MASTER IN ENVIRONMENTAL ENGINEERING 2024/2025

WATER QUALITY IN URBAN STREAMS

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Abstract

This report addresses the multifaceted challenge of urban stream in Portugal, focusing on a specific stream impacted by contamination and infrastructural limitations. The study aimed to propose and technically-economically evaluate integrated solutions for its revitalization and water quality improvement. After collecting various samples at 12 distinct points along the rivers, it was possible to identify the most critical areas in terms of *E. coli* and enterococci contamination. These areas were mapped following a detailed graphical analysis of data collected over a four-month period, allowing for a clear understanding of the distribution and intensity of bacterial pollution., categorizing them based on their suitability for different intervention strategies.

The methodology involved the strategic recommendation of three key technologies: video inspections for culverted and highly urbanized sections, daylighting for open and greener areas, and UV disinfection for critical discharge points (Point 2).

Results indicate that while initial investment for daylighting and advanced disinfection can be substantial, a life-cycle perspective reveals long-term benefits that significantly outweigh these costs. Video inspections emerged as a crucial diagnostic tool, optimizing remediation efforts by precisely identifying contamination sources. Daylighting projects are anticipated to restore ecological function and provide significant social and aesthetic value to urban landscapes. The implementation of UV disinfection, specifically targeting fecal contamination indicators like *E. coli* and Enterococci, is expected to drastically reduce microbial loads, safeguarding public health and downstream ecosystems without chemical residuals.

In conclusion, this integrated approach presents a viable and effective strategy for urban stream revitalization in Portugal. It not only addresses immediate contamination concerns but also promotes ecological restoration, climate resilience, and enhanced urban living quality, setting a precedent for sustainable water management in similar urban environments.

Declaração

Declara, sob compromisso de honra, que este trabalho é original e que todas as contribuições não originais foram devidamente referenciadas com identificação da fonte.

Porto, 10 de Junho de 2025

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Glossary

PAH – Polycyclic Aromatic Hydrocarbons

COD – Chemical Oxygen Demand

TOC – Total Organic Carbon

UV – Ultraviolet

BOD5 – Biological Oxygen Demand

DO - Dissolved Oxygen

EPA – Environmental Protection Agency

APA – Agência Portuguesa do Ambiente

CFU – Colony-Forming Unit

ROV -Remotely Operated Vehicles

WQI - Water Quality Index

1 Framework

Urban streams are vital components of cities, playing a crucial role in stormwater drainage and the regulation of the hydrological cycle. Furthermore, they offer a range of benefits for the well-being of populations, providing recreational spaces and contributing to flood control and mitigation (e.g., Konrad et al., 2016). However, intense urbanization and increasing pressure on these ecosystems have resulted in the degradation of water quality and the loss of important ecological and social functions.

Despite efforts to minimize the discharge of sewage effluents into urban streams, water pollution persists as a significant challenge. Contamination by sewage, industrial, and other pollutants compromises the health of aquatic ecosystems, restricts the recreational use of water, and poses a risk to public health (e.g., Masoner et al., 2019). Moreover, soil impermeabilization and the channeling of watercourses have exacerbated flood problems, exposing populations to increased risks (e.g., Bernhardt et al., 2017).

Considering this scenario, it is imperative to investigate and evaluate measures to improve water quality in urban streams, focusing on solutions applicable to situations of both point and non-point source pollution. The main objective is to identify and analyze effective strategies for the rehabilitation of these ecosystems, considering the diagnosis of pollution, the evaluation of remediation technologies, integrated management strategies, and the benefits for the well-being of populations.

This research will contribute to the development of scientific and technological knowledge in the area of urban stream rehabilitation, providing sustained information for the implementation of intervention projects. The results of the thesis may assist in informed decision-making, aiming at the protection and enhancement of these important ecosystems, for the benefit of present and future generations.

1.1 Goals

This master's thesis embarks on a comprehensive study to investigate and implement solutions for enhancing the quality of urban surface waters, with a primary focus on a Stream, located in Portugal. The central aim is to develop and propose a resilient methodology that facilitates the rehabilitation of urban watercourses, tailored to specific local environmental characteristics and the identified types of pollution, all while adhering to the relevant legal frameworks.

Given the intricate challenges posed by increasing urbanization and the consequent pressure on water resources, it is imperative to acknowledge the critical importance of aligning rehabilitation endeavors with both national and European water quality legislation. This study recognizes that the Water Law (Law No. 58/2005) and its associated directives, such as Decree-Law No. 69/2023, which addresses drinking water quality, and Decree-Law No. 135/2009, which pertains to bathing water quality, are fundamental in evaluating and proposing effective improvement solutions. Furthermore, the implications of wastewater treatment, as outlined in Decree-Law No. 152/97, and the control of agricultural pollution, as detailed in Decree-Law No. 236/2015, will be thoroughly considered within the context of urban river health.

To achieve this overarching objective, an extensive state-of-the-art study has been conducted to identify and analyze a spectrum of solutions for treating both point and non-point source pollution in urban watercourses. This analysis serves as the cornerstone for the development of a detailed work plan, encompassing several specific objectives. ´

Initially, the study will focus on mapping and analyzing the primary vulnerabilities of the Stream. Subsequently, a comprehensive investigation and evaluation of various water quality improvement solutions will be conducted. This includes exploring advanced water treatment technologies, bioretention systems, and riverbank renaturalization measures, with the aim of determining the most suitable options for the specific context of the study area, while considering legal compliance and sustainability. Furthermore, the research will provide a detailed characterization of Stream. This will encompass an analysis of historical and current water quality data, the identification of pollution sources, and an assessment of the watercourse's ecological status, all in accordance with established legal quality parameters. Moreover, the study will utilize monitoring data and spatial analyses to pinpoint critical zones where pollution is most concentrated, and to determine the potential origins of these pollution hotspots, with a particular focus on sources regulated by existing legislation. Finally, the research will culminate in the proposal of a methodology for selecting the most appropriate water quality improvement solutions. This methodology will consider the site's unique characteristics, the identified pollution types, and the criteria of sustainability, technical feasibility, and economic viability, ensuring adherence to the relevant legal framework.

1.2 Contribution to the Sustainable Development Goals (SDGs)

In 2015, the United Nations established the Sustainable Development Goals (SDGs) as a comprehensive framework to guide global development efforts over the next 15 years. The SDGs build upon the successes and challenges of the Millennium Development Goals, emphasizing an integrated approach that balances social equity, economic growth, and environmental protection. They recognize the interconnectedness of global issues, highlighting the need for collaborative action across sectors and regions to achieve a sustainable and inclusive future for all.

The United Nations Sustainable Development Goals (SDGs) are a universal call to action to end poverty, protect the planet, and ensure prosperity for all by 2030. These 17 interconnected goals address global challenges including environmental degradation, public health, and sustainable urban development. Improving water quality in urban streams through innovative treatment technologies and ecological restoration directly supports several key SDGs, creating multifaceted benefits for communities, ecosystems, and cities. The following section outlines how this work contributes to specific SDGs. Figure 1 below illustrates the SDGs:

Figure 1: Sustainable Development Goals (UN, 2019).

The implementation of advanced water treatment technologies, such as UV disinfection combined with protective infrastructure in urban streams, along with ecological restoration practices like daylighting and regular video inspections to monitor water quality and infrastructure integrity, directly supports multiple United Nations Sustainable Development Goals (SDGs). These integrated approaches foster environmental sustainability, enhance public health, and promote community well-being by ensuring cleaner, safer, and more resilient urban waterways.

SDG 6 – Clean Water and Sanitation

Ensuring the availability and sustainable management of water resources is central to SDG 6. The deployment of UV disinfection systems in urban streams effectively reduces microbiological contamination without harmful chemicals, improving water quality for ecosystems and human use. This treatment enhances the safety of urban water bodies, prevents waterborne diseases, and supports sustainable sanitation practices by reducing the burden on wastewater treatment facilities.

SDG 3 – Good Health and Well-being

By improving water quality and limiting exposure to pathogens through effective disinfection, the project helps protect public health. Cleaner urban water bodies reduce risks of infections among local communities and recreational users, contributing to better health outcomes and reduced healthcare costs associated with waterborne illnesses.

SDG 11 – Sustainable Cities and Communities

Urban daylighting and water quality improvement contribute to more resilient and sustainable cities. Restoring natural stream functions and maintaining clean water enhance urban biodiversity, promote recreational spaces, and improve the overall quality of life for residents. This aligns with SDG 11’s goal of making cities inclusive, safe, resilient, and sustainable.

SDG 13 – Climate Action

Improving the resilience of urban waterways to pollution and extreme weather events supports climate adaptation efforts. Clean and well-managed streams act as natural buffers against flooding and help mitigate climate-related risks, contributing to SDG 13’s aim of combating climate change and its impacts.

SDG 15 – Life on Land

Protecting and restoring freshwater ecosystems through effective water treatment and physical infrastructure preserves biodiversity and ecosystem services. By preventing contamination and promoting natural habitats along urban streams, the initiative supports the conservation and sustainable use of terrestrial and freshwater ecosystems.

1.3 Dissertation structure

This dissertation is divided into four parts, with the first chapter providing a general approach to the study topic and a description of the work's objectives.

The second chapter presents the state of the art, which includes a global overview of water quality in urban rivers, the microbiological and chemical parameters analyzed, and possible causes and consequences. This chapter also includes the global framework at the national level for surface and bathing waters, aiming to ensure the health of ecosystems and the well-being of populations living in urban areas.

Chapter 3 delves into the comprehensive methodology employed and the subsequent results obtained for the microbiological and chemical parameters crucial to assessing water quality. This chapter features a detailed case study that integrates various aspects of the water stream's environmental health.

The case study begins by outlining the Physical and Geographical Characteristics of the study area, providing essential context for the water quality analysis. We then address Water Quality and Pollution, presenting the findings from the evaluated parameters. The discussion extends to the Monitoring strategies implemented and the Challenges and Measures encountered throughout the study. Finally, the chapter concludes with the Presentation and Discussion of Results, followed by a thorough Technical Analysis of Solutions aimed at improving water quality in the stream.

The fourth chapter presents the conclusions based on the results obtained. Also, the limitations encountered during this study and possible technologies to be implemented for improvement are identified.

2 Introduction

2.1 Literature Review – State of Art

Urban rivers are critical components of the urban ecosystem, providing essential ecological and socioeconomic functions, contributing to the health, prosperity, and well-being of cities. They offer spaces for recreation, relaxation, and interaction, fostering both public welfare and community livelihood. However, increasing urbanization and industrialization have led to significant degradation of these vital ecosystems worldwide (e.g., Grimm et al., 2008). This degradation is primarily attributed to anthropogenic activities, including industrial discharges, untreated wastewater, agricultural runoff, and urban stormwater runoff (Carpenter et al., 1998; Paul & Meyer, 2001; Walsh et al., 2005). These sources introduce a wide range of pollutants, such as heavy metals, organic contaminants, nutrients, and pathogenic microorganisms, compromising water quality and ecological integrity (Vörösmarty et al., 2010; Smith et al., 2013; Liu et al., 2017). Urban diffuse pollution, originating from cities and transport, carries pollutants from roads and impervious surfaces into storm drains and watercourses at numerous points along the river (Novotny & Chesters, 1981; Arnold & Gibbons, 1996; Fletcher et al., 2015).

Water quality conditions are commonly assessed using indicators like physicochemical parameters, fecal indicator bacteria, and polycyclic aromatic hydrocarbons (PAHs). The latter pose significant risks to human health due to their association with waterborne pathogens during recreational activities. Guideline values for freshwater recreational water, first established by the World Health Organization (WHO, 2003), suggest a tolerable impact of <1–5% gastrointestinal disease for voluntary recreational activities. Many countries use *Escherichia coli* (*E. coli*) as a primary indicator, with a threshold of 100 cfu/100 mL, reflecting the presence of fecal pollution from warm-blooded animals. A preliminary analysis of water quality in an urban Mediterranean river highlights the importance of such indicators (Papadaki et al., 2023). In 2012, the Environmental Protection Agency (EPA) updated its water quality criteria recommendations, incorporating both *E. coli* and *Enterococci* as indicators for fecal contamination, particularly for primary contact recreational uses.

In the present case study, microbiological and physicochemical monitoring was carried out at multiple points along the watercourse during selected temporal intervals. These analyses included microbiological parameters (*E. coli*, *Enterococci*) and physicochemical indicators such as chemical oxygen demand (COD), biological oxygen demand (BOD_5), dissolved oxygen (DO), conductivity, and total organic carbon (TOC). The results revealed consistently elevated concentrations of *E. coli* and *Enterococci*, especially in highly urbanized sections of the stream. These findings confirmed the presence of significant fecal contamination and reinforced concerns regarding public health and ecological integrity.

Based on these results, a multifaceted intervention strategy was explored, considering the spatial patterns of pollution and the nature of the surrounding land use. It was concluded that a combined approach involving daylighting of buried stream segments, targeted video inspections (particularly at structurally critical points), and ultraviolet (UV) disinfection could offer an effective solution to reduce microbiological contamination. Daylighting increases the accessibility and transparency of the watercourse, enabling easier detection and correction of illicit discharges; video inspections assist in identifying pollution entry points in the drainage system; and UV treatment targets the inactivation of fecal indicator bacteria by disrupting their genetic material and reducing their infectivity.

To comprehensively assess the spatial and temporal variations in water quality, a robust monitoring network is essential. This network should include strategically located sampling sites along the river, from its source to the estuary, with sufficient sampling frequency to capture seasonal variations and potential pollution spikes (e.g., USEPA, 2006). Beyond standard physicochemical parameters (pH, DO, BOD, COD, nutrients, and heavy metals), it is recommended to analyze fecal coliforms to evaluate fecal contamination and associated health risks. The presence of persistent organic pollutants (POPs) and microplastics should also be investigated, given each region's anthropogenic pressures (e.g., Rochman et al., 2013). Statistical analysis of the collected data enables the identification of trends, spatial patterns, and temporal variations, facilitating the correlation of water quality changes with environmental and anthropogenic factors (e.g., Helsel & Hirsch, 2002).

Identifying the primary pollution sources is crucial for developing effective management strategies. This requires a detailed survey of human activities within the catchment, encompassing point sources (industrial discharges, wastewater treatment plant effluents, urban runoff points) and diffuse sources (urban runoff from impervious surfaces, atmospheric deposition) (Schueler, 1999; Paul & Meyer, 2001; Dudgeon et al., 2006). Chemical markers can help trace the origin of pollutants, with specific heavy metals indicating industrial sources and elevated nutrient levels suggesting agricultural activities (He & Honeycutt, 2005; Zhang et al., 2014). Engaging with the local community and stakeholders provides valuable insights into perceived pollution problems and their potential causes (Reed, 2008; Beierle & Konisky, 2001).

Assessing the ecological health of an urban river involves analyzing biological indicators such as benthic macroinvertebrates, fish assemblages, and algal communities. These indicators offer valuable information on water quality, the presence of toxic pollutants, and the overall ecosystem integrity. Habitat assessments and evaluations of the river's longitudinal and lateral connectivity are also essential for understanding ecological health (e.g., Ward et al., 1999). A site-specific water quality index (WQI), constructed using a combination of physical, chemical, and biological indicators, will facilitate a rapid and integrated assessment of the river's ecological status (e.g., Tyagi et al., 2013).

The quality of water in urban rivers is a topic of increasing relevance, particularly due to anthropogenic pressures from urbanization, improper effluent disposal, and hydromorphological alterations. Studies indicate that water quality is severely affected by discharges of domestic and industrial effluents, urban surface runoff, and alterations in the hydrological regime. Key degradation parameters include fecal coliforms, chemical oxygen demand (COD), and nutrients such as nitrogen and phosphorus, which lead to eutrophication and affect biodiversity (Smith et al., 1999; Allan, 2004; Paul & Meyer, 2001). Hydromorphological alterations, such as channelization and bank impermeabilization, also negatively impact the natural flow and self-regeneration capacity of these watercourses (Meyer et al., 2005; Poff et al., 1997).

Innovative technologies have shown potential in improving water quality. Biological filtration through biofilter systems has proven effective in removing dissolved contaminants (Qian et al., 2021). Micro-nano bubble technology, which increases dissolved oxygen levels, contributes significantly to microbial reconstitution of the aquatic ecosystem (Wu et al., 2019). Automated monitoring, via real-time sensors, enables rapid responses to water quality variations, facilitating more efficient and precise water resource management (e.g., Jarvis et al., 2016).

Rehabilitation projects have been implemented in various urban regions to mitigate pollution impacts and restore water quality. Examples include the Rio Tinto in Porto, where requalification involved removing clandestine discharges, increasing riparian vegetation, and controlling urban runoff (Lemos, 2010), and the Ribeira da Costa/Couros in Guimarães, where flood control and water quality improvement were achieved through retention basins and ecological connectivity (Vieira et al., 2008).

Managing water quality in urban rivers requires an integrated approach combining efficient monitoring, advanced treatment, and ecological rehabilitation strategies. Implementing emerging technologies and engaging with the community are fundamental to ensuring the sustainability and resilience of these urban aquatic ecosystems. A multidisciplinary and collaborative approach is essential to reverse degradation and promote the conservation of these vital water bodies (e.g., Moss, 2010).

2.2 Legal Framework

The water quality in urban rivers is a topic of increasing importance, given the challenges of urbanization and the pressure on water resources. In Portugal, the legislation on water quality is vast and comprehensive, including the quality of surface and bathing waters, aiming to protect this essential resource and ensure its sustainable use.

The complexity of water quality management in urban rivers requires a detailed legal framework that considers the multiple dimensions of this challenge. In Portugal, this framework is built upon a set of laws, decree-laws, and regulations that interconnect to ensure the protection and sustainable management of these ecosystems.

The Water Law (Law No. 58/2005, of December 29), transposing the Water Framework Directive (Directive 2000/60/EC), establishes the fundamental principles for water resource management. In the context of urban rivers, this law defines specific environmental quality objectives that consider the importance of these ecosystems for biodiversity, public health, and the well-being of populations. Water Law also defines planning instruments, such as river basin management plans, which establish the measures to be implemented to achieve quality objectives.

Decree-Law No. 77/2006, of March 30, further complements the transposition of the Water Framework Directive (Directive 2000/60/EC). This decree-law provides the technical specifications necessary for characterizing the waters of hydrographic regions, including the criteria for classifying the ecological and chemical status of surface water bodies such as rivers. It defines specific reference conditions for different types of surface water masses, encompassing general elements and specific pollutants, and establishes the technical specifications for the analysis and monitoring of relevant parameters. This decree-law is a crucial instrument for Portugal to meet the objectives of the Water Framework Directive, aiming to protect, improve, and restore all surface and groundwater bodies. It outlines the criteria for assessing ecological and chemical status, which dictates whether a water body is in 'good' status or requires improvement. By setting these detailed technical standards, Decree-Law No. 77/2006 ensures a consistent and scientifically sound approach to evaluating and managing the quality of Portugal's rivers and other surface waters in line with European Union requirements.

Decree-Law No. 69/2023, of August 21, which transposes European directives related to the quality of water intended for human consumption, is relevant to urban rivers, as they can be sources of water for human consumption, directly or indirectly. The quality criteria established in this decree-law, particularly concerning microbiological and chemical parameters, can be used as a reference for assessing the quality of surface waters in urban rivers. The presence of pollutants such as nitrates, phosphates, heavy metals, and pathogenic microorganisms in urban rivers poses a significant risk to public health, justifying the application of rigorous quality criteria.

The protection of urban rivers is also ensured by specific legislation on wastewater treatment and protection against agricultural pollution. Decree-Law No. 152/97, of June 19, which transposes Directive 91/271/EEC, concerning urban wastewater treatment, establishes standards for urban wastewater treatment, aiming to minimize surface water pollution. Decree-Law No. 236/2015, of October 16, which establishes the regime for protection against pollution by nitrates of agricultural origin, defines measures to control and minimize nitrate pollution from agricultural activities, which can have a significant impact on water quality in urban rivers.

Regarding bathing waters, it is known that the quality of bathing waters is a crucial aspect of public health and tourism in Portugal, with an extensive coastline and various inland bathing areas. Portuguese legislation on this matter is robust, aiming to ensure the safety and well-being of users, as well as the protection of aquatic ecosystems.

Decree-Law No. 113/2012, of May 18, establishes the regime for the protection of surface water and groundwater against pollution caused by certain dangerous substances and transposes Directive 2006/11/EC. This legal instrument defines the dangerous substances whose discharge into the aquatic environment must be prevented or limited, setting environmental quality standards for these substances in surface waters, including rivers. It is particularly relevant for urban rivers as they can be subject to various industrial and urban discharges containing these dangerous substances. The decree-law outlines measures for monitoring these substances and implementing strategies to achieve the defined environmental quality standards, contributing to the overall protection of water quality in these sensitive ecosystems.

In the specific context of urban rivers, Portuguese legislation establishes the need to protect these fragile ecosystems, which play an important role in regulating the hydrological cycle, maintaining biodiversity, and ensuring the quality of life for populations. Legislation requires the implementation of land management and planning measures that minimize the impacts of urbanization on rivers, such as the creation of protection zones, river section denaturalization, proper stormwater management, and pollution prevention.

The Portuguese Environment Agency (APA) plays a central role in the application of environmental legislation and the monitoring of water quality in urban rivers. The APA is responsible for the preparation of river basin management plans, the definition of environmental quality standards, and the regular monitoring of water quality. The APA also promotes the implementation of measures for the protection and recovery of water resources, through environmental education programs and technical support to municipalities and other entities responsible for the management of urban rivers.

In addition to national legislation, Portugal is also bound by international agreements and European directives that impact the management of water quality in urban rivers. The Water Framework Directive (Directive 2000/60/EC), for example, establishes the framework for the protection of surface and groundwater in the European Union, requiring Member States to achieve good ecological status of water bodies.

In summary, the legal framework for water quality in urban rivers is complex and comprehensive, covering a variety of laws, decree-laws, regulations, and European directives. The effective application of this legal framework, together with the implementation of appropriate management measures, is essential to ensure water quality, ecosystem health, and the well-being of populations living in urban areas.

3 Case Study

The present study focuses on assessing water quality in urban rivers, with a specific focus in a urban stream located in Portugal. This river serves as a typical example of an urban waterway prone to environmental degradation due to its proximity to various pollution sources. The primary objective is to investigate the impacts of urbanization on river pollution and its implications for recreational use by evaluating the physicochemical and microbial quality of this river.

The analyzed stream is a typical urban watercourse that discharges in the Atlantic Ocean. It deserves special attention due to the challenges it faces in terms of water quality. Over the years, this stream has been a source of indignation for the local population regarding pollution, several cases of surfers and swimmers contracting gastroenteritis after visiting the beaches surrounding it were recorded. Given its location and the urbanized environment, it crosses, the stream faces several challenges in terms of pollution and stormwater management.

The Stream analyzed is a watercourse that deserves special attention due to the challenges it faces in terms of water quality. Over the years, this stream has been a source of indignation for the local population regarding pollution, with concerns even being raised about "illegal drainage". Figure 2 below illustrates the Sampling points for investigation.

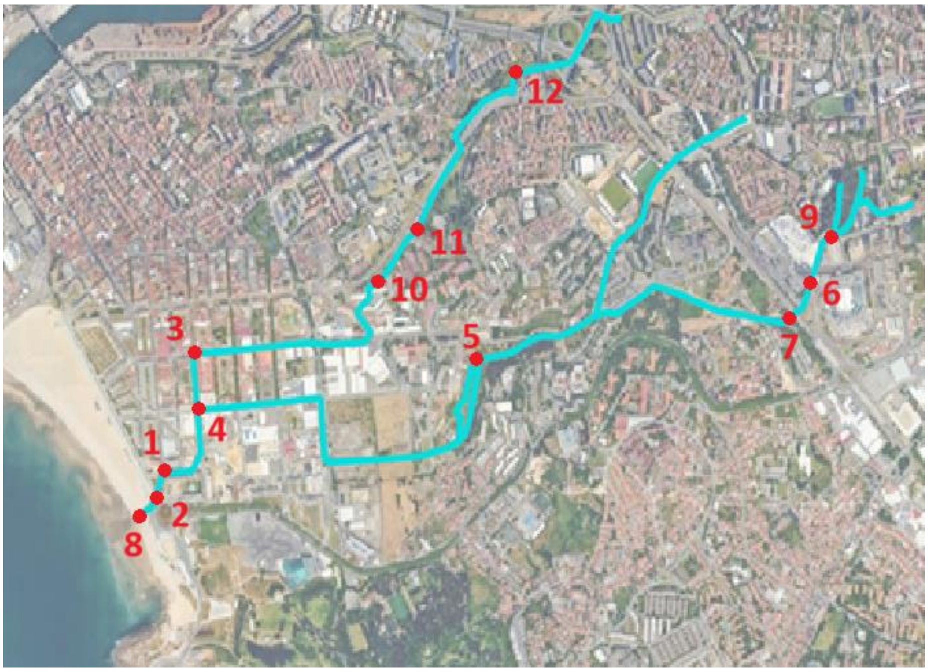

Figure 2: Sampling point for the investigation

This watercourse features two main branches that traverse areas with distinct land use patterns before converging. One branch flow predominantly through industrial and commercial zones, where soil impermeabilization and the intensity of human activities contribute to the presence of diffused pollutants and contamination loads. The other branch runs mainly through residential and mixed-use areas, interspersed with small green spaces and urban infrastructure. Throughout their course, both branches are heavily influenced by the surrounding dense urban fabric, which amplifies anthropogenic impacts on hydrological dynamics and water quality, exacerbating issues such as contaminated surface runoff, localized erosion, and the reduction of ecological connectivity.

Due to privacy and data protection considerations, the exact location of the study area remains confidential. All analyses and results are presented without disclosing identifiable geographic information, ensuring compliance with ethical and institutional guidelines.

3.1 Physical and Geographical characteristics:

The urban stream under study presents distinct physical and geographical characteristics that shape its behavior and interact with the surrounding urban environment. The river crosses intensely urbanized areas before flowing into an important beach. Its discharge is a significant convergence point, reflecting the interaction between the watercourse and the public space.

One of the most striking characteristics is its passage through densely urbanized zones. This reality imposes a high degree of anthropogenic pressure on the watercourse, with direct impacts on its quality and dynamics. A significant portion of its course is channeled, an alteration that substantially modifies its natural characteristics, affecting the flow, biodiversity, and self-purification capacity of the river (National Research Council, 2009).

The stream has been identified as a significant source of pollution, with the presence of organic, inorganic, and microbiological pollutants detected within its waters. The primary sources of this contamination are attributed to discharges of untreated or poorly treated wastewater, urban runoff carrying a variety of pollutants from impervious surfaces, and the potential presence of clandestine connections that directly introduce untreated sewage into the river. This confluence of pollution sources poses a substantial threat to the ecological health of the river and its surrounding environment.

The pollution originating has a direct and detrimental impact on the bathing water quality of beaches, a popular coastal area. This contamination adversely affects the health of beachgoers and surfers, who are exposed to the polluted waters. Episodes of microbiological contamination, often leading to elevated levels of fecal indicator bacteria such as *Escherichia coli* and intestinal enterococci, have been recorded, and there have been reported cases of gastroenteritis among individuals who have come into contact with the water. These incidents underscore the urgent need for effective pollution control measures to protect public health and maintain the recreational value of the beach.

3.2 Monitorization

To assess the extent of pollution and implement appropriate mitigation strategies, a comprehensive and multifaceted water quality monitoring program is conducted by APA both within the stream and the adjacent coastal zone. This monitoring is essential for evaluating the ecological status of these urban ecosystems, identifying pollution sources, and ensuring compliance with environmental legislation. The monitoring process involves a series of meticulously planned steps, from the strategic selection of sampling points and the careful collection of water samples to detailed laboratory analyses and the subsequent interpretation of the results. The data generated through this monitoring program is made publicly available through the National Water Resources Information System (SNIRH), providing transparency and facilitating access to information for researchers, decision-makers, and the public.

The planning phase of water quality monitoring begins with the establishment of clear objectives, which may include assessing the ecological status of the river, identifying pollution sources, verifying compliance with environmental legislation, and evaluating the effectiveness of mitigation measures (European Commission, 2018). The selection of sampling points is conducted strategically to represent the diversity of conditions along the river, considering the location of potential pollution sources, areas of increased vulnerability, and discharge points into the coastal zone (U.S. Environmental Protection Agency, 2006).

Sample collection adheres to rigorous protocols to ensure data representativeness and quality. Samples are analyzed in accredited laboratories using standardized methods for the determination of microbiological, physicochemical, and hydrological parameters (American Public Health Association, 2017). Microbiological analyses include the quantification of fecal indicator bacteria, such as Escherichia coli and intestinal enterococci, which pose a risk to public health (World Health Organization, 2003). Physicochemical analyses encompass the measurement of parameters such as pH, dissolved oxygen, nutrients (nitrates and phosphates), heavy metals, and organic compounds, providing insights into water quality status and pollutant presence (U.S. Environmental Protection Agency, 2012). Hydrological monitoring includes the measurement of flow rate, water velocity, and riverbed morphology, which are essential for understanding water flow dynamics and pollutant transport.

The interpretation of monitoring results involves statistical tools and water quality models to identify trends, patterns, and anomalies. Data are compared with environmental quality standards established in legislation to assess the river's status and identify areas of concern (European Commission, 2018). The information obtained is used to inform decisions on the implementation of management measures, such as improvements to wastewater treatment, implementation of stormwater retention systems, and restoration of riparian habitats (U.S. Environmental Protection Agency, 2013).

The dissemination of water quality information is a fundamental aspect of monitoring. Results are made available to the public through various channels, including the websites of the APA and municipal councils, environmental information platforms, and technical reports. This transparency allows citizens to track the evolution of the river's health, participate in environmental management, and advocate for protection and restoration measures.

In Portugal, the responsibility for water quality monitoring, encompassing urban rivers, largely falls upon the Portuguese Environment Agency (APA) through the National Water Resources Information System (SNIRH). This nationwide monitoring effort is of paramount importance for the effective management and protection of Portugal's aquatic ecosystems. It provides crucial data for assessing the overall health of water bodies, identifying pollution hotspots, tracking the effectiveness of environmental policies, and ensuring compliance with both national and European legislation related to water quality.

The SNIRH and the APA play a pivotal role in Portugal's national water monitoring framework. The SNIRH (Sistema Nacional de Informação de Recursos Hídricos) serves as the central hub for the collection, storage, processing, and dissemination of comprehensive water-related information across the country. This platform compiles a wide range of data, including raw monitoring results for surface and groundwater quality—covering physical-chemical, microbiological, and hydrological parameters—as well as synthesized information, cartographic outputs, and integrated assessments of water body status (Agência Portuguesa do Ambiente [APA], 2024; Bluefocus, 2003).

As the national environmental authority, the APA is responsible for designing and managing the monitoring networks that feed into SNIRH. This includes ensuring that data collection and analysis protocols follow standardized methodologies, in compliance with

European and national legislation. The data collected through these networks—comprising over 1,500 stations and more than 250 parameters—is made publicly accessible through the SNIRH platform, supporting transparency, public participation, and informed decision-making (APA, 2024; APA, n.d.-a; APA, n.d.-b).

Within the National Water Resources Information System (SNIRH), various parameters were analyzed for specific monitoring points strategically selected and its surrounding environment, such as points situated near the coastline where the stream's influence may be observed.

On the SNIRH portal, it is possible to find information about all the parameters analyzed, as well as the number of samples and the analysis period, as shown in Figure 3.

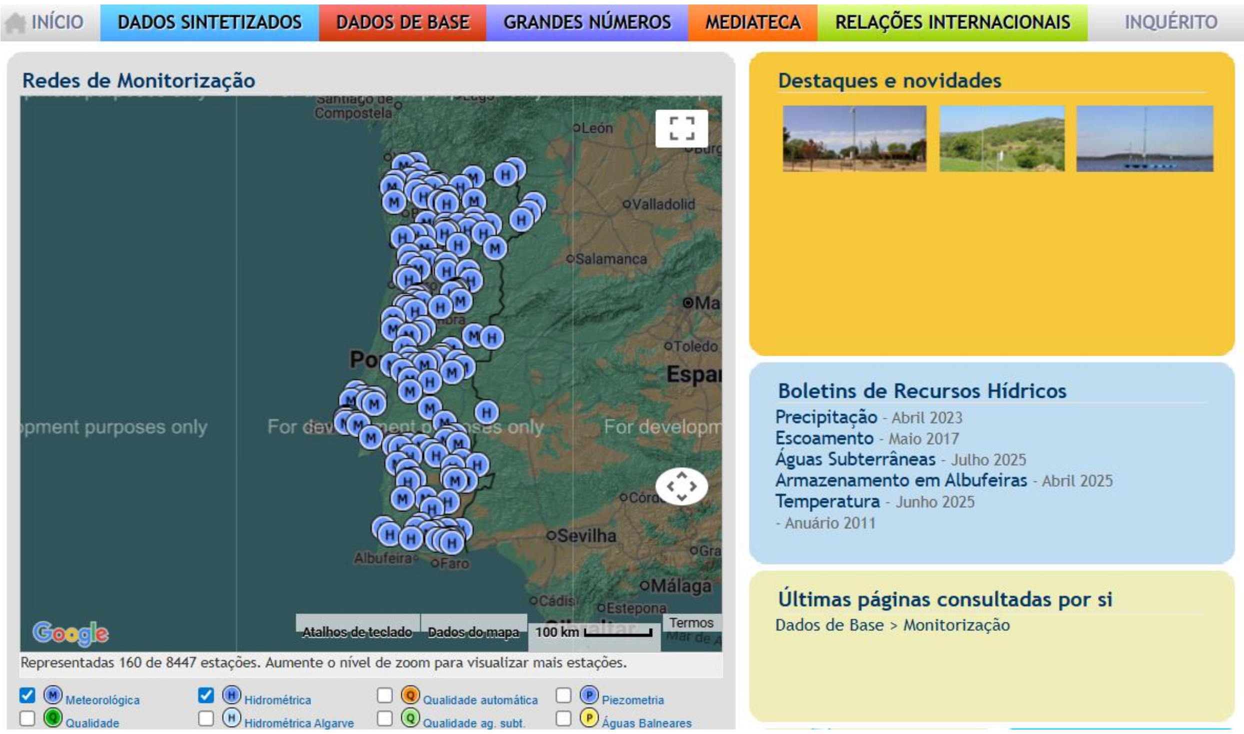

Figure 3: Parameters monitored by SNIRH for the three stations near the study area.

In summary, the monitoring of water quality in urban rivers is a complex and essential process for the protection of these ecosystems. The data obtained through monitoring is fundamental for informed decision-making and the implementation of effective management measures, ensuring public health, environmental protection, and the sustainability of water resources.

3.3 Water quality and Pollution

Currently, this coastal region, and particularly its local streams, are under intense investigation and study due to the consistent detection of microbiological and physicochemical parameters that exceed the limits established by the environmental quality standards of the national legislation. This situation has generated significant concerns regarding public health reports, with cases of people potentially harmed and contaminated after contact with these waters or adjacent areas. It is suspected that there has been the influence of untreated urban and industrial discharges as potential sources of this contamination, impacting not only the health of aquatic ecosystems but also the well-being of local communities and the quality of nearby bathing areas. The urgent need to identify the sources of pollution and implement effective corrective measures has made these streams a priority focus for environmental and public health authorities in the region.

Sampling campaigns have been conducted by the management utility, at several locations along the watercourse. The objective of these efforts is to analyze the concentrations of each parameter and delineate critical areas requiring subsequent remediation interventions.

Based on a detailed analysis of the temporal and spatial evolution of water quality at the 12 sampling points defined along the river course, consistent patterns of microbiological contamination were identified in specific sections. This analysis included the assessment of fecal indicator concentrations, namely *Escherichia coli* and *Enterococci*, over different seasonal periods, allowing for the observation of variations associated with land use characteristics and urban density at each location.

From the results obtained, four critical zones were identified, exhibiting persistently high levels of these microbiological parameters, posing a greater risk to public health and ecological balance. These areas largely coincide with zones of higher urbanization and potential irregular discharge of wastewater. Clearly identifying these contamination hotspots represents a crucial step toward defining targeted and effective corrective measures, such as structural interventions and intensified monitoring actions.

From these samples, it was possible to obtain values for the key microbiological indicators *Enterococcus* and *E. coli*. The microbiological quality graphs for the watercourse indicate that sampling points P1, P3, P7, and P12 show elevated concentrations of *E. coli* and Enterococcus. The figure 4 below illustrates the scenario for Point 1.

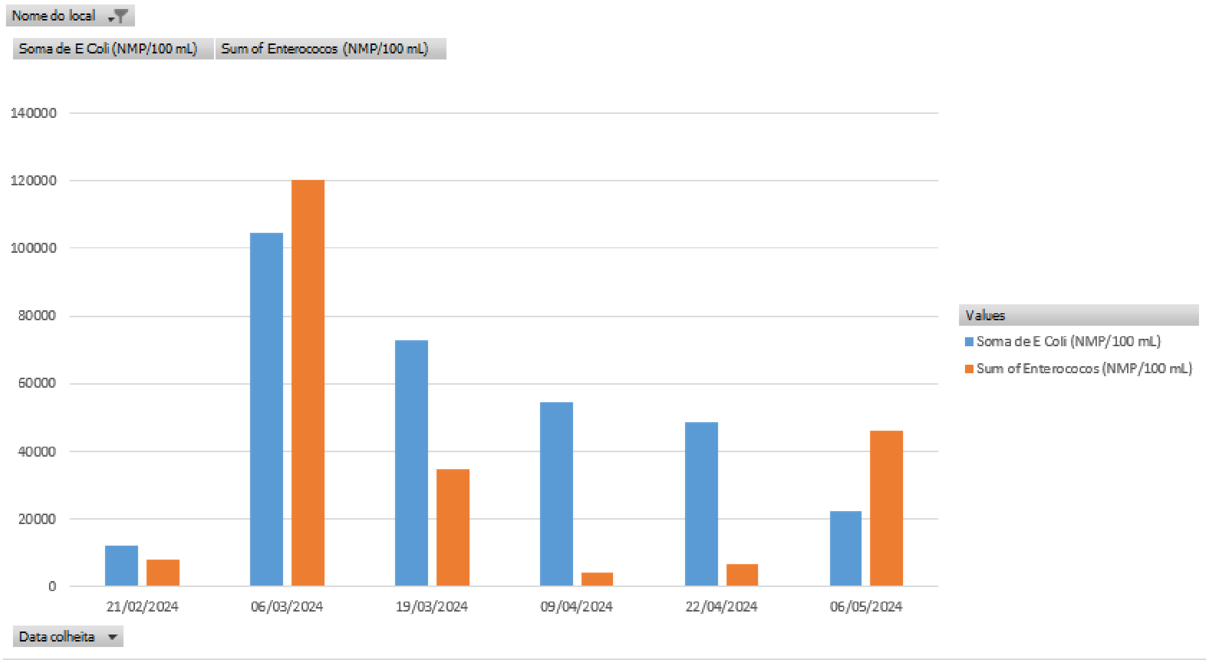

Figure 4: Values for Point 1

At sampling point 1, *Escherichia coli* concentrations reached up to 104,600 MPN/100 mL, while *Enterococci* levels peaked at 120,300 MPN/100 mL. These values greatly surpass the current Portuguese legal thresholds for bathing waters, established under Decree-Law No. 113/2012 (Diário da República, 2012), which amends Decree-Law No. 135/2009.

For point 3, the values were recorded and shown in the figure 5:

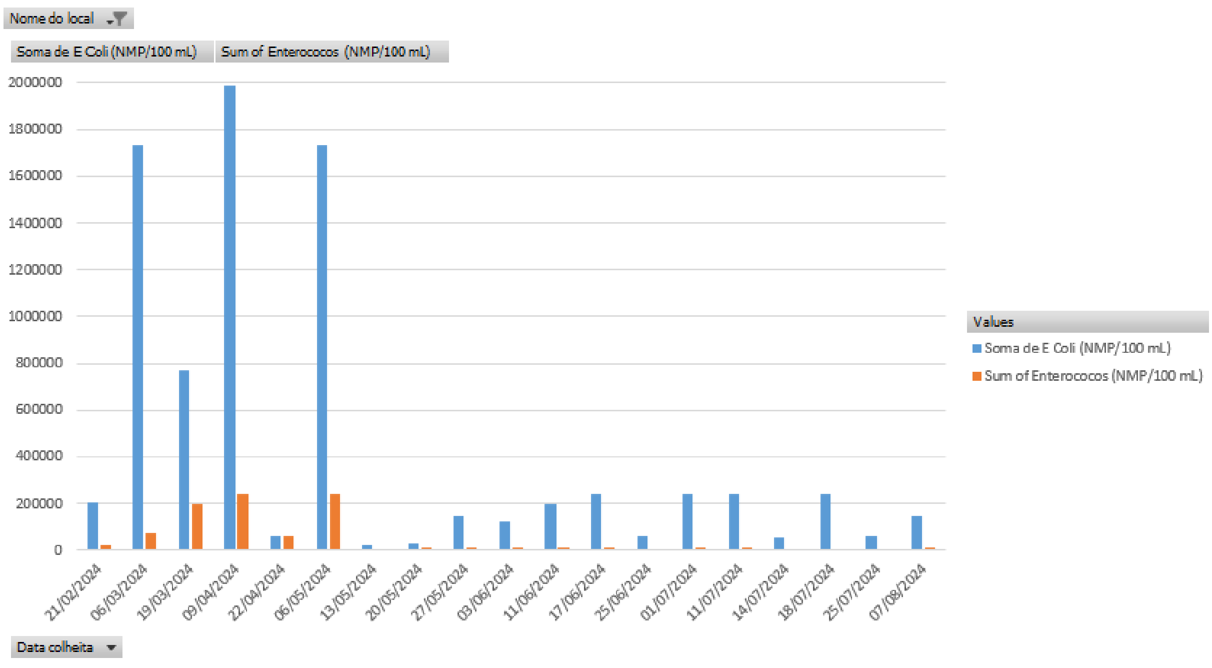

Figure 5: Values for Point 3

At sampling point 3, *Enterococci* concentrations reached up to 240,000 MPN/100 mL, while *Escherichia coli* levels peaked at an extremely high 1,986,000 MPN/100 mL. These values far exceed the current Portuguese legal thresholds for waters as established under Decree-Law No. 135/2009 (Diário da República, 2009).

Through graphical analysis, the following values were observed for point 7, illustrated by the figure 6:

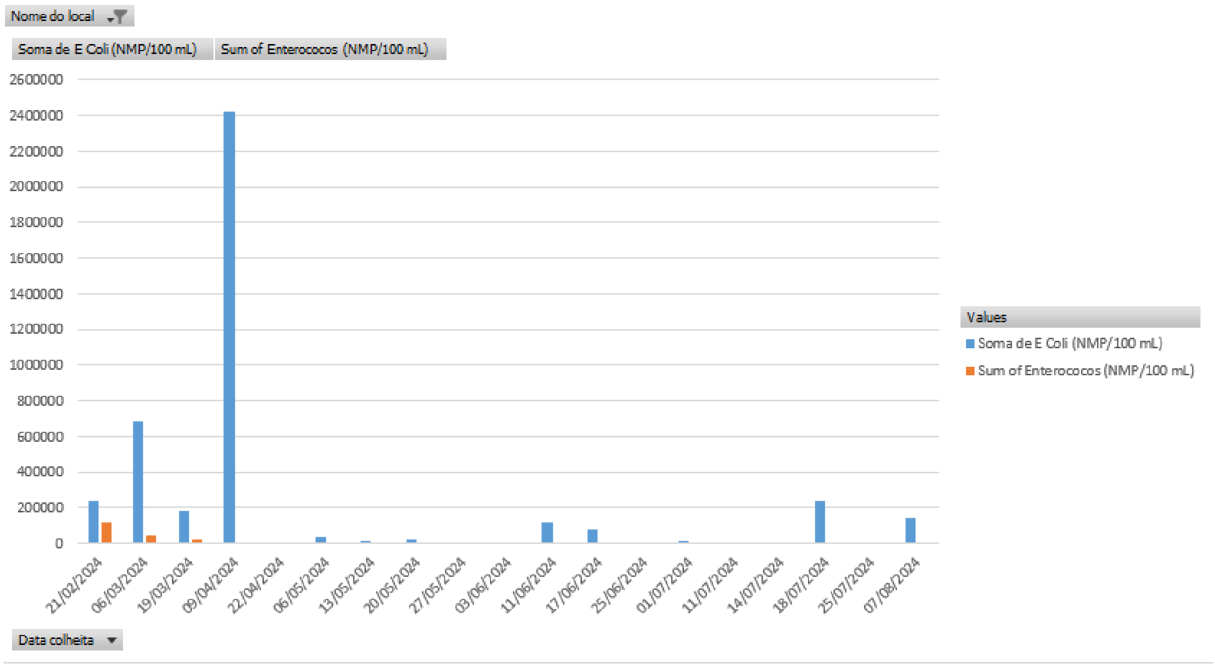

Figure 6: Values for Point 7

At sampling point 7, *Enterococci* levels reached up to 120,300 MPN/100 mL, while *Escherichia coli* concentrations soared to an alarming 2,420,000 MPN/100 mL. These measurements greatly surpass the permissible limits established by Portuguese legislation for bathing waters, specifically outlined in Decree-Law No. 135/2009 (Diário da República, 2009).

Finally, the fourth point selected among the four most critical zones was point 12, where the following values were recorded. Figure 7 below shows the values for point 12.

At sampling point 12, Enterococci concentrations peaked at 66,000 MPN/100 mL, while Escherichia coli levels reached a critical high of 2,400,000 MPN/100 mL. These figures far exceed the legal thresholds set forth in Portuguese legislation for recreational waters, as detailed in Decree-Law No. 135/2009 (Diário da República, 2009).

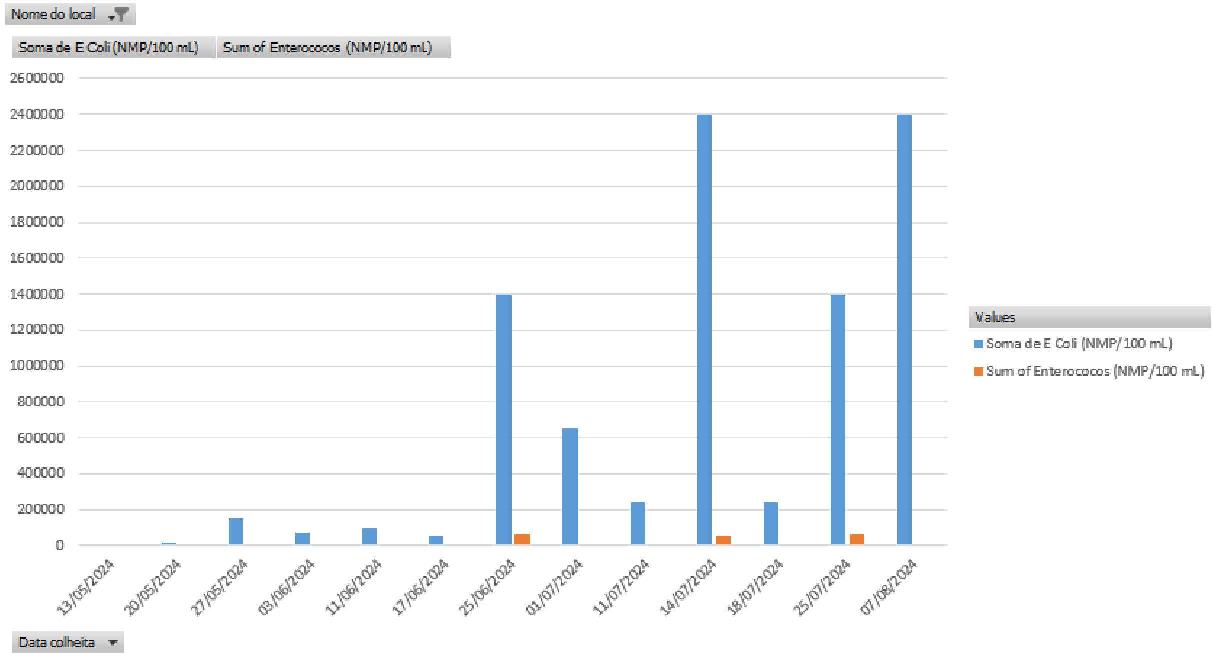

Figure 7: Values for Point 12

When analyzing the concentrations of *E. coli* and Enterococci at the four critical sampling points, and comparing them with the limits established by Decree-Law No. 135/2009, it becomes clear that the observed values significantly exceed the thresholds defined by legislation. As can be seen in Table 1 below.

Table 1: Legal requirements for Microbiological Parameters

	Parameter	Maximum Allowed Value (Excellent Quality)	Maximum Allowed Value (Good Quality)	Units	Legal Requirements
Coastal Bathing Water	E. coli	≤ 250	≤ 500	CFU/100 mL	Decree-Law 135/2009
	Intestinal Enterococci	≤ 100	≤ 200	CFU/100 mL	Decree-Law 135/2009
Inland Bathing Water	E. coli	≤ 500	≤ 1,000	CFU/100 mL	Decree-Law 135/2009
	Intestinal Enterococci	≤ 200	≤ 400	CFU/100 mL	Decree-Law 135/2009

This exceedance highlights the severity of microbiological contamination at these critical points and reinforces the need for urgent and targeted intervention measures to mitigate public health risks and improve water quality.

Through the investigation and the collected samples, it was also possible to determine values for various physicochemical parameters, such as Total Organic Carbon, BOD_5, COD, dissolved oxygen, and water conductivity (Table 2). These values were provided by the municipal authority responsible for managing the stream, further supporting the analysis and interpretation of the water quality conditions.

Physicochemical Parameters						
Date	Sample points	Total Organic Carbon (mg/L)	BOD5 (mg/L)	COD (mg/L)	Dissolved Oxygen (mg/L)	Conductivity at 20°C (µS/cm)
Legal Requirements		≤ 5	≤ 3	≤ 35	6.0-8.0	300-800
24/07/2024	Ribeira - Montante	3.43	< 3	< 35	6.9	403
07/08/2024	Ribeira - Montante	30.4	< 3	< 35	7.3	421
28/08/2024	Ribeira - Montante	15	< 3	< 35	8.1	410
11/09/2024	Ribeira - Montante	2.25	< 3	< 35	8.5	433
24/07/2024	Ribeira - Jusante	4.03	< 3	< 35	8	445
07/08/2024	Ribeira - Jusante	29.3	< 3	< 35	6.8	429
28/08/2024	Ribeira - Jusante	4.14	< 3	< 35	7.9	391
11/09/2024	Ribeira - Jusante	3.75	< 3	< 35	8	401
24/07/2024	Ribeira - Intermédia	5.06	< 3	< 35	7.9	549
07/08/2024	Ribeira - Intermédia	22.2	< 3	< 35	6.9	447
28/08/2024	Ribeira - Intermédia	5.03	< 3	< 35	8	589
11/09/2024	Ribeira - Intermédia	2.25	< 3	< 35	8.5	559

Table 2: Physicochemical Parameters in the stream.

The Total Organic Carbon (TOC) values observed in the samples ranged from 2.25 to 30.4 mg/L, revealing considerable variation across dates and sampling points. According to Decree-Law No. 236/98, the recommended threshold for TOC in surface waters intended for abstraction and conventional treatment (Class A1) is ≤ 5 mg/L. Based on APA technical references and national water quality frameworks, TOC concentrations can generally be interpreted as follows:

- ≤ 5 mg/L – *Good/Acceptable quality*
- 5–10 mg/L – *Moderate/Sufficient quality*
- > 10 mg/L – *Poor quality*, indicating potential organic pollution.

In this context, several values—particularly the 30.4 mg/L and 29.3 mg/L recorded on August 7th at upstream and downstream points—fall into the *poor-quality* category, exceeding both the legal and referential thresholds. These elevated concentrations suggest a substantial input of untreated or insufficiently treated organic matter, likely from urban runoff or illegal discharges. Conversely, lower TOC readings, such as those between 2.25 and 5.06 mg/L, align with the *acceptable* category and may reflect temporary improvements in water quality, seasonal dilution, or reduced pollutant input.

Overall, the presence of such elevated TOC peaks highlights the urgent need for strengthened pollution control, targeted remediation, and continued water quality monitoring to safeguard ecosystem and public health.

The Biochemical Oxygen Demand over 5 days (BOD_5) values recorded in the analyzed samples were consistently reported as < 3 mg/L, across all sampling points and dates. According to Decree-Law No. 236/98, for surface waters intended for abstraction and treatment for human consumption (Class A1), the maximum allowable BOD_5 is 3 mg/L. Similarly, APA technical guidance classifies BOD_5 values as follows:

- ≤ 3 mg/L – *Good/Acceptable quality*
- 3–6 mg/L – *Moderate/Sufficient quality*
- > 6 mg/L – *Poor quality*, indicating elevated levels of biodegradable organic matter.

The consistent readings of < 3 mg/L suggest that the sampled waters maintain a good level of organic matter decomposition, with relatively low oxygen demand. This indicates limited presence of readily biodegradable pollutants and, from a biochemical perspective, reflects a positive status in terms of water quality.

The Chemical Oxygen Demand (COD) measures the amount of oxygen required to chemically oxidize organic and inorganic substances in water, offering a broad indication of pollution levels. Under Decree-Law No. 236/98, the acceptable limit for COD in surface waters intended for abstraction for human consumption after conventional treatment (Class A1) is ≤ 35 mg/L.

According to APA technical guidelines and national monitoring practices, COD water quality thresholds can be interpreted as:

- ≤ 35 mg/L – *Good/Acceptable quality*
- 35–75 mg/L – *Moderate/Sufficient quality*
- > 75 mg/L – *Poor quality*, indicating a high load of oxidizable pollutants.

In the present dataset, all COD values were reported as < 35 mg/L, placing them within the *acceptable quality* range as defined by Portuguese legislation. This suggests that, during the sampling period, the water in the studied sections of the stream did not exhibit excessive levels of chemically oxidizable pollutants such as industrial effluents, synthetic compounds, or persistent organic substances.

Regarding Dissolved Oxygen (DO), this parameter is crucial for maintaining the ecological integrity of aquatic systems, as it directly influences the survival of aerobic organisms. According to Decree-Law No. 236/98, which establishes water quality standards in Portugal, a minimum concentration of 5 mg/L is required for surface waters classified as A1 (intended for drinking water with simple treatment). However, environmental monitoring guidelines and APA reports generally consider values above 6 mg/L as *good*, with concentrations exceeding 7 mg/L often classified as *excellent*. Values between 4 and 5 mg/L are typically interpreted as *sufficient*, while those below 4 mg/L indicate ecological stress, and levels under 3 mg/L are associated with hypoxic conditions that may threaten aquatic biodiversity. In the sampling data analyzed, DO levels ranged from 6.8 to 8.5 mg/L, consistently above the regulatory minimum and indicative of *good to excellent* oxygenation status, suggesting a favorable condition for aquatic life in terms of oxygen availability.

The conductivity values measured across the three sampling locations ranged from 391 to 589 µS/cm, falling within the generally acceptable range for urban surface waters. Although Portuguese legislation, namely Decree-Law No. 236/98, does not establish a fixed maximum threshold for electrical conductivity in surface waters, reference values provided by the Portuguese Environment Agency (APA) suggest that levels between 300 and 800 µS/cm are typically considered acceptable in urban contexts. These values indicate a moderate presence of dissolved salts and are not, by themselves, indicative of severe pollution. However, consistent readings above 500 µS/cm may reflect anthropogenic influence, such as urban runoff or residual discharges, especially when accompanied by elevated organic matter or microbiological indicators. Therefore, while the measured conductivity values do not raise immediate legal concerns, they warrant continuous monitoring to ensure early detection of any deterioration in water quality.

3.4 Critical Zones

Considering the elevated concentrations of *E. coli* and *Enterococcus* detected at sampling points P1, P3, P7, and P12, it was possible to indicated in yellow, in Figure 8 below, the most critical zones in terms of contamination, where a significant increase in the concentration of these microbiological parameters occurs.

Figure 8: The most critical zones in terms of contamination

The persistence of such high values in these locations suggests the occurrence of continuous or intermittent pollution sources, resulting in a significant increase in the concentration of these microbiological parameters along these specific segments of the watercourse. The presence of these microorganisms at high levels may pose a risk to public health and the environmental quality of the stream, requiring further investigation to identify the sources of contamination and implement effective corrective measures.

3.5 Mapping

To have a more comprehensive understanding of the critical points within the stream, the Google Earth Engine (GEE) platform was utilized for detailed mapping and analysis. By leveraging GEE's capabilities, we were able to pinpoint and analyze the specific characteristics of these critical sections, providing invaluable insights for targeted interventions and the strategic placement of monitoring and treatment technologies.

Following the detailed mapping and analysis using the Google Earth Engine (GEE), it was observed that points 1 and 3 of the stream are located within dense urban areas, flowing beneath streets and heavy traffic. Figure 9 below represents the surrounding area of point 1.

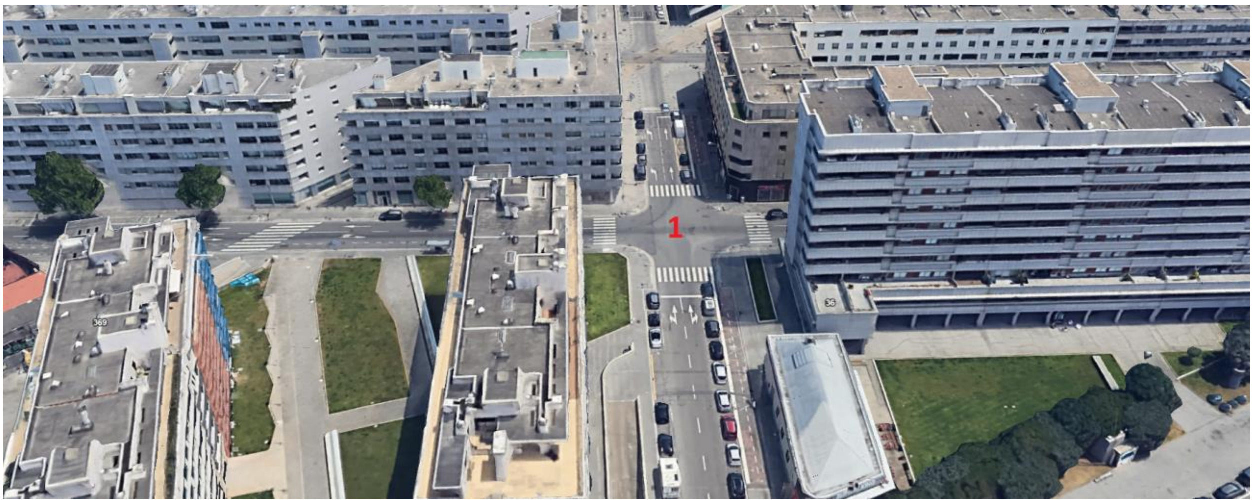

Figure 9: Panoramic view of point 1 (Google Earth Engine).

Similar to Point 1, Point 3 is also situated in an extremely urbanized area, surrounded by buildings and flowing beneath heavy traffic, as indicated in Figure 10:

Figure 10: Panoramic view of point 3 (Google Earth Engine).

Also considering the detailed mapping and analysis, particularly utilizing the Google Earth Engine (GEE) platform, it became clear that points 7 and 12 of the stream are situated in more open and green areas. Figure 12 illustrates the characteristics of point 7, where it's visible that the stream passes beneath a roundabout. This location features both a green area and a sandy patch.

Figure 11: Surrounding view of point 7 (Google Earth Engine).

For Point 12, it's visible that although it passes through an area near residential buildings, it consists of open, green terrain, which also facilitates the implementation of daylighting, as shown on figure 13.

Figure 12: Surrounding view of point 12 (Google Earth Engine).

Beyond its intrinsic characteristics, point 2 was also selected for a detailed mapping due to your geography, it is an important point of the stream due to its proximal location to the discharge zone. This strategic positioning ensures that an intervention in this point would be significantly positive to the stream, and the treated water, with its reduced microbial load, directly benefits the receiving environment, maximizing the impact on water quality where it matters most. The figure 13 below shows the panoramic view of point 19.

Figure 13: Panoramic view of point 12 (Google Earth Engine).

3.6 Challenges and Measures:

Having gained a comprehensive understanding of the context surrounding each critical point through detailed spatial analysis, it is now possible to formulate targeted strategies and measures that are specifically tailored to the unique characteristics of each location.

This stream faces significant challenges that sustain a comprehensive approach that includes effective stormwater management and public engagement. Inadequate stormwater management is a major contributor to the urban streams pollution, particularly during periods of intense rainfall. The rapid flow of rainwater over impervious urban surfaces carries a multitude of pollutants, including heavy metals, hydrocarbons, and debris, directly into the river. To mitigate this, the implementation of sustainable drainage systems (SuDS) is crucial. These systems, such as green roofs, permeable pavements, and bioretention basins, are designed to mimic natural hydrological processes, reducing runoff volume and filtering pollutants before they enter the river.

This dynamic is particularly evident in the case of the stream studied, where water quality is closely tied to rainfall patterns. During storm events, the stream receives abrupt inflows of runoff that carry accumulated pollutants from urban surfaces, resulting in sudden spikes in contamination levels. This "first flush" effect leads to elevated concentrations of nutrients, pathogens, suspended solids, and chemical substances that degrade aquatic health and compromise downstream ecosystems, including nearby recreational coastal waters. Monitoring data consistently show that periods of high precipitation correspond with increased turbidity, reduced dissolved oxygen, and higher levels of microbial contamination in the stream. Therefore, establishing a clear link between pluviometric events and water quality is essential to inform targeted interventions. Integrating stormwater management with nature-based solutions, such as SuDS, not only reduces pollutant loads but also fosters greater public awareness and community involvement in protecting urban waterways.

Alongside technical solutions, raising public awareness and promoting environmental education are fundamental to safeguarding the watercourse. Public engagement can significantly reduce pollution and foster sustainable practices among residents and businesses. Environmental education campaigns can take various forms, including workshops, community clean-up events, and educational programs in schools. These initiatives can highlight the importance of responsible waste disposal, the impact of household chemicals on water quality, and the benefits of water conservation. Furthermore, public awareness campaigns can leverage social media and local media outlets to disseminate information about the river's ecological significance and the actions individuals can take to protect it. By fostering a sense of ownership and responsibility, these initiatives can empower communities to become active stewards of the brook.

Despite the significant pollution challenges this urban aquatic ecosystem faces, its long-term sustainability critically depends on active public involvement. Continuous monitoring, the implementation of appropriate management measures, and public engagement are essential to protect this watercourse and ensure the water quality of the adjacent coastal zone. Effective stormwater management, through the implementation of sustainable drainage systems, and robust wastewater treatment, combined with comprehensive public awareness and education programs, are crucial for the long-term health and sustainability.

Based on the characteristics of the study case and the current water quality situation, the measures presented in the following subchapters can be recommended.

3.6.1 Video inspections

For specific critical points such as points 1 and 3, the most viable and recommended approach involves regular video inspections and surveys to monitor their condition, identify potential issues, and ensure proper maintenance.

Conducting surveys and video inspections in the most critical stretches, identified by the elevated concentrations of *E. coli* and enterococci, represents the application of a crucial improvement measure. This proactive approach will allow for the direct visualization of potential irregular discharges, sewer network ruptures, improper connections, or other anomalies that may be contributing to the persistent contamination in the stream.

Specialized cameras designed to operate underwater are used. The camera is carefully launched into the stream or waterway (Figure 11). Depending on the equipment and the characteristics of the location, these cameras can be mounted on remotely operated vehicles (ROVs), aquatic drones, or on cable and extendable pole systems.

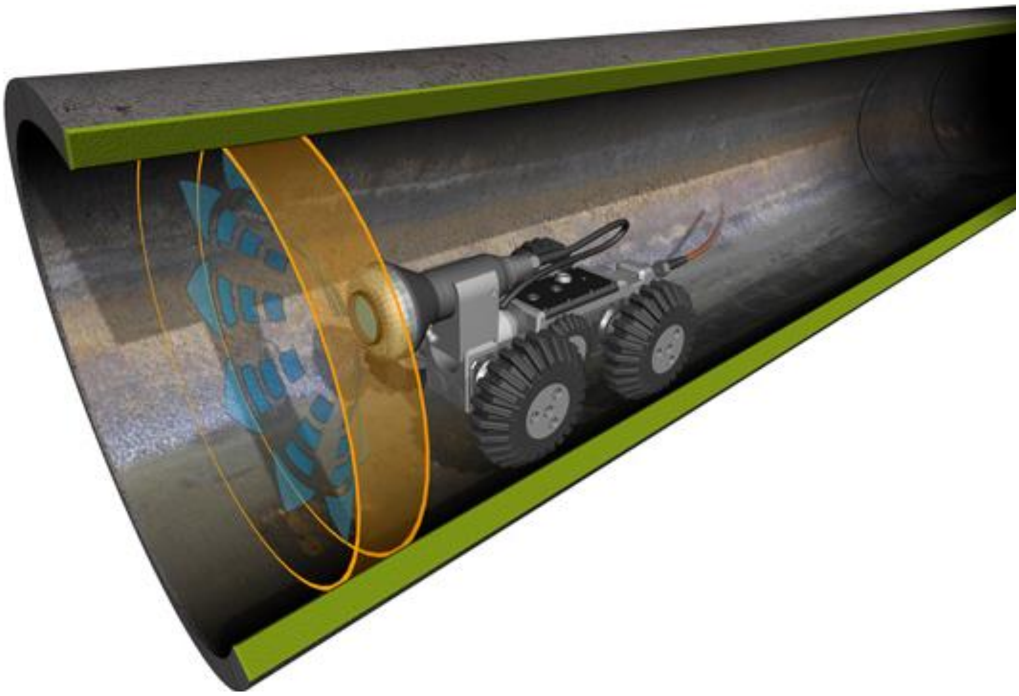

Figure 14: Robot operation mode from Camilo de Souza Mota & Filhos (2024).

The implementation of a video inspection plan in the most critical sections, specifically points 1 and 3, will allow obtaining crucial results for the identification of pollution source points. The main benefits of the procedure are:

- Accurate and Comprehensive Identification of Illicit Connections:
  - Exact location: Video inspection will allow mapping the precise location of all domestic or industrial sewage connections that are improperly discharging into the storm drain or directly into the river. This precision is vital for planning corrective interventions (Smith & Johnson, 2020).
  - Quantification and characterization: It will be possible to determine the number, type (domestic, industrial), and, in some cases, the approximate volume of illicit discharges, providing essential data for prioritizing remediation actions (Doe et al., 2019).

➢ Detailed Infrastructure Diagnosis:

- Structural assessment: The camera will reveal cracks, ruptures, corrosion, root intrusions, or other structural damage to the collectors that may be allowing sewage to infiltrate the soil or overflow into the stream (Brown, 2021).
- Obstructions and accumulations: Identification of obstructions (sediment, grease, debris) that may be causing accumulations and overflows of wastewater (Green & White, 2018).

➢ Support for Decision Making:

- The visual and georeferenced data from the inspections will provide the basis for creating a phased intervention plan, prioritizing the most urgent repairs with the greatest impact on reducing pollution (Taylor, 2022).

- It will allow validating the effectiveness of previous interventions and detecting the reappearance of problems (Miller & Clark, 2020).

Detailed information obtained through video inspections is essential for the development and implementation of effective and targeted corrective measures, aiming to improve water quality and mitigate risks to public health and the environment. In the context of the case study, such inspections will be particularly important at points 3 and 1, as these correspond to highly urbanized areas where diffuse pollution is more likely.

Given the recorded high concentrations of *Escherichia coli* and intestinal enterococci at these locations, the identification of structural failures or illicit discharges through video inspection will support more informed and precise decision-making.

The cost of video inspection can range from €2 to €8 per linear meter, depending on the pipe diameter, depth, complexity of access, and the need for prior cleaning (Water Environment Federation, 2014). For critical sections that may total several kilometers, the initial investment for a comprehensive inspection campaign could range from €20,000 to €200,000, depending on the extent and density of the network to be inspected (European Commission, 2018). However, these are diagnostic costs that prevent much larger expenditures on unnecessary or ineffective interventions (U.S. Environmental Protection Agency, 2013). The main implementation costs are:

- Equipment Costs: If the managing entity doesn't own the equipment, there will be the cost of acquisition (inspection cameras, robots, recording and analysis software) or, more commonly, the cost of contracting specialized services (Water Environment Federation, 2014).

- Labor Costs: Specialized technicians are needed for operating the equipment and analyzing the images (U.S. Environmental Protection Agency, 2013).
- Preparation Costs: Prior cleaning of the sections to be inspected (de-obstruction, sediment removal) is necessary to ensure camera visibility (European Commission, 2018).
- Data Processing Costs: This includes the analysis, cataloging, and georeferencing of detected anomalies (International Society of Automation, 2015).

3.6.2 Daylighting

Critical points such as Points 7 and 12 seem suitable sites for the implementation of daylighting. These characteristics are essential for the implementation of daylighting projects, as they provide ideal conditions for exposing and restoring previously culverted or hidden sections.

Implementing daylighting at points 7 and 12 of the stream has the potential to generate a robust set of benefits, leading to measurable improvements in water quality and the urban environment.

The long-term benefits, particularly the ecological, social, and public health advantages, significantly outweigh the initial costs when properly valued. For example, reducing microbiological contamination not only protects the health of bathers and the community but also lessens the burden on wastewater treatment plants and reduces the need for expensive corrective interventions in the future.

Furthermore, daylighting significantly enhances the ease and continuity of control, vigilance, and monitoring. With the stream exposed, visual inspections become straightforward, allowing for immediate identification of pollution sources or anomalies. This increased visibility facilitates regular sampling and the deployment of continuous monitoring equipment, leading to more accurate and timely data on water quality. Ultimately, daylighting transforms the stream into a more accessible and manageable system for ongoing environmental oversight.

Daylighting involves exposing sections of waterways that were previously culverted or buried in conduits, returning them to their natural, surface-level course. This intervention transforms a closed drainage infrastructure into an open fluvial ecosystem, integrated directly into the urban landscape (Figure 14).

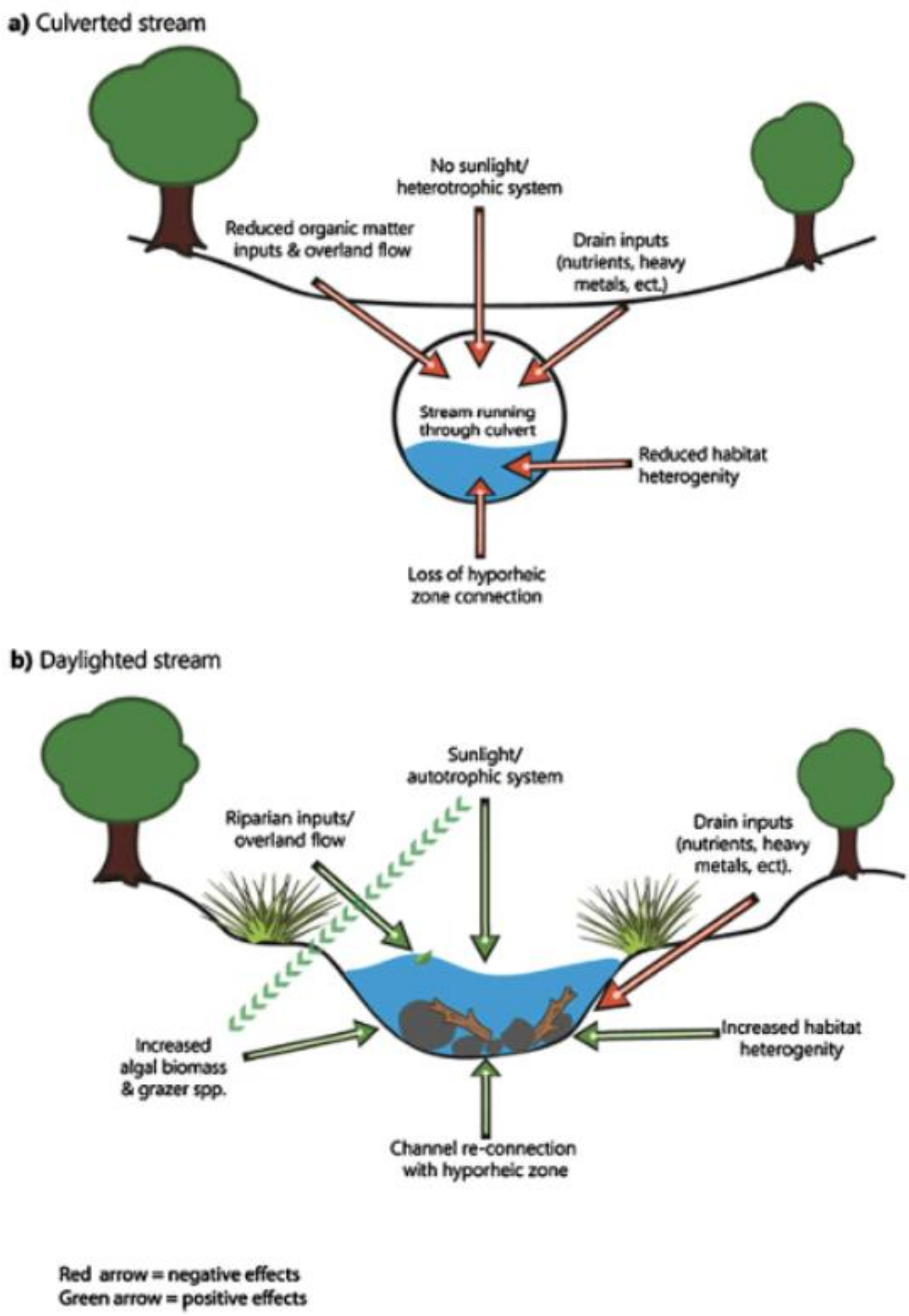

Figure 15: Benefits and examples of river and stream daylighting. From NUWAO (n.d.).

Implementing daylighting projects is a strategic and highly beneficial approach that has the potential to generate a robust set of advantages, leading to measurable improvements in both water quality and the urban environment. The main benefits of this approach are:

- Reduction of Microbiological Load
    - Significant reduction in the concentrations of Escherichia coli and Enterococcus in the intervened sections and downstream. Exposure to sunlight (natural UV) and the

aeration inherent to an open watercourse are powerful and continuous disinfection mechanisms. This reduction will be quantifiable through periodic monitoring of water quality.

- Greater oxygenation and the presence of biological processes in the bed and banks will contribute to the degradation of organic matter that serves as a substrate for bacterial growth.

➢ Improvement of Physical-Chemical Parameters

- Significant increase in Dissolved Oxygen (DO): Contact with the atmosphere will promote reoxygenation of the water, raising DO levels and bringing them closer to the requirements for healthy aquatic life.

- Reduction of BOD5 and COD: The greater availability of oxygen and the biological self-purification processes will lead to a decrease in the Biochemical Oxygen Demand (BOD5) and Chemical Oxygen Demand (COD) values, indicating a lower organic load in the water.

- Conductivity Moderation: Although more influenced by geology and pollution sources, a healthier environment and the removal of potential illicit discharges associated with plumbing can lead to a stabilization or slight improvement in conductivity values.

➢ Ecological and Environmental Benefits:

- Recovery of Aquatic and Riparian Biodiversity: The creation of a functional river ecosystem will attract fish, aquatic insects, birds and will enable the establishment of native vegetation on the banks, promoting local biodiversity.

- Habitat Creation: Renaturalizing the watercourse creates habitats for native flora and fauna (fish, amphibians, insects, birds), increasing local biodiversity.

- Water-Landscape Reconnection: Integration of the river as a natural and visible element in the urban fabric, contributing to water resilience and rainwater management, with greater infiltration and retention capacity.

- Thermal Regulation: Vegetation and the presence of water contribute to reducing the urban "heat island" effect, improving thermal comfort in surrounding areas.

- Social and Urban Benefits:

  - Real Estate and Tourism Value: Environmental and landscape requalification tends to increase the value of adjacent properties and attract visitors.

  - Environmental Education and Awareness: The visibility of the river and its improvement offer educational opportunities for the local community on the importance of water and environmental protection.

  - Flood Risk Reduction: A natural riverbed, with wider banks and vegetation, can increase water retention and infiltration capacity, helping to manage runoff volumes and reduce the risk of flooding in extreme events.

Additionally, opening the watercourse through daylighting facilitates gas exchange with the atmosphere, significantly increasing dissolved oxygen levels. This enhancement is essential for the health of the aquatic ecosystem and accelerates natural self-purification processes. By allowing sunlight to penetrate the water, daylighting promotes photosynthesis, further benefiting aquatic life and improving overall water quality (American Rivers, 2016; Wisconsin DNR, 2016).

The combination of these factors contributes to a significant reduction in the microbiological load, making the water safer for the environment and for potential downstream uses.

Beyond the direct benefits in microbiological treatment, daylighting at these specific points—namely points 7 and 12—offers an important advantage regarding the detection and prevention of pollution and promotes aesthetic and social enhancement. According to American Rivers (2016), daylighting not only improves water quality but also revitalizes urban areas, making them more attractive and accessible to the community. Figure 15 illustrates an example of an urban river daylighted.

Opening the watercourse in the sections—particularly at points 7 and 12—greatly enhances the visibility and accessibility of the stream, allowing clandestine sewage connections and other irregular discharges to be more easily detected by the competent authorities. In densely built-up environments where drainage networks are often complex and partially concealed, this increased transparency is especially valuable. It facilitates the rapid identification of pollution sources, supports more efficient corrective interventions, and reinforces accountability mechanisms, contributing to the long-term preservation of water quality and ecological function.

Figure 16: Stream daylighted (Halff, 2018).

Although river *daylighting* can offer significant ecological and urban benefits, it also carries potential drawbacks if not carefully planned. Key concerns include increased flood risk in densely built environments, disruption or removal of existing infrastructure, high implementation and maintenance costs, and temporary negative impacts such as noise, dust, and traffic diversion during construction. Moreover, re-exposing polluted waterways without concurrent remediation efforts can lead to unpleasant odors, vector proliferation, and community opposition. Therefore, the success of daylighting projects depends on an integrated approach that considers local hydrology, water quality, and the surrounding urban context.

While the initial investment for daylighting can be substantial, a thorough techno-economic analysis must adopt a life-cycle perspective. This implementation must be supported by an analysis that considers the costs of implementation versus the long-term benefits, both those quantifiable monetary and those of intangible value.

The main implementation costs are:

- Demolition Costs: Removing existing channelized structures like conduits, cover slabs, and retaining walls (European Commission, 2018).
- Excavation and Bed Remodeling Costs: Shaping the streambed and banks to create a natural and functional profile (Fletcher et al., 2013).

- Construction Costs: Earthworks, installation of natural substrates, erosion control elements, and planting of riparian vegetation (Palmer et al., 2010).
- Adjacent Infrastructure Costs: Adapting surrounding infrastructure, including sanitation networks, bridges, access points, and urban landscaping (walkways, lighting, street furniture) (U.S. Environmental Protection Agency, 2013).
- Contaminated Sediment Management Costs: If excavation uncovers sediments with high pollutant levels, there will be additional costs for their removal, treatment, or proper disposal (Mason et al., 2016).
- Licensing and Approval Costs: Navigating bureaucratic processes with relevant authorities (e.g., APA, City Council).

Urban daylighting projects can vary significantly in cost. For stream sections with the characteristics under study, the cost per linear meter can range from €1,500 to €5,000, depending on the complexity of excavations, the need for slope stabilization, and the adaptation of surface infrastructure. For the two proposed points, considering specific lengths (e.g., 50-100 meters per point), the initial investment could range from €150,000 to over €1,000,000. A detailed project study is crucial for a precise estimate. (Based on European River Restoration Cost Studies, such as those by JRC and MDPI, and experience in urban environmental engineering projects).

Ultimately, the implementation of daylighting represents an investment in environmental health and urban quality of life, transforming currently underutilized areas into greener, more resilient, and more pleasant spaces.

3.6.3 UV disinfection

Strategic points such as Point 2 seem perfect for the implementation of a disinfection system. This strategic positioning ensures that an intervention in this point would be significantly positive to the stream.

The installation of an ultraviolet (UV) disinfection system in the stream, combined with a protective grate to safeguard the equipment, can significantly improve water quality by eliminating harmful microbiological agents and promoting public health (U.S. Environmental Protection Agency, 2016). This implementation should be supported by a detailed cost-benefit analysis considering both the direct installation and operational costs and the environmental and social benefits resulting from improved water quality (World Health Organization, 2008).

A central pillar in treating microbiological parameters in wastewater is the implementation and evaluation of ultraviolet (UV) light disinfection technology.

However, before any advanced treatment can occur, particularly the implementation of a UV disinfection system, preliminary treatment through screening is essential. This crucial step involves the installation of screens or gratings at the entry point of the watercourse or treatment section. The primary purpose of this grading is to remove larger solid materials such as litter, branches, leaves, and other debris that could otherwise impede the proper functioning Without effective screening, these solids pose a significant risk. They can obstruct pipes and channels, leading to reduced flow rates and potential blockages. More critically, for a UV disinfection system, large solids can create shadowing effects, shielding microorganisms from the UV light and severely reducing the system's disinfection efficiency. Furthermore, abrasive materials can cause physical damage to the UV lamps and quartz sleeves, leading to costly repairs and downtime. Therefore, implementing robust screening is not merely a preliminary step, it's a fundamental requirement to ensure the longevity, efficiency, and overall success of the entire water treatment process, including the disinfection stage. Figure 17 shows a screen for pre-treatment.

Figure 17: Example of screening

For the case study, a partnership was established with the company *Linha d'Água Engenharia*, which provided technical support in designing a customized hydraulic screen. Based on the specific characteristics of the selected stream section, the company was able to appropriately size the screen to ensure effective performance and compatibility with the local hydraulic and environmental conditions.

The selected screen model, *HidroRake*, was designed to handle a treatment flow rate of approximately 14,400 m^3/h, with water surface and flow parameters calculated based on a velocity of 1 m^3/s. The unit features a monoblock design, with a channel width of 2,500 mm and a channel height of 4,000 mm. The estimated water surface level is 3,376 mm (subject to confirmation), and the discharge height from the support floor is 1,500 mm. The screen is installed at a 75º inclination, with 20 mm bar spacing. The frame of the filtering screen is made of U-folded sheet metal, and the bars have a length of 3,576 mm. The system includes a removable cleaning rake, guided by a 100x100x2 mm tube and supported by two guide bushings, ensuring efficient debris removal and system maintenance.

UV light disinfection is emerging as a crucial technology in current water resource management, particularly for urban streams. Unlike chemical methods that can create undesirable byproducts or have residual impacts on the aquatic environment, UV disinfection offers a physical, clean, and highly effective solution for inactivating a wide range of microorganisms (Sensorex, 2023), as illustrated in figure 18 below:

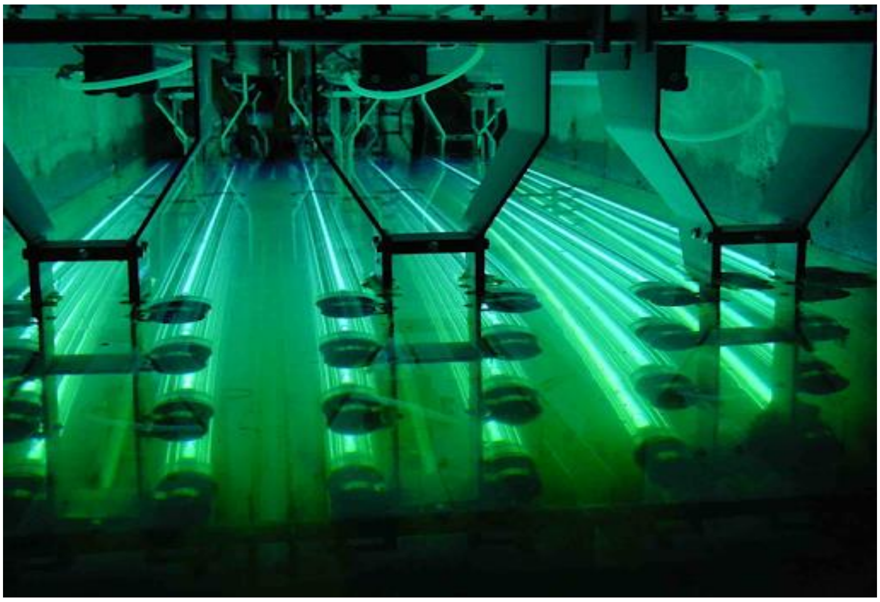

Figure 18: Example of UV lamps used for disinfection (water and Wastewater, 2020).

As referred previously, the presence of E. Coli and Enterococci in water bodies is a particular concern. While not all *E. coli* strains are pathogenic, their presence in aquatic environments strongly indicates fecal contamination. This, in turn, suggests the potential presence of other more virulent pathogenic microorganisms (like viruses and protozoa) that also reside in the human digestive tract. Similarly, Enterococci (such as *Enterococcus faecalis* and *Enterococcus faecium*) are bacteria found in the gastrointestinal tracts of humans and animals. They're recognized as reliable indicators of fecal contamination and are often preferred for recreational water testing due to their greater persistence in aquatic environments compared to *E. coli*.

By targeting the inactivation of fecal contamination indicators—*E. coli* and Enterococci—using UV light, the objective is to disrupt the microorganisms' genetic material (DNA or RNA), therebypreventing replication and, consequently, their capacity to cause infection, as illustrated in Figure 19.

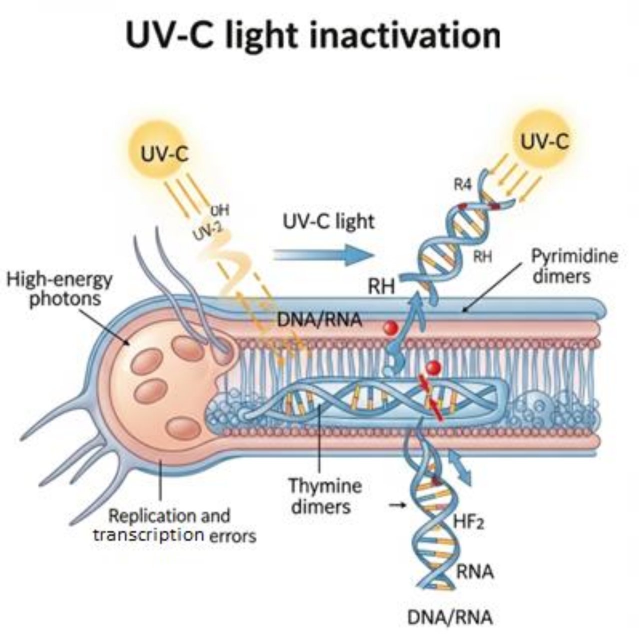

Figure 19: Process of inactivation (Google Images).

This technology represents a significant step forward in the pursuit of safer, ecologically balanced waters. It minimizes risks to public health and contributes to the revitalization of river ecosystems. Integrating UV disinfection into stream treatment systems not only optimizes the water's microbiological quality but also supports broader initiatives for restoring and preserving these valuable aquatic corridors (U.S. Environmental Protection Agency, 2022).

The power of UV light for disinfection lies in its ability to directly interfere with the genetic material (DNA and RNA) of microorganisms. Here's a breakdown of the process:

1. UV-C Spectrum: The disinfection process primarily uses ultraviolet C (UV-C) light, which is a specific wavelength (typically 200-280 nanometers, with 254 nm being highly effective) of the UV spectrum. Unlike UV-A and UV-B, UV-C light is largely absorbed by the Earth's atmosphere, but it can be generated artificially by specialized lamps (U.S. Environmental Protection Agency, 2022).

2. Penetration and Absorption: When water containing microorganisms (like *E. coli* or Enterococci) passes through a UV disinfection unit, it's exposed to this high-energy UV-C light. The UV rays penetrate the cell wall and membrane of the microorganism, reaching its core where the genetic material is located (Hijnen et al., 2006).

3. DNA/RNA Damage: The key step occurs when the DNA or RNA molecules within the microorganism absorb the UV-C energy. This absorption causes a photochemical reaction, primarily leading to the formation of dimers (e.g., thymine dimers) in the DNA strand. Imagine it like a kink or a knot forming in a ladder; it's a structural change that distorts the DNA helix (Sinha et al., 2018).

4. Inactivation, Not Killing: It's important to understand that UV light doesn't "kill" the microorganisms in the traditional sense, like heat or chemical disinfectants might. Instead, it inactivates them. The damage to the DNA or RNA prevents the microorganism from performing essential cellular functions, most critically replication (reproducing) (U.S. Environmental Protection Agency, 2022).

5. Loss of Infectivity: With its genetic code compromised, the microorganism can no longer multiply or carry out its metabolic processes effectively. This means it loses its ability to infect hosts and cause disease. Even if the organism remains physically intact, it's rendered harmless from a public health perspective (Hijnen et al., 2006).

6. No Residuals: A significant advantage of UV disinfection is that it's a physical process, meaning no chemicals are added to the water. This eliminates the formation of harmful disinfection byproducts (DBPs) and ensures there are no residual chemicals left in the treated water that could affect aquatic life or downstream users (U.S. Environmental Protection Agency, 2022).

In essence, UV disinfection acts like a highly targeted, non-chemical genetic disruptor, making it an environmentally friendly and efficient method for controlling microbial contamination in water.

As part of the case study, technical collaboration was established with *Linha d'Água Engenharia* to support the implementation of the UV disinfection system. The company conducted a detailed assessment of the site-specific conditions—such as flow rate, channel geometry, and water quality—in order to define the most appropriate configuration and capacity of the UV lamps. This tailored approach ensured that the system design met both the operational demands and the treatment objectives for that particular stretch of the stream.

The UV disinfection system was designed to treat a flow rate of 4,000 L/s, with a maximum total suspended solids (TSS) concentration of 10 mg/L. The system operates with a UV transmittance of ≥ 70% and is calibrated to deliver a validated dose of 20 mJ/cm^2 (MS2 RED), verified through independent bioassays. It guarantees a disinfection standard of 1,000 CFU of fecal coliforms per 100 mL, based on a 30-day geometric mean.

The installation includes the construction of three disinfection channels, each with a minimum length of 10 meters, maximum depth of 2.4 meters, and width of 1.44 meters. The proposed configuration consists of 6 lamp banks (2 per channel), with 20 UV lamps per bank, totaling 120 lamps. Each lamp operates at 1,000 W, resulting in a maximum system power of 126.4 kW.

The complete setup includes 3 power distribution cabinets, 1 monitoring and control unit, 3 hydraulic systems, 3 motorized gate-type level controllers, 3 UV intensity sensors, 3 water level sensors, and 1 online UVT monitoring system, ensuring continuous and efficient operation adapted to the specific conditions of the stream section.

After implementing this integrated series of measures—encompassing video inspections, daylighting projects, filtration, and advanced UV disinfection—a significant reduction in *E. coli* and Enterococci concentrations is expected in the waterways. Decreasing these fecal contamination indicators will directly improve public and environmental health, raising bathing water standards, protecting marine life, and revitalizing the recreational and ecological value of the adjacent coastal zone.

The main costs associated with implementing this system include:

According to the budget provided by *Linha d'Água Engenharia*, the estimated cost for implementing the proposed treatment systems includes both the hydraulic screening and UV disinfection components. The automated hydraulic screen (HIDRORAKE) is priced at €76,178.00, based on the technical specifications required for the site. The UV disinfection system (Trojan Signa for gravity channel) accounts for the most significant portion of the investment, with a supply cost of €1,285,715.00, and an additional €107,410.00 for installation, commissioning, and startup.

The total projected investment, as outlined by *Linha d'Água Engenharia*, amounts to €1,469,303.00. This estimate reflects the financial requirements for implementing an effective, technically adapted solution for improving water quality in the urban stream, aligned with environmental and public health standards.

In addition to equipment and installation, further cost categories estimated in similar treatment projects include:

- Civil works and infrastructure, covering foundations, channel modifications, structural supports, and maintenance access. Such costs typically range from €10,000 to €30,000, depending on the site's terrain and complexity (U.S. EPA, 2013).
- Operational and maintenance costs (O&M) include electricity consumption, periodic UV lamp replacement, grate cleaning, and regular inspections. Annual costs are estimated between €5,000 and €10,000 (International Ultraviolet Association, 2019).
- Licensing and regulatory approvals, such as fees for permits and authorizations from the Portuguese Environment Agency (APA) and local municipalities, which can amount to up to €5,000 (APA, 2019 – typical range used in Portugal-based infrastructure permitting).

The overall cost associated with the implementation of the UV disinfection system represents a significant, yet justified, investment in improving urban water quality. When considering not only the equipment and installation but also the necessary infrastructure works, regulatory procedures, and anticipated operational demands, the financial commitment reflects the complexity and scale of such an intervention. Despite the high initial cost, the long-term benefits—such as improved public health, compliance with legal standards, and enhanced ecological conditions—underscore the value and necessity of this type of solution in urban water management.

4 Conclusions

The escalating global concern over urban water quality, particularly in coastal areas impacted by contaminated freshwater discharge, underscores the urgent need for effective intervention strategies. A thorough analysis of the current state-of-the-art reveals that traditional approaches often fall short in addressing the complex interplay of factors contributing to urban stream degradation. This report, therefore, focuses on a comprehensive and technically grounded approach to improving water quality and fostering environmental revitalization within an urban stream in Portugal.

The intervention in the urban stream in Portugal, as detailed in this report, demonstrates a multifaceted and technically grounded approach to improving water quality and environmental revitalization. The proposed technologies, such as daylighting, video inspections, and UV disinfection, despite the initial investment, will provide long-term benefits far outweigh the costs, especially when considering the intangible value for public health and the ecosystem.

Video inspections, while representing a diagnostic cost, are an indispensable tool. At points 1 and 3, located in dense urban areas where daylighting isn't feasible, these inspections play a crucial role. By precisely identifying contamination sources and structural anomalies in the underground conduits, they optimize remediation investment, avoid unnecessary spending, and enhance infrastructure efficiency, ensuring proactive and informed management of the stream.

This inspection procedure shouldn't be a one-off; it needs to be maintained over time. When combined with a robust monitoring campaign, these ongoing inspections are vital for continually defining and re-evaluating the critical zones within the stream. This allows for an adaptive management approach, ensuring that interventions remain targeted and effective as conditions evolve.

Conversely, daylighting at points 7 and 12, made viable by their location in more open and green areas, promises a deeper transformation. Exposing and renaturalizing these sections will not only directly contribute to water quality improvement through natural self-purification processes but also bring significant environmental and social benefits. Increased property values, the creation of green spaces for the community, and enhanced biodiversity are clear examples of how this intervention translates into gains beyond the financial aspect, promoting climate resilience and reconnecting the population with the fluvial environment.

Finally, UV light disinfection emerges as an essential pillar in controlling microbiological contamination, with a primary focus on reducing *E. coli* and Enterococci. Its application at point 2, strategically chosen due to its proximity to the discharge zone, ensures that water released into the receiving environment has a significantly reduced pathogenic load. The non-chemical nature of UV disinfection ensures no harmful byproducts are formed or residual impact on the aquatic environment, making it a clean and effective solution for protecting the health of marine ecosystems and bathers.

In summary, the integrated application of these measures—targeted surveillance, ecological restoration, and advanced disinfection—will culminate in a significant reduction in fecal contamination indicator concentrations. This outcome not only validates the proposed multifaceted approach but also promises substantial improvements in water quality, elevating bathing water standards, protecting marine life, and revitalizing the recreational and ecological value of the adjacent coastal zone. Implementing these technologies represents a fundamental step towards a future where urban streams in Portugal are not only functional water corridors but also valuable environmental and social assets.

This significant investment, as detailed by Linha d'Água Engenharia, amounts to a total estimated cost of €1,469,303.00, covering both the automated hydraulic screening system and the UV disinfection components. Although the upfront cost is considerable, it reflects a solution specifically tailored to the site's unique conditions, including infrastructure, installation, and commissioning. When factoring in ongoing expenses such as annual maintenance, electricity consumption, periodic UV lamp replacement, and regulatory fees, the project maintains a favorable cost-benefit ratio for large-scale urban water quality interventions.

Regarding treatment efficiency, the UV disinfection system is designed to deliver a validated dose of 20 mJ/cm^2, ensuring a significant reduction of microbial indicators like fecal coliforms to levels below 1,000 CFU per 100 mL based on a 30-day geometric mean. This performance, supported by independent bioassays, directly contributes to improving water quality and protecting public health and adjacent marine ecosystems. The integrated application of these technologies offers a robust treatment approach aligned with current environmental regulations and international best practices.

4.1 Future Works

Based on the results obtained and the methodologies applied in this study, several future research directions can be explored to deepen the understanding of the studied system and to develop more efficient and sustainable solutions for mitigating pollution in urban watercourses.

One promising avenue involves conducting a more detailed analysis of water transmittance, which would provide crucial data for the precise sizing of UV disinfection systems. By gaining a more accurate understanding of how UV radiation is absorbed by the constituents of the water, it would be possible to optimize the selection of lamp intensity and quantity, thereby enhancing microbiological efficacy while improving energy efficiency.

Additionally, future work could explore the implementation of nature-based solutions, particularly the use of floating islands with macrophytes. These vegetated structures can function as natural biofilters, promoting the removal of nutrients, heavy metals, and organic matter. They also contribute to the visual improvement of urban water bodies and support aquatic biodiversity enhancement.

Another valuable direction would be the development of hydrodynamic and water quality models, capable of predicting the spatial and temporal dispersion of pollutants and simulating the outcomes of various intervention scenarios. When combined with real-time monitoring systems, these models could provide decision-makers with powerful tools for adaptive watershed management.

Finally, future research could also include microbiological risk assessments based on real human exposure scenarios, particularly in urban areas with frequent recreational contact with water. This would help strengthen public health protection strategies and support the implementation of targeted remediation measures.

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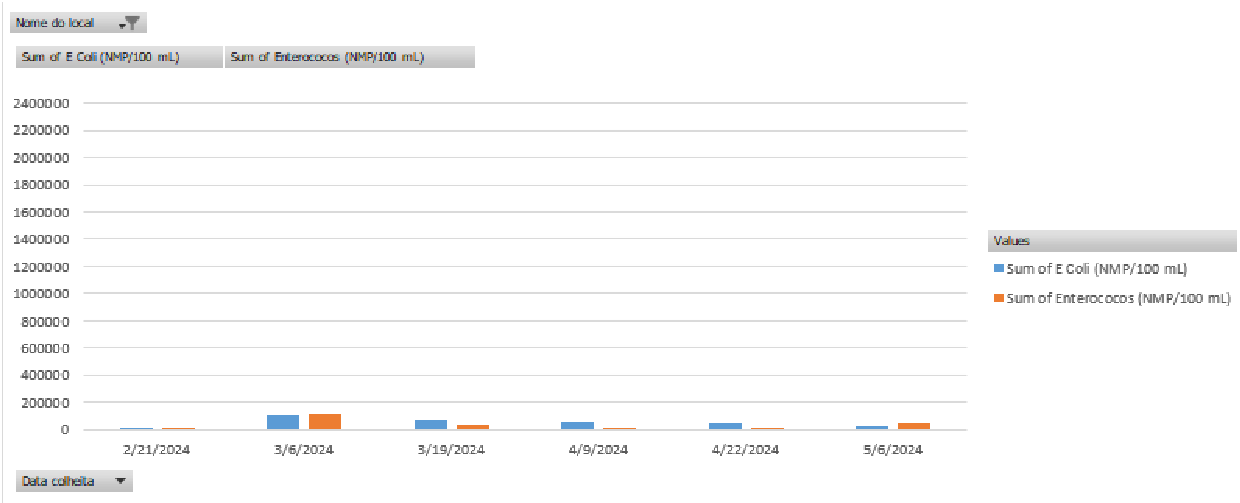
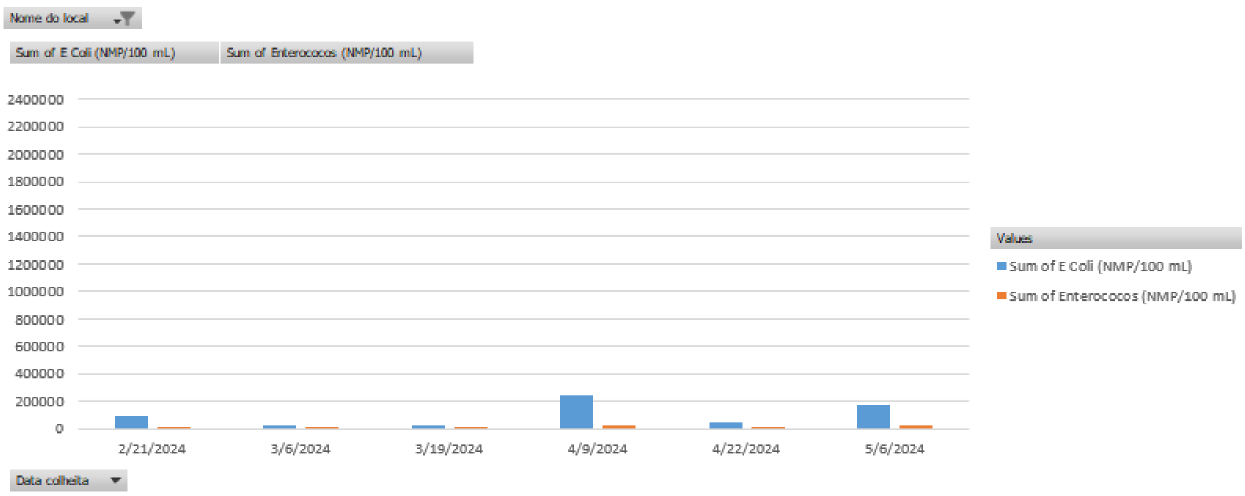
Appendix A

GRAPHICS OF MICROBIOLOGICAL PARAMETERS IN THE SAME SCALE TO COMPARISION

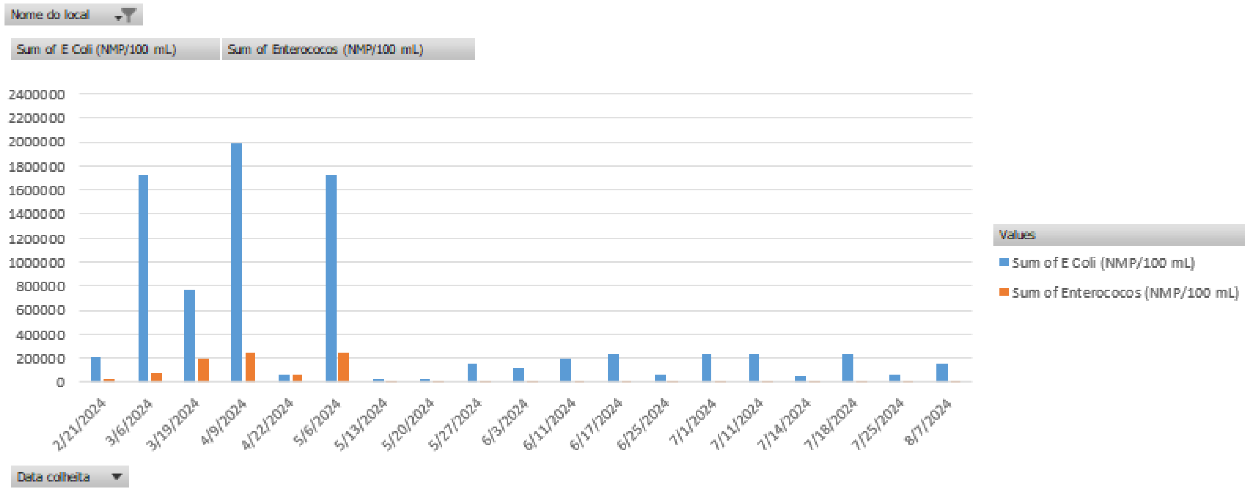
- Point 1



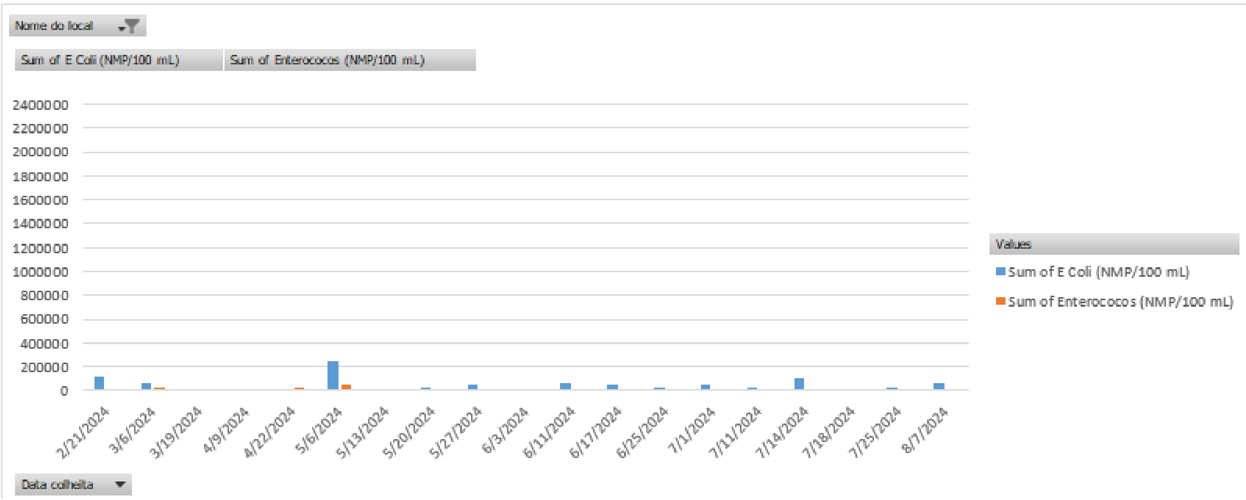
- Point 2



- Point 3



- Point 4



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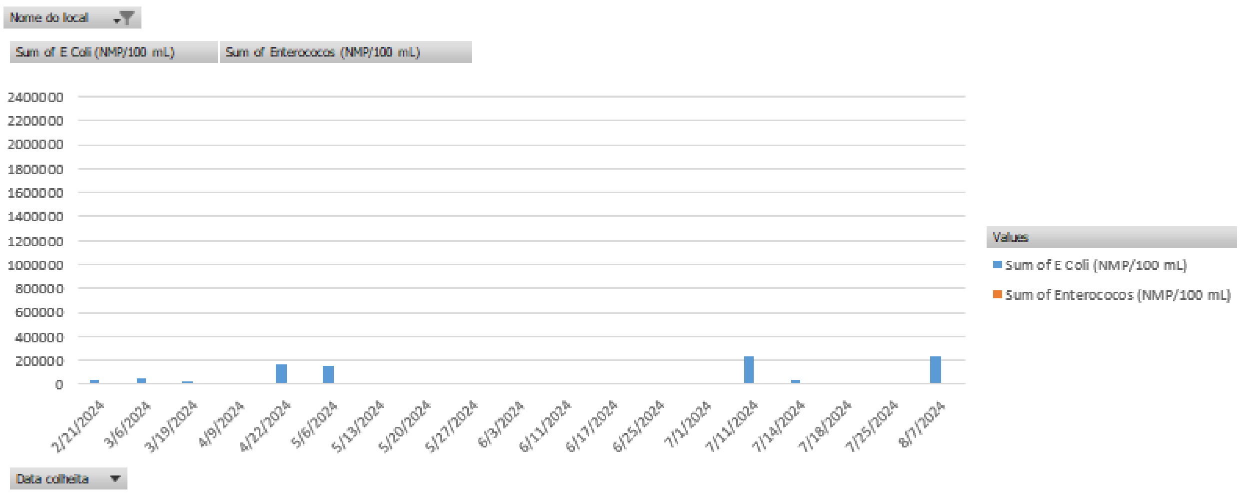

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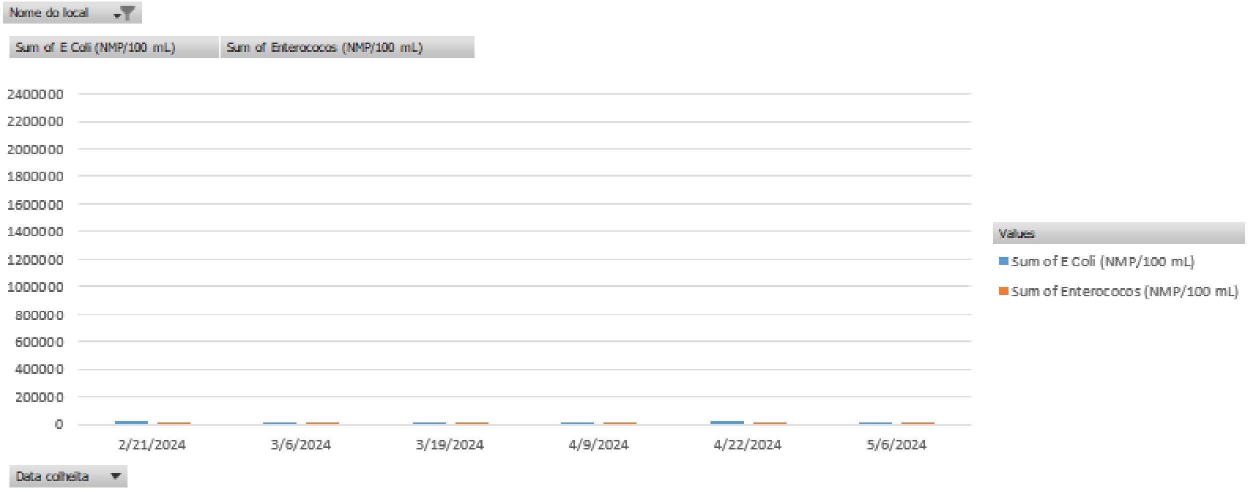

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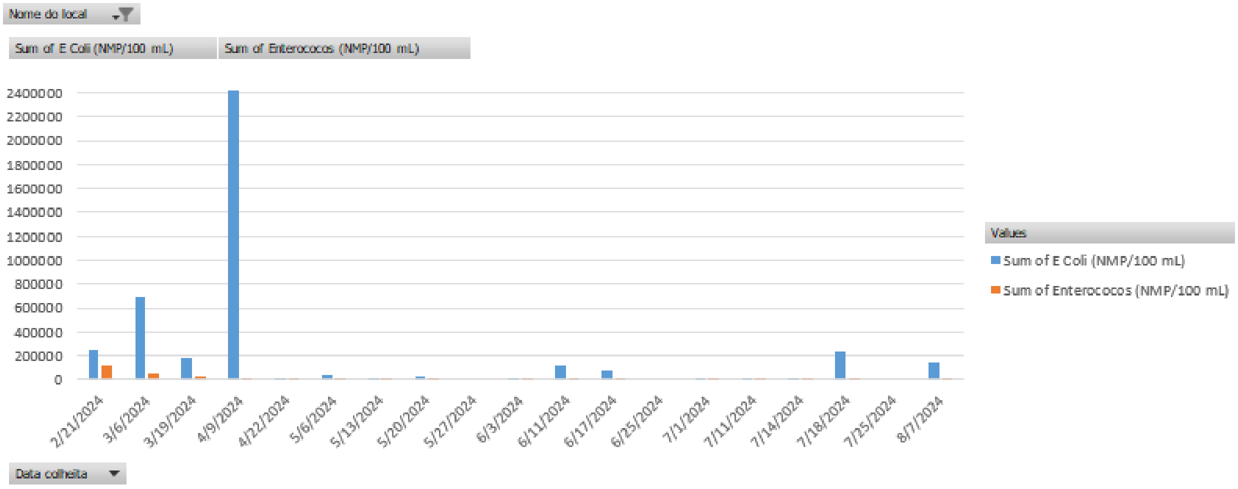

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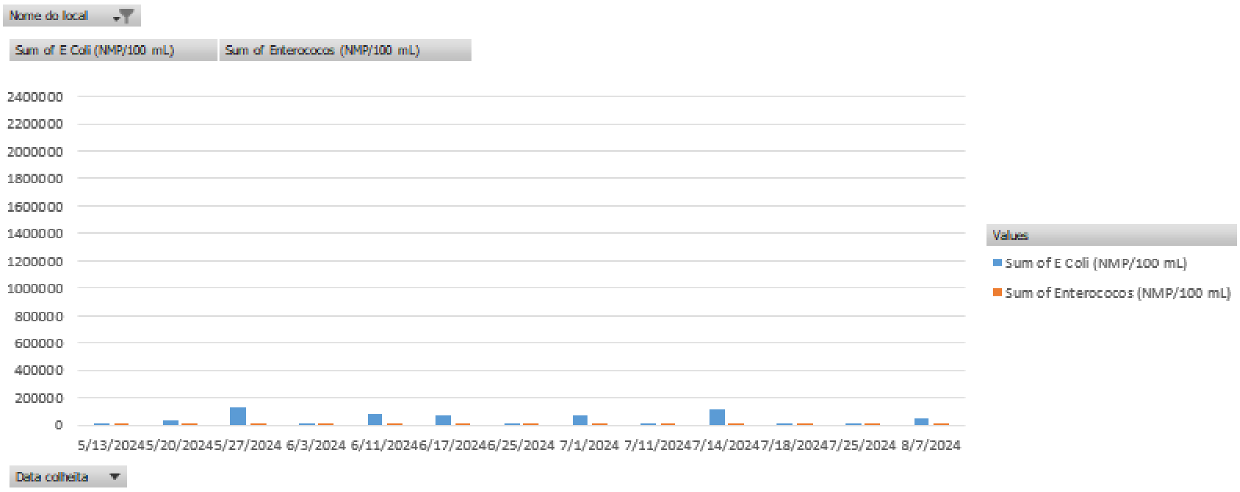

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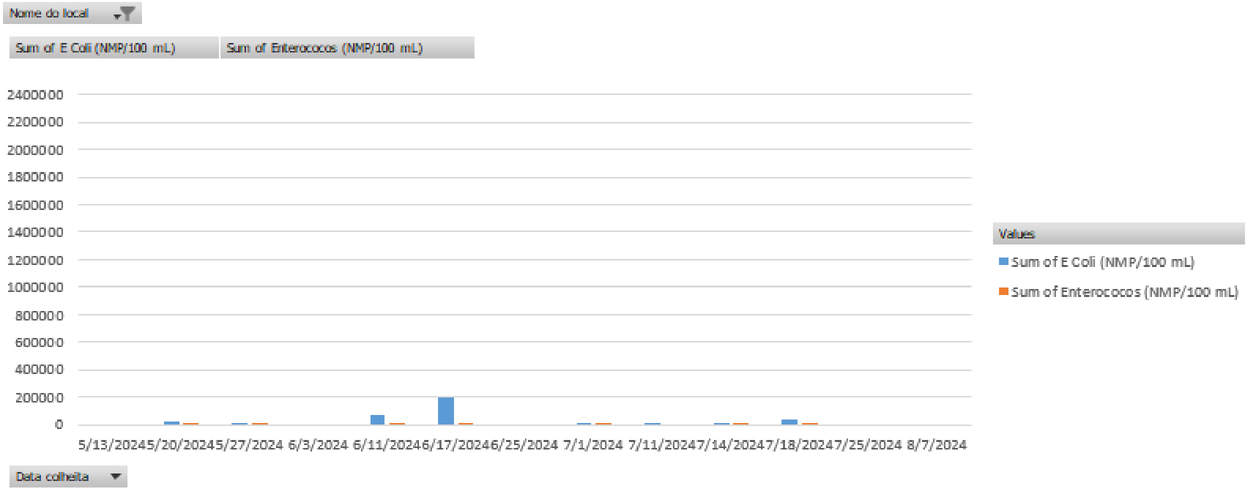

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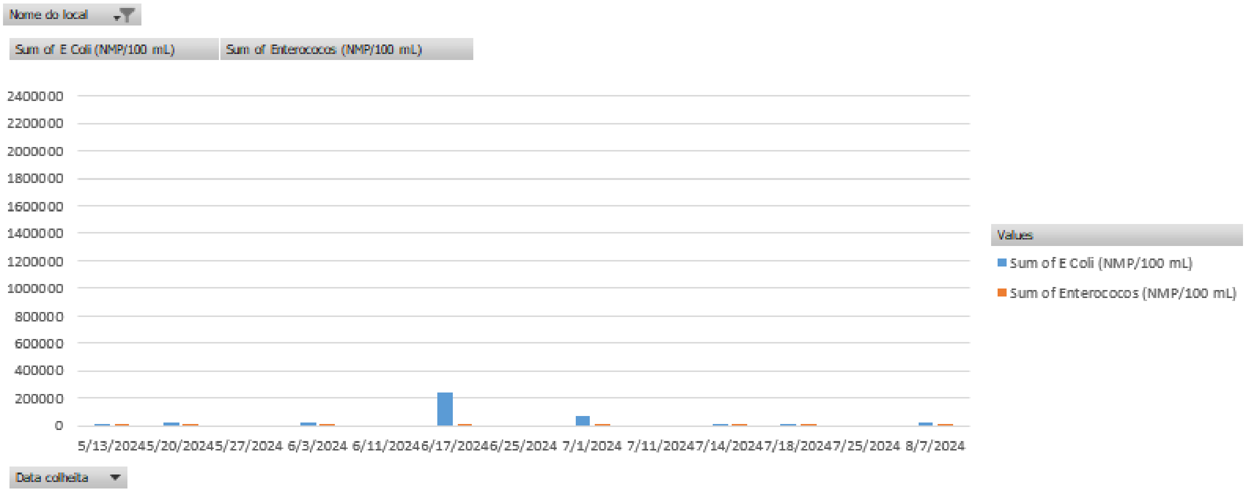

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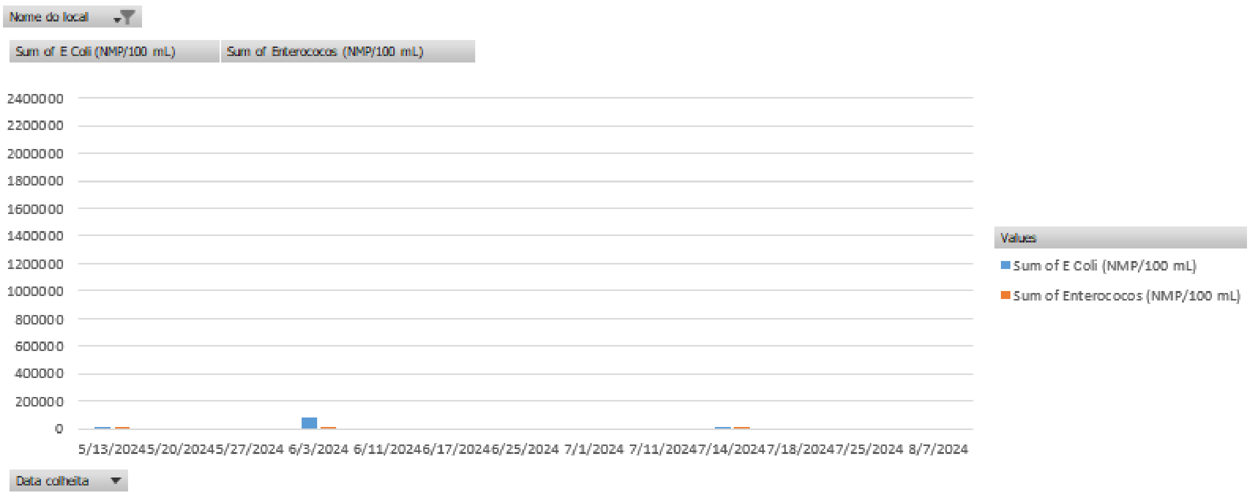

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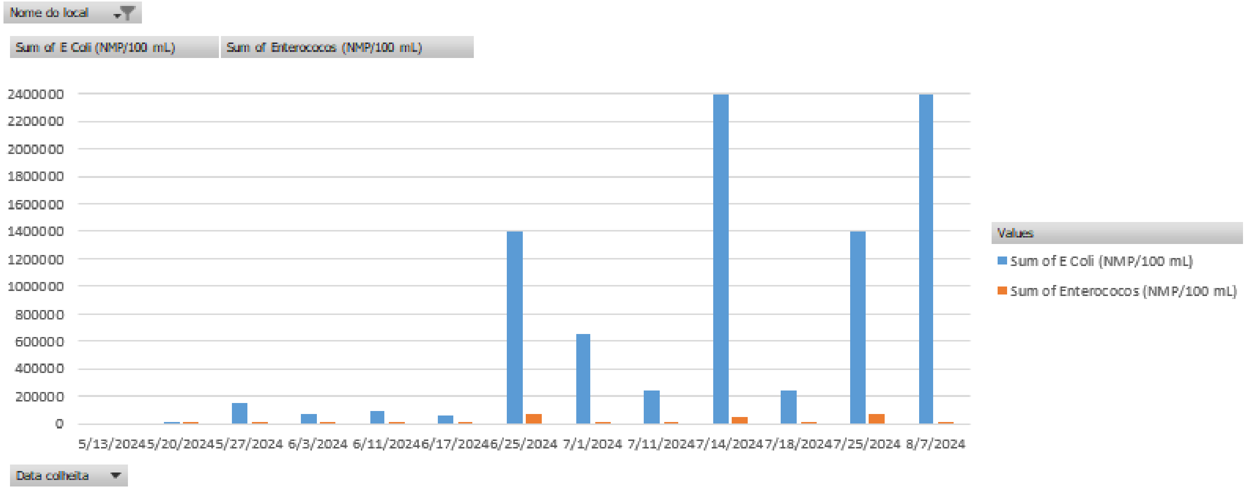
Nome do local
Sum of E Coli (NMP/100 mL)
Sum of Enterococos (NMP/100 mL)
2400000
2200000
2000000
1800000
1600000
1400000
1200000
1000000
800000
600000
400000
200000
0
5/13/2024
5/20/2024
5/27/2024
6/3/2024
6/11/2024
6/17/2024
6/25/2024
7/1/2024
7/11/2024
7/14/2024
7/18/2024
7/25/2024
8/7/2024
Data colheita
Values
Sum of E Coli (NMP/100 mL)
Sum of Enterococos (NMP/100 mL)