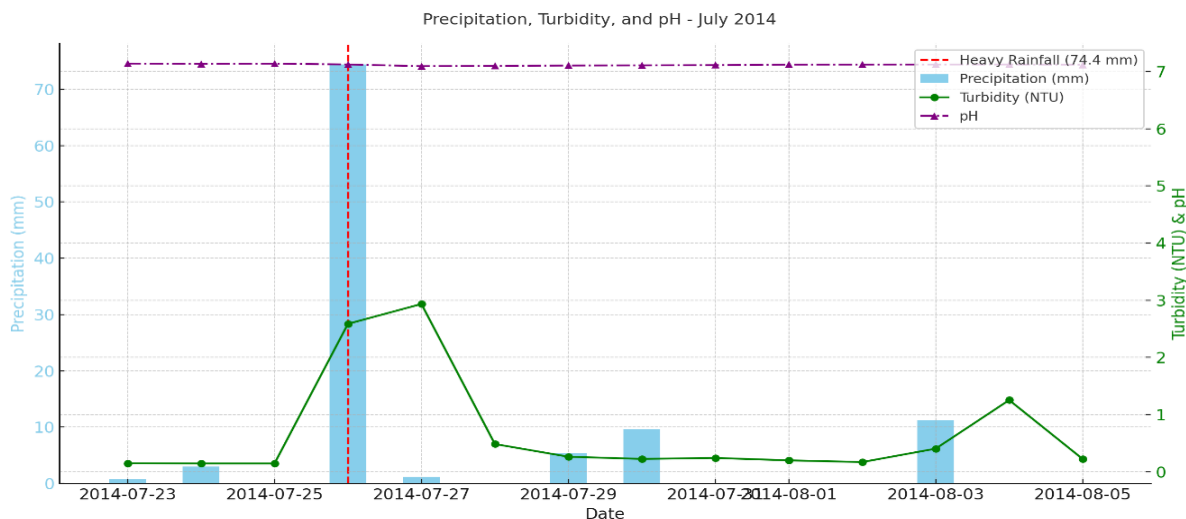


Figure 6. 12 Response curve of turbidity and pH as a result of the weather event significant day 26/07/2014

The findings from Figure 6.12 indicate a short, approximately 1-day lag between precipitation events and turbidity peaks. This rapid response is consistent with surface runoff dynamics, where suspended solids are quickly transported into the water source following intense rainfall. In contrast, the analysis in Figure 6.2 revealed that microbiological contamination, as indicated by Coliform presence, is best correlated with rainfall events occurring three days earlier. This longer lag is likely due to the time needed for microorganisms to infiltrate into groundwater or be transported through soil layers before reaching the source.

Regarding Figures 6.4, 6.6, and 6.8, no specific time lags were initially applied during the correlation analysis. These were based on same-day or near-immediate comparisons between precipitation and microbiological indicators. However, the stronger correlation observed with a 3-day lag in Figure 6.2 highlights the potential value of incorporating time-shifted analyses in future studies. This approach could improve the predictive understanding of microbial risks following rainfall events, and help refine early-warning thresholds in water quality monitoring systems

(b) response Curve of turbidity in the day 10/11/2014

This second period is characterized by a series of weather events that is not too intense, but rather frequent, although some minor. In the days before the significant event was seen as the source water had already been affected by a significant increase in turbidity, which was then returned to fall until the day of November 10. The arrival of the precipitation is more intense has helped to increase the turbidity up to very high values, almost next to 5 NTU, even if the effects are to be found the next day. This was also repeated for the two rainfall events that occurred at the end of the period, where the turbidity in the source showed an increase only in the next day.

Also in this case, the value of pH has not changed, remaining ever constant.

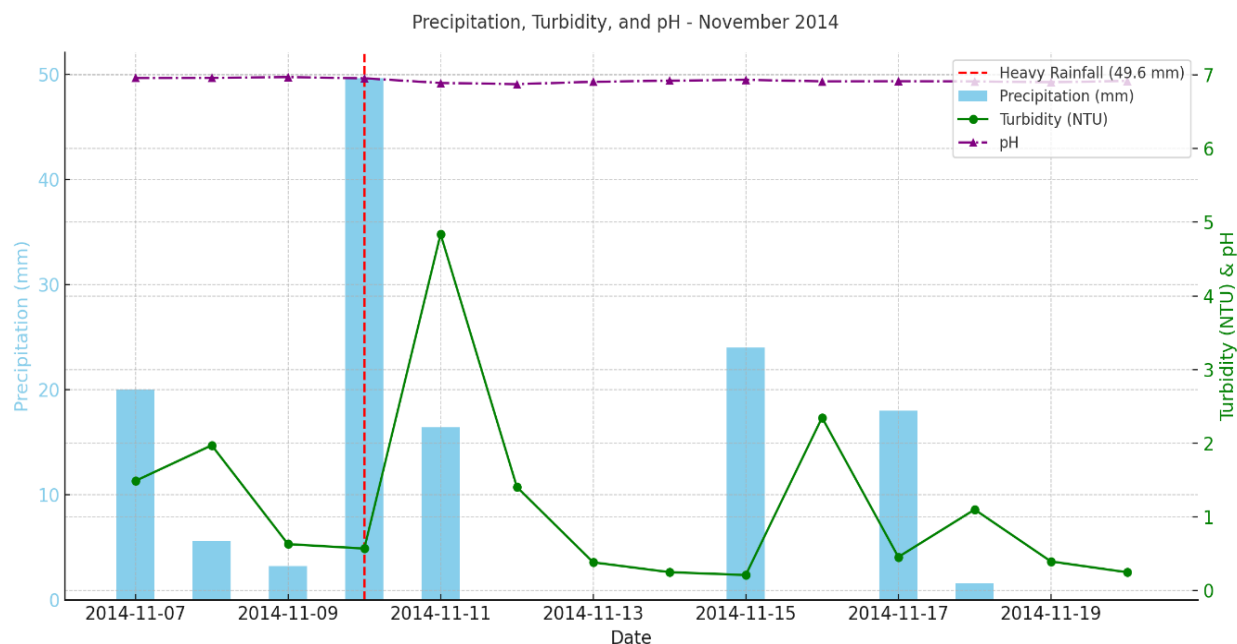


Figure 6.13 Response curve of turbidity and pH as a result of the weather event significant day 10/11/2014

c) response Curve of turbidity in the event meteor shower of the 04/04/2019

This case study follows the same pattern observed previously, with the main difference being the phase lag between the meteorological event and the peak turbidity. Before the event, turbidity levels were practically non-existent, but in the following days, a sharp increase was observed, peaking after two days at nearly 5 NTU, before gradually stabilizing at lower values. Towards the end of the period, despite weaker rainfall events, a slight increase in turbidity was still noticeable, though at very low levels. Meanwhile, the pH remained constant throughout, showing no significant variations despite changes in turbidity.

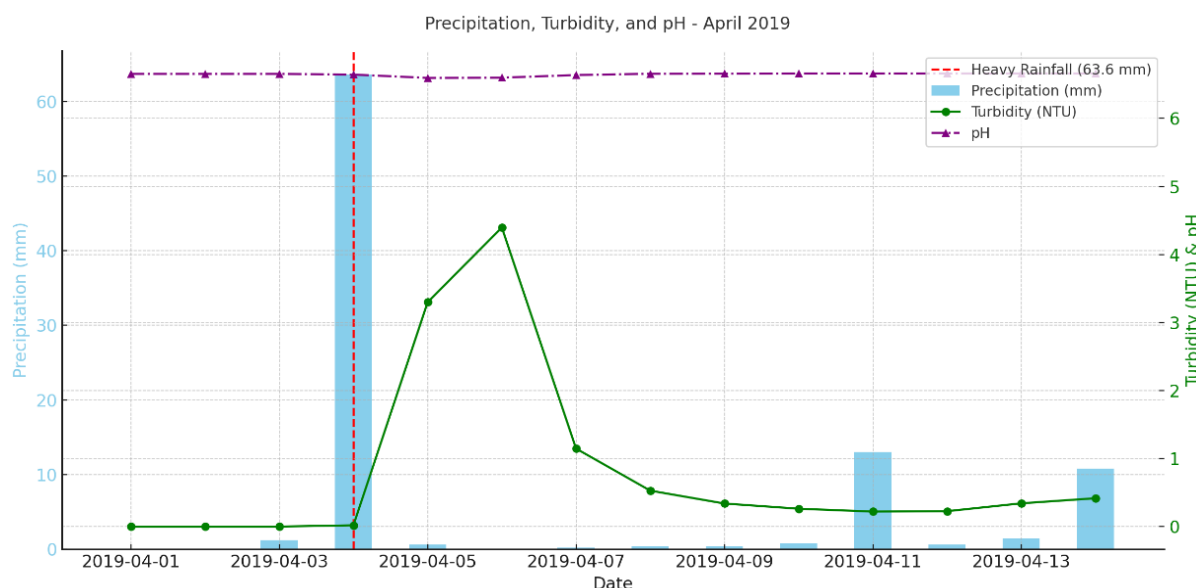


Figure 6. 14 Response curve of turbidity and pH as a result of the weather event significant day 04/04/2019

d) response Curve of turbidity in the event meteor shower of the 18/01/2023

This last period analyzed is particularly dry, in fact, you do not notice any large changes in the turbidity if not because of the two meteorological events in a row, the first of which is much more intense. Also in this case, the peak turbidity is reached, the second of the two days following the critical event and then returns stably to the minimum values.

In this case in figure 6.15, in view of the presence of the continuous measurement of the concentration of nitrates was also added this information. So, as far as the pH, also for nitrate concentration did not change, remaining constant and below the EU regulatory limit of 50 mg/l imposed by the legislation.

At the conclusion of this analysis, we can confirm the hypothesized initially that the source is particularly prone to undergo changes in turbidity, and this is found more consistently because of weather events critical or time periods in which rainfall of less and intensity, but with greater frequency. In some cases, the peak is reached on the same day as the event of rain, but in others it has a phase difference of a maximum of 1-2 days.

There was no correlation between the critical event and the variation of the pH of the incoming water to the source, which does not seem to be affected by the change in weather due to the precipitation or sudden variation of turbidity in the source.

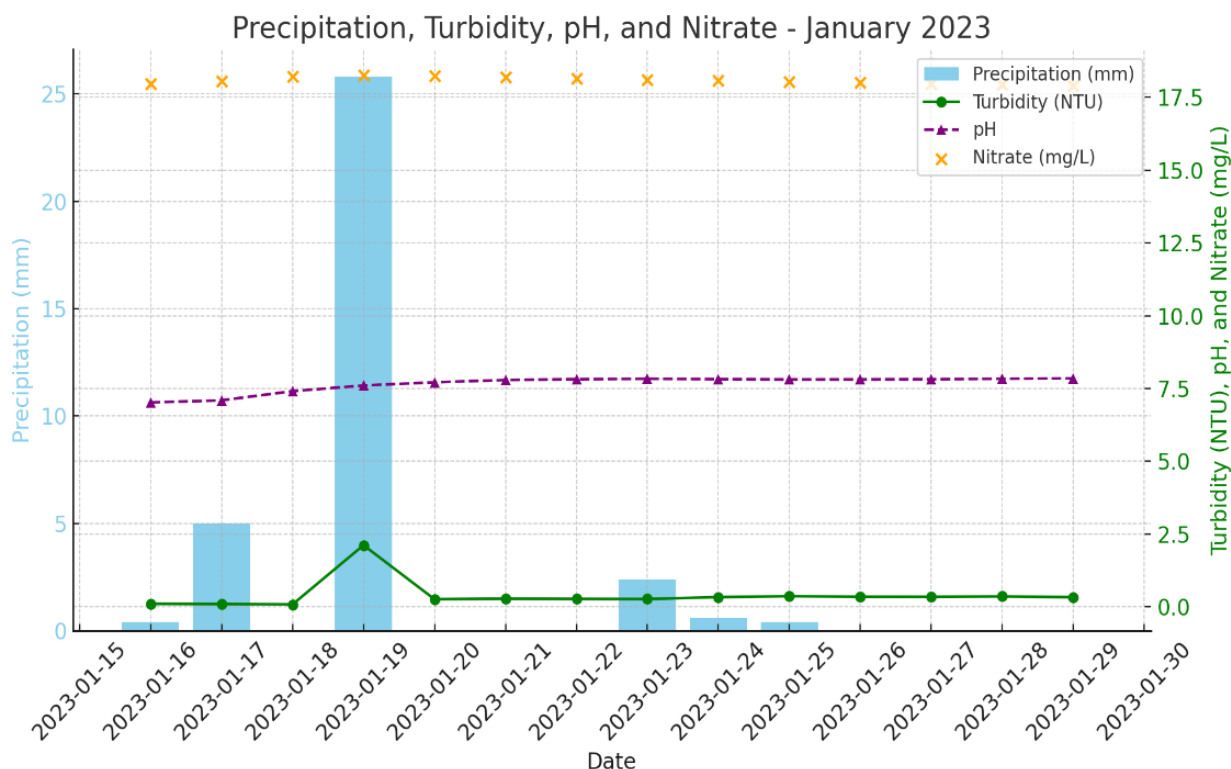


Figure 6. 15 Response curve of turbidity and pH as a result of the weather event significant day 18/01/2023

6.2.3 Analysis of UV absorbance

During the initial analysis of UV absorbance data, the absorption curve for wavelengths between 200 nm and 700 nm revealed two distinct peaks. One peak appears at the minimum wavelength of 200 nm, while the other occurs in the range of 210–235 nm. The peak between 200 - 220 nm is likely due to the presence of nitrates, as they strongly absorb UV light in this range and are consistently found in the incoming raw water.

The second peak (around 210–235 nm) requires further investigation since it may result from other compounds affecting the water source. For this reason, a more detailed analysis focused on the 210–235 nm range.

As an initial step, the analysis was conducted on the average daily UV absorbance for different wavelengths, using the 15th day of each month as a reference. This approach was chosen by overusing monthly averages, which were sometimes incomplete or unavailable. To ensure accuracy, the chosen daily data was compared with the available monthly averages. The differences were negligible, confirming the reliability of the selected data.

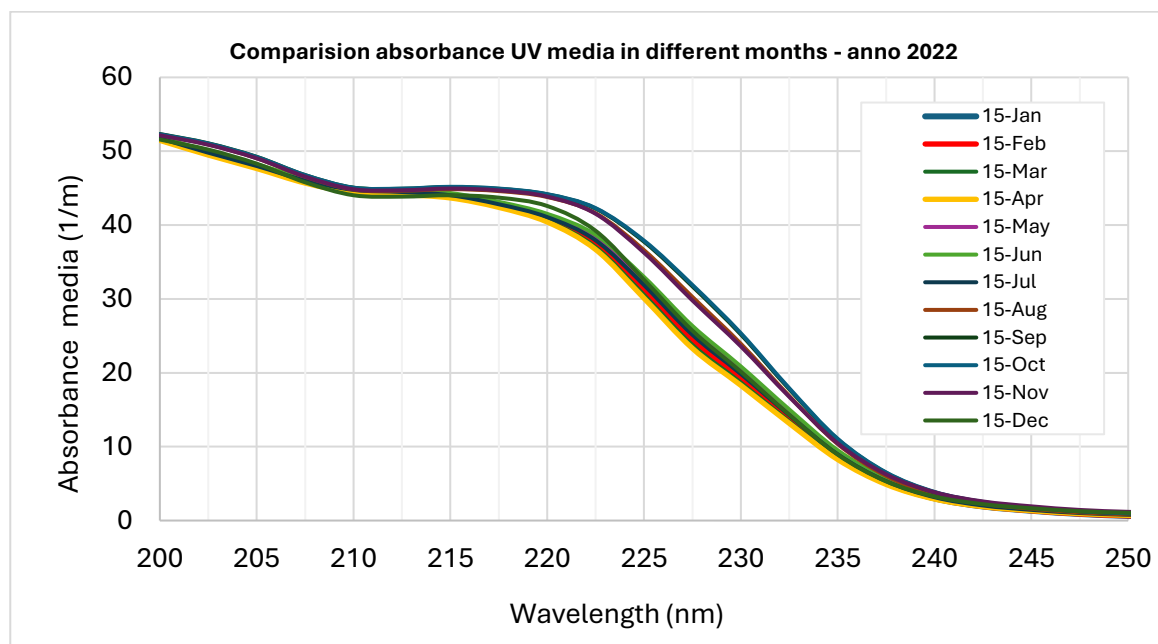


Figure 6. 16 Comparison of UV Absorbance Values Recorded on the 15th Day of Each Month in 2022

By comparing the reference days across each month in 2022, a series of absorbance curves was generated (Figure 6.16). This comparison helped identify which periods of the year showed higher UV absorbance, indicating the presence of compounds that might impact water quality. Similar trends were observed in Figure 6.16, which displays data grouped by seasons to assess potential seasonal correlations.

Overall, the UV absorbance curves showed consistent trends across reference days. Notably, at 225 nm, the months of October and September recorded the highest UV absorbance, followed by The most notable deviation occurred at 227.5 nm. The difference between November (purple curve) and June (green curve) was 3.45 m^{-1} . The largest overall deviation, 8.6 m^{-1} , was between October (blue dashed line) and April (yellow dashed line).

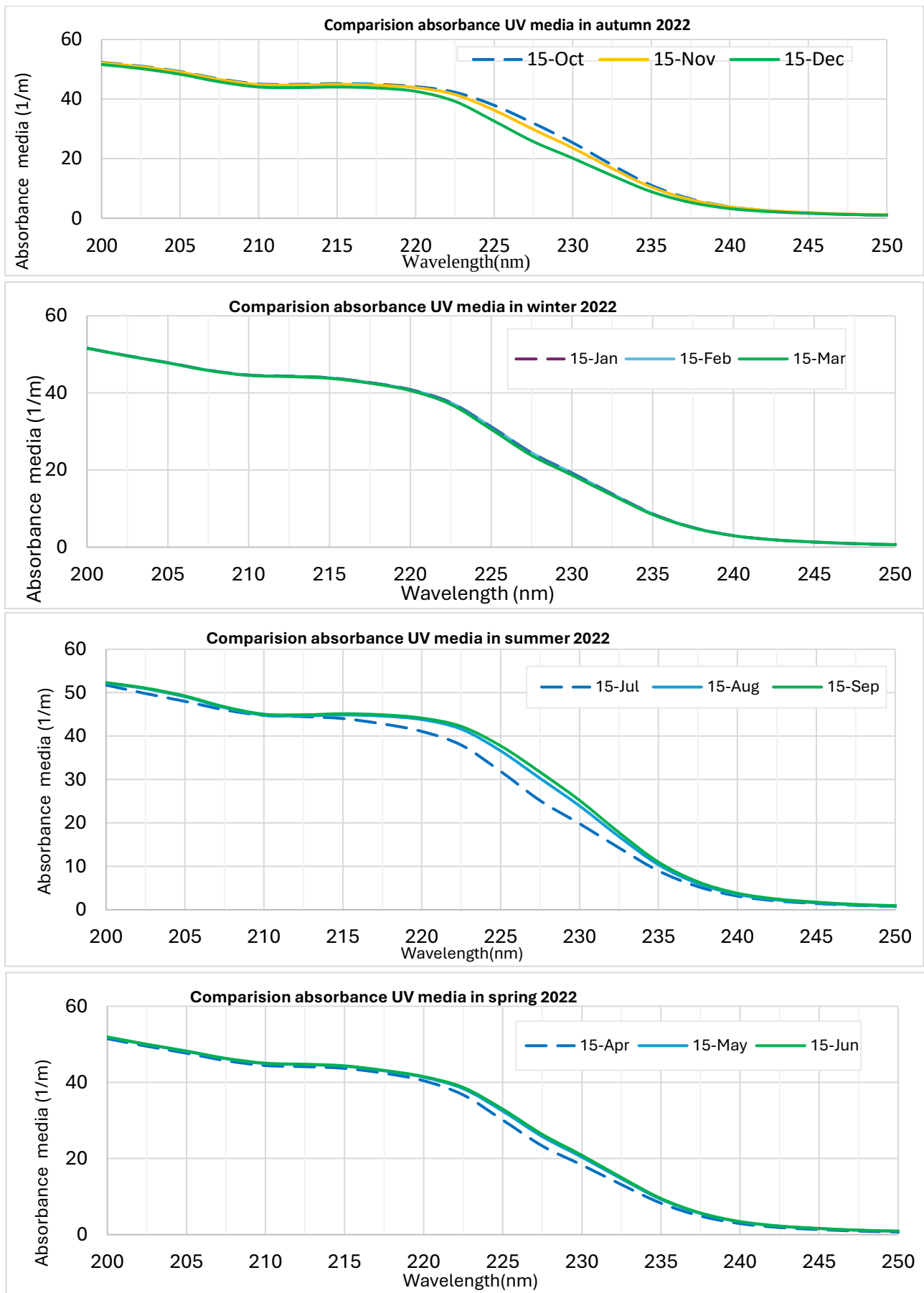


Figure 6.17 Comparison of UV absorbance for the seasons.

This comparison focuses on UV absorbance values between 220 nm and 235 nm, where noticeable variations were observed during different times of the year. UV absorbance gradually decreases as the wavelength increases from 200 nm to 250 nm.

- During summer and autumn, UV absorbance shows significant variation, especially in July and October.
- In contrast, winter and spring display more stable UV absorbance patterns.

These seasonal trends suggest that certain environmental factors or compounds in the raw water fluctuate throughout the year, affecting UV absorption.

6.3 Distribution network

6.3.1. Foutain water temperature variation

Research on variations in tap water temperature is a crucial factor in evaluating water quality and its impact on biological processes within water distribution systems. In Brescia, tap water temperature can be influenced by air temperature, depending on geographical factors such as sunlight exposure, shade, or population density.

The water sampling process at various taps in Brescia from 11/2022-8/2023, focuses on analyzing water temperature at the following locations in Figure 6.18, 6.19

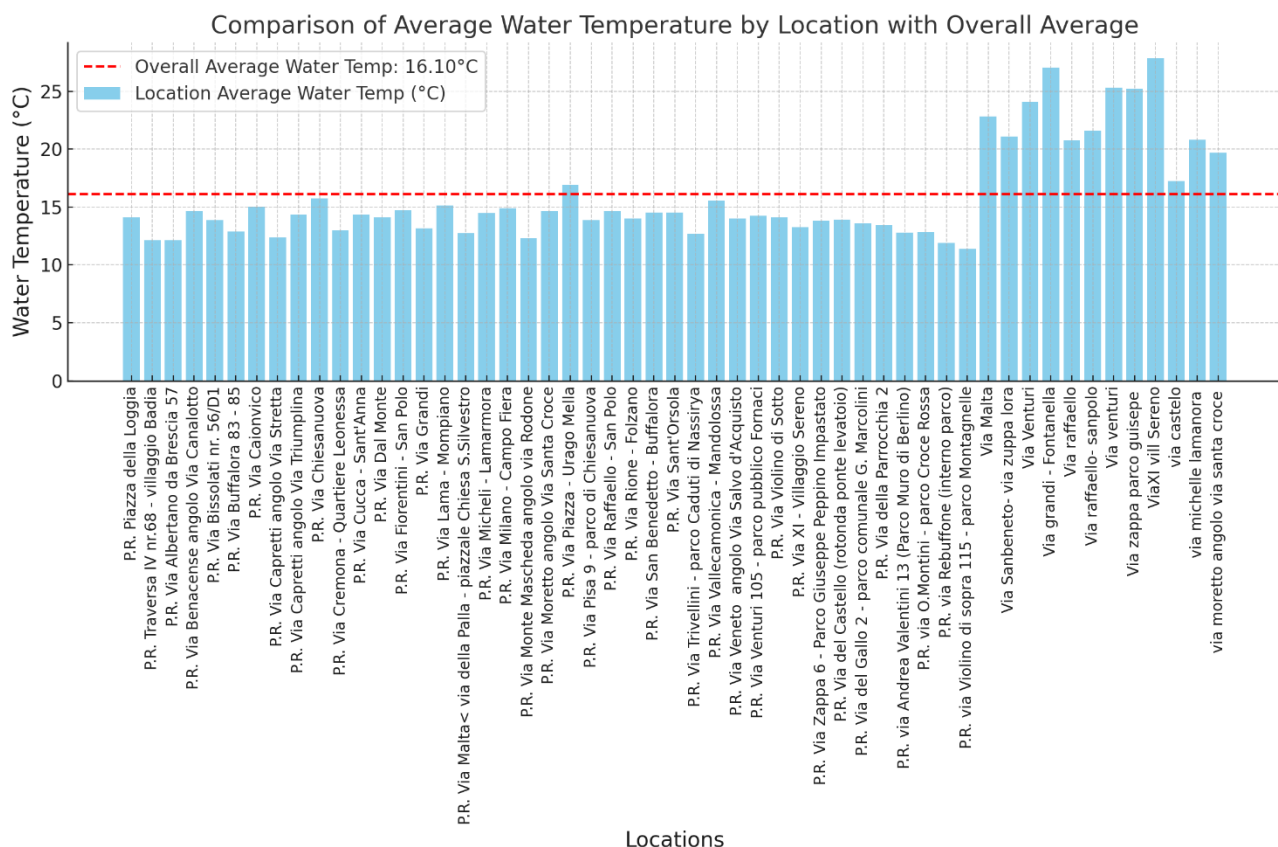


Figure 6. 18 The chart of average water temperature at various locations is intended to compare the differences between these sites

Figure 6.19 compares trends in water temperature over time for the five locations with the highest average water temperatures from 1/8/2023 to 8/9/2023

Locations with higher water temperatures, as identified in the analysis, such as Via XI Sereno, Via Grandi, Via Venturi, and (in Parco Guisepe) in Via Giancarlo Zappa, are often situated near heat sources or influenced by local environmental factors (e.g., direct sunlight and reduced shade), resulting in above-average water temperatures.

The differences in water temperature between locations highlight potential impacts on water quality and biological processes within the water distribution network. According to the WHO, the temperature of drinking water at customers' taps should not exceed 25°C. To limit the regrowth of microorganisms, the World Health Organization also recommends adhering to this maximum value (WHO, 2006).

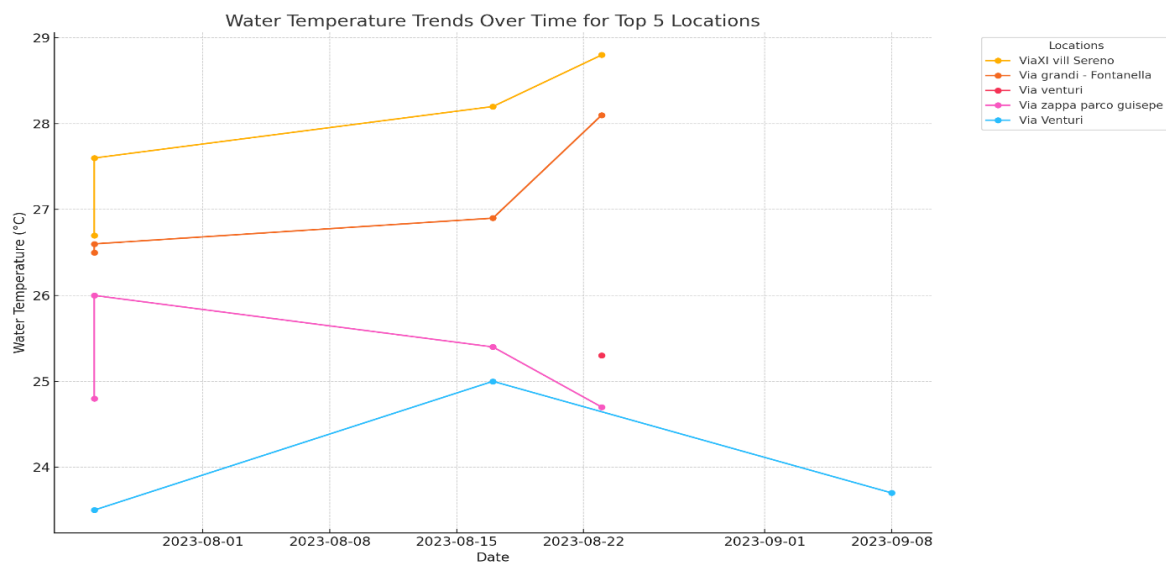


Figure 6. 19 Comparison of water temperature trends over time for the 5 locations with the highest average temperatures, from 1/8/2023 to 8/9/2023

To analyze the impact of air temperature on water temperature, several key steps can be undertaken. First, a scatter plot can be used to visually observe the relationship between air temperature and water temperature, helping to identify trends or unusual data patterns. Next, linear analysis using a regression equation can be performed to determine whether the relationship between these two factors is linear and to model the relationship. Predictions of water temperature can then be made based on air temperature.

Figure 6.20 the trend line added to the scatter plot is linear, which models the relationship between air temperature and water temperature with a straight line. This is appropriate given the strong positive correlation (≈ 0.89), suggesting that as air temperature increases, water temperature generally increases in a proportional manner.

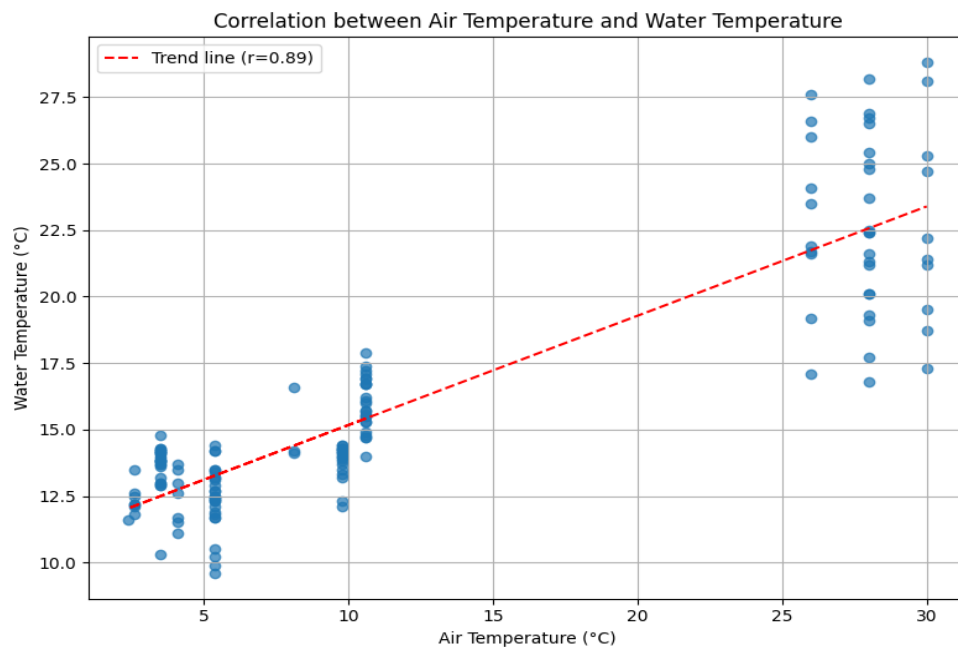


Figure 6. 20 The trend line added to the scatter plot is linear, which models the relationship between air temperature and water temperature with a straight line

Additionally, managers have implemented online monitoring devices such as Oniax.

A2A WATER CYCLE has collaborated to deploy a remote monitoring system for drinking water quality using IoT micro-laboratories, specifically the NEMO device. NEMO is the first mobile chemical laboratory integrated with a battery and remote data transmission capabilities, designed to monitor the physico-chemical parameters of water in real time.

This device is equipped with specialized electrochemical probes capable of monitoring parameters such as pH, free chlorine, turbidity, and conductivity. Its compact size (120x150x60mm) allows for easy installation in manholes or water source control points, simplifying the installation process and minimizing space requirements.

As part of the partnership with A2A, NEMO has been installed in the city of Brescia to conduct detailed monitoring of the water network, ensuring efficient, high-quality, and sustainable service for residents.

The use of NEMO enables integrated water service managers to remotely monitor water quality, reducing the intervention time of laboratory technicians and enhancing the efficiency of the water distribution network. This solution aligns with digital transformation requirements and supports the objectives of the National Recovery and Resilience Plan (PNRR) in improving the efficiency and safety of water systems.

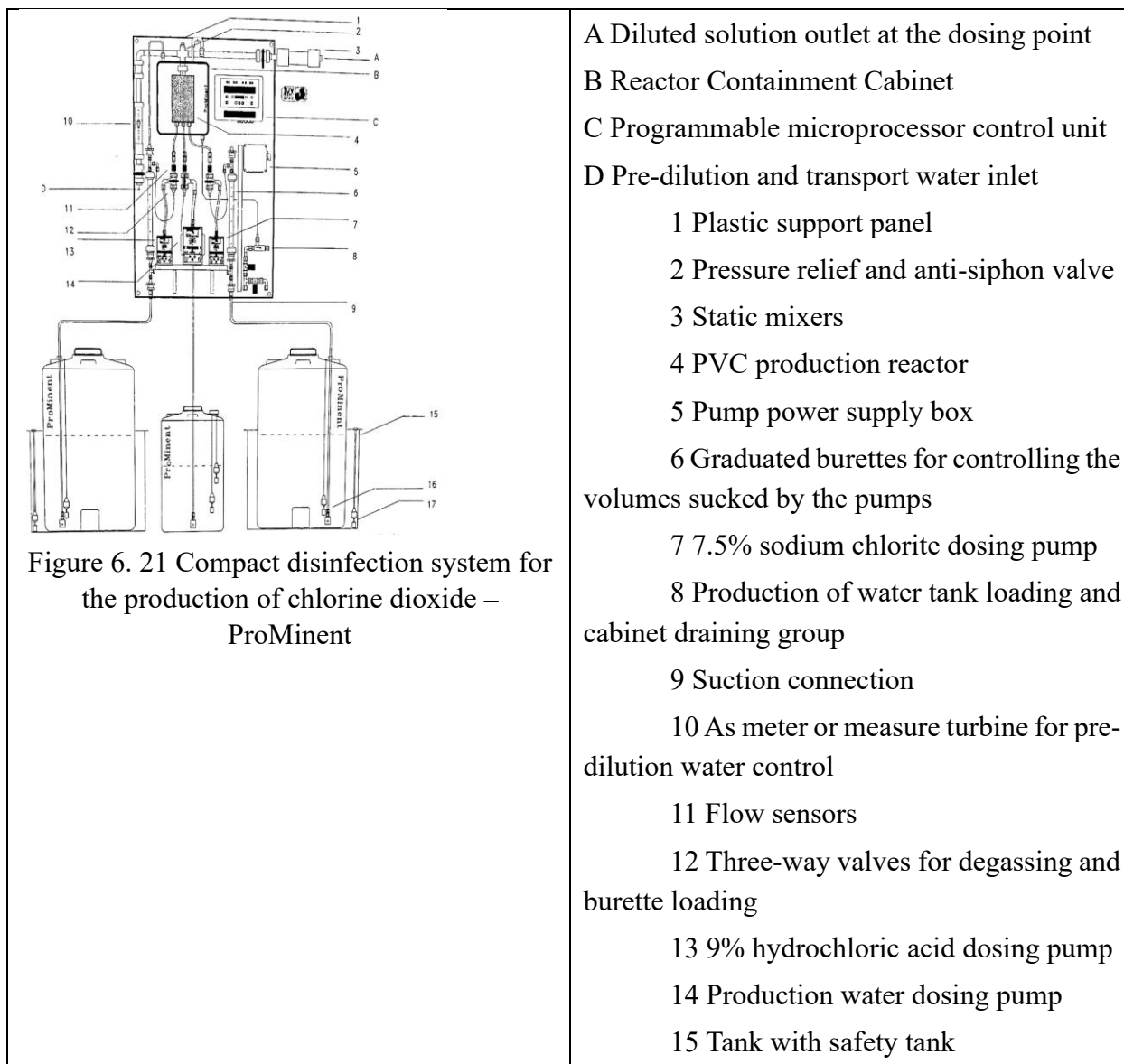
Combined with a below effective disinfection system, it aids in managing and safeguarding public health.

As for the treatment system, it consists only of disinfection using chlorine dioxide (ClO_2). Chlorine dioxide is a gas, with a typical pungent odor, very soluble in water but also unstable; at high concentrations it can give rise to potentially explosive mixtures. Its storage would entail multiple risks within a plant, with serious consequences for both employees and the plant itself. Chlorine dioxide is thus produced chemically by mixing sodium chlorite (NaClO_2) and hydrochloric acid (HCl), generally according to the reaction:



Below is one of the disinfection systems that the integrated water service manager, “A2A”, normally uses for the “underground aquifer well” collection system. Thus, it is possible to observe: the containers containing the two reagents, the dip tubes, the dosing pumps from which the two reagents are drawn respectively, the electrical control panel and the reactor to produce chlorine dioxide. The system is in compact form produced according to the “ProMinent” patent.

The reagents used are Hydrochloric Acid in 9% solution and Sodium Chlorite in 7.5% solution. Unlike chlorine, for which there is a strong independence from the pH, chlorine dioxide carries out bactericidal activity in a very wide range (5-9) thus representing the ideal reagent for the disinfection treatment of water. However, it is not free from disadvantages. If chlorine has by-products such as trihalomethanes, haloacetic acids, chloroform etc..., chlorine dioxide, through slow reactions, of “dismutation”, produces chlorite ion ClO_2^- and chlorate ion ClO_3^- , potentially dangerous. By increasing the dosage of hydrochloric acid in the reaction previously reported, the reaction kinetics accelerate significantly with chlorine dioxide production yields of up to 95%, solving the problem of by-products. The dioxide dosage is calibrated to have chlorine concentrations that comply with legal limits



	16 Suction group with bottom valve and two-stage float for pre-alarm and reagent end alarm
	17 Safety float for tank breakage alarm

Furthermore, action relate to parameters for risk assessment in internal distribution systems follow D. Lgs. 18/2023, Allegato I, Parte D. Legionella | UFC/l (colony-forming units) | < 1000. Legionella is a genus of Gram-negative bacteria that thrives in aquatic environments and can cause serious diseases in humans, particularly Legionnaires' disease, a severe form of pneumonia. This bacterium grows best in warm water environments between 25°C and 42°C and is commonly found in hot water systems, showers, air conditioning systems, and mist-producing devices. Legionella pneumophila is the most common pathogenic species, especially serogroup 1. Other species such as L. longbeachae, L. micdadei, and L. bozemanii can also cause infections in humans.

According to recent reports, the Lombardy region has recorded the highest number of Legionella infections in Italy. Notably, in 2022, over 250 cases were reported in this region, accounting for a significant portion of the total national cases. The primary cause is linked to poorly maintained hot water and air conditioning systems according to the National Surveillance System, a total of 3,111 legionellosis cases were reported across Italy in 2022, with Lombardy accounting for 9.9% of these cases. The overall incidence was 51.9 cases per million inhabitants, reflecting a geographic gradient with higher rates in northern regions compared to the south. (Laganà et al., 2023)

In Southern Italy, a study in Messina from January to May 2022 analyzed 120 samples of water and aerosols from 30 car washes. Results showed that 8.3% of the samples tested positive for Legionella, with 11.7% in water samples and 5% in aerosol samples (Laganà et al., 2023) Detected serogroups included L. pneumophila serogroups 1, 7, 10 and Legionella gormanii. Additionally, in Sardinia, 61.3% of 112 inspected accommodation facilities were found to be colonized by Legionella. (Laganà et al., 2023)

However, Legionella does not spread from person to person. It primarily transmits through the inhalation of contaminated water droplets (aerosols) from infected water systems. High-risk environments include:

- Hot and cold-water systems in large buildings
- Cooling towers of air conditioning systems
- Hot tubs, showers, and mist-producing devices

Legionella causes two main types of illnesses:

1. Legionnaires' Disease (severe pneumonia): Symptoms include high fever, cough, shortness of breath, muscle aches, and fatigue. This disease can be fatal if not treated promptly.
2. Pontiac Fever: A milder illness resembling flu-like symptoms, which typically resolves without treatment.

Traditional detection methods, such as bacterial culture, take around 15 days to yield results. Drinking water safety regulations, such as the EU Directive 2020/2184, recommend maintaining cold water temperatures below 20°C to limit Legionella growth. This standard is implemented in public

water systems, hospitals, hotels, and large infrastructure. Based on analysis and monitoring frequency in Bresica in summer 2023 The pie chart illustrates the proportion of different Legionella species detected in the tested samples. From this pie chart, the risk level can be assessed. Although the results are all below the permissible limit (< 1000 CFU/L according to European standards), the chart shows which type of Legionella appears most frequently, especially serogroup 1 as it is the most dangerous. Continuous monitoring is still necessary, based on evaluating the relationship between Legionella results and other environmental parameters.

This analysis is crucial for understanding the prevalence and distribution of different Legionella species in the dataset, supporting risk assessment and water quality monitoring efforts.

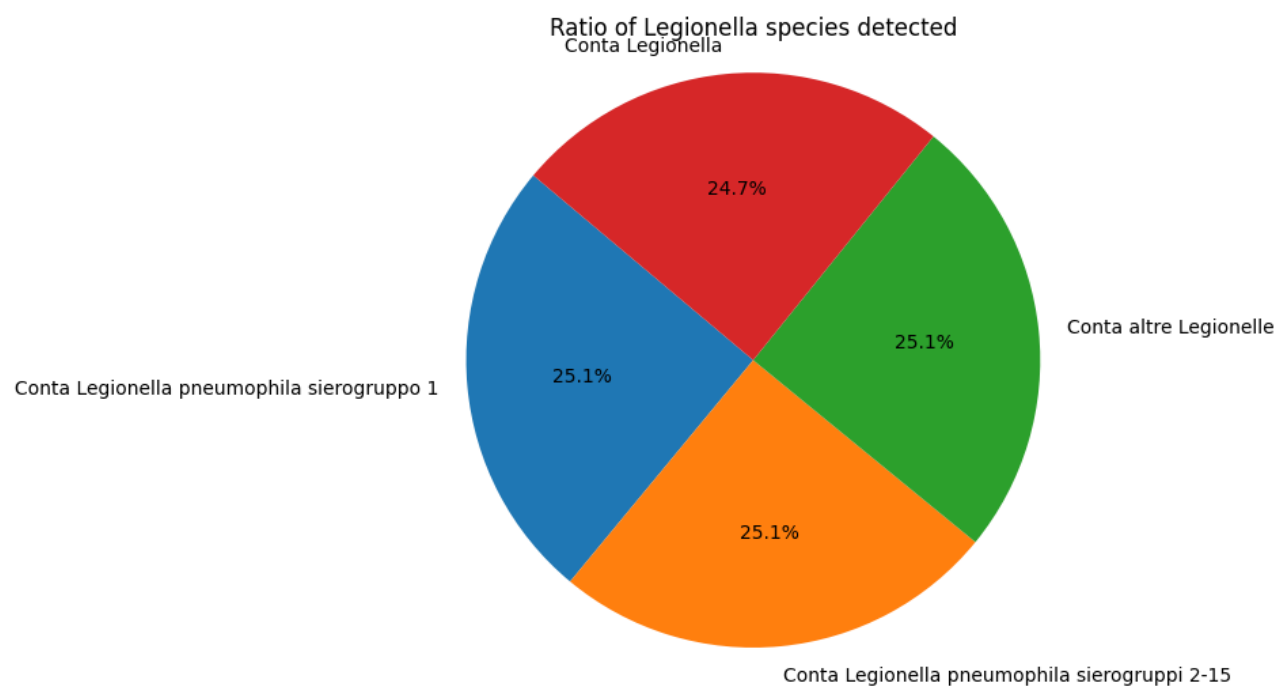


Figure 6. 22 Illustrates the proportion of different Legionella species detected in the 61 tested samples in Via XI Sereno, Via Grandi, Via Venturi, and and in Parco Giuseppe via Giancarlo Zappa in summer 2023



Figure 6. 23 Illustrates water temperature in fountain some location in Via XI Sereno, Via Grandi, Via Venturi, and in Parco Giuseppe via Giancarlo Zappa in summer 2023

6.3.2 Analysis of the Correlation Between Water Temperature and Chlorine

Analyzing water quality based on water temperature is a crucial factor in assessing the stability and safety of water. At high temperatures (above 25°C), the degradation rate of chlorine increases, reducing its disinfection efficiency and raising the risk of microbial activity. Conversely, at low temperatures (below 10°C), chlorine remains more stable; however, pH can be affected due to CO₂'s solubility.

The study of chlorine degradation in relation to temperature examined three main wells in Brescia: Pozzo Bornata, Ripompaggio Mainera and Via della Monte Valley. These wells play an important role in the city's water supply system, with continuous monitoring of parameters such as Redox, pH, chlorine (Cl₂), conductivity and temperature at Pozzo Bornata, while chlorine concentrations were measured at Ripompaggio Mainera and Via della Monte Valley.

Impact of temperature on chlorine degradation, the data below showed a strong correlation between temperature and chlorine degradation. In the summer of 2023 (August), chlorine concentrations exceeded 0.2 mg/l at Pozzo Bornata and Via della Monte Valley, correlated with higher temperatures (concentrations were still below the permissible limit), higher temperatures accelerate chlorine degradation, affecting disinfection efficiency. while in the winter of 2023 (November), Ripompaggio Mainera recorded Cl₂ values above 0.2 mg/l.

Influence of distribution pipe materials and environmental factors: In addition to temperature, the material of the pipeline also significantly affects the stability of chlorine. Metal pipes, especially pipes containing iron and manganese, can react with chlorine and reduce the disinfection efficiency of chlorine. Fe²⁺ and S²⁻ can reduce chlorine dioxide (ClO₂) to chlorite (ClO₂⁻), resulting in a decrease in the amount of available disinfectant. In addition, Mn²⁺ interacts with ClO₂ to form MnO₂, which can absorb and catalyze oxidation, indirectly affecting the effectiveness of chlorine (B. Yang et al., 2021)

Remote Monitoring System for Water Stabilization: To ensure a stable and safe water supply, an advanced remote monitoring system (NEMO by Onyax and A2A) was deployed. This system provides real-time water quality monitoring, integration with existing infrastructure, and improved management efficiency. The ability to track chlorine degradation patterns and other key parameters allows for proactive adjustments, ensuring regulatory compliance and preventing potential microbial contamination.

Future research directions and key questions: This study raises important questions for optimizing water disinfection: How do pressure and elevation affect chlorine retention in these wells? What is the relationship between pumping rate and chlorine levels? Why does the water pumped from underground reservoirs have significantly lower chlorine levels? These questions highlight the need for further research into optimizing chlorine application and improving the water distribution network.

The findings suggest that water infrastructure design, pipe materials, and thermal degradation of chlorine must be considered together to maintain a safe and effective disinfection process. Implementing smarter monitoring systems and re-evaluating material choices could significantly improve water quality management in Brescia.

6.3.2.1 The Pozzo Bornata

The Pozzo Bornata station was selected to study the correlation between water temperature and key parameters such as chlorine, pH, and conductivity.

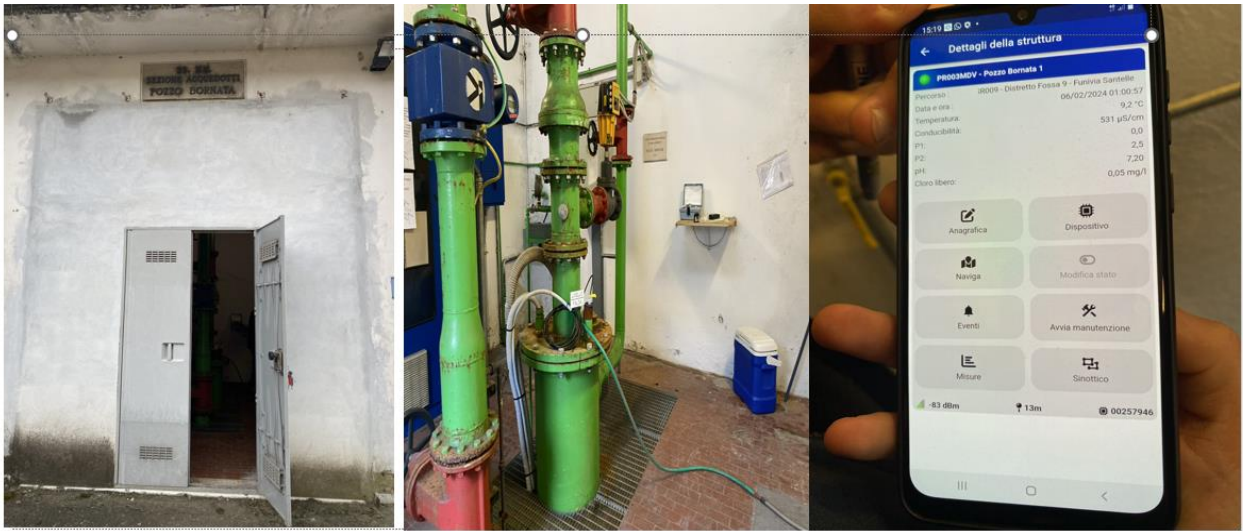


Figure 6. 24 Well at Bornata with some parameters in real time data

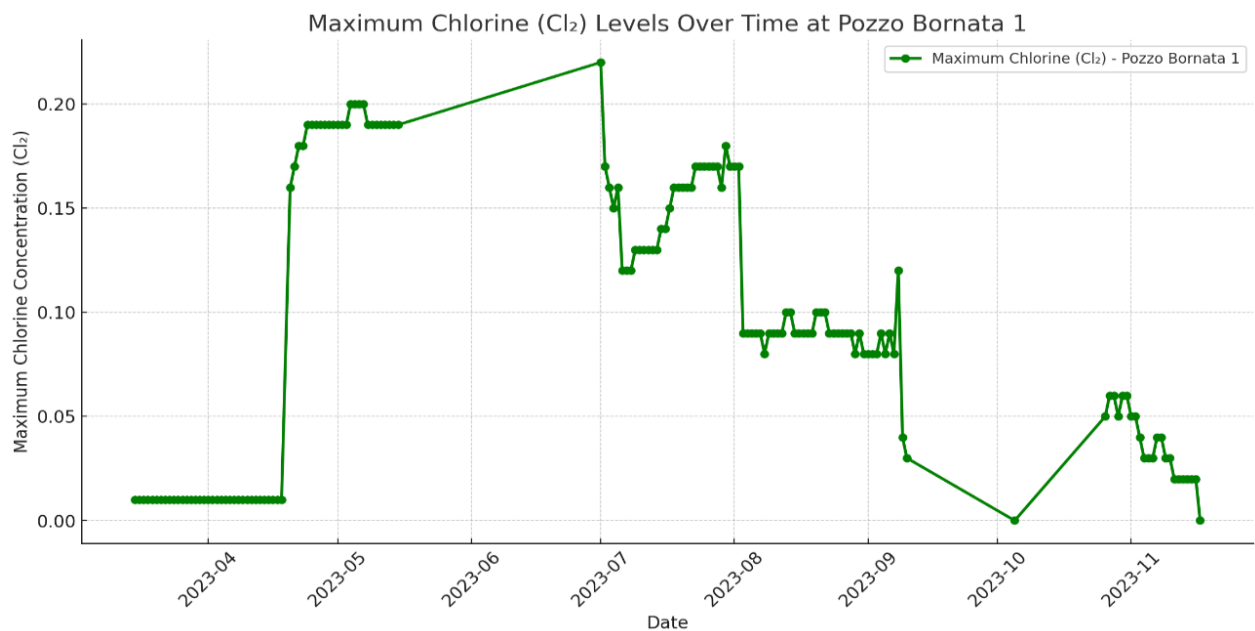


Figure 6. 25 Maximum Chlorine (Cl₂) level over time at Pozzo Bornata 1

The correlation matrix illustrates in Figure 6.25 the relationship between temperature and various water parameters, with values ranging from -1 to 1. A value close to 1 indicates a strong positive linear relationship, meaning that an increase in one variable corresponds to an increase in the other. Conversely, a value close to -1 signifies a strong negative linear relationship, where an increase in one variable results in a decrease in the other. A value of 0 indicates no linear relationship.

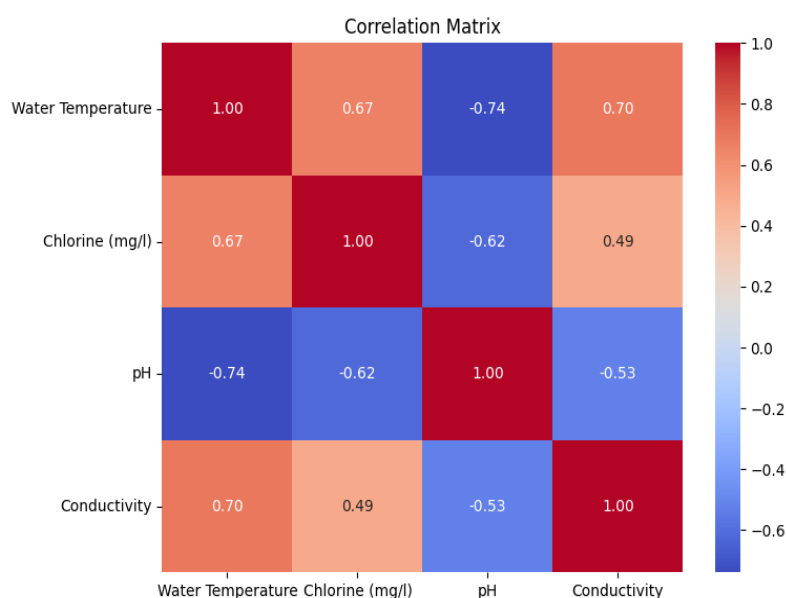


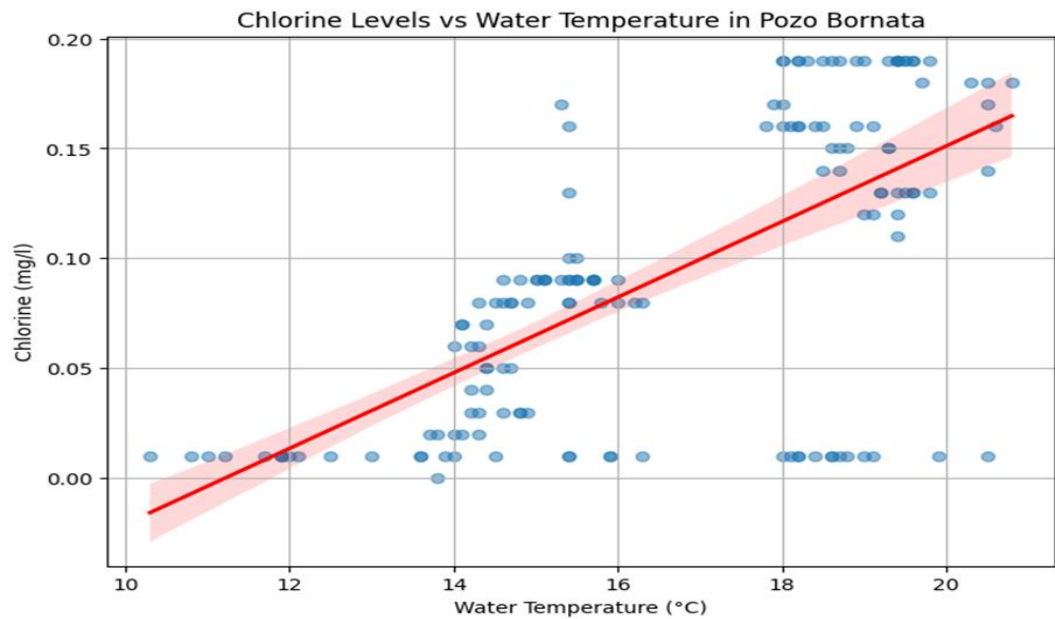
Figure 6. 26 Heatmap

The correlation matrix illustrates in Figure 6.26 the relationships between water temperature, chlorine concentration (mg/l), pH, and conductivity, highlighting key interactions that influence water quality. A moderate positive correlation (0.67) between water temperature and chlorine suggests that as temperature rises, chlorine levels tend to increase, though this may be influenced by seasonal dosing adjustments. There is a strong negative correlation (-0.74) between temperature and pH, indicating that higher temperatures are associated with lower pH values, which can impact chlorine stability. Temperature also shows a moderate positive correlation (0.70) with conductivity, likely due to increased ionization and mineral dissolution at higher temperatures. Chlorine concentration is negatively correlated with pH (-0.62), confirming that alkaline conditions reduce chlorine efficiency, while its moderate positive correlation with conductivity (0.49) suggests that chlorine levels fluctuate with ionic variations in water. Lastly, pH and conductivity exhibit a moderate negative correlation (-0.53), indicating that changes in pH influence the ionic balance. These findings emphasize the complex interdependencies in water quality management, demonstrating that temperature plays a crucial role in chlorine decay, pH affects chlorine's disinfection efficacy, and conductivity reflects the overall chemical interactions. To ensure effective disinfection, continuous monitoring and adaptive treatment strategies are essential.

The scatter plot in Figure 6.27 illustrates the relationship between chlorine levels (mg/l) and water temperature (°C) in Pozo Bornata, revealing a clear positive correlation between the two variables. As temperature increases, chlorine concentrations tend to rise, with the red regression line indicating a linear trend. Chlorine levels remain near zero at lower temperatures (10–12°C), while above 14°C, concentrations become more variable and generally increase, exceeding 0.05 mg/l beyond 16°C and reaching values above 0.15 mg/l near 20°C. The shaded confidence interval highlights some variability around the trend, though the overall pattern is consistent.

While this relationship might suggest that temperature directly influences chlorine dynamics possibly through increased reaction kinetics or microbial activity it is more likely attributed to operational practices. This seasonal pattern likely reflects higher chlorine dosages set by operators during warmer months to compensate for increased microbial growth or chlorine decay. Therefore,

although temperature and chlorine levels are positively correlated, this may not indicate a direct causative link, and further analysis is needed to isolate the role of environmental and operational factors.



0.6667586173706399

Figure 6. 27 Analysis of Chlorine Levels and Temperature in Pozzo Bornata

The time-series plot illustrates in figure 6.27 the relationship between water temperature (°C, blue line) and chlorine levels (mg/L, red line) over time, with a correlation coefficient of 0.67, indicating a moderate positive correlation. From April to August 2023, both temperature and chlorine levels show an upward trend, with temperature rising from 10°C to over 20°C, while chlorine levels increase correspondingly, peaking above 0.175 mg/L. Around September 2023, chlorine levels drop sharply to near zero, while water temperature remains high, suggesting an external factor affecting chlorine presence, such as treatment adjustments or changes in water retention time. From October onward, both temperature and chlorine levels decline, with temperature falling below 12°C in November, and chlorine levels fluctuating at very low values. The strong seasonal pattern suggests that chlorine dynamics are temperature-dependent, but other operational and environmental factors also play a role in maintaining chlorine stability in the water distribution system.

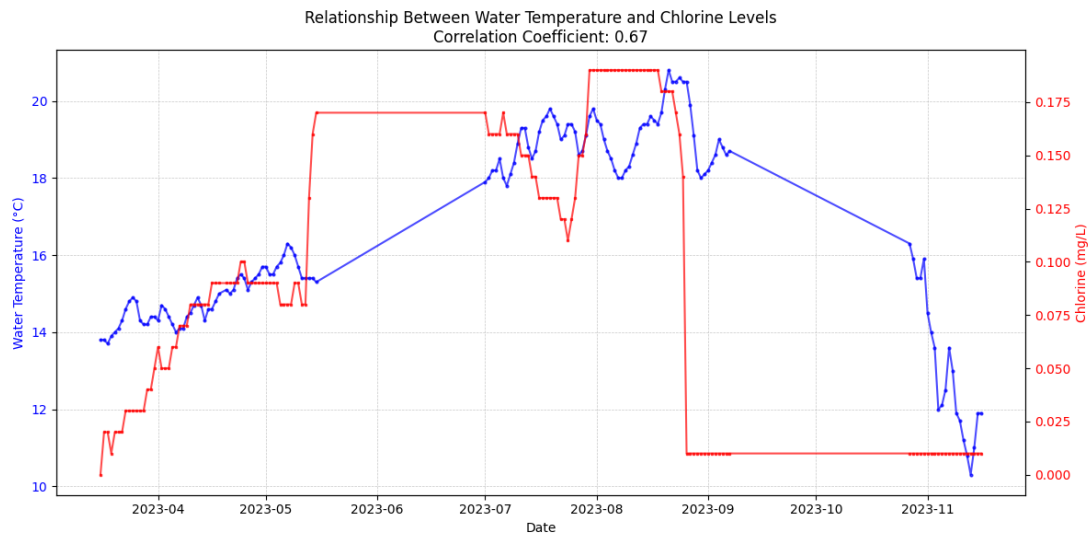


Figure 6. 28 Analysis visualizes the relationship between water temperature and chlorine levels over time in Pozzo Bornata

6.3.2.2 The pozzo monte della valley

Figure 6.29 shows a SCADA (Supervisory Control and Data Acquisition) system interface used for monitoring water quality and system performance at Serbatoio Costalunga, which is part of the Rete Rossa (Red Network). The interface displays real-time data from Lange analyzers, measuring various water quality parameters including turbidity (0.04 NTU), pH (7.15), conductivity (590.72 $\mu\text{S}/\text{cm}$), and redox potential (733.87 mV). At the top right, the system is connected to a PLC Siemens S7-1214C (CIC51), which communicates via GPRS (MODBUS protocol). The timestamp indicates that the data was last updated on February 14, 2024, at 14:53:36.

The schematic at the bottom represents the water flow process, showing connections between Rete via Monte Della Valle, Ripompaggio Monte Della Valle, and Ripompaggio Costalunga, which are part of the water distribution and pumping system. The tank at Costalunga shows real-time water level monitoring, with an inlet flow rate of 3.75 meters and an outlet flow rate of 1.75 l/s.



<https://maps.app.goo.gl/6f3cYKKCK7Q8ePSK8>

Figure 6. 29 SCADA (Supervisory Control and Data Acquisition) via Monte Della Valle

This SCADA system is essential for remote monitoring and management of the water distribution network, ensuring optimal water quality and system efficiency.

Chlorine levels at Via Monte Della Valle exhibit in figure 6.30 distinct seasonal trends, with a steady increase from the beginning of the year, peaking in mid-2023, followed by a sharp decline and subsequent stabilization at much lower values. From August onward, chlorine levels remained consistently low with minimal fluctuations. To improve accuracy, negative values were removed, eliminating artificial drops in the dataset. The updated 2024 plot in figure 6.31, after eliminating these distortions, reveals a stabilized trend in the early months, a gradual increase in chlorine concentration from March to June, and a sharp rise in June, with levels peaking around 0.09 mg/L. These fluctuations suggest that chlorine degradation follows a seasonal pattern, likely influenced by higher summer temperatures accelerating chlorine decay, while treatment adjustments ensure residual chlorine remains within safe limits throughout the year.

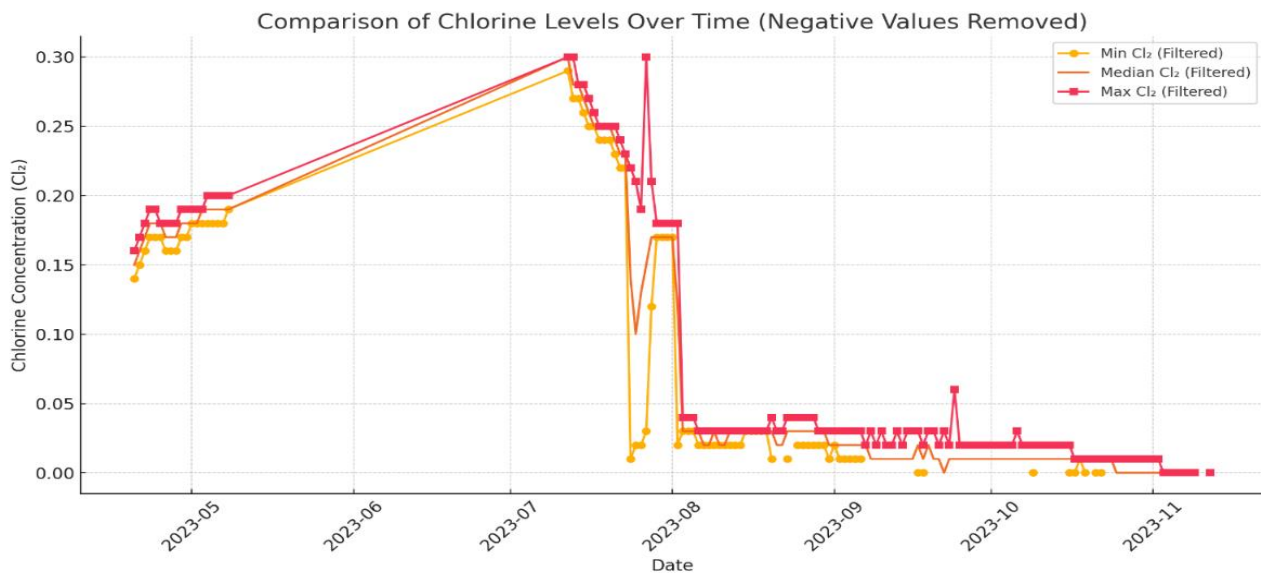


Figure 6. 30 Comparison of Chlorine levels at Via Monte Della Valle over time

- Early Increase: Chlorine levels steadily increased from the beginning of the year, peaking in mid-2023.
- Sharp Decline: After reaching the peak, concentrations dropped sharply and stabilized at much lower values.
- Stable Low Levels: From August onward, chlorine levels remained consistently low, showing minimal fluctuations.

-Eliminated Distortions: Removing negative values eliminated artificial drops, resulting in a more accurate analysis.

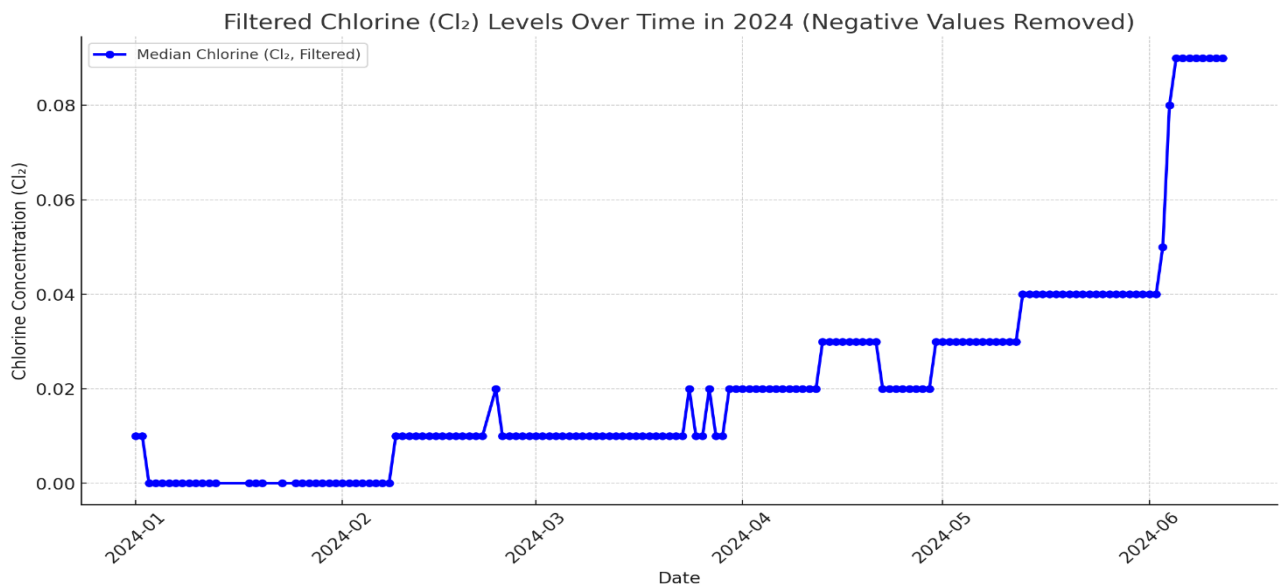


Figure 6. 31 Filtered Chlorine (Cl₂) levels at Via Monte Della Valle overtime in 2024

The updated plot figure 6.31 shows the median chlorine (Cl₂) concentrations in 2024 with all negative values removed with Chlorine levels in early 2024 remained low and stable, showing minimal fluctuations. However, a gradual increase was observed from March to June, followed by a sharp rise in June, with concentrations peaking at approximately 0.09 mg/L.

6.3.2.3 The pozzo Ripompaggio

This pozzo used a mobile monitoring system for Ripompaggio Mainera within the A2A water cycle network in Brescia, displaying real-time water quality parameters. The system tracks temperature, conductivity, pressure, pH, and chlorine levels, with chlorine concentration appearing relatively low. The interface includes options for device management, navigation, event logging, maintenance, and measurements, ensuring efficient remote monitoring and control of the water distribution system. Connectivity indicators show network signal strength and system distance, supporting real-time data transmission for operational management.

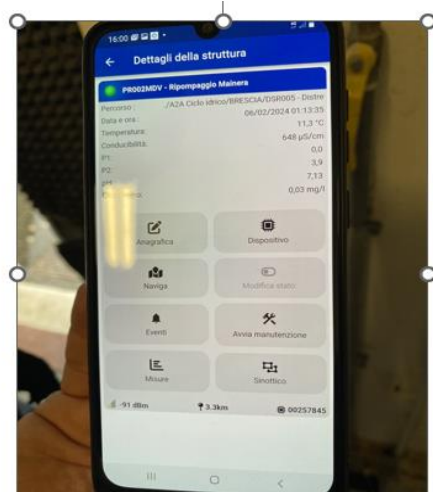


Figure 6. 32 Casa della acqua used mobile monitoring system in pozzo Ripompaggio

At Ripompaggio Mainera, chlorine concentrations remained moderate yet stable throughout the observed period, consistently within the safety range generally adopted for drinking water quality. Although D. Lgs. 18/2023 does not establish a strict maximum limit for free residual chlorine, standard operational practices typically maintain levels between 0.2 and 0.5 mg/L to ensure effective disinfection while preserving water palatability.

As shown in Figure 6.33, chlorine levels at Ripompaggio Mainera initially maintained a stable maximum concentration around 0.30 mg/L until early August 2023, after which they dropped significantly to approximately 0.02 mg/L and remained at that level until the end of the year. This sharp decline may reflect either a real reduction in chlorine dosing or a shift in detection reporting. It is important to note that the frequent 0.02 mg/L values could indicate measurements below the detection limit of the analytical method used meaning chlorine may have been non-detectable, rather than strictly present at 0.02 mg/L.

Compared to the more temperature-dependent fluctuations observed at Via Monte Della Valle, the chlorine trend at Ripompaggio Mainera appears more controlled and stable. This likely reflects more consistent treatment operations, possibly adjusting chlorine dosing based on seasonal or microbial risk assessments.

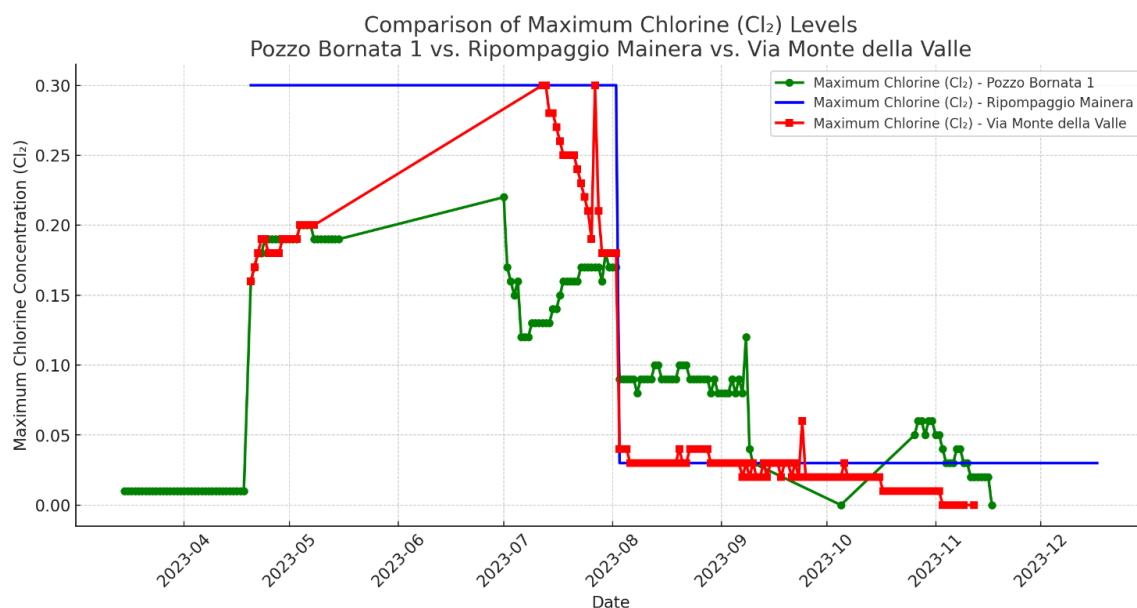


Figure 6. 33 Comparison of Maximum Chlorine (Cl₂) levels Pozzo Bornata 1 vs. Ripompaggio Mainera vs. Via Monte della Valle

The comparison of maximum chlorine (Cl₂) in figure 6.33 concentrations across the three sites reveals distinct trends. Pozzo Bornata 1 consistently shows the lowest chlorine levels, with minimal fluctuations and values remaining close to zero. In contrast, Ripompaggio Mainera exhibits moderate and more variable chlorine concentrations than Pozzo Bornata 1, with peaks reaching approximately 0.3 mg/L, which remain within safe limits. Via Monte della Valle displays the highest variability in chlorine levels, with noticeable spikes over time. Some of these peaks approach the upper safe limit but still comply with the typical regulatory range of 0.2–0.5 mg/L.

Overall, Pozzo Bornata 1 maintains the most stable and lowest chlorine levels, Ripompaggio Mainera has moderate yet stable concentrations, and Via Monte della Valle shows the greatest fluctuations while remaining within the safety standards set by Italian D. Lgs. 18/2023.

6.3.3 Evaluation of IDEXX Equipment for Detecting Microorganisms in Drinking Water

Ensuring the safety and quality of drinking water is a critical concern, particularly given risks such as environmental contaminants, microbial threats, and infrastructure vulnerabilities. Traditional microbiological monitoring methods, such as the heterotrophic plate count (HPC), have been used for over a century to evaluate water quality. However, these methods are labor-intensive, time-consuming, and often underestimate microbial load, making them inadequate for early detection of contamination events.

Adding to these challenges, climate change, with its extreme rainfall events, has exacerbated bacterial contamination in raw water sources such as Mompino. Moreover, 40 DWTP (Drinking Water Treatment Plant) utility managers reported issues with microbiological control, highlighting the difficulty in addressing contamination risks effectively with current approaches. Despite the growing need for real-time solutions, there are currently no automated devices from manufacturers like Lange or Isoil capable of performing such analyses. This lack of automation further limits the ability to continuously monitor and respond to contamination risks.

Choosing the right monitoring method depends heavily on specific needs, including sensitivity, specificity, cost constraints, and the urgency of results. However, current monitoring systems do not fully capture real-time managerial responses and adaptation strategies to climate impacts. Understanding how operators adjust in real-time, the challenges they face, and the measures they implement is crucial for bridging the gap between technical solutions and practical applications. This research aims to use real-time data to emphasize the importance of water safety and contamination detection, addressing these pressing issues.

The Heterotrophic Plate Count (HPC) method, also known as the standard plate count, is a traditional method used to estimate the number of viable heterotrophic bacteria in water. Unlike the IDEXX method, it measures the overall bacterial load without specifically targeting coliforms or *E. coli*. The HPC method is based on the cultivation of bacteria from water samples on a nutrient-rich medium. After an incubation period, bacterial colonies grow, and the number of colony-forming units (CFU) is counted to estimate the bacterial concentration in the sample.

IDEXX Colilert tool is a US EPA-approved system for automated water microbiology testing, specifically designed to detect *E. coli* and total coliforms. The testing process involves incubating a 100 mL water sample with the Colilert reagent for 24 hours at a controlled temperature of $35 \pm 0.5^{\circ}\text{C}$, following the manufacturer's protocol. Water samples that are more than 24 hours old upon arrival at the laboratory are not analyzed to maintain accuracy. After incubation, the sample is first observed under natural light. A color change from clear to red indicates the presence of total coliforms, caused by the enzyme β -galactosidase metabolizing ortho-nitrophenyl- β -galactoside (ONPG). If a color change is detected, the sample is further examined under ultraviolet (UV) light. Fluorescence in the sample signals the presence of *E. coli*, resulting from the enzyme β -glucuronidase metabolizing 4-methylumbelliferyl-beta-D-glucuronide (MUG). The test is highly sensitive, capable of detecting as little as 1 colony-forming unit (CFU) per 100 mL. This tool provides a reliable, rapid, and specific

method for identifying microbial contamination in water, ensuring the safety and quality of drinking water supplies.

The Cartridge Design is Unique and Critical

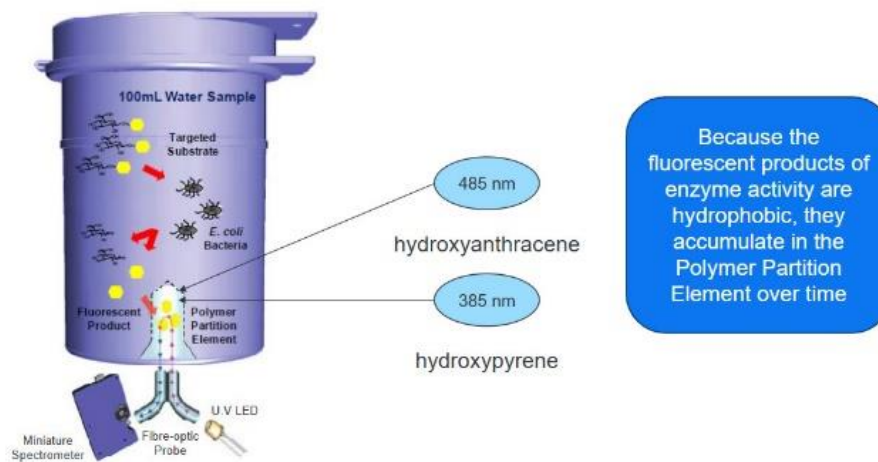


Figure 6. 34 The cartridge design for microbiological and substrates

Total 41 sampling were conducted in Brescia distribution between source “casa dell acqua” and some fountain “fontanelle”. The operational process for using a rapid automated microbiology testing system to detect bacteria in water involves three simple steps. First, the appropriate cartridge is selected and opened. Next, the water sample is added to the cartridge, ensuring it reaches the 100 mL fill line. Finally, the cartridge is securely closed and gently swirled to dissolve the reagent fully. This straightforward procedure enables accurate preparation for microbiological analysis, making it efficient and user-friendly.

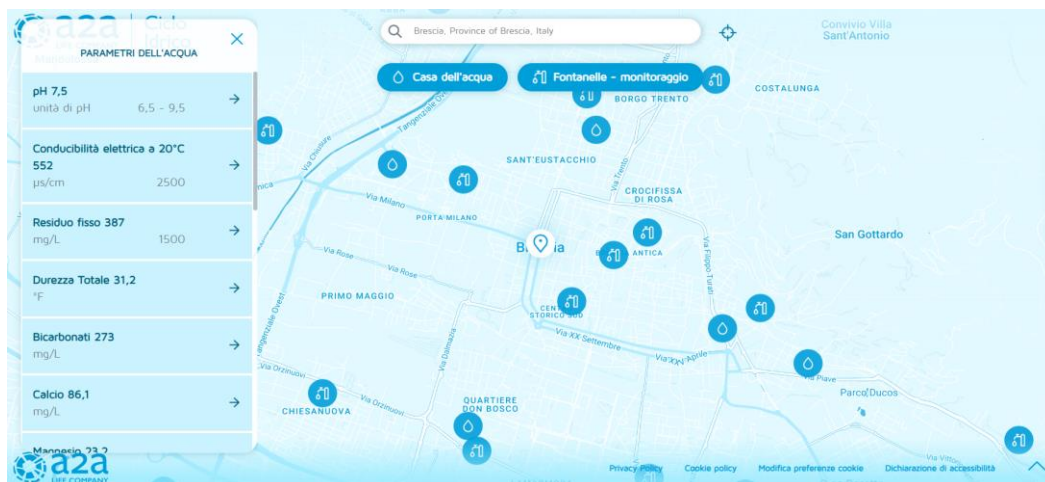


Figure 6. 35 Map of distribution of Casa dell'acqua and fontanelle in Brescia

A2A: <https://qualitaacqua.a2aciclodirico.eu/QualitaH2oWeb/mappa.action#>

We utilized statistical tools in both Excel and Python to assess the correlation between the IDEXX (Tectra) and HPC methods for measuring total coliforms in water samples

The figure 6.36 illustrates the relationship between temperature, precipitation, and *E. coli* concentrations measured using HPC and Tectra methods over time. Peaks in *E. coli* levels coincide with high precipitation and elevated temperatures, suggesting that rainfall and warmer conditions contribute to bacterial contamination. The Tectra method consistently detects higher *E. coli* concentrations compared to HPC, indicating greater sensitivity. These findings highlight the influence of environmental factors on microbial contamination and the importance of integrating sensitive detection methods with environmental monitoring for effective water safety management.

Compares total coliform levels measured using Tectra and HPC methods with precipitation

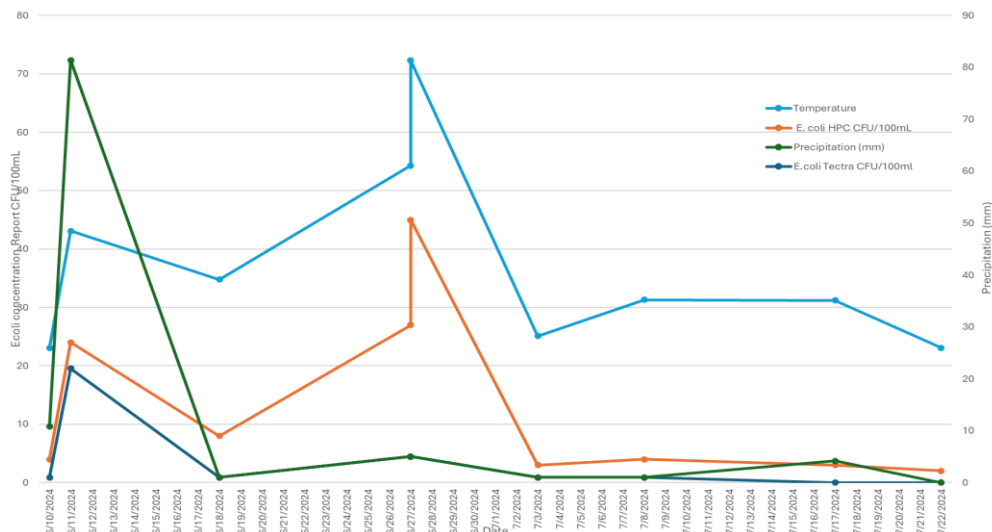


Figure 6. 36 Compares total coliform levels measured using Tectra and HPC

and temperature over time. A sharp increase in total coliform levels coincides with high precipitation and elevated temperatures, indicating a strong influence of environmental factors on bacterial contamination. The Tectra method specifically targets *E. coli* and shows measurable levels. The HPC method detects general bacteria and reports higher counts, but it does not specifically identify *E. coli*. Therefore, HPC and Tectra measure different things, and their results should not be directly compared for *E. coli* sensitivity. These trends underscore the importance of incorporating sensitive detection methods alongside environmental monitoring to better manage water safety risks.

The comparison between Total Coliform Tectra, Total Coliform HPC, and precipitation reveals a clear relationship between rainfall and the increase in bacterial concentrations in water. Notably, on days with heavy rainfall, such as June 11th (59.4 mm), the Total Coliform Tectra level spiked to 618 CFU/100ml in raw water (sorgente), significantly higher than on dry days. This suggests that rainfall may wash contaminants from the environment into water sources, leading to elevated coliform bacteria levels. Meanwhile, Total Coliform HPC also increased but showed less fluctuation, indicating that Tectra might be more sensitive to environmental changes. On days without rain, bacterial concentrations tended to decrease or stabilize, further supporting the idea that rainfall is a major factor influencing water quality. Although temperatures gradually rose during this period, there was no notable impact on bacterial levels, suggesting that rainfall has a stronger effect than temperature. Overall, these findings emphasize the importance of managing and monitoring water quality, especially after heavy rainfall, to ensure the safety of drinking water sources.

We analyzed the data in the context of rainfall and temperature records by used Time Series Analysis of Coliform Counts and Climatic Factors:

Follow figure 6.37 Key observations include:

- There doesn't appear to be a clear trend or strong correlation between temperature and *E. coli* concentrations.
- Most data points are clustered at lower *E. coli* counts regardless of temperature.
- This suggests that temperature alone may not be a strong predictor of *E. coli* concentrations and that additional factors (e.g., precipitation, water turbidity) should be considered for more reliable predictions

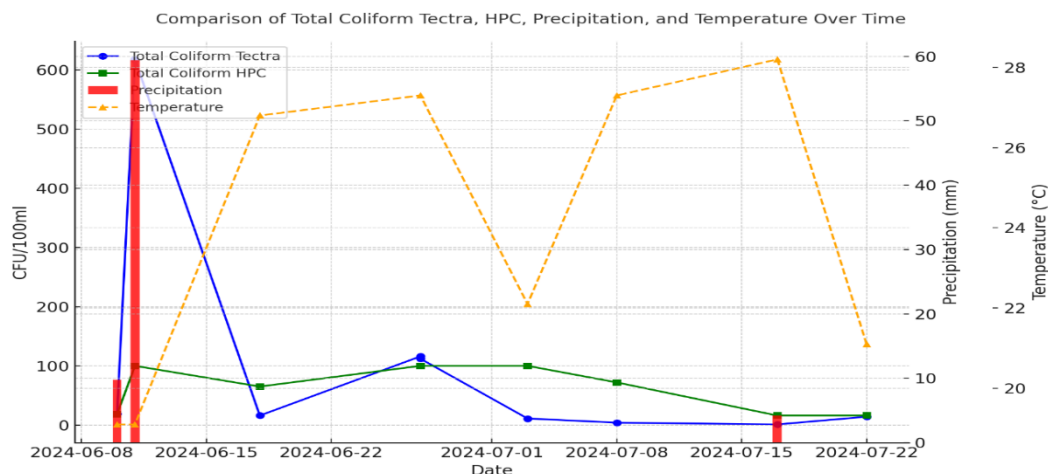


Figure 6. 37 Correlation Temperature and Precipitation with Total Coliform HPC and Total Coliform Tectra

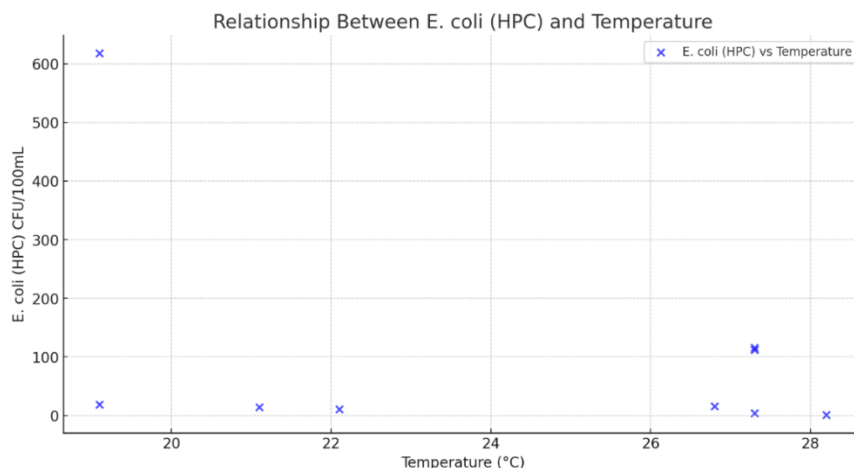


Figure 6. 38 The scatter plot illustrates the relationship between *E. coli* (HPC) concentrations and temperature (°C)

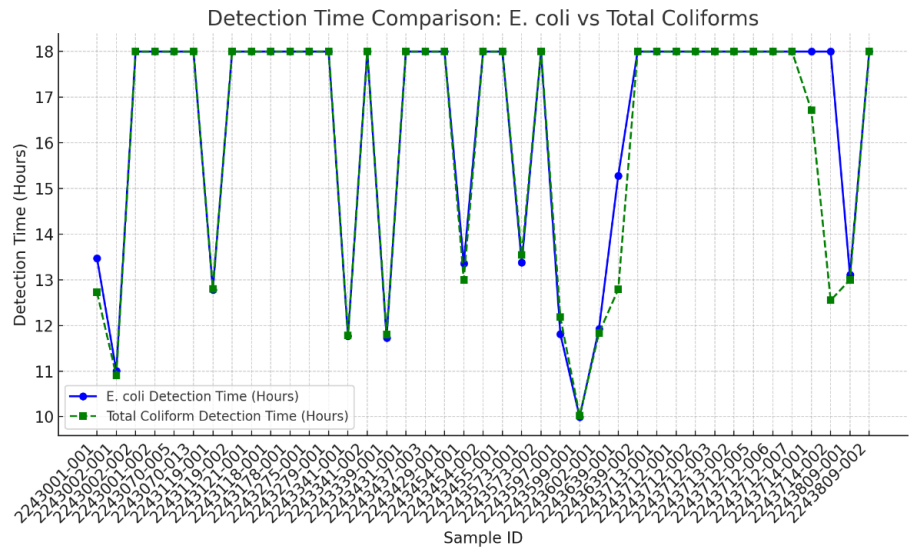
The analysis of 41 water samples demonstrates that the microbial testing method, particularly for *E. coli* and Total Coliforms, fully meets the criteria for speed, high sensitivity, and applicability in emergency monitoring. Specifically, the detection time for *E. coli* ranged from 11.00 hours to 18.00 hours, while Total Coliforms ranged from 10.90 hours to 18.00 hours. This proves that the method

can provide rapid and reliable results within 24 hours, outperforming traditional methods that typically take 24 to 48 hours to deliver results in figure 6.39

Additionally, this method can detect bacteria with high sensitivity, reaching levels as low as 1 CFU/100 mL (colony-forming units per 100 mL). This capability ensures precise identification of the presence of *E. coli* and Total Coliforms, allowing for the early detection of contamination even at minimal levels.

With its ability to deliver fast and accurate results, this testing method is highly suitable for real-time monitoring and emergency response situations. Water supply systems can promptly detect issues and issue timely warnings, thereby minimizing the risk to public health.

These results confirm that the microbial testing method not only ensures speed and accuracy but also offers high sensitivity and effectively meets the demands of emergency monitoring, playing a crucial role in protecting water quality and public health.



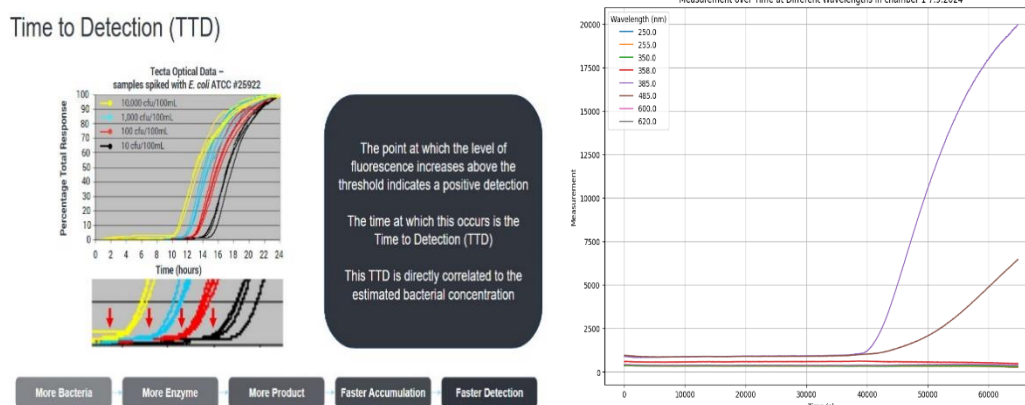


Figure 6. 40 Time to detection: more bacteria short time to detect

Traditional Laboratory Methods:

- Often measure total microbial content without identifying specific bacteria.
- Require lengthy processing times, which delay response in emergencies.
- While useful as a reference, they are less effective for real-time decision-making or early-warning needs.

Climate-related increases in microbial content underscore the necessity of tools like IDEXX for better risk management.

The use of the IDEXX Colilert tool demonstrated several advantages:

- Faster detection and quantification of specific microbes (*E. coli* and coliforms).
- Enhanced reliability for early-warning systems and emergency responses.
- Real-time data generation for improved water safety planning.

However, some challenges remain:

- Traditional laboratory methods are still needed for cross-validation and comprehensive microbial analysis.
- The lack of widespread online systems limits the ability to continuously monitor microbial trends over time.

Understanding these strengths and weaknesses is essential for developing an integrated approach to managing microbial contamination. Combining traditional methods with modern tools like IDEXX can ensure better bacterial control, especially in emergency situations or during critical periods of heightened risk. This proactive approach aligns with the Water Safety Plan framework, focusing on prevention, timely detection, and adaptive management to protect public health.

6.4 Recommendations for practice

The findings from Chapter 5 can be integrated into daily utility operations by incorporating the following actions into the Water Safety Plans (WSPs):

- Install automated alert systems based on turbidity and redox fluctuations.
- Use conductivity and redox potential as baseline indicators for anomalies.
- Develop a climate-event-specific response plan linked with WSP critical control points.

- Train operators to interpret real-time data dashboards and initiate predefined corrective measures.

This study examined the impact of climate change on the water quality of the Mompiano water source, a crucial supply for Brescia. By analyzing physical, chemical, and microbiological parameters in relation to climatic factors such as rainfall and temperature, valuable insights were gathered to improve future monitoring and risk management.

The findings revealed that annual rainfall increased from 2017 to 2020 but has declined sharply since then, with extreme rainfall events becoming less frequent after 2020. At the same time, average annual temperatures have been rising since 2010, reaching their highest levels in 2022, with an increase of 3.2°C above 1995 levels. While no immediate risks to water quality have been linked to temperature changes, potential future threats remain. Microbiological contamination, including *E. coli* and Enterococci, was observed sporadically, especially after heavy rainfall, but effective disinfection has prevented major issues. However, increasing temperatures and nutrient levels could enhance microbial regrowth, necessitating further monitoring.

The study also confirmed that nitrate levels remained stable between 15-30 mg/L, with a slight reduction during colder months, indicating minimal impact from precipitation events. Turbidity spikes, which often delay water supply due to exceeding safe limits, were recorded after significant rainfall. If extreme weather events become more frequent, turbidity management will require enhanced treatment measures to comply with the new legal thresholds set by D.Lgs. 18/2023. Other parameters, including pH and UV absorbance, showed no critical changes, though occasional UV peaks suggested the presence of nitrates or organic compounds. Additionally, emerging contaminants such as PFAS, bisphenol A, and uranium, which were introduced under D.Lgs. 18/2023, are not currently a concern.

To address these challenges, several recommendations were proposed. Enhanced monitoring is essential, with the installation of real-time microbiological probes to detect contaminants, continuous temperature tracking, and turbidity sensors with automated alerts for exceedances above 0.3 NTU. Infrastructure improvements should include a dedicated treatment system for turbidity to maintain high water quality. Furthermore, a weather-event response strategy should be developed, allowing for adaptive treatment measures following heavy rainfall to prevent microbial contamination and excessive turbidity. Long-term strategies, such as integrating climate data analytics and prediction models, will help anticipate future risks and allow for proactive interventions. Additionally, regular reporting and compliance monitoring for emerging contaminants will ensure adherence to updated regulations while maintaining transparent communication with stakeholders about potential risks and mitigation measures.

Overall, the Mompiano water source currently maintains good water quality with effective preventive measures in place. However, to mitigate climate-related risks, it is crucial to implement real-time monitoring, upgrade infrastructure, and adopt proactive management strategies. By integrating climate-based predictive modeling and adaptive treatment solutions, Brescia can ensure the long-term safety and resilience of its drinking water supply.

Future research could focus on how climate data can be integrated into water management systems for more effective risk assessment and adaptation.

CONCLUSION

The thesis was aimed at evaluating the effects of climate change on drinking water supply systems by reviewing the literature, gathering feedback from integrated water service managers, and analyzing a case study conducted in the municipality of Brescia (Mompiano drinking water supply system). Several key activities were conducted, including identifying current practices and control measures for operating water plants in Italy and Vietnam, distributing questionnaires to understand the views of water managers and the challenges posed by climate change, comparing treatment technologies across plants, and monitoring water quality at a pilot scale to assess compliance with legal standards. The findings are presented across six chapters.

The introduction in Chapter 1 outlines the objectives and methods, while Chapter 2 provides a theoretical framework and literature review on climate change impacts on water quality and treatment processes. Chapter 3 discusses survey results on how climate change affects inlet water quality and treatment stages of nearly 40 plants in Italy and 20 in Vietnam, and Chapter 4 highlights insights from field visits five plants in Italy, focusing on current practices and challenges. Chapter 5 presents a detailed analysis of water quality data and treatment technologies, emphasizing the need for improvements to manage climate-related challenges. Finally, Chapter 6 summarizes the findings, identifying key gaps and areas for improvement.

The survey shows significant gaps in understanding and managing the impacts of climate change on water supply systems. Stakeholders, particularly in Italy, expressed concerns about climate variability and highlighted the importance of integrating WSPs into their practices. Key challenges include variability in inlet water quality, extreme weather events affecting treatment processes, and the lack of early-warning systems for critical parameters like turbidity and microbiological contamination. The survey recommends implementing real-time monitoring systems for water quality parameters special microbiology, optimizing treatment technologies to handle sudden changes in water quality, and integrating these insights into climate-responsive WSPs. Future research should explore other water sources and distribution systems to identify vulnerabilities, while capacity-building efforts should aim to equip water managers with the skills needed to address these challenges. Overall, the study lays a foundation for managing climate-related risks to water supply systems and highlights the need for ongoing research and improvements.

More details are suggested by five water utilities (chapter 4), that investigate challenges in water supply systems and the solutions adopted by managers. For rivers, issues like pH fluctuations, chloride spikes (saltwater intrusion), and turbidity during heavy rains are addressed with hydrochloric acid, mobile reverse osmosis unit's techniques. In lakes and reservoirs, algal blooms, aluminum spikes (from runoff), and turbidity are managed using coagulant reagents, ultrasonic probes, and oxidizing agents. Surface water sources face diverse anomalies due to environmental and climate factors, unlike groundwater, which remains relatively stable. Managers have implemented advanced technologies and procedures aligned with Water Safety Plans to enhance system resilience and water safety.

Chapter 5, concerning the Mompiano water source in Brescia, currently maintains good water quality, supported by effective preventive measures. However, to address future risks posed by climate change, several enhancements are recommended. Installing microbiological detection tools at critical points would enable early warning monitoring of contaminants such as *E. coli*, Enterococci, and coliforms, while online temperature monitoring at the source and fountains could help identify

correlations between rising temperatures and water quality changes. Additionally, turbidity sensors with automated alerts should be implemented to detect and address spikes caused by significant weather events. To comply with new legal standards (D.Lgs. 18/2023), a dedicated water treatment plant for turbidity management should be considered, alongside optimizing the existing chromium reduction system to address broader water quality issues. A weather-event response plan is essential for addressing water quality fluctuations following heavy rainfall, with treatment adjustments to manage microbiological and turbidity risks.

Long-term strategies should include integrating climate data analytics to predict risks and using automated systems with real-time data inputs to model water quality changes. Periodic evaluation of emerging contaminants, such as PFAS and bisphenol A, is crucial to ensure compliance with updated regulations, while regular reporting and transparent communication with stakeholders will help build trust. These measures will strengthen the resilience of the Mompiano source against climate-related challenges, ensuring safe and reliable water quality for the future.

Based on the findings of this study, several recommendations are proposed to enhance water quality management for the future.

- Firstly, continuous monitoring of key water quality parameters, such as turbidity, pH, temperature, and electrical conductivity, should be maintained. These parameters are straightforward to measure and provide early warnings of sudden changes in water quality, enabling managers to take proactive and timely action to restore normal conditions, in alignment with Water Safety Plan principles.
- Secondly, microbiological monitoring should be strengthened using tools like the IDEXX Colilert system, which is highly effective for detecting microbial contamination, such as *E. coli* and coliform bacteria, in water. This method allows for quicker (results available in 9 hours instead of 18 hours), more reliability, and more frequent testing compared to traditional laboratory methods, providing a faster response to any potential microbiological risks.
- Thirdly, the ongoing study of UV absorbance patterns should be expanded, focusing on identifying the causes of peaks observed at specific wavelengths during periods of the year. Annual comparisons of UV absorbance data could help uncover underlying trends and seasonal variations.
- Finally, the research scope should be broadened to evaluate other water supply sources and the overall distribution system. This would help identify whether similar vulnerabilities exist in other parts of the system, particularly in the context of climate change, ensuring a more comprehensive understanding of water quality challenges. By implementing these measures, water supply systems can become more resilient and better prepared to maintain high water quality standards in the face of future challenges.

In the future studies should expand case studies to include different water sources, such as groundwater-dependent versus surface water systems, examine the effectiveness of AI-driven climate modeling in forecasting water quality fluctuations, and develop a standardized risk assessment framework for integrating climate resilience into WSPs across diverse geographic regions. Assessing the socio-economic feasibility of AI-based early warning systems and predictive analytics for water treatment optimization is also a critical area for future research.

This thesis establishes a critical foundation for climate adaptation in drinking water supply systems, emphasizing technological, operational, and policy-driven approaches. By implementing the recommended real-time monitoring strategies, treatment optimizations, and regulatory improvements, water managers can enhance system resilience against climate-induced risks. Addressing these challenges proactively will ensure sustainable and safe drinking water management in the face of climate uncertainty. Moving forward, the integration of climate science with water quality management, combined with data-driven decision-making and real-time adaptation strategies, will be essential for ensuring safe and resilient drinking water supplies worldwide.

ANNEXES

Circular promulgating National technical regulations and regulations on inspection and monitoring of clean water quality used for domestic purposes; assessed according to QCVN 01-1:2018/BYT [1] National technical regulations on clean water quality used for domestic purposes

ANNEX 1 – Chapter 1

Table guideline values defined by WHO for health-relevant chemicals in drinking water.

Table 1. 1 Table guideline values defined by WHO for health-relevant chemicals in drinking water

Chemical	Guideline value		Remarks
	mg/l	µg/l	
Acrylamide	0,0005 ^a	0,5 ^a	
Alachlor	0,02 ^a	20 ^a	
Aldicarb	0,01	10	Applies to aldicarb sulfoxide and aldicarb sulfone
Aldrin and dieldrin	0,00003	0,03	For combined aldrin plus dieldrin
Antimony	0,02	20	
Arsenic	0.01 (A, T)	10 (A, T)	
Atrazine and its chloro-s-triazine metabolites	0,1	100	
Barium	0,7	700	
Benzene	0,01 ^a	10 ^a	
Benzo[a]pyrene	0,0007 ^a	0,7 ^a	
Boron	2,4	2 400	
Bromate	0.01 ^a (A,T)	10 ^a (A,T)	1
Bromodichloromethane	0,06 ^a	60 ^a	
Bromoform	0,1	100	
Cadmium	0,003	3	
Carbofuran	0,007	7	
Carbon tetrachloride	0,004	4	
Chlorate	0,7 (D)	700 (D)	
Chlordane	0,000 2	0,2	
Chlorine	5 (C)	5 000 (C)	For effective disinfection, there should be a residual concentration of free chlorine of ≥ 0.5 mg/l after at least 30 min contact time at pH < 8.0. A chlorine residual should be maintained throughout the distribution system. At the point of delivery, the minimum residual concentration of free chlorine should be 0.2 mg/l.
Chlorite	0,7 (D)	700 (D)	
Chloroform	0,3	300	
Chlorotoluron	0,03	30	
Chlorpyrifos	0,03	30	
Chromium	0,05 (P)	50 (P)	For total chromium

¹ In Table 1.6, the letters in parentheses (D, C, A, T) next to certain guideline values represent specific considerations for the respective chemicals. Here's what they typically mean in WHO drinking water guidelines:

(D) - Derived: The guideline value is based on data from drinking water studies or direct exposure evidence rather than extrapolated toxicological data.

(C) - Disinfection: The guideline value is influenced by its role in water disinfection, meaning it is not just a contaminant but also a necessary component for maintaining water safety.

(A) - Analytical: The value is based on analytical limits of detection or practical quantification limits.

(T) - Toxicological: The value is primarily determined based on toxicological data, such as long-term health risks.

(P) designation typically stands for "Provisional". This means that the guideline value is temporary or subject to revision

Copper	2	2 000	Staining of laundry and sanitary ware may occur below guideline value
Cyanazine	0,0006	0,6	
2,4-D ^b	0,03	30	Applies to the free acid
2,4-DB ^c	0,09	90	
DDT ^d and metabolites	0,001	1	
Dibromoacetonitrile	0,07	70	
Dibromochloromethane	0,1	100	
1,2-Dibromo-3-chloropropane	0,001 ^a	1 ^a	
1,2-Dibromoethane	0.0004 ^a (P)	0.4 ^a (P)	
Dichloroacetate	0.05 ^a (D)	50 ^a (D)	
Dichloroacetonitrile	0,02 (P)	20 (P)	
1,2-Dichlorobenzene	1 (C)	1 000 (C)	
1,4-Dichlorobenzene	0,3 (C)	300 (C)	
1,2-Dichloroethane	0,03 ^a	30 ^a	
1,2-Dichloroethene	0,05	50	
Dichloromethane	0,02	20	
1,2-Dichloropropane	0,04 (P)	40 (P)	
1,3-Dichloropropene	0,02 ^a	20 ^a	
Dichlorprop	0,1	100	
Di(2-ethylhexyl)phthalate	0,008	8	
Dimethoate	0,006	6	
1,4-Dioxane	0,05 ^a	50 ^a	Derived using tolerable daily intake approach as well as linearized multistage modelling
Edetic acid	0,6	600	Applies to the free acid
Endrin	0,000 6	0,6	
Epichlorohydrin	0,000 4 (P)	0,4 (P)	
Ethylbenzene	0,3 (C)	300 (C)	
Fenoprop	0,009	9	
Fluoride	1,5	1 500	Volume of water consumed and intake from other sources should be considered when setting national standards
Hexachlorobutadiene	0,000 6	0,6	
Hydroxyatrazine	0,2	200	Atrazine metabolite
Isoproturon	0,009	9	
Lead	0.01 (A, T)	10 (A, T)	
Lindane	0,002	2	
MCPA ^e	0,002	2	
Mecoprop	0,01	10	
Mercury	0,006	6	For inorganic mercury
Methoxychlor	0,02	20	
Metolachlor	0,01	10	
Microcystin-LR	0,001 (P)	1 (P)	For total microcystin-LR (free plus cell-bound)
Molinate	0,006	6	
Monochloramine	3	3 000	
Monochloroacetate	0,02	20	
Nickel	0,07	70	
Nitrate (as NO ₃) ⁻	50	50 000	Short-term exposure

Nitrilotriacetic acid	0,2	200	
Nitrite (as NO ₂ ⁻)	3	3 000	Short-term exposure
N-Nitrosodimethylamine	0,000 1	0,1	
Pendimethalin	0,02	20	
Pentachlorophenol	0.009 ^a (P)	9 ^a (P)	
Selenium	0,04 (P)	40 (P)	
Simazine	0,002	2	
Sodium	50	50 000	² As sodium dichloroisocyanurate
dichloroisocyanurate	40	40 000	As cyanuric acid
2,4,5-T ^f	9	9	
Terbutylazine	7	7	
Tetrachloroethene	4	40	
Simazine	0,002	2	
Sodium	50	50 000	As sodium dichloroisocyanurate
dichloroisocyanurate	40	40 000	As cyanuric acid
Styrene	0,02 (C)	20 (C)	
2,4,5-T ^f	0,009	9	
Terbutylazine	0,007	7	
Tetrachloroethene	0,04	40	
Toluene	0,7 (C)	700 (C)	
Trichloroacetate	0,2	200	
Trichloroethene	0,02 (P)	20 (P)	
2,4,6-Trichlorophenol	0,2 ^a	200 ^a (C)	
Trifluralin	0,02	20	
Trihalomethanes			The sum of the ratio of the concentration of each to its respective guideline value should not exceed 1
Uranium	0,03 (P)	30 (P)	Only chemical aspects of uranium addressed
Vinyl chloride	0,0003 ^a	0,3 ^a	
Xylenes	0,5 (C)	500 (C)	

ANNEX 2 – Chapter 1

Minimum requirements for parameter values used to assess the quality of water intended for human consumption (EU Directive 2020/2184).

PART A - Microbiological Parameters.

Table 2.1 Microbiological Parameters.

Parameter	Parameter value	Unit of measurement	Notes
Intestinal Enterococci	0	number/100 ml	For waters packaged in bottles or containers, the unit of measurement is "number/250 ml"
Escherichia coli (E. coli)	0	number/100 ml	For waters packaged in bottles or containers, the unit of measurement is "number/250 ml"

PART B - Chemical Parameters.

Table 2.2 Chemical Parameters

Parameter	Parameter value	Unit of measurement	Notes
Acrylamide	0,1	µg/l	The parameter value of 0.10 µg/l refers to the residual monomer concentration in water calculated according to the specifications of the corresponding maximum polymer release upon contact with water.
Antimony	10	µg/l	
Arsenic	10	µg/l	
Benzene	1	µg/l	
Benzo(a)pyrene	0,01	µg/l	
Bisphenol A	2,5	µg/l	
Boron	1,5	mg/l	The parameter value of 2.4 mg/l applies where desalinated water is the main source of the supply system in question or in regions where geological conditions could cause high levels of boron in groundwater.
Bromate	10	µg/l	
Cadmium	5	µg/l	
Chlorate	0,25	mg/l	When a disinfection method that generates chlorate, particularly chlorine dioxide, is used for disinfection of water for human consumption, the parametric value of 0.70 mg/l shall be applied. Where possible, Member States shall endeavor to apply lower values without compromising disinfection. This parameter is measured only if the disinfection methods in question are used.
Chlorite	0,25	mg/l	When a disinfection method that generates chlorite, particularly chlorine dioxide, is used for disinfection of water intended for human consumption, the parameter value of 0.70 mg/l shall be applied. Where possible, Member States shall endeavor to apply lower values without compromising disinfection. This parameter is

			measured only if the disinfection methods in question are used.
Chrome	25	µg/l	The parametric value of 25 µg/l must be met no later than January 12, 2036. The parametric value for chromium until that date is 50 µg/l.
Copper	2	mg/l	
Cyanide	50	µg/l	
1,2-dichloroethane	3	µg/l	
Epichlorohydrin	0,1	µg/l	The parameter value of 0.10 µg/l refers to the residual monomer concentration in water calculated according to the specifications of the corresponding maximum polymer release upon contact with water.
Fluoride	1,5	mg/l	
Haloacetic acids (HAAs)	60	µg/l	This parameter is measured only if disinfection methods that are likely to generate haloacetic acids are used for disinfection of water for human consumption. It is the sum of the following five representative substances: monochloro-, dichloro-, and trichloro-acetic acid, mono- and dibromoacetic acid.
Lead	5	µg/l	The parametric value of 5.0 µg/l must be met no later than January 12, 2036. The parametric value for lead until that date is 10 µg/l.
			After that date, the parametric value of 5.0 µg/l must be met at least at the point of delivery of domestic distribution systems. For the purpose of Article 11(2), first subparagraph (b), the parameter value of 5.0 µg/l for tap water shall apply.
Mercury	1	µg/l	
Microcystin-LR	1	µg/l	It is necessary that this parameter be measured only in case of potential efflorescence in the spring water (increasing density of cyanobacterial cells or potential efflorescence formation).
Nickel	20	µg/l	
Nitrates	50	mg/l	Member States shall ensure that the condition: $\frac{[\text{nitrate}]}{50} + \frac{[\text{nitrite}]}{3} \leq 1$ is met, where square brackets express the concentration in mg/l for nitrate (NO ₃) and nitrite (NO ₂), and the parametric value of 0.10 mg/l for nitrite is achieved in water from treatment plants.
Nitrites	0,5	mg/l	Member States shall ensure that the condition: $\frac{[\text{nitrate}]}{50} + \frac{[\text{nitrite}]}{3} \leq 1$ is met, where square brackets express the concentration in mg/l for nitrate (NO ₃) and nitrite (NO ₂), and the parametric value of 0.10 mg/l for nitrite is achieved in water from treatment plants.

Pesticides	0,1	µg/l	By "pesticides" we mean: - organic insecticides - organic herbicides - organic fungicides - organic nematicides - organic acaricides - organic algaecides - organic rodenticides - organic slimicides - Related products (among other growth regulators) and its metabolites within the meaning of Article 3(32) of Regulation (EC) No 1107/2009 of the European Parliament and of the Council (1) considered relevant to water intended for human consumption. A pesticide metabolite is considered relevant for water intended for human consumption if there are reasons to believe that it possesses intrinsic properties, comparable to those of the parent substance, in terms of target pesticide activity or that it generates (itself or its transformation products) a health risk to consumers.
			The value of to each individual parameter of 0.10 µg/l is applied antiparasitic. In the case of aldrin, dieldrin, heptachlor and heptachlor epoxide, the parameter value is 0.030 µg/l.
			Member states shall define an indicative value to manage the presence of non-significant metabolites of pesticides in water intended for human consumption. Monitoring is required only for pesticides that are likely to be present in a given supply. Based on data reported by member states, the Commission may establish a database of pesticides and their metabolites taking into account their possible presence in water intended for human consumption.
Pesticides - Total	0,5	µg/l	"Pesticides - total" means the sum of all individual pesticides - specified above - detected and quantified in the monitoring procedure.
PFAS Total	0,5	µg/l	"PFAS - total" means the totality of per- and polyfluoro alkyl substances. This parameter value applies only after technical guidelines for monitoring this parameter have been developed in accordance with Article 13(7). Member States may then decide to use one or both of the parameters "PFAS - total" or "Sum of PFAS."
Sum of PFAS	0,1	µg/l	"Sum of PFAS" means the sum of all per- and polyfluoroalkyl substances deemed to be of concern with respect to water for human consumption in Annex III, Part B, point 3. It is a subset of "PFAS - total" substances containing either a perfluoroalkyl group with three or more carbon atoms (i.e. -C _n F _{2n} -, n ≥ 3) or a perfluoroalkyl group with two or more carbon atoms (i.e. -C _n F _{2n} OC _m F ₂ m-, n and m ≥ 1).
Polycyclic aromatic hydrocarbons	0,1	µg/l	Sum of the concentrations of the following specific compounds: benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(ghi)perylene and indeno(1,2,3-cd)pyrene.
Selenium	20	µg/l	The parameter value of 30 µg/l applies for regions where geological conditions could result in high levels of selenium in groundwater.

Tetrachloroethylene and trichloroethylene	10	µg/l	Sum of the concentrations of these two parameters.
Trihalomethanes - Total	100	µg/l	Where possible, member states shall endeavor to apply lower parameter values without compromising disinfection. It is the sum of the concentrations of the following specific compounds: chloroform, bromoform, dibromochloromethane, and bromodichloromethane.
Uranium	30	µg/l	
Vinyl chloride	0,5	µg/l	The parameter value of 0.50 µg/l refers to the residual monomer concentration in water calculated according to the specifications of the corresponding maximum polymer release upon contact with water.

- (1) Regulation (EC) No 1107/2009 of the European Parliament and of the Council of October 21, 2009 concerning the placing of plant protection products on the market and repealing Council Directives 79/117/EEC and 91/414/EEC (OJ L 309, 24.11.2009, p. 1).

PART C - Indicator parameters

Table 2.3 Indicator parameters

Parameter	Parameter value	Unit of measurement	Notes
Aluminum	200	µg/l	
Ammonium	0,5	mg/l	
Chloride	250	mg/l	Water must not be corrosive.
Clostridium perfringens spores included	0	Number/100 ml	This parameter should be measured if indicated as appropriate by the risk assessment.
Color	Acceptable to consumers and without abnormal variations		
Conductivity	2 500	µS cm ⁻¹ at 20 °C	The water must not be aggressive.
Hydrogen ion concentration	≥ 6,5 e ≤ 9,5	pH unit	The water must not be aggressive. For non-sparkling waters packaged in bottles or containers, the minimum value may be reduced to 4.5 pH units. For waters packaged in bottles or containers that are naturally rich in carbon dioxide or artificially enriched, the minimum value may be lower
Iron	200	µg/l	
Manganese	50	µg/l	
Smell	Acceptable to consumers and without abnormal variations		
Oxidability	5,0	mg/l O ₂	If analyzing the TOC parameter, it is not necessary to measure this value.
Sulfate	250	mg/l	Water must not be corrosive.
Sodium	200	mg/l	
Taste	Acceptable to consumers and without abnormal variations		

Colony counting at 22 °C	Without abnormal variations		
Coliform bacteria	0	Number/100 ml	For water packaged in bottles or containers, the unit of measurement is "number/250 ml."
Total organic carbon (TOC)	Without abnormal variations		It is not necessary to measure this parameter for water supplies of less than 10 000 m ³ per day.
Turbidity	Acceptable to consumers and without abnormal variations		

Water must not be aggressive or corrosive. This particularly applies to water undergoing treatment (demineralization, softening, membrane treatment, reverse osmosis, etc.).

If water for human consumption is derived from a treatment that demineralizes or significantly softens it, calcium and magnesium salts may be added to correct the hardness of the water in order to reduce the potential negative impact on health, as well as in order to reduce the corrosiveness and aggressiveness of the water, and to improve its taste. Minimum concentrations of calcium and magnesium or total dissolved solids in softened or demineralized water could be defined considering the characteristics of the water subjected to these processes.

PART D - Relevant parameters for risk assessment of domestic distribution systems

Table 2.4 Relevant parameters for risk assessment of domestic distribution systems

Parameter	Parameter value	Unit of measurement	Notes
Legionella	< 1 000	CFU/l	This parameter value is defined for the purposes of Articles 10 and 14. Actions under these articles could also be considered below the parameter value, for example, in cases of infections and outbreaks. In such cases, the source of infection should be confirmed and the species of Legionella identified
Lead	10	µg/l	This parameter value is defined for the purposes of Articles 10 and 14. Member States should strive for a lower attainment value of 5.0 µg/l at the latest 15 years after January 12, 2036.

* In cases where the disinfection method used does not generate chlorate, the parameter value of 0.25 mg/l must be met no later than January 12, 2026. In cases where a disinfection method that generates chlorate, particularly chlorine dioxide, is used for disinfection, the parameter value of 0.70 mg/l shall be applied. Where possible, water and drinking water managers shall endeavor to apply lower values without compromising disinfection. This parameter is measured only if these disinfection methods are used.

** In cases where the disinfection method used does not generate chlorite, the parameter value of 0.25 mg/l must be met no later than January 12, 2026; until January 11, 2026, the chlorite parameter value is 0.7 mg/l. In cases where a disinfection method that generates chlorite, especially chlorine dioxide, is used for disinfection, the parameter value of 0.70 mg/l shall apply. Where possible, water and drinking water managers shall endeavor to apply lower values without compromising disinfection. This parameter is measured only if disinfection methods in general are used.

*** The parametric value of chromium must be met no later than January 12, 2026. The parameter value of chromium until January 11, 2026 is 50 mg/l.

**** The parametric value of 5.0 mg/l must be met by January 12, 2036, at the latest. The parameter value for lead until that date is 10 mg/l. After that date, the parameter value of 5.0 mg/l must be met at the point of delivery. I

*in cases where the disinfection method used does not generate chlorite, the parameter value of 0.25 mg/l must be met no later than January 12, 2026; until January 11, 2026, the chlorite parameter value is 0.7 mg/l. In cases where a disinfection method generating chlorite, particularly chlorine dioxide, is used, the parameter value of 0.70 mg/l applies. Whenever possible, water suppliers are encouraged to apply lower values without compromising disinfection. This parameter is measured only if the specific disinfection methods are used.

The parameter value for chromium must be met no later than January 12, 2026. The chromium parameter value until January 11, 2026, is 50 µg/l.

*The parameter value for lead, which is 5.0 µg/l, must be met no later than January 12, 2036. The lead parameter value until that date is 10 µg/l. After that date, the 5.0 µg/l parameter value must be met at the point of delivery.

ANNEX 3 - Chapter 1

Table with the parameters established by the regulations, and their limits, with analysis of the concentrations detected during sampling at the Mompiano spring (2014-2023). The new parameters introduced by Legislative Decree 18/2023 compared to the old Legislative Decree 31/2001 are written in red color.

Table 3.1 Table with the parameters established by the regulations, and their limits, with analysis of the concentrations detected during sampling at the Mompiano spring (2014-2023)

PART A - Microbiological Parameters.	Number of detections	Minimum	Maximum	Median	25%	75%	Limit value Legislative Decree 31/2001	Limit value Legislative Decree 18/2023.	Unit of measurement
Intestinal Enterococci	31	0	100	4	3	8	0	0	number/100 ml
Escherichia coli (E. coli)	31	0	83	5	3	17	0	0	number/100 ml

PART B - Chemical Parameters.	Number of detections	Minimum	Maximum	Median	25%	75%	Limit value Legislative Decree 31/2001	Limit value Legislative Decree 18/2023.	Unit of measurement
Acrylamide	-	-	-	-	-	-	0,1	0,1	µg/l
Antimony	21	0,28	< 1,2	< 1	< 1	< 1,2	5	10	µg/l
Arsenic	30	0,4	2	< 1	< 1	< 1	10	10	µg/l
Benzene	20	0	< 0,2	0,15	< 0,1	< 0,2	1	1	µg/l
Benzo(a)pyrene	21	0	< 0,003	< 0,003	< 0,003	< 0,003	0,01	0,01	µg/l
Bisphenol A	1	< 0,1	< 0,1	< 0,1	< 0,1	< 0,1	-	2,5	µg/l
Boron	21	0,00013	< 0,1	0,0706	< 0,05	0,1	1	1,5	mg/l
Bromate	-	-	-	-	-	-	10	10	µg/l
Cadmium	28	0	< 1	< 0,5	< 0,5	< 0,5	5	5	µg/l
Chlorate	-	-	-	-	-	-	-	0,7*	mg/l
Chlorite	25	< 10	86	< 50	< 50	< 50	200	250**	µg/l
Chrome	178	< 2	13	< 5	< 5	< 5	50	25***	µg/l
Copper	21	0	< 0,1	< 0,01	< 0,005	< 0,1	1	2	mg/l
Cyanide	20	0	< 5	< 5	< 5	< 5	50	50	µg/l

1,2-dichloroethane	24	0	1	< 0,2	< 0,2	0,3	3	3	µg/l
Epichlorohydrin	-	-	-	-	-	-	0,1	0,1	µg/l
Fluoride	22	0,05	0,2	< 0,1	< 0,1	< 0,1	1,5	1,5	mg/l
Haloacetic acids (HAAs)	-	-	-	-	-	-	-	60	µg/l
Lead	28	0,11	10	< 2	< 1	< 2	10	5****	µg/l
Mercury	21	0	< 0,2	< 0,1	< 0,1	< 0,2	1	1	µg/l
Microcystin-LR	-	-	-	-	-	-	-	1	µg/l
Nickel	21	1,71	3,3	< 2	< 2	< 2	20	20	µg/l
Nitrates	52	14	27,1	18,6	16,45	21,2	50	50	mg/l
Nitrites	1	0,02	0,02	0,02	0,02	0,02	0,5	0,5	mg/l
Pesticides	-	-	-	-	-	-	0,1	0,1	µg/l
Pesticides - Total	20	0	< 0,05	< 0,05	< 0,05	< 0,05	0,5	0,5	µg/l
PFAS Total	-	-	-	-	-	-	-	0,5	µg/l
Sum of PFAS	2	< 0,005	< 0,005	< 0,005	< 0,005	< 0,005	-	0,1	µg/l
Polycyclic aromatic hydrocarbons	21	0	< 0,03	< 0,03	< 0,01	< 0,03	0,1	0,1	µg/l
Selenium	21	< 0,5	< 1	< 1	< 1	< 1	10	20	µg/l
Tetrachloroethylene	26	1	3,9	1,5	1,1775	1,95	10	10	µg/l
Trichloroethylene	26	0	< 0,5	< 0,2	< 0,1	< 0,2	10	10	µg/l
Trihalomethanes - Total	25	0	< 0,5	< 0,1	< 0,1	< 0,5	30	30	µg/l
Uranium	1	< 3	< 3	< 3	< 3	< 3	-	30	µg/l
Vanadium	21	1,55	< 5	< 5	< 5	< 5	50	140	µg/l
Vinyl chloride	10	< 0,1	< 0,1	< 0,1	< 0,1	< 0,1	0,5	0,5	µg/l

PART C - Indicator parameters	Number of detections	Minimum	Maximum	Median	25%	75%	Limit value Legislative Decree 31/2001	Limit value Legislative Decree 18/2023.	Unit of measurement
Aluminum	22	0	59	< 20	13,175	31,975	200	200	µg/l
Ammonium	30	0	< 0,4	< 0,05	< 0,05	< 0,05	0,5	0,5	mg/l
Chloride	51	8	14	10	9,2	11,75	250	250	mg/l

Clostridium perfringens (including spores)	15	0	15	1	1	3,5	0	0	Number/100 ml
Color	19	0	1	0	0	0	Acceptable to consumers and without abnormal variations	Acceptable to consumers and without abnormal variations	
Conductivity	51	490	633	576	566	589,5	2500	2 500	μS cm ⁻¹ at 20 °C
Hydrogen ion concentration	-	-	-	-	-	-	≥ 6,5 e ≤ 9,5	≥ 6,5 e ≤ 9,5	pH unit
Iron	33	6,9	103	< 20	11,5	26	200	200	μg/l
Manganese	30	0,13	8,7	2,16	< 2	< 5	50	50	μg/l
Smell	2	0	0	0	0	0	Acceptable to consumers and without abnormal variations	Acceptable to consumers and without abnormal variations	
Oxidability	21	0	1,7	0,6	0,32	0,8	5	5,0	mg/l O ₂
Sulfate	51	11	20,4	15,3	14	17	250	250	mg/l
Sodium	52	3,9	43	7,2	6,675	7,925	200	200	mg/l
Taste	2	0	0	0	0	0	Acceptable to consumers and without abnormal variations	Acceptable to consumers and without abnormal variations	
Colony counting at 22 °C	32	1	448	55	32,75	103,25	Without abnormal variations	Without abnormal variations	
Coliform bacteria	32	0	664	52,5	17,5	94	0	0	Number/100 ml
Total organic carbon (TOC)	12	0,304	3,6	0,584	0,5045	0,9515	Without abnormal variations	Without abnormal variations	mg/l

Turbidity	21	0,1	3,7	0,55	0,4	0,8	Acceptable to consumers and without abnormal variations	Acceptable to consumers and without abnormal variations	

PART D	Number of detections	Minimum	Maximum	Median	25%	75%	Limit value Legislative Decree 31/2001	Limit value Legislative Decree 18/2023.	Unit of measurement
Legionella	-	-	-	-	-	-	-	< 1 000	CFU/l
Lead	-	-	-	-	-	-	-	5*****	µg/l

* In cases where the disinfection method used does not generate chlorate, the parameter value of 0.25 mg/l must be met no later than January 12, 2026. In cases where a disinfection method that generates chlorate, particularly chlorine dioxide, is used for disinfection, the parameter value of 0.70 mg/l shall be applied. Where possible, water and drinking water managers shall endeavor to apply lower values without compromising disinfection. This parameter is measured only if these disinfection methods are used.

** In cases where the disinfection method used does not generate chlorite, the parameter value of 0.25 mg/l must be met no later than January 12, 2026; until January 11, 2026, the chlorite parameter value is 0.7 mg/l. In cases where a disinfection method that generates chlorite, especially chlorine dioxide, is used for disinfection, the parameter value of 0.70 mg/l shall apply. Where possible, water and drinking water managers shall endeavor to apply lower values without compromising disinfection. This parameter is measured only if disinfection methods in general are used.

*** The parametric value of chromium must be met no later than January 12, 2026. The parameter value of chromium until January 11, 2026 is 50 mg/l.

**** The parametric value of 5.0 mg/l must be met by January 12, 2036 at the latest. The parameter value for lead until that date is 10 mg/l. After that date, the parameter value of 5.0 mg/l must be met at the point of delivery. I

*in cases where the disinfection method used does not generate chlorite, the parameter value of 0.25 mg/l must be met no later than January 12, 2026; until January 11, 2026, the chlorite parameter value is 0.7 mg/l. In cases where a disinfection method generating chlorite, particularly chlorine dioxide, is used, the parameter value of 0.70 mg/l applies. Whenever possible, water suppliers are encouraged to apply lower values without compromising disinfection. This parameter is measured only if the specific disinfection methods are used.

The parameter value for chromium must be met no later than January 12, 2026. The chromium parameter value until January 11, 2026, is 50 µg/l.

*The parameter value for lead, which is 5.0 µg/l, must be met no later than January 12, 2036. The lead parameter value until that date is 10 µg/l. After that date, the 5.0 µg/l parameter value must be met at the point of delivery.

ANNEX 4 – Chapter 1

Modification of NOM bulk and fractional characteristics through various radical-driven advanced oxidation processes (AOPs).

Table 4.1: Modification of NOM bulk and fractional characteristics through various radical-driven advanced oxidation processes (AOPs). (Li et al. 2023)

Advanced oxidation processes (AOPs).	Experimental Conditions	Alteration of NOM Properties	Reference
UV/H ₂ O ₂	[DOC] = 2.0 mgC/L, [TOC] = 2.12 mgC/L, [H ₂ O ₂] = 23 mg/L, UV = 1140 mJ/cm ²	• UV254 was decreased by 60% • TOC was reduced by 23% • The fractions of molecular weight of >900 Da and 600–900 Da were reduced by 85 and 100%, respectively	Lamsal et al. (2011)
UV/H ₂ O ₂	[DOC] = 4.26 mg/L, [H ₂ O ₂] = 1–10 mM, UV dose = 30,000 mJ, pH = 6	• The mineralization of NOM increased from 8.6% to 20.5% as H₂O₂ concentration increased from 1 mM to 10 mM • The fractions of biopolymer, humic substances, and low molecular weight neutrals were decreased from 0.1% to 0%, 40.6%–37.5%, and 25.2%–22%, respectively, while that of building blocks and low molecular weight acids were increased from 32% to 26.6% and from 1.7% to 3.8%, respectively • Three of the five fluorescent components (i.e., C2, C4, and C5) given by the parallel factor analysis (PARAFAC) were decreased, with higher removal efficiency at higher H₂O₂ dosage, while C1 was first increased and then decreased as the photolysis time increased and C3 reached a plateau after the initial rapid decrease	Ahn et al. (2017)
UV/H ₂ O ₂	[DOC] = 2.3 mgC/L, UV intensity = 3.3 W, [H ₂ O ₂] = 8 mg/L, irradiation time = 1050 min, pH = 7.6	• DOC was reduced by 26.2%	Kleiser and Frimmel (2000)
	450 W high pressure mercury vapor lamp, irradiation of 60 min, Aldrich humic acid (HA) or raw water from Tai-Lake, China	UV254 was reduced by 53% and 85%, respectively, for HA and raw water from Tai-Lake after 30 min • The very hydrophobic acid fractions were rapidly decreased	Lin and Wang (2001)

Advanced oxidation processes (AOPs).	Experimental Conditions	Alteration of NOM Properties	Reference
	Different water samples with TOC ranging from 1.45 to 10 mgC/L, [H ₂ O ₂] = 10 mg/L, UV fluence = 2000 mJ/cm ² , pH = 7.0	A SUVA ₂₅₄ reduction of 19–35% • TOC was reduced by 7.6–25% • Fractions with molecular weight >500 Da were decreased by 27–49% at UV fluence of 2000 mJ/cm	Barzi et al. (2012)
UV/O ₃	[DOC] = 2.0 mgC/L, [TOC] = 2.12 mgC/L, [O ₃] = 4.04 mg/L, UV = 1140 mJ/cm ²	• UV₂₅₄ was decreased by 88% • TOC was decreased by 31% • Fractions of molecular weight >900 Da were 100% reduced	Lamsal et al. (2011)
UV/O ₃	[DOM] = 3.5 mgC/L, [H ₂ O ₂] = 0–20 mg/L, UV fluence from 0 to 1400 mJ/cm ² , pH = 7.0	• Intensity of the three fluorescent components (C1–C3) decreased at H₂O₂ dosage of 20 mg/L • UV₂₅₄ decreased by 6.7% with UV exposure from 0 to 1400 mJ/cm² • <12.9% DOC was removed at UV fluence of 1400 mJ/cm² • TOC removal was 10% UV₂₅₄ was decreased by 6.7% with the increase of UV exposure from 0 to 1400 mJ/cm² About <12.9% of DOC was removed at UV fluence of 1400 mJ/cm² with H₂O₂ dosage of 20 mg/L UV₂₅₄ was decreased from 0.124 to 0.042 DOC was decreased from 2.89 mgC/L to 1.63 mgC/L UV₂₅₄ was reduced by 35–55% TOC was removed by 10%	Zhang et al. (2018) Hua et al (2019)
SO ₄ ²⁻ -involved AOP (UV/persulfate)	[NOM] = 3 mgC/L, [H₂O₂] = 0.2 mM, pH = 7.0, irradiation time = 20 min Three NOM fractions with DOC of 3.89 mgC/L, [H₂O₂] = 1 mM, UV intensity = 0.9 mW/cm², pH = 5 or 4.65, irradiation = 30 min	• Mineralization of NOM increased from 17.9% to 83.3% with PS concentration increase • Biopolymer and humic substances decreased; building blocks and low molecular weight acids increased • Fluorescent components (C1–C5) decreased by 43.7–99.9%	Ahn et al. (2017)

Advanced oxidation processes (AOPs).	Experimental Conditions	Alteration of NOM Properties	Reference
	[DOC] = 4.26 mg/L, [PS] = 1–10 mM, UV dose = 30,000 mJ, pH = 6		
SO ₄ ²⁻ -involved AOP (UV/persulfate)	[NOM] = 3 mgC/L, [PS] = 0.2 mM, photon flux = 3.78 μ E/L/s, irradiation time = 0–20 min, pH = 7.0 Three NOM fractions with DOC of 3.89 mgC/L, [PS] = 1 mM, UV intensity = 0.9 mW/cm ² , pH = 5 or 4.65, irradiation = 30 min	• UV254 decreased from 0.124 to 0.070 and 0.034 after 10 and 20 min irradiation • DOC decreased from 2.89 to 2.30 and 1.83 mgC/L after 10 and 20 min irradiation • UV254 reduced by 55–75% • TOC removal was 35–48%	Hua et al. (2019), Zhang et al. (2021)
UV/persulfate (PS)	[DOC] = 2.5–2.7 mg/L, [PS] = 0.5 mM, UV dose = 585 mJ/cm ²	• DOC was reduced by 11–17% • Fractions of molecular weight >10 kDa, 5–10 kDa, and 1–5 kDa were decreased from 15%, 43%, and 26% to 0, 19%, and 23%, respectively • Fractions of 0.5–1 kDa and <0.5 kDa were increased from 11% to 33% and 25%, respectively	Chu et al. (2015)
Reactive Chlorine Species (RCS-involved AOP (UV/chlorine)	[DOC] = 3 mgC/L, [HOCl] = 200 μ M, average UV irradiance = 227.54 μ W/cm ² , irradiation wavelength = 254, 275, and 310 nm, pH = 8.0	• UV254 was decreased by 74.5%, 87.3%, and 60.9% at 254, 275, and 310 nm, respectively, at UV fluence of 1200 mJ/cm² - DOC was decreased by 41.3%, 54.9%, and 27.8%, respectively, at 254, 275, and 310 nm at UV fluence of 1200 mJ/cm²	Gao et al. (2019)
	[DOC] = 3 mgC/L, [HOCl] = 4 mg/L as Cl ₂ , UV fluence was 8.59 $\times$ 10 ³ , 6.24 $\times$ 10 ³ , and 6.24 $\times$ 10 ⁴ mJ/cm ² at irradiation wavelength of 254, 311, and 365 nm, pH = 6.5 or 8.5 [NOM] = 2 mg/L, [chlorine] = 100 μ M as Cl ₂ , pH = 7.5, UV fluence = 600 mJ/cm ²	SUV254 at pH 6.5 was decreased from 2.01 to 1.78, 1.44, and 1.44 L/mgC/m at 254, 311, and 365 nm, respectively • SUV254 at pH 8.5 was decreased from 2.00 to 1.73, 1.44, and 1.58 L/mgC/m, respectively, at 254, 311, and 365 nm UV254 was decreased by 46.7% DOC was reduced by 18.6% and 15.1%, respectively, for SRNOM and NRNOM • UV254 and fluorescence intensity of SRNOM were decreased by 77.5% and 76.4%, respectively, while those for NRNOM were decreased by 78.6% and	Bulman and Remucal (2020) Li et al (2022b) Wang et al (2017) Cheng et al 2020

Advanced oxidation processes (AOPs).	Experimental Conditions	Alteration of NOM Properties	Reference
	[SRNOM] or [NRNOM] = 10 mgC/L, [HOCl] = 50 mg/L, UV irradiance = 1.80 mW/cm², irradiation time = 30 min, pH = 7.0 (SR: Suwannee River; NR: Nordic Reservoir) [SRNOM] = 3 mgC/L, HOCl/SRNOM mass ratio = 0–2.67, UV irradiance = 4.0 mW/cm², pH = 6.0 or 8.0	80.8%, respectively Wang et al. (2017) [SRNOM] = 3 mgC/L, HOCl/SRNOM mass ratio = 0–2.67, UV irradiance = 4.0 mW/cm ² , pH = 6.0 or 8.0 • UV254 was decreased by 27.9% at pH 6.0 and 50.0% at pH 8.0 at a HOCl/SRNOM mass ratio of 2.67	

Table 2. 2 Impact of Pre-Oxidation by SO₄^{•-}-Involved AOPs on Formation of DBPs in Post-Chlorination

AOPs	Experimental Condition	Impact on DBP Formation in Post-Chlorination	Ref.
UV/PS	Water samples collected from three Chinese drinking water treatment plants with DOC of 2.3, 2.5, and 2.7 mg/L, respectively; [persulfate] = 0–5 mM, UV dose of 585 mJ/cm ² , chlorination for 24 h with residual chlorine of 1 ± 0.5 mg/L, pH = 7.5	• UV/PS reduced the formation of HAcAm by 79.4%, 91.1%, and 87.2%, respectively, for the water samples. • UV/PS reduced the BIFs of HAcAms with increasing PS doses from 0.05 to 5 mM. UV/PS decreased the formation of DCAN, TCAM, DCNM, TCNM, DCAcAm, and TCACAm by 60–100% for raw water with high dissolved organic nitrogen	Chu et al. (2015)
	[DOC] = 3 mg/L, [PS] = 200 μM, photon flux = 3.78 E/L/s, irradiation for 20 min, [chlorine] = 15 mg/L, chlorination for 24 h with residual chlorine > 1 mg/L, temperature at 25°C	The yields of TCM and DCAN were decreased by 50% and 54%, respectively, with UV/PS pre-oxidation, and the yields further decreased with increasing irradiation time to 30 min • The yields of CH, 1,1,1-TCP and TCNM were increased by 217%, 136%, and 153%, respectively, with UV/PS pre-oxidation, while they were slightly decreased as irradiation time prolonged to 30 min • The formation of TCM, CH, 1,1,1-TCP, DCAN and TCNM was increased by 10%, 15%, 27%, 3%, and 5%, respectively, in the presence of 1 mM chloride • The total formation of THMs and HANs was increased by 46% and 115%, respectively, in the presence of 5 μM bromide • The yields of TCM, CH, DCAN, and TCNM were increased by 37%, 3%, 52%, and 34%, while that of 1,1,1-TCP decreased by 6% in the presence of 0.5 mM bicarbonate	Hua et al. (2019)
	[TOC] = 3 mg/L, [PS] = 30 μM, UV irradiation intensity of	The formation of formaldehyde, acetaldehyde and acetone was increased from n.d., 1.32 μM,	Xie et al. (2015)

	3.3 W for 10 min, [chlorine] = 15 mg/L, chlorination for 72 h at pH 7.0, temperature at 25 ± 1 °C	and n.d. to 0.65, 2.14, and 0.21 µM • Formation of TCM, HAAs, and DCP was increased appreciably, while the formation of N-DBPs decreased slightly • The variation of DBPs investigated was less than 25% at three different pHs as pH 4.0, 7.0, and 9.0	
Pre oxidation by OH [*] - based AOPs on formation of DBPS in post – chlorination.			
			Ref
UV/H ₂ O ₂	[DOC] = 2.0mgC/L, [TOC] = 2.12 mgC/L, [H₂O₂] = 23 mg/L, UV = 1140 mJ/ cm² [TOC] = 0.86 or 1.51 mg/L for two water samples, [H₂O₂] = 5 or 10 mg/L, UV incident irradiance of 2.0 mW/cm², irradiation for 10s before chlorine, chlorination for 24 h to maintain a residual chlorine of 1 mg/L, temperature at 22 ± 1 °C [DOC] = 2.2 or 2.3 mg/L for two water samples (ZQ and MH water), [H₂O₂] = 5 mg/L, UV incident irradiation intensities of 585 mJ/cm², chlorination for 24 h to maintain a residual chlorine of 1 ± 0.5 mg/L, temperature at 25 ± 0.5 °C	THMFP and HAAFP were reduced by 77 and 62%, respectively Pre-oxidation by low pressure UV/H₂O₂ increased the total THMs formation by 103% and 143% for two raw waters, while those were increased by 9 µg/mgC and 13 µg/mgC by medium pressure UV/H₂O₂ Pre-oxidation by UV/H₂O₂ increased the formation of carboneous DBPs (C-DBPs), i.e., THM formation increased by 49.5%, THMs formation by 55.5% for ZQ water. HAA and haloacetaldehydes (HAL) formation in ZQ water also increased after UV/H₂O₂ preoxidation • Pre-oxidation by UV/H₂O₂ decreased the formation of nitrogenous DBPs (N-DBPs), i.e., HAN decreased by 70% and HNMs by 80.6% for ZQ water, while HNMs from MH water decreased by 84.3% • UV/H₂O₂ pre-oxidation decreased BSFs of THMs and DHAAs in ZQ water, while it increased those of THMs and HAAs in MH water	Lamsal et al (2011) Dotosn et al (2010) Ding et al (2019)
	DOC = 3 mg/L, [H ₂ O ₂] = 200 µM, photon flux = 3.78 µE/L/s, [chlorine] = 15 mg/L, chlorination for 24 h with residual chlorine >1 mg/L, temperature at 25 °C	• The yields of trichloromethane (TCM) and dichloroacetoneitrile (DCAN) were decreased by 40% and 54%, respectively, with UV/H₂O₂ pre-oxidation, while those of chloral hydrate (CH), 1,1,1-trichloropropane (TCP) and TCNM (trichloronitromethane) were increased by 527%, 117%, and 350%, respectively, under the same conditions	Hua et al 2019
	[TOC] = 3 mg/L, [H ₂ O ₂] = 30 µM, UV irradiation tensity of 3.3 W for 10 min, [chlorine] = 15 mg/L, chlorination for 72 h at pH 7.0, temperature at 25 ± 1 °C	UV/H ₂ O ₂ pre-oxidation increased the formation of all the DBPs investigated, especially for HALs, HKs, and N-DBPs. The formation of dichloroacetaldehyde, CH, dichlor opropane (DCP), TCP, DCAN, and TCNM was increased by 127%, 63%, 796%, 122%, 219%, and 138%	Xie et al 2015
	[DOC] = 2–3 mg/L, UV contact time 60 min, [H ₂ O ₂] = 0.01% in volume, [chlorine] = 100 mg/L	[DOC] = 2–3 mg/L, UV contact time 60 min, [H ₂ O ₂] = 0.01% in volume, [chlorine] = 100 mg/L	Linand Wang (2011)
	DOC ranging between 2.3 and 2.7 mg/L for filtered water samples from three drinking water treatment plants (MH, ZA, and SY), [H ₂ O ₂] = 0–50 mg/ L, UV	HAcAms formation decreased with an increase in UV dose at a specific H ₂ O ₂ dosage or with increasing H ₂ O ₂ dosage (0–20 mg/L) at a specific UV dose, while it decreased at high H ₂ O ₂ doses (20–50 mg/L) • The formation of DCAN, TCAN,	Chu et al 2014

	irradiation for 30 min to achieve six different UV doses from 0 to 585 mJ/ cm ² , chlorination for 24 h at pH 7.5 to obtain chlorine residual of 1 ± 0.5 mg/L, temperature at 25 ± 1 °C	DCNM, TCNM, dichloroacetamide (DCAcAm), and trichloroacetamide (TCAcAm) were reduced by 50–92% after UV/H ₂ O ₂ pre-oxidation of ZQ filtered water	
		THMs formation potential increased by 41% after irradiation of 180 min	Kleiser and Frimmel 2000
	[DOC] = 2.3 mg/L, [H ₂ O ₂] = 8 mg/L, UV irradiation intensity of 3.3 W, [chlorine] = 10 mg/L, chlorination for 48 h at pH 7.6 • THMs formation potential increased by 41% after irradiation of 180 min (Kleiser and Frimmel, 2000) [DOC] = 3.5 mg/L, [Br ⁻] = [I ⁻] = 10 µM, [H ₂ O ₂] = 0–2	UV/H ₂ O ₂ pre-oxidation enhanced the formation of THMs, while it decreased iodinated THMs (I-THMs) by 23% (UV dose of 460 mJ/cm ² and 20 mg/L)	Zang et al (2018)

Table 4.2 Guidelines to Select Mitigation Solutions for Controlling DBPs regulated by the EU Directive 2020/2184 at WTPs

DBPs	Causes of generation	Mitigation solutions
All regulated	Disinfectant dose, type, and point of addition	- Move the point of disinfection downstream. - Lower disinfectant dose. - Avoid/minimize intermediate disinfection. - Use two or more different disinfectants/oxidants (e.g., substitute chlorine as a preoxidant with alternative oxidants; use an alternative disinfectant for final disinfection).
THMs	Chlorination and related operating conditions	- Move the point of disinfection downstream. - Lower chlorine dose. - Avoid/minimize intermediate chlorination. - Use two or more different disinfectants/oxidants (e.g., substitute chlorine as a preoxidant with alternative oxidants; use an alternative disinfectant for final disinfection).
	High levels of precursors in water	- Add a preoxidation process with ClO₂, O₃, Fe(VI), or Mn(VII). - Promote organic precursor removal via enhanced coagulation/flocculation processes, PAC/GAC adsorption, and O₃/BAC. - Enhance the removal of inorganic precursors (e.g., bromide) by high-pressure membranes (RO, NF, EDR, etc.) or ion exchange if economically feasible.
	Others/general	- Lower pH to slow the THMs formation. - Remove THMs by adsorption, even though low effective.

		- Remove THMs by aeration, although nonvolatile DBPs will remain in solution.
HAAs	High dose of disinfectant	- Move the point of disinfection downstream. - Lower chlorine dose. - Avoid/minimize intermediate chlorination. - Use two or more different disinfectants/oxidants (e.g., substitute chlorine as a preoxidant with alternative oxidants; use an alternative disinfectant for final disinfection).
	High levels of precursors in water	- Advanced removal of organic precursors by selected preoxidation, enhanced coagulation, adsorption on PAC/GAC, O₃/BAC. - Enhance the removal of inorganic precursors (e.g., bromide) by high-pressure membrane (EDR, RO, NF, etc.) or ion exchange if economically feasible. - Use two or more different disinfectants/oxidation
Bromate	O ₃ doses (in high brominated waters)	- Reduce HAAs by biological filtration. - Optimize O₃ dosing and contact time. - Add ammonia or H₂O₂ as inhibitors but pre-test is strongly advised. - Lower pH may decrease bromate formation but pre-test is strongly advised. - Implement membrane technologies (NF, RO, EDR, etc.) to remove BrO₃⁻, if economically feasible.
Chlorite	ClO ₂ dose	- Lowering the ClO₂ dose through improvement of water quality (e.g., removal of NOM before adding ClO₂, even though ClO₂ is often used as a preoxidant). - Optimize ClO₂ dosing.
	Others/general	- Removal of ClO₂⁻ via reduction by i) addition of reducing compounds, such as sulfur dioxide and sodium sulfite, ferrous chloride, and ferrous sulfate; ii) addition of powdered (PAC). - Combine the use of ClO₂ with O₃ or free Cl₂, but ClO₃⁻ will be formed. - Removal of ClO₂⁻ via reduction by GAC filtration at low pH, high EBCT (>15 min), and mesoporous mineral-based GAC.
Chlorate	ClO ₂ dose	- Check the chlorite impurities in the stock solution of sodium hypochlorite. - Lowering the ClO₂ dose through improvement of water quality (e.g., removal of NOM before adding ClO₂, even though ClO₂ is often used as a preoxidant). - Optimize ClO₂ dosing.

Table 4.3 Review some research Climate change effect on water quality

Impacts on Water Sources	Water Quality Parameters	Methods	Key Findings	Authors
Enhancing climate adaptation capacity for drinking water treatment	pH, salinity, and treatment efficiency	Infrastructure assessments, adaptation strategy modeling	Improving adaptation strategies can enhance drinking water safety	(Levine et al., 2016)

Observed changes in flow regimes in the Mekong River basin	Flow variability, sediment load	Hydrological modeling and flow analysis	Flow changes significantly impact sedimentation and water availability	(D. Li et al., 2017)
Role of UV-based advanced oxidation processes on NOM alteration	Natural organic matter (NOM), disinfection by-products (DBPs)	Laboratory experiments on NOM and DBPs	UV-based treatments can reduce NOM but may influence DBP formation	(R. Li & Merchant, 2013)
Evaluation of water safety plan implementation at provincial water utilities in Vietnam	Pathogen levels, residual chlorine, turbidity	Field surveys, implementation case studies	Implementing safety plans improves resilience against climate-induced risks	(V.-A. Nguyen et al., 2023)
Climate change impacts on water salinity and health	Salinity, health-related indicators	Health impact assessments, water salinity modeling	Increased salinity poses health risks, particularly in coastal regions	(Vineis et al., 2011)
Impact of climate change on stream flow and water quality in a drinking water source area	Streamflow rates, nutrient concentrations	Watershed and water quality modeling	Climate change alters streamflow and nutrient dynamics, affecting drinking water quality	(X. Wang et al., 2018b)

ANNEX 5: QUESTIONNAIRE

Put 1. Data related to the contact person		
Name of the contact person		
Contact persons availability		
Name of workplace and water supply unit		
2. Drinking water supply area		
No. of operated drinking water treatment plants		
No. of residents served		
No. of settlements served		
3. Raw water bases		
Sources of raw water (the percentage of produced water volume, or the produced water volume for the given raw water source in m3/year and m3/day units or m3/day unit, please enter the daily average value, so we can identify seasonal/temporal operating systems)		
Ground water		
Deep well water		
River		
Lake		
Reservoir		
Bank filtration		
Karst water		
Spring water		
Other		
4. Impact of climate change on water supply – general aspects, effects on quantity/quality of raw water.		
Have you experienced climate change affecting your drinking water supply systems?		
Please select from drop down menu.		Yes/No
If yes, please describe in detail how you experienced the impact of climate change.		
Please select from drop down menu:		
Drought periods becoming more frequent		Yes/No
Floods becoming more frequent		Yes/No

Rising air temperature		Yes/No
Increasing precipitation intensity		Yes/No
Precipitation events becoming more frequent		Yes/No
Increased frequency of inland excess water		Yes/No
Increasing water demands		Yes/No
Decrease in the amount of available water resources		Yes/No
Increase in water temperature in drinking water bases		Yes/No
Changes in water quality of drinking water bases		Yes/No
If you have experienced another phenomenon, please explain:		

Please select, based on your experience, how climate change affects each type of water bases (please choose from the drop-down menu):									
Type of raw water /experienced phenomenon	Ground water	Deep water	River	Lake	Reservoir	Bank filtration	Karstic water	Spring water	Oth.
Increasing water flows									
Declining water flows									
Rising water levels									
Falling water levels									
Increasing microbial pollution									
Increasing chemical pollution									
Increasing water temperature									

Increase in algae numbers									
Please describe if you have experienced other effects of climate change in addition to the previously listed:									

5. Impact of climate change on water supply – effects on the applied water treatment technologies.
If you operate different types of water bases, we ask you to give one typical answer for each type of water bases (of course it is also possible to fill out a questionnaire for each water treatment technology, but we believe that this would be very time-consuming if you operate many water treatment plants, so we recommend that in this case you enter one typical water technology per type of water base). You can find questions about technologies by water base type on the following worksheets. If a water base is not located in your supply area, leave the worksheet for that water base blank.
Questions regarding technology if water base is ground water:
Briefly describe the process of water treatment technologies (e.g., dosing sodium hypochlorite in raw water tank + KMnO ₄ dosing + rapid filtration + post disinfection with chloride dioxide + clean water tank). If you operate different type of water bases, please present one typical water treatment technology line for each type of water base.
If available, please attach flow charts and pictures of the technology used to complete questionnaire.

The following questions apply to each technological unit. Please indicate with a Yes/No answer which effect of climate change you have experienced for each technological unit:		
5.1. Pre – Oxidation		
Increased concentration of disinfection by-products		Yes/No
Shorter hydraulic residence time		Yes/No
Increasing demand for oxidants		Yes/No
Increased hydraulic residence time		Yes/No
Please describe if, in addition to the aspects listed, you also experienced other effects of climate change during pre-oxidation:		
5.2. Coagulation – Flocculation		
Increased turbidity of raw water		Yes/No
Increased coagulant demand		Yes/No
Increased demand for flocculants		Yes/No
Shorter hydraulics residence time		Yes/No
Increased hydraulic residence time		Yes/No
Please describe if, in addition to the aspects listed, you experienced other effects of climate change during coagulation – flocculation:		
5.3. Clarification		
Increased turbidity of raw water		Yes/No
Shorter hydraulic residence time		Yes/No
Increased hydraulic residence time		Yes/No
Please describe if, in addition to the aspects listed, you also experienced other effects of climate change during clarification:		

5.4. Rapid Filtration		
Incoming water has an increased content of suspended solids		Yes/No
Increased filtration velocity		Yes/No
Decreased filtration velocity		Yes/No
Please describe if, in addition to the aspects listed, you also experienced other effects of climate change during rapid filtration:		
5.5. Granular Activated Carbon (GAC)		
Incoming water has an increased content of suspended solid		
Increased concentration of dissolved pollutants arriving at the GAC		
Increased residence time on GAC		
Decreased residence time on GAC		
Please describe if, in addition to the aspects listed, you also have experienced other effects of climate change during rapid filtration:		
5.6. Post-disinfection		
Increased bacteriological contamination of incoming water		
Increased number of precursors in the water entering the disinfection unit		
Higher demand for disinfectants		
Increased amount of disinfection by products		
Increased residence time		
Decreased residence time		
Please describe if, in addition to the aspects listed, you also experienced other effects of climate change during post-disinfection:		

5.7. Other technological units (e.g., membrane filtration, ozonisation – if not used as pre-oxidation)
Please describe if you have other technological units in addition to the technological units already listed in 5.1 – 5.6. please list how you have experienced the impact of climate change on these technological units:

6. impacts of climate change on water supply – effects on drinking water supply networks.		
Please indicate with yes/no answer which of the following phenomenon you have experienced in the drinking water supply network as a result of the change in the quality of water pumped to the drinking water distribution system.		
More intense biofilm formation		Yes/No
More intense biocorrosion in the drinking water distribution system		Yes/No
Increased concentration of disinfection by – products		Yes/No
Increased water temperature		Yes/No
Changes in water chemistry parameters		Yes/No
The decrease in disinfectant concentration in the network becomes intense		Yes/No
Please describe if, in addition to the aspects listed, you have experienced other effects of climate change in the drinking water supply network:		

7. Measures
Please indicate with yes/no answer whether measures have been taken to reduce the effects of climate change and if so, what kind of measures.

Intervention taken so far		Yes/No
The problem has been identified		Yes/No
The issue is being intensively monitored		Yes/No
Control and operation processes have been modified a		Yes/No
A Risk analysis has been carried out (related to Water Safety Plan)		Yes/No
Please describe if, in addition to the listed activities, other interventions are used to reduce the effects of climate change.		
8. Other Notes		
Please describe if you have any comments/information about the impact of climate change on drinking water supply that was not asked in the questionnaire.		

FS or sand separator; Optional treatment for arsenic and solvents; UV treatment if needed; A sand separator or arsenic remover may also be used; In some cases, GAC (Granular Activated Carbon)

ANNEX 6: List of Drinking water treatment plant in Italy and Vietnam

List of DWTP in Italy

Utilities (Gestori)	Number of drinking water treatment plants managed	Number of municipalities served	Number of inhabitants served (Arera data 2021)
G1	164	77	715913
G2	26	2	1403314
G3	51	74	593285
G4	5	126	1203640
G5	94	46	1234292
G6	24	164	2900000
G7	1	11	100000
G8	0	31	167050
G9	0	8	46195
G10	4	3	11148
G11	4	7	50000
G12	30	84	330000
G13	159	186	526563
G14	60	9	190000
G15	45	10	92722
G16	57	31	208430

G17	1	39	341627
G18	5	9	113147
G19	11	18	70300
G20	2	38	493960
G21	4	36	1184097
G22	6	42	243665
G23	1	1	350
G24	1	136	500000
G25	47		
G26	289	103	
G27	4	12	174273
G28	12	108	497288
G29	94	290	2199854
G30	68	227	2285000
G31	20	45	416420
G32	40	40	132447
G33	74	113	349178
G34	36	16	90000
G35	12	24	100025
G36			
G37	2	126	432144
G38	5	44	1136145
G39	16	35	240350
G40	50	42	150000

List of Drinking water treatment plant in Italy

Utilities	Treatment	Note
G1	FS+GAC+Dis	FS o dissabbiatore
G2	FS+Sed+GAC+Aer+RO+Dis	-
G3	Pre-ox+FS+Dis Pre-ox+GAC+Dis	-
G4	Pre-ox+UV+Dis	-
G6	Pre-ox+FS+GAC+Dis	-
G7	GAC	-
G9	Dis	-
G10	GAC+Dis	-
G11	Ox	-
G12	Ox	Eventuale trattamento Arsenico e solventi
G13	Ox+FS+GAC+Dis	-
G14	Dis	-
G15	GAC+Dis	Eventualmente UV
G17	Dis	-

G18	GAC+UV+RO+Dis FS+UV+RO+Dis FS+GAC+Dis	-
G21	Dis	-
G24	Coag/Floc+FS+GAC+Dis	-
G26	Dis GAC+Dis Ox+FS+GAC	In caso viene usato anche dissabbiatore o dearsenificatore
G27	Coag/Floc+FS+GAC	-
G28	Pre-ox+FS+Ox+GAC+Dis	-
G30	Pre-ox+FS+GAC+Dis GAC+Dis UV+RO+Dis	-
G31	Dis Pre-ox+Chiar+FS+GAC+Dis	-
G32	FM+GAC	-
G33	Degas+Ox+Coag/Floc+FS+GAC+Dis	-
G34	Pre-ox+FS+GAC+Dis	-
G35	FS+GAC+RO+Ox	-
G37	GAC	-
G38	Dis	-
G39	FS+Ox+Dis	In alcuni casi anche GAC
G40	Dis	-

Pre-ox= Pre-oxidation;FS= Filtration sand;GAC/PAC=Granular active carbon/Powder Dis=Disinfection;Sed=Sedimentation; Aer=Aeration;RO= osmosi;UV= treatment by Ultraviolet;Ox=oxidation; Coag=coagulation; Floc=flocculation; FM=filtre membrane;Dec= decantazione; MF=micro filtration; FC=filtre cyclone UF=Ultra filtration; Pre-sed = pre sedimentation

No	WTP	Water Source	Treatment Steps	Disinfectant	Feature characteristic
	Northern Vietnam				
N1	An Dương	River and sea water/ groundwater	Coagulation/flocculation, sedimentation, filtration Using U-BCF biological filter tank to treat Organic, Ammonium, and Manganese pollution	Chlorine	Upflow Biological Carbon Filter
N2	Bát Tràng	River	Coagulation/flocculation, sedimentation, filtration	Chlorine	Conventional filtration
N3	Lương Yên	River	Coagulation/flocculation, sedimentation, filtration	Chlorine	

N4	Yên Phụ	Groundwater	Aeration iron removal, sedimentation, filtration	Chlorine	
N5	Vĩnh Hùng, Vĩnh Lộc	Surface water	Pre-oxidation, coagulation/flocculation, sedimentation, filtration	Chlorine	Two-stage sand filtration
N6	Bắc Giang	Surface water	Coagulation/flocculation, sedimentation, filtration	Chlorine	
N7	Swater Kankyo	River and seawater/ groundwater	Aeration, coagulation/flocculation, activated carbon filtration, filtration	Sodium hypochlorite (Javen)	
N8	Quảng Ninh	River	Coagulation/flocculation, sedimentation, filtration	Chlorine dioxide	Disinfection by UV
N9	Lạng Sơn	Ground water	Aeration, coagulation/flocculation, filtration	Chlorine	(PAC Poly aluminum Chloride, PAM Polyacrylamide, SODA) "SODA" could also refer to "Sodium Carbonate," which is used in water treatment for pH adjustment and precipitation of certain impurities
	Central Vietnam				
C1	Đà Nẵng (DAWACO)	River	Coagulation/flocculation, sedimentation, filtration	Chlorine	
C2	Quy Nhơn	Ground water	Ground water, Through aeration towers, precipitation, sedimentation, sand filtration, and chlorine disinfection.	Chlorine	
C3	Bình Thuận	River	Coagulation/flocculation, sedimentation, filtration	Chlorine	
C4	Ca Giang- Bình Thuận	River	Coagulation/flocculation, sedimentation, filtration		

C5	TP Hue	River	Coagulation/flocculation, sedimentation, filtration		GAC tank
	Southern Vietnam				
S1	Thủ Đức	River	Coagulation/flocculation, sedimentation, filtration		
S2	Tan Hiep (THW)	River and sea water/ groundwater	Aeration, coagulation/flocculation, sedimentation, activated carbon filtration, filtration	RO for salt intrusion	pH low, salt intrusion
S3	Hoa Khanh Tay, Long An	River	Coagulation/flocculation, sedimentation, filtration		
S4	Đông Nai	River	Coagulation/flocculation, sedimentation, filtration		
S5	HCM	River and sea water/ groundwater	Coagulation/flocculation, sedimentation, filtration		

ANNEX 7: LIST OF TECHNOLOGY TREATMENT IN DRINKING WATER TREATMENT UTILITIES IN ITALIA

NORD G3 – A2A

- Groundwater: oxidation (O2) - sand filtration - disinfection (ClO2)
- Groundwater: oxidation (O2) - ferric chloride - sand filtration - disinfection (ClO2)
- Groundwater: ferrous sulphate - GAC filtration - disinfection (ClO2)
- Spring water: microfiltration - disinfection (NaClO)

NORD G6 – HERA Group

- Groundwater - Oxidation with air/oxygen; sand filtration; activated carbon filtration - Disinfection (chlorine dioxide)
- Surface - accumulation basins (presedimentation); pre-oxidation (Ozone or permanganate); coagulation/flocculation (PAC-HB); Sand filtration; Oxidation/disinfection with ozone; Activated carbon filtration - Disinfection (chlorine dioxide)
- Sources: disinfection with sodium hypochlorite

NORD G11 – Acquadotti Tirreni

- chlorination

NORD G12 – Lario Reti

- Lake: Centralized plant for the production of chlorine dioxide

Pre-disinfection with chlorine dioxide, Clariflocculation with alpacar, Filtration on silica sand, Disinfection with chlorine dioxide, Backwash water treatment

- Aquifer: Chlorination, in some cases Arsenic treatment plant, solvent treatment plant
- Source: Chlorination, in some cases solvent treatment plant

NORD G23 – Acque Bienta

- decantation + chlorination

NORD G26 – Alfa Varese

- Groundwater 1: disinfection (NaClO or UV)
- Groundwater 2: sand trap + disinfection (NaClO or UV)
- Groundwater 2: activated carbon filters (GAC) + disinfection (NaClO or UV)
- Groundwater 3: dearsenifier (ferric hydroxide filters) + disinfection (NaClO)
- Groundwater 4: Fe and Mn oxidation (chemical oxidation with NaClO + sand filters + activated carbon filters)
- Lake: sand filters + disinfection (NaClO)
- Sources 1: disinfection (NaClO or UV)
- Sources 2: dearsenifier (ferric hydroxide filters) + disinfection (NaClO)
- Sources 3: cyclonic filter + clarification-reflocculation (coagulation with ferric chloride + sedimentation) + sand filters + disinfection (NaClO)

NORD G32 – Cordar Spa

- Surface water (river, stream): sand filters, activated carbon filters, hypochlorite disinfection;
- Underground water (wells): membrane filters, activated carbon filters
- Spring water: sodium hypochlorite disinfection, UV lamps

NORD G35 – Egea

- Sand filters, activated carbon filters, reverse osmosis, ozone system

NORD G39 – Tea Spa

• groundwater collection - quartz sand filtration and oxidation for removal of iron, manganese and ammonium. In some cases also GAC and/or iron hydroxide filters. If arsenic is present, removal by ferric chloride. Disinfection (mainly dioxide and in some cases hypochlorite or UV).

NORD G14 – Novareti

• Sodium hypochlorite water purification plants, chlorine dioxide plants and arsenic abatement plants.

NORD G15 – Acque del Chiampo

- Well: activated carbon filter, NaClO and/or UV disinfection
- Source: NaClO and/or UV disinfection

NORD G17 – Piave Servizi

- for sources: ONLY disinfection (NaClO);
- only for some underground aquifer sources: disinfection (hypochlorite or chlorine dioxide);
- in some underground aquifer sources: no treatment

NORD G21 – Veritas Group

• River: chemical pre-oxidation (chlorine dioxide ClO₂) - coagulation/flocculation (ferric chloride FeCl₃ or polyaluminium chloride PACl) - possible ammonia reduction at breakpoint with sodium hypochlorite NaClO - sand filter - activated carbon filter - final disinfection (sodium hypochlorite NaClO)

- Aquifer: disinfection only

NORD G28 – Acque Venete

• FOR SURFACE WATERS: • river draft via submersible pumps; • reagent dosing (oxidants, flocculants and acidifiers); • longitudinal clarification/flocculation/decantation; • filtration on granular support; • adsorption/filtration on activated carbon, after oxidation; • final disinfection with chlorine dioxide; • accumulation in tank and relaunch into network.

• FOR DEPTH WATER: • draft by means of vertical-axis submersible pumps placed inside wells drawing from the second confined aquifer; • pre-oxidation with air; • filtration on granular support; • oxidation with ozone or sodium hypochlorite; • adsorption/filtration on activated carbon; • disinfection with chlorine dioxide.

NORD G30 – Iren Group

• River/Subalveo • Coagulation, pre-oxidation, sand filtration, GAC filtration (not always present), final disinfection • Ultrafiltration, final disinfection

• Lake • Chairiflocculation, pre-oxidation, sand filtration, final disinfection

• Well • Fe, Mn, NH₄: pre-oxidation (air or chemical), sand filtration, GAC filtration (not always present), final disinfection • Solvents: GAC or stripping towers, final disinfection • Nitrates: UV disinfection, reverse osmosis, final disinfection

NORD G40 – Riviera Acqua

- NaClO disinfection

CENTRO G5 – Publiacqua S.p.a

- See very detailed attached file

CENTRO G31 – Gaia S.p.A

- underground aquifer: disinfection;
- river: ClO₂/NaClO filtration + NaClO disinfection;
- underground aquifer (karst aquifer): pre-disinfection ClO₂ + Sand removal + Clariflocculation + Sand filtration + GAC filtration + Post-disinfection with ClO₂

SUD G24 – Molise acque

- general nature: coagulation/flocculation (FeCl₃) - sand filter - activated carbon filter - disinfection (NaClO)

ISOLE G4 – Siciliacque

- Artificial reservoir water - Ancipa / Fanaco water purifier: Pre-chlorination / demetallization with ClO₂ - coagulation – flocculation with PAC and cationic polyelectrolyte - KMnO₄ dosage - clarification in turbocirculator with sludge recirculation – filtration on quartz sand - post-disinfection with ClO₂ and/or NaClO dosage

- Artificial reservoir water - Gela water purifier: Pre-chlorination/demetallization with ClO₂ - FeCl₂ dosage - coagulation – flocculation with PAC and cationic polyelectrolyte - KMnO₄ dosage - clarification with accelerated clariflocculators of the Actiflo Veolia type - pressure filtration on quartz sand - post-disinfection with ClO₂ and/or NaClO dosage

- Artificial reservoir water - Sambuca water treatment plant: Pre-chlorination/demetallization with ClO₂ - FeCl₂ dosage - coagulation – flocculation with polychloride of aluminum sulphate and cationic polyelectrolyte - KMnO₄ dosage - clarification in sludge recirculation clariflocculators - filtration on sand - post-disinfection with ClO₂ and/or NaClO dosage

- River water – Blufi water treatment plant: Pre-chlorination/demetallization with ClO₂ – coagulation and flocculation with PAC (polyaluminium chloride) - – removal of algae and/or any micropollutants present with PAC (powdered activated carbon) - clarification by means of a honeycomb lamellar pack decanter - filtration on a bed of quartz sand - filtration with GAC - post-disinfection with dosing of ClO₂ and/or NaClO

- Spring Water – Groundwater: Disi

SUD G24 – Molise acque

- general nature: coagulation/flocculation (FeCl₃) - sand filter - activated carbon filter - disinfection (NaClO)

- Spring Water – Groundwater: Disinfection with NaClO Groundwater: Disinfection with NaClO + ClO₂ + UV

ISOLE G38 – Amap

- groundwater: disinfection with NaClO;
- surface water: chemical pre-oxidation with ClO₂ (in 1 case also with KMnO₄), coagulation/flocculation (high basicity Polyaluminium chloride) - sand filter - final disinfection (ClO₂)