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Assessment of and Response to Climatic Impacts on Water Quality in Berlin

Olaf Wagner*, Alejandro Lorente

Freie Universität Berlin, Institut für Chemie und Biochemie, Arnimallee 22, 14195 Berlin, Germany

Correspondence to: Olaf Wagner (olaf.wagner@fu-berlin.de)

Abstract. Climatic changes will impact our water bodies and pose challenges for water resource managers. As public discourse is mostly focused on water supply, the impacts on water quality seem to be disregarded. As extreme weather conditions such as heavy rainfall can cause flooding, stormwater runoff, and combined sewer overflows in urban areas, climate impacts become water quality challenges. In Berlin, where a semi-closed water cycle relies on bank filtration, maintaining surface water quality is particularly critical. This study provides an overview of Berlin's current surface water quality, key pollutants, and their sources, analyzing their connection to climate change trends. Furthermore, mitigation strategies, including advanced treatment technologies, digital monitoring, and flood management measures, are evaluated to enhance urban water resilience in a changing climate.

1 Introduction

Climate change leads to extreme weather conditions such as heavy rainfall events and dry periods. Consequences include flooding, combined sewer overflows, and the growing risk of declining groundwater levels.(Feldbauer et al. 2020; "AR6 Synthesis Report: Climate Change 2023 — IPCC," n.d.)

The majority of Berlin drinking water supply comes from bank filtration and artificial groundwater recharge. Bank filtration is a water withdrawal method in which water is pumped from the ground near a river or lake. The abstracted water is basically surface water that has received an intensive filtration treatment by passing a substantial distance through sediments and soil. Bank filtration was first applied in Germany's capital, Berlin, more than 100 years ago. For the past 70 years, it produced approximately 60% of the city's drinking water.(Gillefalk et al. 2018)

The semi-closed water cycle of Berlin consists of consumers, wastewater treatment plants, (WWTP), receiving surface waters and bank filtration. Wastewater from consumers is passing through WWTP, is released into surface waters from which water is extracted via bank filtration and provided for consumers again (Fig. 1).

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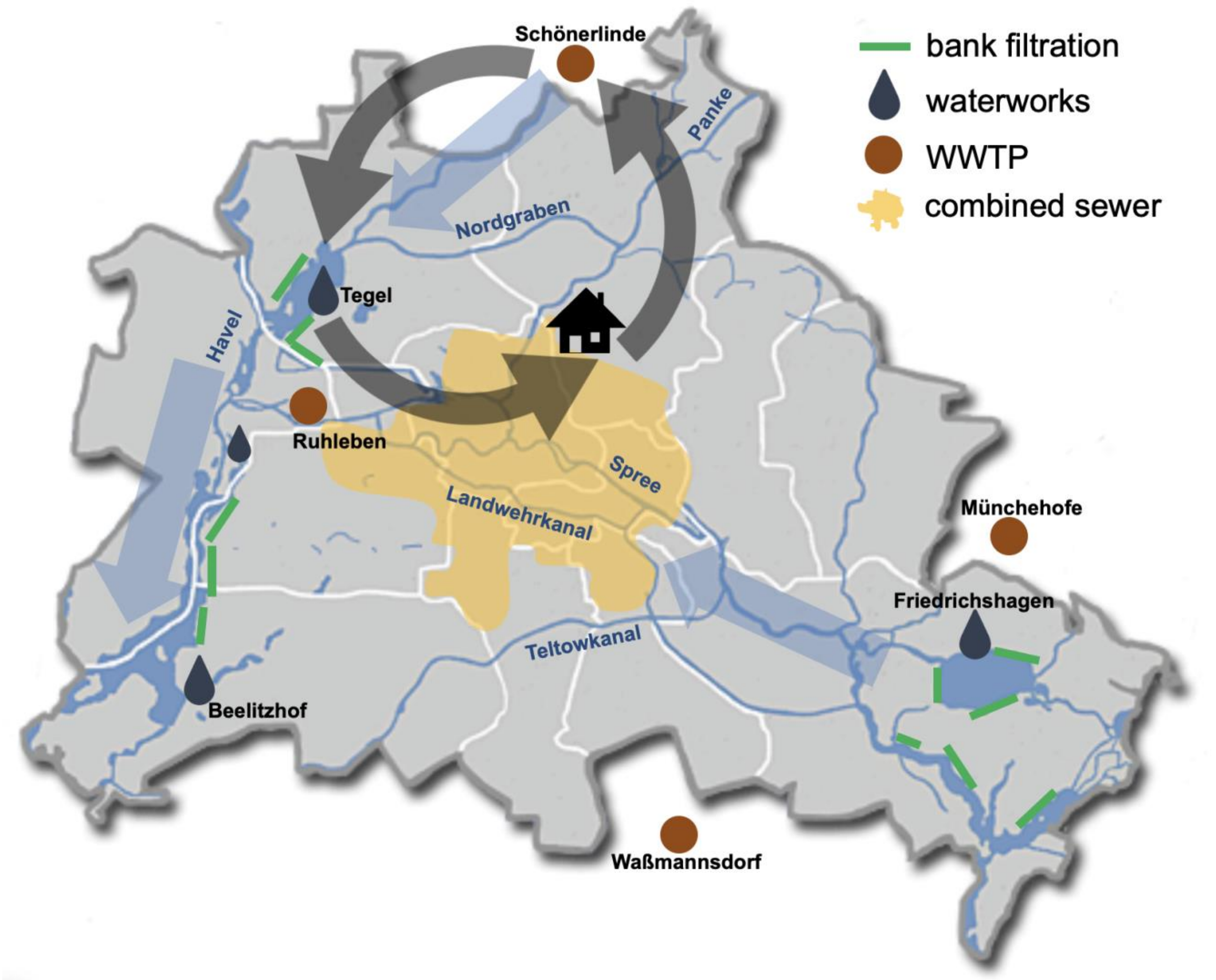

Figure 1: Schematic map of Berlin surface waters and an exemplary semi-closed water cycle in the north-west of Berlin.

Climatic and demographic changes likely contribute to an increase of organic pollutants and pathogens in aquatic ecosystems.(Astaraie-Imani et al. 2012; Jekel et al. 2013)

Climatic impacts, such as higher temperatures and less summer precipitation, can lead to higher concentrations of nutrients and pollutants which can cause a shift to more anaerobic conditions retarding the contaminants degradation. On the other hand, extreme precipitation is expected to intensify. Following the Clausius-Clapeyron relationship, a warmer atmosphere holds 7% more moisture, per degree Celsius. More extreme precipitation, heavy rainfall, likely lead to an increase in the number and intensity of flooding events. It was already found that hydroclimatic conditions, such as droughts and wet periods, have a

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measurable influence on the Berlin river Panke, with dry years generally improving water quality due to less runoff, while wet years have increased pollutant levels due to enhanced runoff of contaminants into water bodies.(Marx et al. 2023)
This paper gives an overview of Berlin's water quality, the key pollutants and their sources and highlights climate-induced trends while outlining mitigation measures such as advanced treatment, digital monitoring, and flood management.

2 Status of Berlin waters

Water pollution by urban activities can result from both chemical and biological contaminants. In Berlin's waters, biological pollution is primarily driven by microbial contaminants or indicators thereof, such as Escherichia coli and intestinal enterococci, which often exceed official limits during and after rainfall events. These bacteria originate from sewage overflows and stormwater runoff, indicating fecal contamination that poses a health risk to those using the waters for recreation.
Chemical pollution in Berlin's waters is characterized by a range of pollutants that surpass environmental quality standards. The chemical status of Berlin's surface water bodies is assessed according to the EU Directives 2008/105/EC and 2013/39/EC. These directives include a list of 45 priority substances as outlined in Annex 8 of the German Ordinance on Surface Waters (OGewV 2016). As of 2020, none of Berlin's surface water bodies achieved good chemical status due to the presence of mercury (Hg) and brominated diphenyl ethers (BDE) in biota.(SenUVK 2020) BDE are flame retardants known for their high persistence and they have been banned from production entirely. Mercury can be released into the environment through coal combustion.
Nine of Berlin's surface water bodies show exceedances of tributyl tin compounds (TBT), which were previously used as biocides in antifouling coatings for ships but have been internationally banned since 2008.(SenUVK 2020) Additionally, four surface water bodies in Berlin exceed limits for polycyclic aromatic hydrocarbons (PAHs), which originate from the combustion of materials like wood, coal, and oil, as well as from softening oils in car tires, tar, and asphalt.
The Berliner Wasserbetriebe (BWB), the water utility company in Berlin, provides information and recent data on Berlin's water systems on their website (www.wasserportal.berlin.de). The site offers various resources for residents, researchers, and policy makers about the water conditions, such as water levels, quality, and flow rates of rivers and lakes.

2.1 Recreational water bodies

The guidelines for managing pollution in Berlin's bathing waters (LaGeSo 2024) set limits for various pollutant classes, including specific thresholds for bacteria such as E. coli and intestinal enterococci, which are indicators of critical water quality. The European Bathing Water Directive (EU 2014) requires that the quality of bathing waters be classified based on these microbiological indicators, with limits set at 1,800 colony-forming units (CFU) per 100 ml for E. coli and 700 CFU per 100 ml for intestinal enterococci. In Berlin, the quality of bathing waters is subject to fluctuation due to factors like rainfall, which can cause short-term pollution spikes from runoff and sewage overflow. These exceedances necessitate frequent monitoring and implementation of early warning systems to protect public health. Temporary closures of a bathing site can occur several

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times per year, especially in areas with combined sewer overflows, where bathing bans are imposed when the forecast predicts potential short-term pollution.

At major bathing sites, water samples are taken by the respective authorities (Landesamt für Gesundheit und Soziales (LaGeSo)) every three weeks and analyzed in the laboratory. The assessment of whether there is an increased risk of bathing after heavy rainfall is determined by an algorithm, based on estimated overflows and rainfall amounts in the relevant area.(KWB 2019)

Bathing sites in Berlin faced temporary closures when these limits were exceeded, particularly after heavy. The status of Berlin's bathing sites, including any closures or warnings, is regularly updated and can be checked online (at www.badestellen.berlin.de) with real-time information to the public.

The ambitious initiative "Fluss Bad Berlin" is aiming to transform a section of the Spree into a natural swimming area. It should be located in the city center along a historic stretch adjacent to Museum Island (Museumsinsel). The Kupfergraben canal, a 1.8 km long waterway that runs between the Lustgarten near the Berlin Cathedral (Berliner Dom) and the Bode Museum. The project is part of a broader effort to improve the water quality of Berlin's urban waterways, making them safe and accessible for recreational use, and addresses the ongoing challenges posed by urban runoff, combined sewer overflows, and other sources of pollution. It can be considered safe to swim at the canal, except during combined sewer overflow events.

2.2 Drinking water

Berlin's drinking water is sourced from about 650 deep wells, extracting groundwater from 30 to 140 m. It is pumped from waterworks through 7,827 km pipelines and 280,000 house connections, supplying around 560,000 cubic meters daily.(BWB 2022)

Berlin's drinking water quality is generally maintained to high standards, adhering to the limits specified by the German Drinking Water Ordinance (Trinkwasserverordnung).(Bundesministerium für Gesundheit 2023) However, in context of the semi-closed water cycle of Berlin, the entry of persistent, mobile trace substances (PMT) into Tegeler See, a drinking water resource, has been assessed as a potential risk.(Jekel and Ruhl, n.d.) One category of PMT called per- and polyfluoroalkyl substances (PFAS) publicly called “forever chemicals,” are highly persistent and widely distributed in the environment, even reaching remote areas potentially contaminating Berlin drinking water sources. Their long half-lives pose risks to human health and interconnected ecosystems lead to regulatory action. Limit values for PFAS were just recently included in the European drinking water directive.(Directive (EU) 2020/2184, 2020) In a recent study, 89 drinking water samples from all over Germany were tested and the sum concentration of PFOS, PFOA, PFHxS, and PFNA exceeded the German limit value of 20 ng/L in two samples.(Ingold, Kämpfe, and Ruhl 2023) In Berlin the maximum concentration of PFOS detected was 15.3 ng/L while the sum concentration of 20 PFAS ranged from 56.7 ng/L to 5.4 ng/L.(Ingold, Kämpfe, and Ruhl 2023) These results highlight the importance of addressing this issue.

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3 Pathways of Pollutant Entry

Flowing through the capital, the Spree serves as a source of surface water for drinking water production, is crucial for urban drainage, and receives treated wastewater and stormwater runoff, which impacts its water quality. Due to its slow flow, it is vulnerable to pollution accumulation. In the Lausitz region southeast of Berlin, lignite mining and the practice of discharging sulfate-rich mine water into the Spree is a significant factor in the river's sulfate levels. Currently, mining water pumped from the mines into the Spree makes up 50% of the river flow at Cottbus or even up to 75% during dry summer months.(Weyrauch et al. 2010) The planned closure of lignite mines by 2038 is expected to sharply reduce the volume of pumped mine water entering the Spree. So, ironically the sulfate-laden mine water is crucial for maintaining water levels and dilution of pollutants. And its reduction will significantly impact the region's hydrology. It could lower groundwater levels in the Spreewald, potentially causing the Spree to flow backward into Müggelsee, which could introduce contaminants into bathing and drinking water supplies.

Berlin’s urban water pollutants can be categorized into four groups:

1. Banned chemicals that are still present
2. Pollutants from stormwater
3. Pollutants from overflow events of combined sewer

3.1 Persistent pollutants

Despite being banned, both BDE and TBT continue to persist in Berlin's surface waters at levels that can exceed environmental safety limits.(SenUVK 2020) BDE were banned in the European Union between 2004 and 2008 under the European Restriction of Hazardous Substances (RoHS) Directive and fully phased out by 2019 under the EU Persistent Organic Pollutants (POPs) Regulation.

Similarly, TBT, an antifouling biocide, was internationally banned in 2008 by the International Maritime Organization (IMO) due to its toxic effects on marine life. However, the persistence of these compounds in the environment, coupled with their long half-lives, means that they continue to exist in Berlin's water bodies long after their use has ceased.

This should remind us about the concerns around per- and polyfluoroalkyl substances (PFAS). Like BDE and TBT, PFAS have been widely used in industrial and consumer applications. However, their widespread environmental presence and potential health risks have led to growing regulatory actions aimed at banning them. Despite these efforts, the environmental legacy of PFAS, much like BDE and TBT, suggests that they will continue to be detected in ecosystems and drinking water long after their production and use have been curtailed.(Ingold, Kämpfe, and Ruhl 2023) The continued presence of these chemicals underscores a significant challenge in environmental management: the legacy effects of persistent pollutants.

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3.2 Pollutants from stormwater

Heavy rainfall events are expected to become more intense and frequent. Without adaptation measures, this will likely increase the severity and likelihood of urban flooding. In a study from 2021, 13 micropollutants in stormwater runoff and 8 in the receiving Berlin rivers exceeded German quality standards during storm events.(Wicke et al. 2021) Four surface water bodies in Berlin exceed limits for PAH. These compounds enter waterways primarily through rainwater runoff from sealed surfaces, with significant contributions from road traffic, including tire abrasion, brake wear, and exhaust fumes.

During wet weather events at the Panke river, the concentrations of 8 compounds, including copper (Cu) and zinc (Zn), exceeded the maximum allowable concentrations, with levels being 5 to 20 times higher than during dry weather.(Wicke et al. 2021) Major roads were identified as the primary source of traffic-related substances. Microplastic particles from tire abrasion can enter surface waters and leach out pollutants like heavy metals, PAH and other toxic rubber additives.(Venghaus and Barjenbruch 2021)

Additionally, other land-use types contributed specific pollutants: commercial areas showed higher levels of flame retardants, while catchments dominated by single-family homes had elevated pesticide levels. This indicates that different land uses contribute distinct pollutants to the river, particularly during wet weather conditions.(Wicke et al. 2021)

3.3 Pollutants from overflow events of combined sewer

The Berlin combined sewer system located in the city center (Fig. 1) covers an area of 100 km². To prevent overloading of pressure pipes and wastewater treatment plants, the combined sewer system is relieved during heavy rainfall through approximately 500 overflow structures. These combined sewer overflows (CSOs) occur around 30 times a year, in which untreated sewage is discharged directly into water bodies.(Wolfgang Seis et al. 2019)

In the high precipitation year of 2017 in Berlin, the water volume of sewer overflow increased by ca. 250% to 4 million m^3 for the Spree.(Wolfgang Seis et al. 2019) CSO can carry a mix of raw sewage and storm water into the surface water: pathogens, pharmaceuticals, pesticides, microplastic, organic matter and nutrients. Organic matter and nutrients entering the surface water can cause rapid growth of microorganisms and aquatic plants which increase the demand for oxygen. A rapid depletion of dissolved oxygen in the water body can lead to hypoxic conditions and eutrophication. Additionally, CSO can introduce harmful bacteria and viruses into the water. These pathogens can contaminate the water, making it unsafe for recreational use. Exacerbating the CSO event, the "first flush effect" can increase the bacteria load additionally. This effect refers to the initial surge of pollutants, including organic matter, nutrients, and pathogens, that accumulated in sewer pipes and is washed off with the first flush through the pipe.

The experiment "Fließende Welle" measured concentrations of indicator bacteria and viruses in the Spree following a CSO event in July 2016. The contamination was tracked over a distance of 5 km and a period of about 98 hours, taking the flow velocity of the water into account. The overflow caused E. coli concentrations to increase by more than 4 log levels and adenovirus concentrations to rise by about 3-4 log levels.(Rouault et al. 2019)

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In addition to being an issue for bathing sites, CSO are a pollution source of organic trace substances like pharmaceuticals or industrial chemicals. Since approximately 60% of Berlin's drinking water comes from bank filtration, where lake water is filtered through banks into groundwater, the these contaminants in the water can accumulate in the environment and affect drinking water quality.(Heberer and Adam 2004)

4 Climate induced trends

The total water consumption in Berlin will increase with population growth and rising temperatures, while seasonal variations are increasing, as well.(Monninkhoff et al. 2023) Rising temperatures due to climatic changes lead to increased evaporation rates, which might decrease surface water levels in Berlin and Brandenburg.
In context of water quality, reduced water volumes reduce dilution of pollutants, which cause higher concentrations and greater environmental impacts of the contaminants.(Coffey et al. 2014) Heavy rainfall events are projected to occur more often and more intense with climatic changes.(Kotz et al. 2024) Radar data from the past 20 years suggest only a slight increase in the frequency of heavy rainfall events in Germany.(Lengfeld et al. 2021) A recent Berlin specific study(Nissen et al. 2024) projects that under climate change scenarios, heavy rainfall events are expected to become more intense and frequent for all durations from one hour to five days due to increased anthropogenic warming. It found for instance that heavy rain events that historically occurred only once every 10 years between 1961 and 1990 are projected to occur 2 to 3 times more often by the end of the 21st century.(Nissen et al. 2024) More frequent and severe heavy rainfall events lead to more runoff from stormwater in the city carrying higher loads of pollutants. And more frequent and higher volumes of stormwater also cause more frequent and severe CSO events. Rising water temperatures could further boost bacterial growth and the chance of eutrophication of these CSO events.

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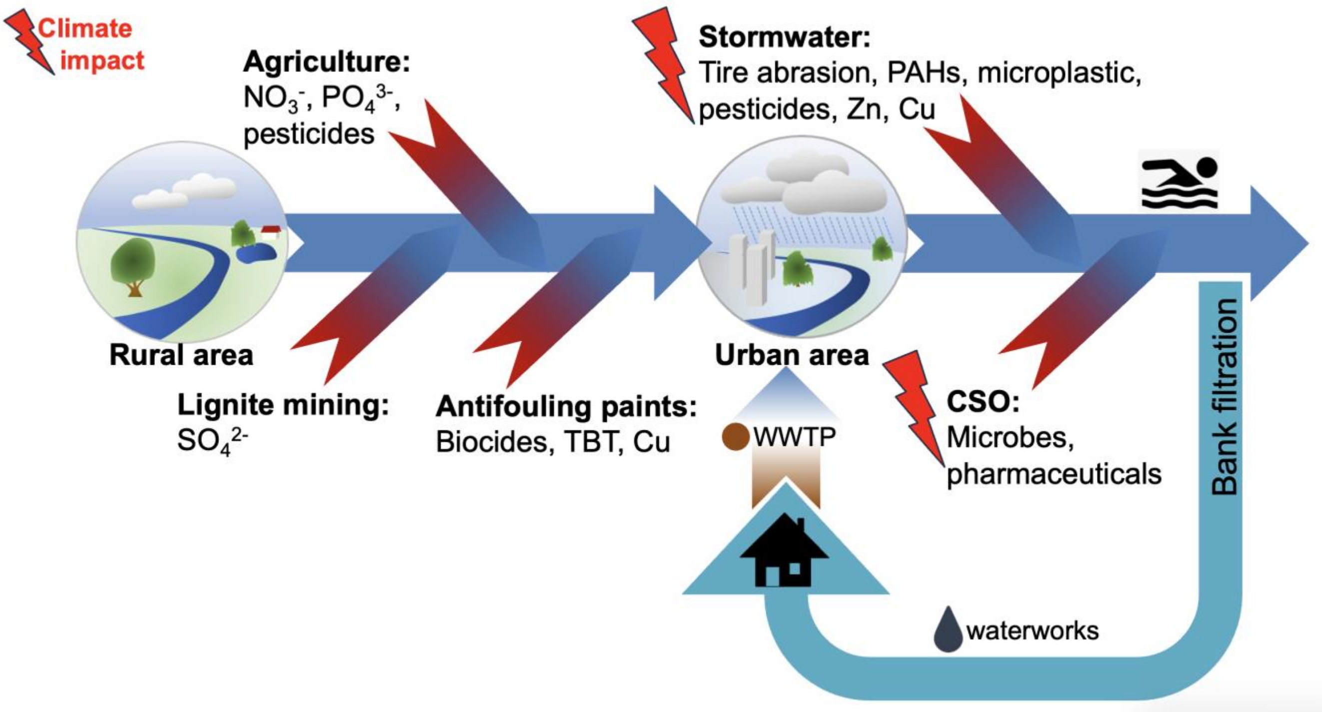

Figure 2: Schematic overview of Berlin's water bodies, its semi-closed water cycle, and pollution sources impacted by climate change; stormwater runoff and CSO.

185 ## 5 Measures to reduce climate impacted water pollution

To reduce negative impacts of climate change influenced water pollution and thereby mitigate the climate change impact on water quality, several measures and technologies at different locations can be introduced.

5.1 At their source

Most effective in reducing water contaminant concentrations is to prevent them from entering at their sources. Industrial facilities would significantly lower their pollutant output by adopting a green chemistry approach and treat their wastewater by advanced systems before discharge. Homeowners can reduce their impacts by using environmentally friendly cleaning agents, proper disposal of medications. Concerning the main stormwater runoff contaminants, fewer cars would result in less PAH from emissions and microplastic from tire and brake wear.

5.2 In their spreading

While stormwater cannot be reduced directly, one of its major consequences, CSO can be mitigated through prevention strategies. This includes the construction of retention basins, which are designed to temporarily hold excess stormwater during

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heavy rainfall events, preventing the immediate overload of sewer systems. Integrated in the infrastructure, the concept of a "sponge city" including permeable surfaces, green roofs, and urban wetlands could absorb and naturally infiltrate stormwater. The goal is to reduce CSO even in the face of increased heavy rainfall by implementing these structural measures. The BWB has been actively working towards this goal by undertaking infrastructure improvements. To prevent sewer overflows in the city center, reserve capacities are being built. The recently built combined water storage tank at the Waßmannsdorf wastewater treatment plant, with its 50,000 cubic meters of storage capacity, and the storage tank still under construction at the Schönerlinde treatment plant, with a capacity of 40,000 cubic meters, are important contributions. A total of 253,000 cubic meters of underground storage for combined wastewater (of planned 300,000 cubic meters in 1998) has been constructed in Berlin's inner districts. Additionally, wastewater treatment plants outside the city will be equipped with 90,000 cubic meters of storage.(BWB 2022) In total, this compares to a rainfall amount of about 10 l/m² over the area of Berlin-Mitte.

To keep the current city water pipe system intact and thus to prevent leakages, BWB and Kompetenzzentrum Wasser Berlin (KWB) developed SEMA-Berlin to simulate wastewater pipe aging. By combining internal data (e.g., pipe age, material) with open city data (e.g., soil type, groundwater levels) using artificial intelligence (AI) and statistical methods, the tool enables precise investment planning and accurate modeling of aging processes.(BWB 2020)

5.3 By removing them

The pollutants addressed above can be removed from water through several methods at different stages of water management. Modern WWTP include several different treatment processes for removing suspended solids, organic matter, nutrients, etc. As an example, the water quality in the Panke catchment has significantly improved over the years due to various water management measures and the establishment of modern WWTP. The implementation of advanced treatment technologies, such as chemical phosphate precipitation, biological phosphorous removal, and denitrification, has led to substantial reductions of phosphate, ammonium and nitrate.(Marx et al. 2023) However, conventional wastewater treatment stages do not fully remove organic trace substances such as pharmaceuticals or pesticides. Since treated wastewater is discharged into Berlin's surface water, and around 60% of the city's drinking water is sourced from bank filtration of this surface water, it is the common goal to keep the concentrations of persistent, mobile, and potentially toxic chemicals (PMT) as low as possible.

A so called fourth treatment stage could feature several technologies that specifically target PMT. Adsorption technologies use materials with a high surface area like activated carbon to trap these substances. Another technology called ozonation uses ozone, a strong oxidizing agent, to break down organic molecules into potentially less harmful compounds. At the point of discharge, constructed wetlands can provide additional filtration and biological degradation of pollutants.(Brunsch et al. 2019) The combination of ozonation and constructed wetlands was successfully tested at the Schönerlinde wastewater treatment plant, to remove organic trace substances and microbial contamination from conventionally treated effluent.(Brunsch et al. 2019)

Several projects are being realized the Schönerlinde WWTP including ozonation for trace substance removal, flocculation filtration and a new wastewater discharge system. Additionally, the plant will generate its own energy entirely via three wind turbines and in multiple combined heat and power plants (Blockheizkraftwerk) by combustion of digester gases from sewage sludge. At the Ruhleben WWTP, UV disinfection was installed to ensure that swimming remains possible in downstream waters despite discharge into the Spree arm.(BWB 2022)

6 Conclusion

To mitigate the impact of climate change on water quality, reducing pollution at its source is the most cost-effective strategy, minimizing the need for extensive treatment infrastructure. Effective stormwater management through measures like rainwater infiltration and retention basins can reduce CSO, offering multiple benefits by preventing contaminants from entering water systems. Advanced treatments in WWTP will be necessary to remove persistent pollutants. As building and maintaining these systems will be costly, source pollution reduction is an important component to mitigate the impact of climate change on water quality in Berlin.

Future research on these issues will be crucial for mitigating climate change impacts on urban water quality. Studies on emerging contaminants (e.g., PFAS) and their sources and removals will improve pollution mitigation strategies. Advancing engineered, nature-based solutions, such as biofilters or biomaterial filters have the potential to tackle water pollution with local renewable resources.

Author contributions

OW conducted the literature review. The interpretation of findings was carried out by OW and AL. The initial draft of the manuscript and the figures were prepared by OW. OW and AL reviewed and edited the following draft versions.

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