Safe drinking water production in view of global threats including climate change. Technological solutions and gaps.

Paper coordinators and authors:

- Ahmed Mahmoud, Wetsus, Netherlands (Executive summary, Ch. 1, 3, 8, and overall review)
- Irene Jubany, Eurecat, Spain (Ch. 1, 4, 8, and overall reviewing)

Chapter leaders and authors:

- Rui C. Martins, University of Coimbra, Portugal (Ch. 2, and overall review)
- Manuela Antonelli, Politecnico di Milano, Italy (Ch. 4, 5 and overall review)
- Daniela Meilmann, DHVmed, Israel (Ch. 6 and overall review)
- Cynthia Kalweit, UBA, Germany (Ch. 7 and overall review)

Other authors:

- Agapios Agapiou, University of Cyprus, Cyprus (Ch. 7)
- Beatrice Cantoni, Politecnico di Milano, Italy (Ch. 4, and 5)
- Christoph Sprenger, Berlin Centre of Competence for Water, Germany (Ch. 3)
- Christos Makropoulos, National Technical University of Athens (NTUA), Greece (Ch. 2)
- Cristina Villanueva, ISGlobal, Spain (Ch. 5)
- Demetrios Eliades, KIOS Research and Innovation CoE, University of Cyprus, Cyprus (Ch.4 and 6).
- Despo Fatta-Kassinos, University of Cyprus, Cyprus (Ch. 5)
- George Bariamis, National Technical University of Athens (NTUA), Greece (Ch. 2)
- Henrietta-Essie WHYTE, IMT Atlantique France (Ch. 3)
- Hilde Passier, Deltares, Netherlands (Ch. 3)
- Isabel Gamallo Paz, Cetaqua - Water Technology Centre, Spain (Ch. 5, and 6)
- Leon Kors, PWN, Netherlands (Ch. 2)
- Luísa Durães, University of Coimbra, Portugal (Ch. 2)
- Maria Karekla, University of Cyprus, Cyprus (Ch. 6)
- Onno Kramer, Waternet, Netherlands (Ch. 2)
- Panagiotis Kossieris, National Technical University of Athens (NTUA), Greece (Ch. 2)
- Sara Espinosa Martínez, Cetaqua – Water Technology Centre, Spain (Ch. 6)
- Silvia Lacorte, CSIC, Spain (Ch. 2)
- Sonia Sanchis, Leitat, Spain (Ch. 2)
- Stelios Vrachimis, KIOS Research and Innovation CoE, University of Cyprus, Cyprus (Ch. 4, and 6).
- Vasiliki Beretsou, University of Cyprus, Cyprus, (Ch. 5 and 7)
- Vasiliki Thomopoulou, National Technical University of Athens (NTUA), Greece (Ch. 2)

Published in August 2025.

Table of Contents

Abbreviations and acronyms

Acronym	Full Term	Acronym	Full Term
AC	Activated Carbon	ML	Machine Learning
ADWG	Australian Drinking Water Guidelines	NBS	Nature-Based Solutions
AI	Artificial Intelligence	PAH	Polycyclic Aromatic Hydrocarbon
AOP	Advanced Oxidation Process	PFAS	Per- and Polyfluoroalkyl Substances
ARG	Antibiotic Resistance Gene	POCIS	Polar Organic Chemical Integrative Sampler
BF	Biofiltration	POP	Persistent Organic Pollutant
CEC	Contaminant of Emerging Concern	QSAR	Quantitative Structure–Activity Relationship
CPS	Ceramic Passive Sampler	RfD	Reference Dose
DBP	Disinfection By-Product	RPF	Relative Potency Factor
DGT	Diffusive Gradients in Thin-films	SDG	Sustainable Development Goal
DWD	Drinking Water Directive	SDWA	Safe Drinking Water Act
DWDN	Drinking Water Distribution Network	SDWQ	Standard for Drinking Water Quality
DSS	Decision Support System	TDI	Tolerable Daily Intake
EPA	Environmental Protection Agency (United States)	TFA	Trifluoroacetic acid
EBM	Effect-Based Monitoring	TRL	Technology Readiness Level
EU	European Union	UV	Ultraviolet
IoT	Internet of Things	WHO	World Health Organization
IPCC	Intergovernmental Panel on Climate Change	WFD	Water Framework Directive
MAR	Managed Aquifer Recharge	WWTP	Wastewater Treatment Plant
MP	Microplastic		

Executive Summary

Access to clean, safe drinking water is a basic human right, essential for public health, social fairness, and environmental sustainability. It is vital not only for preventing waterborne illnesses and long-term exposure to harmful substances but also for boosting hygiene, food security, and economic stability. Yet, climate change increasingly jeopardizes the quality, availability, and reliability of drinking water supplies across Europe and globally. We are seeing rising temperatures, altered rainfall patterns, and more frequent extreme weather events intensify pollution, damage water infrastructure, and reveal weaknesses in both surface and groundwater systems. This white paper offers a comprehensive summary of climate change's effects on water sources, treatment, and distribution. It highlights the increasing challenge of managing chemical and microbial contamination, especially from emerging pollutants like PFAS, pharmaceuticals, and microplastics, within unpredictable environmental conditions. The paper explains that surface waters face heightened nutrient loads, salt intrusion, and pollution during storms, while groundwater is more susceptible to diffuse pollution, excessive extraction, and saline intrusion. Compounding these issues are aging drinking water networks, where rising temperatures further promote bacterial growth and the formation of disinfection byproducts (DBPs).

A range of technical solutions are being developed to tackle these challenges. These include advanced oxidation processes (AOPs), membrane filtration, managed aquifer recharge (MAR), digital twins, and real-time monitoring systems. Digital solutions, powered by artificial intelligence and the Internet of Things, offer capabilities like predictive modelling, early warning systems, and more responsive drinking water quality monitoring. However, there are still significant information gaps. We have a limited understanding of how emerging pollutants behave and their toxicity, a lack of long-term data on climate-resilient treatment methods, insufficient alignment of monitoring and regulatory frameworks, and persistent issues with public trust and communication.

Summary of policy recommendations

Climate change presents an increasing danger to Europe's drinking water systems, bringing more pollutants, severe weather, and decaying infrastructure. A complete overhaul of how water quality is protected, managed, and regulated is essential to address this. The EU should focus its investments on low-energy, climate-resilient water treatment technologies, such as membrane systems and advanced oxidation techniques, prioritizing modular solutions for rapid implementation. This approach will help develop net-zero water infrastructure and effectively manage new contaminants. Crucially, implementing real-time, intelligent monitoring and digital water infrastructure is also vital. By leveraging smart sensors and AI-powered analytics, water management can shift from reactive to predictive, significantly improving pollution prevention and cross-border collaboration. To safeguard public health, the EU must update its risk assessment frameworks, making them more flexible and forward-looking, and incorporating complex pollutant interactions and climate forecasts. To ensure equitable access and strengthen unity, the EU should boost cross-border and rural water security. This can be achieved by establishing transboundary water quality observatories and providing targeted funding for infrastructure improvements. Finally, restructuring governance through transparent public involvement and integrated collaboration is critical. This involves creating cross-sector platforms, integrating public participation into water initiatives, and transparently sharing data to build trust and foster a proactive, participatory approach to water stewardship. Figure 1 summarizes the main policy recommendations emerging from this white paper.

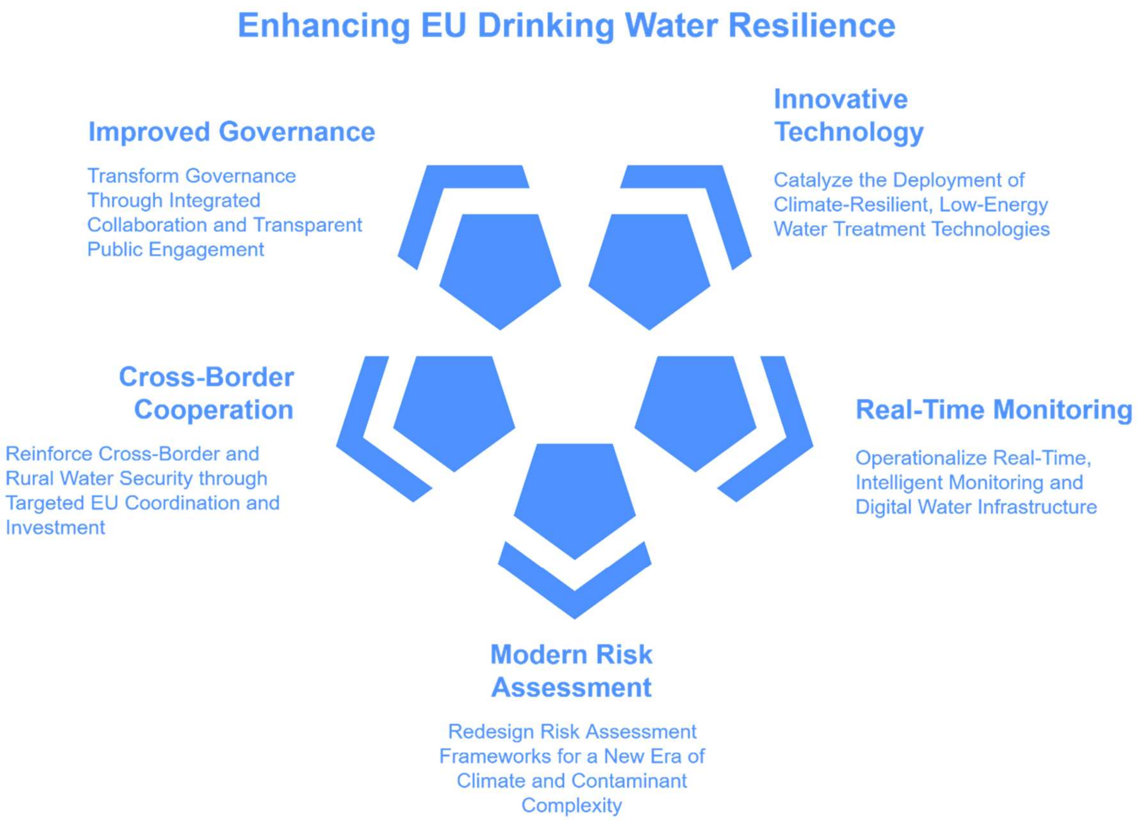

Figure 1. Summary of policy recommendations for enhancing EU drinking water resilience

Summary of knowledge gaps and recommendations

Here are the key information gaps concerning drinking water resilience:

Limited understanding of emerging pollutants	
Gaps: The long-term health impacts of contaminants of emerging concern (CECs), including PFAS, pharmaceuticals, microplastics, and endocrine disruptors, are critically lacking in data, especially when it comes to chronic, low-dose, and combination exposures.	**Recommendations:** To detect minor health repercussions, Europe should invest in longitudinal cohort studies that combine advanced omics technologies, human biomonitoring, and environmental sampling. The creation of a centralized European CEC Data Observatory may make it possible to gather data on the prevalence, toxicity, and effectiveness of treatments of contaminants in real time. Standardized sample procedures, AI-assisted toxicological prediction tools for unidentified or uncontrolled substances, and coordinated, transdisciplinary research spanning toxicology, environmental health, and clinical science are necessary to close this gap.

Unknown climate-pollutant interactions	
Gaps: Knowledge is lacking regarding how climate stresses influence the mobility and persistence of pollutants. Extreme weather events like heatwaves, droughts, and floods can significantly alter how chemical and microbiological pollutants concentrate, move, and transform in water sources. However, current models often treat pollutant dynamics as static.	**Recommendations:** To accurately predict pollutant movement under future climate scenarios and guide targeted mitigation efforts, the EU needs to invest in AI-based simulations, remote sensing techniques, and climate-integrated fate models.
Monitoring capability	
Gaps: Most water systems, especially in rural, decentralized, or local areas, lack the capability for continuous impurity monitoring. Traditional lab-based sampling is simply too slow to detect sudden contamination events caused by severe weather or infrastructure failures.	**Recommendations:** To address this, innovation should focus on developing and deploying affordable biosensors, IoT-enabled devices, and smart monitoring systems. These should be supported by edge computing and artificial intelligence to enable automated anomaly detection and rapid decision-making.
Absence of scalable, efficient treatment	
Gaps: While promising modern treatment methods like membranes, biofiltration, and AOPs exist, their widespread adoption is hampered by high costs and energy consumption, especially for smaller or rural utilities, or a lack of proven scalability.	**Recommendations:** To bridge this gap, targeted funding is crucial for pilot projects, technology readiness testing, and developing modular, decentralized systems. These systems need to be adaptable to local conditions while remaining affordable, efficient, and environmentally friendly.
Public Trust and Communication Deficits	
Gaps: A lack of communication and transparency contributes to a low level of public confidence in drinking water systems. This becomes critical when rolling out new technologies or responding to contamination events.	**Recommendations:** To build trust and boost transparency, the EU should promote multilingual risk communication plans, real-time public dashboards, and citizen science projects that actively involve communities in water quality monitoring and decision-making.

1. Introduction

Safe drinking water is essential for public health and well-being. Access to potable water is recognized by the United Nations and Sustainable Development Goal 6 (SDG 6) as a fundamental human right. Beyond its direct implications for human health and dignity, its provision is critical for achieving social justice, fostering economic development, and maintaining environmental equilibrium. Nevertheless, persistent global challenges, particularly climate change, are increasingly compromising the reliable availability of clean water resources. Defects in quality and quantity cause high social and economic costs. The Drinking Water Directive (DWD) is the main piece of EU legislation in this regard. The DWD regulates the quality of water intended for human consumption. Its overall objective is to protect human health by ensuring that drinking water at the consumer tap is wholesome and clean. The availability of safe drinking water is inextricably linked to robust public health outcomes. Access to potable water facilitates effective hygiene practices, thereby mitigating the transmission of waterborne diseases and generally enhancing community well-being. Contaminated water serves as a primary vector for numerous debilitating and often fatal illnesses, including cholera, typhoid, and dysentery, which collectively contribute to hundreds of thousands of annual fatalities, disproportionately affecting vulnerable populations. Beyond the immediate threat of infectious agents, exposure to toxins and hazardous substances via contaminated water poses significant long-term adverse health consequences.

The hydrologic cycle intricately links drinking water, groundwater, and surface water networks. Groundwater contributes to surface water bodies, sustaining baseflow in streams and rivers, especially during periods of low precipitation. Conversely, surface water sources—including rivers, lakes, and streams—recharge groundwater aquifers through infiltration. This reciprocal relationship dictates that alterations in the quantity or quality of one component can directly impact the others. Pollutants entering surface water—from sources like agricultural runoff, industrial discharge, or urbanization—can infiltrate the ground and contaminate groundwater reserves. Conversely, toxins present in groundwater, such as nitrates from agricultural practices, can migrate into surface water bodies, diminishing their quality. Both surface water and groundwater are critical for drinking water supplies. While surface water directly serves municipal systems in many regions, groundwater is often the primary source for both urban and rural drinking water. The integrity and quality of both surface and groundwater sources are paramount for the functionality of the drinking water network, which delivers treated water to consumers. Contamination of either supply directly impacts public drinking water systems, leading to increased treatment costs and potential public health risks. Therefore, effective drinking water supply management necessitates a comprehensive understanding of the dynamic interactions between surface water, groundwater, and the distribution infrastructure that serves end-users. This holistic approach is critical for ensuring sustainable and safe drinking water provision.

The integrity of European drinking water systems faces escalating threats from a diverse array of chemical and emerging contaminants. This challenge is directly attributable to the continent's intense agricultural practices, extensive industrial legacy, and evolving land-use patterns. Nitrate pollution, primarily driven by the pervasive application of synthetic fertilizers and animal manure, remains the most significant hazard to groundwater resources. Concentrations frequently exceed the maximum admissible limits established by both the EU Nitrates Directive (91/676/EEC) and the Drinking Water Directive (98/83/EC, recently revised by 2020/2184/EU). Furthermore, pesticide residues, encompassing both legacy compounds and newly approved substances, exacerbate the chemical burden on surface and groundwater bodies, thereby challenging the efficacy of conventional water treatment technologies. Heavy metals (notably arsenic, lead, and mercury), polycyclic aromatic hydrocarbons (PAHs), and persistent organic pollutants (POPs) continue to be detected at concerning levels, particularly in regions with a history of intensive industrial activities and mining operations. Emerging contaminants, including per- and polyfluoroalkyl substances (PFAS), pharmaceuticals, and microplastics, have prompted precautionary regulatory measures and increased scientific scrutiny across the European Union. This is largely due to their environmental persistence, bioaccumulative potential, and as-yet-incompletely understood human health impacts.

Despite significant advancements in wastewater treatment and the implementation of robust legislative frameworks, such as the Water Framework Directive (2000/60/EC) and the revised Drinking Water Directive (2020/2184/EU), recent assessments indicate that only a small percentage of European surface water bodies achieve "good chemical status," and approximately one-quarter of groundwater bodies fail to meet chemical quality standards. The diffuse and persistent nature of these contaminants, coupled with increasing pressures from climate change and demographic shifts, underscores the critical need for continuous innovation in monitoring, risk assessment, and advanced treatment methods. Moreover, the integration of digital water management tools and real-time data analytics is increasingly recognized as pivotal for enhancing the resilience and sustainability of Europe's drinking water supply in the face of these complex and evolving risks.

There is widespread scientific consensus that climate change is fundamentally altering global hydrological cycles, with profound and intensifying repercussions for source water quality. The most recent Intergovernmental Panel on Climate Change (IPCC) reports, alongside numerous peer-reviewed studies, confirm that rising temperatures, shifting precipitation patterns, and more frequent extreme weather events—such as floods, droughts, and wildfires—directly impact the safety and reliability of drinking water supplies worldwide. These climatic shifts accelerate the mobilization of existing pollutants, introduce novel contaminants, and impose significant strain on water treatment infrastructure. For instance, wildfires can discharge toxic compounds and heavy metals into reservoirs and supply networks. Conversely, excessive flooding and precipitation events may overwhelm treatment plants, leading to the infiltration of wastewater and industrial contaminants into drinking water sources. Droughts exacerbate water quality issues by concentrating pollutants and organic matter, which can subsequently react with disinfectants to produce hazardous byproducts.

The escalating frequency and severity of water quality emergencies, driven by climate-related events, underscore the critical importance of recognizing and managing these impacts. As climate change intensifies, millions of individuals face increased exposure to harmful substances such as lead, per- and polyfluoroalkyl substances (PFAS), pathogens, and other contaminants, with disproportionately higher hazards in rural and vulnerable areas. Existing water systems, many of which were designed for more stable environmental conditions, are increasingly inadequate to address these heightened demands. Without rapid adaptation and substantial investment in robust infrastructure, enhanced monitoring protocols, and integrated water management techniques, the capacity to provide safe and clean drinking water for all populations is significantly threatened.

The European Union's Drinking Water Directive (DWD) of 2021 is globally recognized for its rigorous and comprehensive approach, setting stringent water quality standards that often surpass WHO guidelines. It proactively addresses emerging contaminants like endocrine disruptors, PFAS, and microplastics, adopting a preventive, risk-based strategy and standardizing materials in contact with drinking water. The DWD also promotes equitable access for vulnerable groups, encourages tap water use, and mandates reduced water leakages and increased transparency to support public health, environmental protection, and social equity. In comparison, the United States regulates drinking water via the Safe Drinking Water Act (SDWA), enforcing limits on over 90 contaminants and requiring risk assessments and emergency preparedness, though state-level variations affect consistency. Australia's framework, based on the non-binding Australian Drinking Water Guidelines (ADWG), emphasizes risk management and regular updates. China's Standards for Drinking Water Quality (SDWQ) set mandatory limits tailored to national and regional challenges, but enforcement varies widely.

The confluence of climate change, water scarcity, aging infrastructure, and increasingly stringent regulatory demands has created an urgent imperative for digitalization within the water sector. This digital transformation enables utilities to transcend traditional, reactive management paradigms by integrating technologies such as IoT sensors, big data analytics, artificial intelligence (AI), and cloud computing across all facets of water operations. These advanced solutions facilitate real-time monitoring of water quality, rapid leak detection, predictive maintenance for infrastructure, and more accurate demand forecasting. Such capabilities are essential for minimizing water losses, optimizing resource utilization, and ensuring the continuous provision of clean drinking water. Digitalization represents more than just a technological upgrade; it signifies a fundamental conceptual shift that empowers utilities to make data-driven decisions, respond promptly to emerging hazards, and enhance overall operational efficiency and sustainability. Initiatives like the IWA Digital Water Programme exemplify the sector's pivot towards smart water systems, fostering the sharing of best practices, accelerating innovation, and bolstering resilience against evolving challenges. Given that the water industry currently lags behind other sectors in digital adoption, expediting this transformation is now considered crucial for safeguarding water security, improving customer service, and meeting both current and future societal expectations.

This White Paper intends to address the challenges that the water sector is facing to produce drinking water, both considering climate change threats and human-induced pollution. Two sections review the challenges, solutions and gaps related to the water sources (surface water and groundwater), one section deals with the drinking water distribution networks, then, another section is dedicated to the human health risk assessment, the adaptation strategies section discusses about the technological solutions available and finally, governance issues are discussed in the last part. The document is finalized with the conclusions and future recommendations.

Each chapter starts with a summary box that identifies the key question addressed, followed by recommendations for policy development and the knowledge gaps identified. Following the box, further details, and underpinning evidence from literature are presented. References for further information regarding each section is compiled at the end of the document.

2. Surface water quality

Key Question: How can we ensure safe drinking water production from surface water sources under increasing climate change pressures and emerging contaminants?

Policy recommendations: Although the legal framework is being adapted by increasing the quality requirements for treated municipal wastewater discharge in the water bodies, there is still a need to address other sources of pollution, such as industrial and hospital effluents, where the contaminants of emerging concern are found at higher concentrations. An effective monitoring strategy involving real-time monitoring infrastructures combined with advanced modelling techniques would allow for the identification of the pollution hotspots that should be tackled. The development of suitable treatment processes encompassing low operation costs and with less energy demand is required to reach the standard treatment levels that protect the water quality.

Knowledge gap: The effect of contaminants of emerging concern on the ecosystems and human health still needs to be addressed. The behavior and fate of these contaminants in the sewage system and the surface waters are not totally known. The effect of climate change on the sources of contamination still needs to be addressed. Moreover, the development of reliable on-site monitoring infrastructures and the models to identify the best location for their deployment are still required. There is still a knowledge gap regarding cost-effective treatment technologies that can remove some contamination while reducing the energy and emissions required.

Surface water encompasses all water bodies on Earth's surface, including oceans, rivers, streams, lakes, ditches, and wetlands. Freshwater is essential for sustaining life on Earth, and surface water is generally the primary source for various human needs, including drinking water. Maintaining high water quality at the source reduces the need for extensive treatment and disinfection, thereby minimizing the formation of harmful disinfection byproducts that pose risks to human health. However, growing water demand, driven by population growth and socio-economic development, is placing significant pressure on water bodies, leading to resource scarcity. Additionally, surface water bodies are highly susceptible to pollution, resulting in declining water quality. This deterioration can be attributed to both natural and human-induced factors.

Natural influences on water quality include atmospheric conditions (e.g. precipitation, air pollution, and temperature fluctuations) and climatic patterns (such as seasonal variations, droughts, and extreme weather events). However, human activities have a much greater impact, particularly through wastewater discharge and agricultural runoff. Contaminants such as heavy metals, fertilizers, and pesticides significantly degrade water quality. Moreover, excessive nutrient loads—primarily nitrogen and phosphorus—combined with rising temperatures accelerate eutrophication, leading to algal blooms especially in lake water bodies. Some of these blooms, especially those caused by cyanobacteria, produce toxins that harm aquatic ecosystems and human health. Consequently, the deterioration of surface water quality necessitates the implementation of advanced water treatment processes in drinking water production facilities, presenting a considerable technical challenge.

The Water Framework Directive (WFD) set a 2015 deadline for European rivers, lakes, coastal, and groundwater bodies to reach good status, but this goal was not met. By 2021, only 29% of Europe's surface waters reached good chemical status.

Chemical pollution remains a major issue, mainly due to atmospheric pollution from coal energy and diffuse agricultural pollution. Persistent pollutants like mercury and brominated flame retardants significantly impact chemical status. Excluding these long-lived pollutants, 80% of surface waters would otherwise meet good chemical status.

The main challenges associated with surface water quality are related to the contamination by pollutants of emerging concern, nutrients, and salt intrusion.

Wastewater treatment plants (WWTPs), industrial effluents, cities runoff (especially during storm events), and diffuse pollution from agriculture and farming, jeopardise water quality with contaminants of emerging concern (CECs) such as pharmaceuticals and pesticides, per- and polyfluoroalkyl substances (PFAS), antibiotic resistance genes (ARG), hydrocarbons, heavy metals, microplastics (MP), and nutrients that lead to eutrophication, among others. Since water bodies are interconnected, contaminants end up in rivers, wetlands, lakes, oceans, and aquifers. Moreover, overexploitation for increased water consumption leads to high pressure on water resources, which also affects their quality. These problems may be exacerbated by global and climate change effects, including prolonged droughts that hinder the natural recharge of aquifers, increased flooding, and rising sea levels that intensify saline intrusion.

As surface waters are often used for drinking purposes, it is important to undertake monitoring studies/programs to early identify and track pollution sources and mitigate their presence in surface waters. Surface water monitoring is contemplated by the European Union to ensure the protection, sustainable use, and improvement of water quality in accordance with the objectives of the Water Framework Directive. The Environmental Quality Standards are set according to Directive 39/2013/EU for a set of substances, and new regulations such as the Watch List or the recent Wastewater Directive provide the need to minimize the release of chemicals from WWTP to receiving waters. Monitoring serves three main purposes: (1) protecting public health as early as possible, (2) optimising treatment performance and operating costs, and (3) demonstrating compliance with regulatory directives. It does this through systematic sampling and laboratory analysis of priority contaminants. To cover a larger number of contaminants, especially CECs, and to reach high sensitivity, passive sampling techniques are being implemented to allow for time-integrated monitoring of trace pollutants at low concentrations, improving detection of episodic events and providing a more representative picture of water quality. Different passive sampling techniques are proposed for surface water monitoring, such as the diffusive thin gradients (DGTs), Polar Organic Chemical Integrative Sampler (POCIS), Chemcatchers, or ceramic passive samplers (CPS). These passive samplers allow multi-component analysis and provide comprehensive information on the water contamination status. Modern schemes now combine on-site sampling with Earth-Observation (EO) data streams—e.g., Sentinel-2 optical imagery for chlorophyll-a and turbidity, Sentinel-1 radar for flood-driven sediment plumes, and thermal sensors for surface-water temperature—to deliver basin-wide, near-real-time intelligence at a cadence unattainable with field work alone. Multi-source Earth-Observation data streams now let operators “see” the whole contamination cascade before it hits the raw-water pumps at Conveyance or water treatment level.

Parcel-level crop maps can pinpoint exactly where and when fertilisers are applied throughout the basin, translating on-farm practices into a precise nutrient-load input for the model. The data obtained in monitoring studies can be used to draw management and decision support conclusions, guide policy development, prioritize of mitigation measures, and assess compliance with environmental objectives.

Although several initiatives and projects have developed actions and tools towards water monitoring, protection, and resilience, additional knowledge is needed to understand the synergistic effects and risks of multiple stressors and pollutants. Moreover, the development of cost-efficient monitoring strategies and technologies for preventing water contamination, as well as early-warning and Decision Support Systems (DSS) for sustainable water governance and management, is still a challenge. The new Urban Wastewater Directive (Directive (EU) 2024/3019) was a step forward to protect the natural watercourses by imposing the monitoring and removal of contaminants of emerging concern in municipal wastewater treatment plants (WWTP). The challenge now is to develop suitable quaternary treatments able to remove those contaminants at low operating costs and with reduced energy demand. Some researchers propose a combination of low-cost Advanced Oxidation Process (AOP) adsorption with activated carbon (AC) and biofiltration (BF) for the removal of CECs, MPs, and ARGs present in WWTPs.

Rising salinity in freshwater sources poses a growing challenge to water security, requiring technological innovation, improved management, and (inter)national cooperation to safeguard quality and supply. The sea level rise and frequent droughts are increasing this problem. Furthermore, extreme drought and reduced river inflows lead to a surge in intake salt concentrations promoting operational disruptions in drinking water treatment. Measures to stabilize supply are applied such as providing additional drinking water and alternative intake strategies, including transporting water from lower-salinity regions via tankers. While emergency measures provided temporary relief, long-term resilience requires investments in desalination technologies, membrane filtration, and adaptive water governance to manage salinity fluctuations more effectively.

Salinity-related water quality issues are a significant challenge across Europe, particularly in coastal and delta regions. Addressing these issues requires a combination of technological, regulatory, and climate-adaptive strategies. Essential measures include enhanced monitoring, improved sluice and discharge management, and greater investment in desalination and advanced filtration technologies to ensure long-term water security. Addressing these challenges requires stronger European cooperation on cross-border water security, joint monitoring efforts, and investment in shared infrastructure solutions.

3. Groundwater quality

Key Question: How can we enhance the groundwater management and monitoring systems to address emerging contaminants and climate change-driven threats while ensuring sustainable water quality for future generations?

Policy recommendations: EU member states should modernize their groundwater management by expanding the range of monitored contaminants and integrating smart, real-time technologies into monitoring networks that reflect the dynamics of groundwater systems. This includes updating the Water Framework Directive (WFD) and the Groundwater Directive to address emerging pollutants such as endocrine disruptors, antibiotic residues, and microplastics, supported by standardized EU-wide threshold values. Enhancing monitoring strategies requires a systemic design approach, greater use of automated sensors in high-risk areas, remote sensing technologies for detecting contamination hotspots, and increased monitoring frequency to capture short-term pollution events. In addition, predictive modelling—using numerical simulations, climate and land-use data, and AI-based analytics—should be employed to forecast pollution risks and guide proactive intervention. These improvements will not only strengthen regulatory enforcement and protect drinking water supplies but also support the EU's Zero Pollution Action Plan and the long-term sustainability of groundwater resources.

Knowledge gap: The long-term impacts of emerging contaminants on groundwater and surface water ecosystems and human health are still largely unknown. Focusing on groundwater, the amount of microplastic that enters groundwater, the duration of survival of pharmaceutical residues, PFAS, and other 'forever chemicals', and the interactions between various pollutants and the effect on microbiology and ecosystems in the groundwater are still unknown. Furthermore, further research is required to pinpoint the geographical consequences and thresholds for ecosystem resilience, even though it is widely acknowledged that climate change influences the hazards of groundwater replenishment and contamination.

Groundwater constitutes the world's largest freshwater reserve, playing a pivotal role in sustaining drinking water supplies, agricultural irrigation, industrial processes, and critical ecosystems. Historically, groundwater management has prioritized quantity over quality, yet emerging evidence underscores the urgent need to address water quality degradation to safeguard this vital resource. Groundwater in the EU is increasingly threatened by pollution and climate change, with significant regional disparities in water quality. Persistent contaminants, including agricultural runoff, industrial chemicals, and emerging pollutants, challenge the sustainability of groundwater as a secure drinking water source. Agriculture remains the primary contributor to groundwater contamination, with 19% of EU groundwater bodies affected by high nitrate concentrations, particularly in France, Spain, and the Netherlands, while pesticides like glyphosate exceed EU limits in 3–7% of monitoring sites. Industrial pollution also plays a major role, with "forever chemicals" such as trifluoroacetic acid (TFA) detected in groundwater across 10 EU countries, reaching extreme concentrations in Belgium's Mehaigne River and Germany's Elbe River. Additionally, emerging contaminants such as pharmaceuticals, antibiotics, and endocrine disruptors like bisphenol-A have been added to the EU's pollutant watchlist due to growing health concerns, as these substances, often linked to wastewater discharge and inadequate filtration, pose increasing challenges for groundwater quality management.

According to the Water Framework Directive (WFD) and Groundwater Directive, the main contaminants monitored by the EU's groundwater monitoring systems are heavy metals, nitrates, and pesticides. These initiatives, however, fall short in addressing new contaminants that are being found more frequently as a result of industrial runoff and wastewater infiltration, including microplastics, medications, PFAS, and antibiotic-resistant genes. Therefore, in the 5th surface water watchlist (March 2025), the Commission has identified 12 pollutants that need to be monitored to determine their potential risks to the environment and human health. These twelve include pesticides, pharmaceuticals, a sunscreen ingredient, and an antioxidant commonly used in tires, all of which have been flagged by EU member states ' experts as potential widespread concerns. Despite increasing hazards from over-extraction, legacy pollution, and climate-induced recharge shifts, deep aquifers—which are sometimes thought to be naturally protected—remain little monitored. Furthermore, manual sampling slows the detection and response to contamination, and occasional monitoring (usually quarterly or biannual) misses short-term pollution increases from extreme weather events. To close existing gaps, the EU must move beyond static, periodic monitoring toward a more dynamic and integrated approach. While real-time monitoring will not be feasible in all locations, combining well-designed monitoring networks with targeted use of innovative real-time data collection, advanced numerical modeling, and AI-driven analytics offers a robust path forward. Monitoring systems tailored to the specific characteristics of groundwater bodies can significantly improve early detection of quality changes and pollution threats. Passive sampling tools can help identify trace contaminants, while in-situ optical and electrochemical sensors—where applicable—enable continuous monitoring of pollutants such as PFAS and pharmaceutical residues. To anticipate contamination hazards and enable preventative measures, AI-driven forecasting models can combine pollution and climatic data.

A comprehensive approach is essential to enhance the effectiveness of environmental monitoring. First, the range of substances monitored under the Water Framework Directive (WFD) and the Groundwater Directive should be expanded to include emerging contaminants such as microplastics and antibiotic residues. This expansion should be supported by the establishment of standardized EU-wide threshold values to enable more reliable risk assessments. Second, improving surveillance requires increasing both the spatial and temporal intensity of monitoring. Utilizing remote sensing technologies to detect contamination hotspots, along with the strategic placement of automated sensor networks in high-risk areas such as industrial and agricultural zones, will be critical. Third, advancing predictive and integrative data management is key. Establishing a centralized, pan-European groundwater quality database and leveraging machine learning algorithms that incorporate land-use and climate data will allow for the proactive identification of contamination risks. Finally, ensuring equitable monitoring capabilities, particularly in rural and economically disadvantaged areas, requires investment in scalable and cost-effective technologies. This can be achieved through EU-funded pilot programs and collaborative public-private partnerships that facilitate the widespread deployment of affordable sensor systems.

Climate change is worsening groundwater quality issues across the European Union by altering recharge patterns and intensifying extreme weather events. These shifts affect both the availability of groundwater and the risk of contamination, making sustainable management significantly more difficult. Variations in precipitation due to climate change are altering groundwater recharge rates, with noticeable regional differences. In some areas, prolonged droughts and reduced rainfall limit the infiltration of water into aquifers, leading to higher concentrations of contaminants such as nitrates and industrial chemicals. In coastal regions, reduced freshwater recharge exacerbates saltwater intrusion, making groundwater unsuitable for drinking or irrigation. Conversely, increased precipitation in certain regions, particularly in northern Europe, can enhance recharge but may also mobilize previously trapped pollutants in sediments. The increase in precipitation could intensify the leaching of PFAS from porous media, leading to contamination of the groundwater system (Holly et al., 2024). The growing frequency and intensity of extreme weather events further threaten groundwater quality. Flooding can overwhelm, agricultural land, and wastewater treatment systems, introducing pesticides, pathogens, and heavy metals into groundwater supplies. The rapid infiltration of these pollutants can go undetected by traditional monitoring systems. On the other hand, extended droughts reduce water dilution, leading to higher contaminant concentrations. As water tables decline, naturally occurring pollutants such as salt, fluoride, and arsenic may become more prominent, rendering previously safe aquifers unsuitable for consumption. Additionally, excessive groundwater extraction during droughts can draw contaminants from nearby polluted sources, further degrading water quality. To mitigate these risks, the EU must integrate climate resilience into groundwater management strategies. Key measures include promoting managed aquifer recharge projects, investing in real-time monitoring systems to detect contamination spikes linked to climate change, and implementing sustainable land-use practices to protect recharge areas. Strengthening pollution controls and improving wastewater management systems are also crucial for reducing groundwater vulnerability to climate-related threats.

4. Drinking water distribution networks

Key Question: How can drinking water distribution networks be optimized to maintain water quality, minimize health risks, and enhance resilience against climate change effects?

Policy recommendations: The main challenge in drinking water distribution networks is to maintain water quality throughout the network in terms of biological content and contaminants content. Climate change and human activities are impacting water source quality and therefore water treatment plants need to intensify the treatments to produce high quality water. Main impact form climate change to the distribution network is the increase of temperature causing an increase in the bacterial growth. For those networks with disinfection, temperature also impacts the kinetics of the disinfection process, the concentration of residual disinfectants and the production of disinfection by-products. Therefore, legislation needs to regulate all potential existing and newly discovered DPBs. Non climate related challenges facing water distribution networks are related to pipe repairing and relining. In this sense new regulations need to adopt guidelines for selection and testing of materials in contact with (disinfected) water to avoid producing harmful compounds. Member states should promote the use of new technologies and tools to increase the knowledge on the processes taking place in distribution networks for a better management to minimize health risks. Some of these are: on-line monitoring tools and sensors, and early-warning systems and digital twins.

Knowledge gaps: There is a lack of knowledge about other effects than temperature affecting drinking water distribution networks. For non-regulated DBPs there is a lack of information on their occurrence, fate and, for some of them, effect on human health. There are also uncertainties on the effect of pipe relining materials on water quality. There is a need for low-cost sensor for reliable water monitoring for DBPs and microorganisms.

One of the main challenges in drinking water distribution networks (DWDNs) is the assurance of the water quality throughout the network until the final consumer. Water quality can mainly deteriorate due to the growth of bacteria. For this reason, disinfection with chemical products having residual disinfection power is mandatory in many countries (like Spain and UK), especially in those with high temperatures. In Europe, chlorine is the most used disinfectant when residual protection is needed, while UV and ozone are typically used when residual disinfectant is not required.

Chlorine is typically added at the drinking water treatment plant and, in some cases, at booster stations throughout the distribution network. Effective network management aims to maintain adequate disinfectant levels, minimize bacterial presence, and keep disinfection by-products within safe limits. Disinfection by-products are produced by the chemical reaction of natural organic matter in the water and the disinfectants. These compounds are regulated in water because they are toxic and/or carcinogenic (*inter alia*: trihalomethanes, haloacetic acids, nitrosamines, bromate). Monitoring programs, according to WFD (2000) should verify that water intended for human consumption at the point of compliance is wholesome and clean and that the most appropriate means of mitigating the risk to human health is identified. Monitoring of the requested parameters is mainly done by grab samples and laboratory analysis, although some online analysers and sensors are being developed and implemented.

Climate change affects drinking water because it disturbs raw water quality (see section 2 for surface water and section 3 for groundwater) and because it changes the phenomena occurring in the network. The increase of water temperature is the main parameter affecting the network. Temperature increases chlorine degradation and volatilization; thus, more chlorine needs to be dosed and therefore more DPBs are being formed. Additionally, temperature also affects DBPs formation kinetics and the predominant species. A higher temperature also promotes bacterial growth favouring regrowth and biofilm formation in networks, creating the habitat for opportunistic pathogens such as *Legionella spp.* This causes locations that are not using disinfection to probably need to use them in the future.

With the networks becoming old in many regions, other issues are arising, such as leakage and water loss, contamination risks, service interruptions, and inefficiencies in water management and use. Pipe repairing and relining can also produce risks for human health in (chlorinated) networks due to the release of potentially toxic compounds or the formation of new DBPs due to the reaction of residual chlorine with released compounds.

There is growing emphasis on interdisciplinary research, integrating microbiology, data science, and engineering. Technological solutions for managing water quality in DWDNs are:

· **Water monitoring: online sensors / analysers**

Current water monitoring is evolving from manual sampling to real-time, continuous monitoring using advanced online sensors. There's a growing adoption of multi-parametric sensors for chemical quality measurement (turbidity, pH, chlorine, conductivity), also deployed as inputs to machine learning models to predict microbial indicators, which are difficult to monitor online. These tools increase spatial and temporal resolution, supporting early detection of anomalies. Challenges include sensor calibration, maintenance, and data management. Sensors for target parameters such as DBPs (trihalomethanes mainly) are also emerging and need field validation before wide full-scale implementation. Biofilm dynamics are a key research focus, influencing microbial water quality and disinfection strategies. Water age and hydraulic residence time significantly affect residual disinfectant decay and microbial regrowth. Novel on-line methods such as on-line flow cytometry are also starting to be tested to identify their potential for predicting undesired microbial growth tendencies.

· **Water monitoring: new analytical methods**

Novel methods such as offline flow cytometry, high-resolution mass spectrometry, omics-based approaches (e.g., metagenomics), and in invitro toxicity tests are enhancing microbial, chemical and toxicity characterization, but their adoption is far from a routine application, both for costs and complexity of implementation and data interpretation. Basic research is needed for the discovery of new DBPs that are still unknown and for the testing of their potential toxicity for humans. Furthermore, applied research is needed to test and validate the applicability of these new monitoring methods for routine DWDN monitoring.

· **Predictive models**

Predictive models are essential for simulating water quality under varying operational scenarios, such as stagnation, temperature shifts, or contamination events. They are also essential for the development of early warning systems and for decision-making in DWDNs management. Hydraulic modelling (residence time in pipes and tanks) is crucial for the development of quality predictive models (for chlorine, DBPs, biofilm…). Hydraulics is usually modelled with software such as EPANET.
Modelling in distribution networks is shifting toward hybrid models, combining physical-hydraulic frameworks with data-driven (AI/ML) approaches. Advances in machine learning enable improved forecasting of chlorine decay, biofilm development, and contaminant spread (Li, 2024). Real-time data from sensors feed into predictive modelling frameworks, allowing dynamic updates and scenario analysis. Data quality and integration remain challenges.

· **Early warning systems and digital twins**

Early warning systems are increasingly designed as real-time platforms integrating sensors, models, and anomaly detection algorithms. They aim to detect deviations from baseline conditions (e.g., sudden turbidity increase, or chlorine drop), enabling timely interventions. Machine learning enhances anomaly classification, reducing false positives and improving event prediction. On the other hand, digital twins, virtual replicas of drinking water treatment and distribution systems, are emerging as tools for simulating operations, training staff, and testing interventions. Therefore, early warning systems development benefits from digital twins and high-frequency data, simulating system responses to disturbances. Challenges involve threshold definition, data fusion, and operator trust in automated alerts. Regulatory frameworks and cybersecurity also play roles in system acceptance and reliability.

5. Human health risk assessment

Key Question: What are the emerging health risks associated with climate change-driven water quality deterioration, and what improvements are needed in risk assessment methodologies to ensure safe drinking water under future climate scenarios?

Policy recommendations: Mandate integrated and dynamic risk assessment frameworks that incorporate climate projections and emerging contaminants, with dynamic regulatory standards that adapt to evolving risk profiles. Establish interdisciplinary task forces through cross-sector collaboration between water utilities, health agencies, and climate scientists to ensure risk assessments are holistic and incorporate the latest scientific advancements in both climate change and public health.

Knowledge gap: Lack of long-term studies on climate-induced shifts in drinking water contaminants presence and persistence. Limited incorporation of machine learning and artificial intelligence (AI) for predictive risk assessment that could improve the risk estimation for novel contaminants for which no toxicological data are available. Gaps in global harmonization of health-based water quality guidelines and risk assessment methodologies, that hinder international collaboration and response to global threats.

Ensuring the safety of final drinking water is crucial for public health protection. Water utilities traditionally manage drinking water treatment plants and distribution systems by monitoring water quality at selected control points and verifying compliance with regulatory limits. While this compliance-based approach has historically safeguarded populations from well-known contaminants, it is increasingly recognized as insufficient in the face of emerging threats and system complexities.

Recent regulatory developments—such as the European Union's recast Drinking Water Directive (EU 2020/2184) and the World Health Organization's advocacy for Water Safety Plans—mark a decisive shift toward risk-based management of drinking water quality. These approaches emphasize the identification, assessment, and proactive control of risks throughout the water supply chain, from catchment to consumer tap. In this context, human health risk assessment becomes a central tool not only for compliance verification but also for anticipating and mitigating potential health threats under evolving environmental and socio-technical conditions such as aging infrastructure, and increased demand from growing populations.

Assessing health risks rather than simply checking against numerical limits is crucial for several reasons. First, chemical and microbial contaminants often exert chronic effects that may not be captured by infrequent monitoring. Second, compliance values typically apply to individual substances, ignoring potential synergistic effects from exposure to contaminant mixtures. Third, regulations may lag behind scientific knowledge, particularly regarding CECs such as pharmaceuticals, new DBPs, PFAS, or endocrine disruptors. Fourth, microbiological assessments often rely on indicator organisms (e.g., *E. coli* or coliforms) that may not adequately represent the presence or behaviour of more resistant or pathogenic microbes such as viruses, protozoa, or emerging microbial threats. Risk assessment methodologies can fill this regulatory gap by providing scientifically grounded estimates of health impacts even in the absence of formal thresholds.

Future drinking water production and supply systems face a triad of converging challenges: (i) climate change; (ii) emerging contaminants; (iii) evolving regulations. To address these challenges effectively, risk assessment approaches must evolve to integrate advanced modelling, probabilistic reasoning, effect-based monitoring, and real-time data analytics. The following sections explore the implications of climate change on final water quality, provide an overview of conventional and emerging risk assessment methods, and highlight innovations that support a transition toward proactive, resilient, and health-focused water management.

Conventional risk assessment frameworks

The conventional human health risk assessment framework applied to drinking water typically includes four main steps: (1) hazard identification, (2) dose-response assessment, (3) exposure assessment, and (4) risk characterization. This structured approach has been widely adopted by international agencies such as the World Health Organization (WHO), the European Food Safety Authority (EFSA), the U.S. Environmental Protection Agency (EPA), and the Australian Guidelines for Water Recycling. Each step involves methodological choices influenced by data availability, regulatory objectives, and the toxicological profile of the contaminant in question.

Exposure assessment considers the concentration of a contaminant in drinking water and the quantity consumed factoring in variability across age groups, dietary patterns, and exposure duration. Dose-response assessment evaluates toxicological data, determining thresholds such as the reference dose (RfD) or tolerable daily intake (TDI). Risk characterization combines these inputs to estimate the potential for adverse health outcomes, either through deterministic or probabilistic calculations (WHO, 2015).

These assessments are often applied in two general ways:

- Deterministic approaches use conservative, fixed values (e.g., maximum concentrations, average intake) to provide a safety-first estimate of potential health risks. This method is relatively easy to implement and is commonly used for initial screenings or regulatory compliance.
- Probabilistic approaches consider variability and uncertainty across a range of inputs (e.g., contaminant levels, intake rates) to estimate the likelihood and severity of health effects. While more data-intensive, they provide a nuanced understanding of risk and are increasingly used in research and policy planning.

Risk assessment strategies must be selected based on context, scale, and data availability. Where specific exposure scenarios are well-characterized, probabilistic models offer detailed risk quantification; where resources are limited, deterministic or semi-quantitative assessments may serve as an initial screening tool.

New technological solutions and methodologies

Traditional health risk assessment frameworks, while robust for regulated contaminants with well-characterized toxicological profiles, struggle to capture the full range of risks associated with complex chemical mixtures, low-level chronic exposures, and newly identified substances. Moreover, climate change introduces new dimensions of uncertainty to drinking water safety by altering contaminant profiles, increasing variability in source water quality, and challenging the effectiveness of traditional treatment systems. To address these evolving risks, new technological solutions are emerging that improve the detection, prediction, and assessment of both known and unknown hazards. To bridge this gap, a suite of novel tools and methodologies is being adopted that combines chemical, biological, and computational approaches. These advanced methods are essential for building climate-resilient water management systems. They support mitigation by enabling earlier detection of climate-induced water quality changes and informing adaptive responses in treatment and risk communication.

Several novel tools and methodologies are currently being investigated:

- Relative Potency Factor (RPF) Approaches: These estimate the combined toxicity of structurally similar compounds, such as PFAS, improving risk estimation in mixtures.

- Effect-Based Monitoring (EBM): Bioassays can detect health-relevant effects even when specific contaminants are unknown or at very low concentrations. They offer an early-warning function for complex mixtures and emerging threats such as the case of disinfection by-products (DBPs).
- Combined Chemical-Microbial Risk Frameworks: Though still under development, integrated assessments of microbial and chemical risks—using a common health metric—could help balance short-term infection risks with long-term toxicological risks, particularly in disinfection strategies.
- Machine Learning and Artificial Intelligence (AI): AI tools help identify patterns in large datasets, predict risks under different climate scenarios, and estimate toxicity for chemicals lacking test data. This is particularly useful for addressing data gaps on emerging contaminants.
- Quantitative Structure–Activity Relationship (QSAR) models: they use chemical structure to predict the toxicity of contaminants, offering a valuable tool when experimental data are lacking. These in silico methods help prioritize substances for monitoring and regulation, especially in complex mixtures.

Challenges and Future Trends

Despite significant advancements, several systemic challenges continue to hinder the effective implementation of robust human health risk assessment for final drinking water:

- Lack of long-term datasets capturing climate-related shifts in contaminant profiles limits the ability to identify trends, establish causality, and develop predictive models. This is central to advancing knowledge on how climate variability affects the quality of finished drinking water. Generating such insight requires decades of high-resolution data on source water quality, treatment operating conditions and performance, and final water composition—data that are typically held by utilities and are not readily accessible to the research community.
- Regulatory inertia and slow adoption of innovative tools—such as bioassays and AI models—impede modernization of risk assessment practices.
- Data gaps in toxicology, particularly for emerging contaminants and their transformation products, make it difficult to set scientifically defensible health-based thresholds.
- Limited harmonization of methodologies across countries prevents coordinated international responses to transboundary water contamination and hinders data comparability.
- Integration of climate change projections into risk models remains rare, despite increasing recognition of its importance for long-term water safety planning.

For future applications, risk assessment methodologies must become more adaptive, integrated, and participatory. This includes developing real-time monitoring and early warning systems, embracing effect-based tools, and fostering collaboration among climate scientists, toxicologists, public health experts, and water managers. Regulatory frameworks must evolve to support dynamic, risk-based thresholds that can respond to new information, shifting baselines, and emerging threats. The transition from static to resilient and anticipatory health risk assessment will be critical to ensuring the safety of drinking water in a rapidly changing world. Investing in interdisciplinary science, infrastructure modernization, and transparent risk communication will be essential components of this shift. To support implementation planning, it is also valuable to situate current and emerging risk assessment tools along a maturity continuum. For example, QSAR models and certain bioassays have reached medium-to-high Technology Readiness Levels (TRLs), with some being embedded in regulatory frameworks (e.g., Australian potable reuse guidelines). AI-based tools and combined microbial–chemical risk approaches, while promising, are mostly at pilot or research stage. Incorporating TRL-level guidance can help decision-makers align tool adoption with practical and policy needs.

In parallel, effective communication of risk assessment outcomes is becoming increasingly important. As methodologies become more sophisticated—employing tools like bioassays, QSARs, and predictive modelling—translating complex findings (e.g., bioassay responses or modelled thresholds) into clear, trustworthy messages is essential for public trust. Risk communication should thus be considered a core element of the methodology, involving co-developed messages with inputs from technical experts, regulators, and communication specialists.

6. Adaptation strategies

Key Question: What adaptation strategies and technological innovations can enhance the resilience of drinking water production systems to climate change impacts?

Policy recommendations: Regulate emerging contaminants to promote the adoption of technology for their abatement. Promote the use of combined technologies to face the multi-pollutant challenges. Promote managed aquifer recharge for protecting groundwater resources with a focus on integrated planning, rigorous treatment protocols, and sustained public engagement. Intensify funds for the development of reliable monitoring tools.

Knowledge gap: It is foreseen that combined advanced technologies can make water systems resilience in front of climate change impacts, however, there is a lack of long-term evidence on their benefits.

Water treatment and management strategies for adaptation

Advanced water treatment technologies are essential for addressing the growing complexity of water pollution under the dual pressures of climate change and global development. As rising temperatures, extreme weather events, and changing hydrological patterns intensify both the frequency and severity of water contamination, traditional treatment systems are increasingly inadequate. Emerging pollutants such as pharmaceuticals, microplastics, PFAS, and endocrine-disrupting compounds now coexist with conventional contaminants like pathogens and heavy metals, demanding innovative, adaptive treatment.

Safeguarding public health and ensuring reliable access to clean drinking water in this new environmental context requires an integrated technological response. Advanced treatment technologies are positioned as the foundation of a modern, resilient water management system:

- Membrane filtration systems are highlighted for their ability to efficiently remove a wide range of contaminants in drinking water treatment. Innovations such as low-pressure membranes and membrane bioreactors further enhance their energy efficiency and effectiveness.
- Nature-based solutions (NBS) are a crucial complement to technological systems. Constructed wetlands, vegetated biofilters, and green infrastructure offer passive, low-energy treatment options while also delivering broader ecological benefits.
- Advanced oxidation processes (AOPs) emerge as a central strategy for degrading complex organic molecules that resist conventional treatments for clean drinking water. Techniques such as solar photo-Fenton reactions, ozone-based systems, and photocatalysis are being tested for their ability to destroy pharmaceuticals, microplastics, and other emerging contaminants. In particular, solar-driven AOPs offer a renewable energy-based pathway.
- Biological treatments are recognized for their ability to sustainably manage organic matter and nutrients. Systems like biofilters and membrane biofilm reactors produce microbiologically stable water while using minimal energy and chemicals.

All these diverse technologies may be combined into hybrid, integrated systems. For example, sequencing nature-based solutions with membrane filtration and AOPs allows for a layered approach: biodegradable pollutants are removed first, followed by recalcitrant compounds.

Designing treatment systems to withstand climate impacts is another core concern. Infrastructure must be flexible and modular, with built-in redundancy and adaptive operating modes to handle variable inflows. Decentralized treatment units—ranging from solar-powered membrane systems to containerized AOP units—are particularly useful in this regard.

Specifically considering groundwater, it is increasingly threatened by overextraction, diffuse pollution from farming, industrial discharges, and the broader effects of a warming planet. One of the most pressing challenges is the widespread degradation of groundwater quality due to pollutants like fertilizers, pesticides, pharmaceuticals, and microplastics. These contaminants are not always efficiently removed by conventional wastewater treatment systems.

To address these challenges, one of the most promising strategies is Managed Aquifer Recharge (MAR) which refers to the intentional process of replenishing groundwater by directing surface water, stormwater, or treated wastewater into aquifers. MAR also serves to mitigate saline intrusion in coastal areas and improve groundwater quality through natural filtration processes in soils and sediments. MAR techniques include infiltration ponds and injection wells, each suited to hydrogeological conditions. MAR strategies are also used combined with water treatment technology before infiltration.

Widespread deployment of MAR still faces numerous challenges. These include the lack of standardized tools to design and evaluate MAR systems, insufficient real-time control mechanisms, and limited availability of cost-effective treatments for emerging contaminants such as PFAS, pharmaceuticals, and microplastics. Equally important is the need to engage stakeholders, governments, communities, and industry in collaborative efforts to prevent contamination and build public trust.

Despite the promise of all these technologies, challenges remain. High capital and operational costs, energy demands, maintenance requirements, and limited technical capacity in some regions constrain large-scale implementation. The absence of standardized regulations for emerging contaminants further complicates adoption. Nonetheless, the integration of digital tools—such as AI-based monitoring, predictive analytics, and automated control systems—offers pathways to improve efficiency and responsiveness while lowering environmental impacts.

Real-time monitoring systems for early detection of water quality changes

Water utilities are increasingly challenged to respond rapidly to sudden fluctuations in water quality. Traditional water testing methods, which rely on time-consuming laboratory analyses, are no longer adequate to detect and manage the rapid emergence of contaminants. The proposed adaptation strategy is centered around real-time data collection, intelligent monitoring systems, and predictive analytics as described here:

- Fiber optic sensors have been tested to measure groundwater flow and detect pollutant intrusion. This allows for early warning of pollutants moving toward drinking water wells.
- IoT-enables sensors are deployed in both water production and distribution systems. These sensors can provide continuous monitoring of parameters such as organic matter, pathogens,

disinfection by-products, and a wide range of emerging contaminants. Data from these sensors can be transmitted through secure communication channels and integrated with supervisory control and data acquisition systems and centralized data servers.

- Local Data Spaces are advanced digital infrastructures to interpret the data generated. They allow for seamless and secure data exchange across multiple applications.
- Machine learning algorithms analyse both real-time and historical data, enabling not only faster detection of anomalies but also predictive insights that anticipate future water quality challenges. These predictive capabilities are further enhanced using Digital Twins—virtual models of the physical water system that simulate hydraulic behaviour and water quality dynamics. By combining live sensor data with these models, operators can explore "what-if" scenarios, test response strategies, and improve decision-making accuracy.
- Sophisticated reactive transport models are used to link these monitoring efforts with practical management strategies. By incorporating real-time sensor data into these models, utilities can better predict the effects of interventions. This modelling is particularly valuable in agricultural areas, where nutrient runoff, pesticide infiltration, and saline intrusion all interact in complex ways.

Although the benefits of real-time monitoring are clear, the ongoing efforts have been facing several challenges. Sensor maintenance can compromise long-term performance. Managing and interpreting vast data streams requires technical expertise and well-designed user interfaces. Moreover, smaller utilities may lack the financial and human resources to implement such advanced systems. Nonetheless, strategies like modular sensor design and cloud-based data management are being developed to mitigate these barriers.

Ultimately, real-time monitoring is not just a technical upgrade but a transformational shift in how water quality is managed. In conclusion, applying these advanced technologies effectively requires a paradigm shift in water treatment and management, one that moves beyond reactive, conventional approaches toward systems that are anticipatory, modular, and climate resilient.

7. Governance

Key question: How can effective governance frameworks ensure the protection of drinking water quality, especially in the face of climate change and evolving public health challenges?

Policy recommendations: To ensure the protection of drinking water quality during climate change and public health challenges, policy recommendations include strengthening collaborative efforts between governments, water utilities, and research institutions, along with ensuring transparent communication to build public trust. Additionally, addressing funding gaps and political will is crucial for investing in resilient water infrastructure and adaptive governance frameworks that can respond to emerging climate and health risks.

Knowledge gap: It arises from limited understanding of the evolving risks posed by climate change and its impact on water quality and availability. Bridging this gap requires enhanced research, data collection, and collaboration between scientific institutions, governments, and water utilities to better predict and mitigate future water challenges.

Context and background: Water plays a key role in human survival, ecosystems, and global stability. Safeguarding drinking water quality in a changing world presents a significant global challenge. Due to climate change and growing human demand, concerns are intensifying, and the idea of building a water-secure future has become an urgent priority. To achieve effective water management strategies, collaborative efforts between government agencies, water utilities, and research institutions are crucial.

Climate situation and its impact on water quality and quantity: As the global climate crisis intensifies, extreme weather events such as floods, droughts, and heatwaves increasingly affect water resources, raising temperature and contamination risks. In drought-prone regions, water scarcity threatens drinking supplies, sanitation, and agriculture, resulting in waterborne diseases (such as cholera), food insecurity, economic instability, and damage to natural habitats and biodiversity. Scarcity also disrupts industries, hampers economic growth, and can lead to conflict over resources.

Securing drinking water must be a priority, requiring well-managed systems to protect sources and improve distribution. Without this, risks to health and socio-economic stability rise, making water a critical factor in national security and regional peace.

The role of institutions and partnerships: Climate change not only threatens water supply systems but also complicates efforts to ensure safe drinking water. Addressing these challenges requires coordinated strategies involving multiple sectors, as no single entity can handle all aspects of water governance alone.

Government agencies play a key role in regulating water resources and ensuring public safety. However, the complexities of climate change demand a deeper understanding of emerging risks and quick adaptation. Research institutions support this by providing crucial data and insights that guide government policies. Water utilities manage supply and treatment infrastructure and must adapt quickly to environmental changes. By collaborating with governments and researchers, utilities can implement flexible strategies, optimize treatment processes, and use technologies like real-time monitoring to respond to contamination events more effectively.

These partnerships strengthen water system resilience by incorporating climate change projections into planning and operations, allowing for proactive management of public health risks

Public perception: Even when drinking water meets safety standards, lack of trust can lead to behaviours like relying on bottled water or rejecting recycled water. This often stems from limited transparency and inconsistent communication. For water utilities and health agencies, addressing this social issue is crucial. If communities perceive water as unsafe, accurate data may be ignored. Social media and fake news can amplify fears, spreading misinformation. Building trust through clear, proactive communication is key.

Political will and funding gaps: Despite its importance, water often lacks enough political attention and financial investment. Universal access to safe drinking water is a global issue, worsened by climate change and a lack of funding and political will. This results in poor infrastructure, maintenance, and long-term planning.

Effective water management must address community needs, but political action is often limited by short-term priorities and financial constraints. Organizations like WHO, UNICEF, and the World Bank highlight the need for more investment, as current funding gaps lead to aging infrastructure, contamination, and service interruptions.

Water laws are not flexible enough to adapt to changing conditions. To tackle these issues, we need more investment, policy changes, and community involvement. Sustainable funding and updated laws are crucial to strengthen infrastructure and improve resilience to climate impacts.

Conclusion: Water security is now an urgent priority, not a distant concern. Public perception, health risks during scarcity, and the need for political and financial support are all closely linked. Without clean drinking water, development stops, public health worsens, and inequality increases.

To protect water amid climate change and rising demand, we need stronger, more inclusive systems and governance. This requires ongoing investment, innovation, and coordinated action. Water is a human right and a shared responsibility—protecting it is a collective mission that must continue.

8. Conclusions and future considerations

Conclusions

The provision of safe drinking water is at a critical juncture, facing complex challenges from climate change, emerging pollutants, aging infrastructure, and evolving public and regulatory expectations. This white paper has highlighted the systemic vulnerabilities throughout the drinking water value chain, from source to tap, and explored the necessary institutional, legislative, and technological solutions. One of our most significant findings is the limited understanding of climate change's impact on water quality. While changes in water quantity, such as droughts and floods, are increasingly evident, the effects on water composition, treatment efficacy, and distribution network stability are more intricate and often unknown. Climate-driven stresses like rising temperatures, severe stormwater events, and prolonged low-flow periods alter the fate, transport, and behaviour of contaminants, including established pollutants and new threats like PFAS, microplastics, and antibiotic resistance genes. These evolving demands necessitate a fundamental rethinking of how drinking water systems are monitored, managed, and governed, alongside the development of technical solutions.

Technology is pivotal in this transition. Advanced treatment technologies—such as membrane filtration, enhanced oxidation, and hybrid systems—are already being developed and tested to remove complex pollutants. Passive sampling methods, real-time sensors, and digital twins offer more detailed and predictive water quality monitoring. Furthermore, nature-based solutions and MAR enhance ecosystem resilience. However, the full potential of these technologies remains largely unrealized. Deployment is often fragmented, and significant impediments like costs, energy consumption, and operational complexity limit their adoption, especially for smaller utilities and cross-border water systems. Prioritizing demonstrations of their real-world benefits—particularly in terms of cost-effectiveness, climate adaptation, and public health impact—is crucial. The digital transformation of the water sector represents both a technological and cultural shift. Integrating digital tools into daily operations enables a shift from reactive to predictive management, facilitating real-time risk prediction, reaction modelling, and intervention optimization. IoT sensors, machine learning, and predictive models are already being used to monitor disinfection byproducts, microbiological dynamics, and pollutant intrusions. Nevertheless, these advancements must be supported by standardized data frameworks, robust cybersecurity, and equitable access across different geographies and utilities.

Risk assessment methodologies must also evolve. Traditional methods are often rigid, chemical-specific, and slow to incorporate new scientific information or real-world combination effects. As water quality risks become more complex and dynamic, risk assessment must become adaptive, integrated, and participatory, accounting for climate forecasts, effect-based monitoring, probabilistic modelling, and cross-media exposure scenarios. While bioassays, QSAR models, and AI-based predictions are expanding the available tools, widespread adoption and regulatory integration are still limited. It is critical to ensure that risk assessment not only informs compliance but also inspires proactive decision-making.

Finally, ensuring drinking water safety cannot rely solely on technology and research. Effective governance—and the trust it fosters—is the cornerstone of resilient water systems. Climate change is exposing disparities in regulatory consistency, financing, and institutional coordination. Strengthening collaboration among governments, utilities, research institutes, and citizens is vital. Transparent communication is essential, particularly regarding drinking water safety and the value of public infrastructure investments. Even scientifically sound technologies may face resistance or underutilization if public trust is lacking. In summary, ensuring safe drinking water amid climate uncertainty, demographic shifts, and chemical complexity demands a new paradigm. This paradigm must integrate scientific innovation, technological advancement, governance reform, and societal participation. Europe has made notable progress, particularly through the Drinking Water Directive and initiatives promoting digital innovation, but further effort is required. Only through collaborative, interdisciplinary, and proactive initiatives can we transform existing vulnerabilities into opportunities for a safer, more equitable, and climate-resilient water future.

Future Considerations

The European Union needs to invest in drinking water resilience for several crucial reasons. Firstly, it is essential for safeguarding public health, as climate change is rapidly worsening water quality, leading to increased exposure to pollutants that disproportionately affect vulnerable groups. Secondly, this investment is key to achieving the goals of the Green Deal and Sustainable Development Goals, (particularly number 6) by fostering the adoption of digital solutions, green infrastructure, and water-smart technologies, all of which contribute to a climate-resilient, zero-pollution, and circular economy. Thirdly, it will help bridge existing gaps in technology and governance, enabling more widespread use of advanced water management systems, especially for smaller or cross-border utilities, thereby boosting overall system resilience. Lastly, investing now ensures long-term economic and security stability by reducing future costs associated with emergency responses, healthcare, and infrastructure failures, while also guaranteeing a secure water supply for all.

To enhance drinking water resilience, the EU needs to invest in several key areas. This includes sophisticated monitoring and treatment technologies, like quaternary treatment and real-time monitoring tools, as current facilities are not equipped to handle emerging pollutants or extreme weather. It's also crucial to accelerate the digital transformation of the water sector by implementing IoT sensors, digital twins, and AI-based forecasting, which allow for proactive risk management and swift responses. The EU should modernize its risk assessment and regulatory frameworks with effect-based monitoring and adaptive thresholds that consider complex pollutant mixtures and climate dynamics. To ensure equitable access and strengthen cohesion, it must support cross-border and rural infrastructure improvements, especially in disadvantaged areas and for transboundary cooperation. Additionally, fostering innovation through public-private partnerships and R&D is critical for scaling promising new technologies. Lastly, improving public communication and trust via transparent platforms and educational campaigns is essential, as public perception significantly impacts overall system resilience.

To strengthen Europe's drinking water resilience, the EU should take the following key actions:

- **Strengthen European task forces on climate-resilient drinking water:** To improve coordination of Member States on monitoring standards, innovation priorities, risk assessment methodologies, and investment strategies, leading to a comprehensive roadmap for a secure water supply in various climate scenarios.
- **Create a dedicated investment window:** Within the EU Green Deal and Horizon Europe, a specific investment window should be set up. This would focus on drinking water safety, advanced monitoring, and adaptive infrastructure, while also supporting collaborative projects, especially in high-risk or under-resourced regions.
- **Revise the Drinking Water Directive implementation plan:** The plan should be updated to encourage Member States to integrate digital tools, real-time monitoring, and emerging

contaminant controls. Performance-based funding would incentivize the early adoption of new technologies.

- **Launch a Pan-European water quality observatory:** This open data platform would provide information on contaminant trends, climate impacts, and treatment performance. It would facilitate knowledge sharing, early warning systems, and cross-border cooperation.
- **Integrate climate adaptation into all drinking water infrastructure projects:** All publicly funded water infrastructure projects should require climate impact assessments. Prioritizing modular and flexible systems will ensure they can adapt to fluctuating water quality and availability over the long term.
- Data Availability and transparency through a Central Knowledge Base available for water utilities, researchers, regulators and policymakers.

9. Further information

Introduction

Campos, L. C., Olago, D., & Osborn, D. (2022). Water and the UN sustainable development goals. *UCL Open Environment*, *4*, e029.

Ejiohuo, O., Onyeaka, H., Akinsemolu, A., Nwabor, O. F., Siyanbola, K. F., Tamasiga, P., & Al-Sharify, Z. T. (2025). Ensuring water purity: Mitigating environmental risks and safeguarding human health. *Water Biology and Security*, *4*(2), 100341. https://doi.org/https://doi.org/10.1016/j.watbs.2024.100341

Frei, R., Frei, K. M., Kristiansen, S. M., Jessen, S., Schullehner, J., & Hansen, B. (2020). The link between surface water and groundwater-based drinking water – strontium isotope spatial distribution patterns and their relationships to Danish sediments. *Applied Geochemistry*, *121*, 104698. https://doi.org/https://doi.org/10.1016/j.apgeochem.2020.104698

Irvine, D. J., Singha, K., Kurylyk, B. L., Briggs, M. A., Sebastian, Y., Tait, D. R., & Helton, A. M. (2024). Groundwater-Surface water interactions research: Past trends and future directions. *Journal of Hydrology*, *644*, 132061. https://doi.org/https://doi.org/10.1016/j.jhydrol.2024.132061

Li, X., Li, Y., & Li, G. (2020). A scientometric review of the research on the impacts of climate change on water quality during 1998–2018. *Environmental Science and Pollution Research*, *27*(13), 14322–14341. https://doi.org/10.1007/s11356-020-08176-7

López-Vázquez, J., Montes, R., Rodil, R., Cela, R., Martínez-Pontevedra, J. Á., Pena, M. T., & Quintana, J. B. (2024). Determination of regulated perfluoroalkyl substances (PFAS) in drinking water according to Directive 2020/2184/EU. *Environmental Science and Pollution Research*, 1–12.

Ma, B., Hu, C., Zhang, J., Ulbricht, M., & Panglisch, S. (2022). Impact of Climate Change on Drinking Water Safety. *ACS ES&T Water*, *2*(2), 259–261. https://doi.org/10.1021/acsestwater.2c00004

Mondejar, M. E., Avtar, R., Diaz, H. L. B., Dubey, R. K., Esteban, J., Gómez-Morales, A., Hallam, B., Mbungu, N. T., Okolo, C. C., Prasad, K. A., She, Q., & Garcia-Segura, S. (2021). Digitalization to achieve sustainable development goals: Steps towards a Smart Green Planet. *Science of The Total Environment*, *794*, 148539. https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.148539

Surface water quality

EEA (2024). Europe's state of water 2024: the need for improved water resilience. European Environment Agency doi: 10.2800/02236 https://www.eea.europa.eu/en/analysis/publications/europes-state-of-water-2024?activeTab=803123fd-75c0-4752-b7b6-793e28895722 Accessed July 2025.

Thomopoulou, V., Kossieris, P., Bariamis, G., Tsoukalas, I., and Makropoulos, C., (2024) "Early Warning System for Nutrient Run-Off in Inland Water Bodies: A Methodological Framework Utilizing Earth Observation Data," *IGARSS 2024 - 2024 IEEE International Geoscience and Remote Sensing Symposium*, Athens, Greece, pp. 5090-5094, doi: 10.1109/IGARSS53475.2024.10640967.

Thomopoulou, V., Iliopoulou, T., Kossieris, P., Bariamis, G., Tsoukalas, I., Efstratiadis, A., Makropoulos C., (2024) A comprehensive approach to building a continuous hydrologic model with Soil

Moisture Accounting using Earth Observation data. *Hydrology Research* ; 55 (12): 1161–1181. doi: https://doi.org/10.2166/nh.2024.190

Groundwater quality

Brunn, H., Arnold, G., Körner, W., Rippen, G., Steinhäuser, K. G., & Valentin, I. (2023). PFAS: forever chemicals—persistent, bioaccumulative and mobile. Reviewing the status and the need for their phase out and remediation of contaminated sites. *Environmental Sciences Europe*, *35*(1), 20. https://doi.org/10.1186/s12302-023-00721-8

Directorate-General for Environment. (2025, March 3). *New substances added to the EU's surface water watchlist*. Https://Environment.Ec.Europa.Eu/News/New-Substances-Added-Eu-Surface-Water-Watchlist-2025-03-03_en. https://environment.ec.europa.eu/news/new-substances-added-eu-surface-water-watchlist-2025-03-03_en

EEA (European Environmental Agency). (2022). *Europe's groundwater - a key resource under pressure*.

Holly, M. A., Gunn, K. M., Keymer, D., & Sanford, J. R. (2024). Evaluation of Per- and Polyfluoroalkyl Substances Leaching from Biosolids and Mitigation Potential of Biochar through Undisturbed Soil Columns. *ACS ES&T Water*, *4*(2), 413–426. https://doi.org/10.1021/acsestwater.3c00414

Jadhav, S. V, Bringas, E., Yadav, G. D., Rathod, V. K., Ortiz, I., & Marathe, K. V. (2015). Arsenic and fluoride contaminated groundwaters: A review of current technologies for contaminants removal. *Journal of Environmental Management*, *162*, 306–325. https://doi.org/https://doi.org/10.1016/j.jenvman.2015.07.020

Lapworth, D. J., Boving, T. B., Kreamer, D. K., Kebede, S., & Smedley, P. L. (2022). Groundwater quality: Global threats, opportunities and realising the potential of groundwater. In *Science of the Total Environment* (Vol. 811, p. 152471). Elsevier.

Manivannan, B., Nallathambi, G., & Devasena, T. (2022). Alternative methods of monitoring emerging contaminants in water: a review. *Environmental Science: Processes & Impacts*, *24*(11), 2009–2031.

Uhl, A., Hahn, H. J., Jäger, A., Luftensteiner, T., Siemensmeyer, T., Döll, P., Noack, M., Schwenk, K., Berkhoff, S., & Weiler, M. (2022). Making waves: Pulling the plug—Climate change effects will turn gaining into losing streams with detrimental effects on groundwater quality. *Water Research*, *220*, 118649.

Drinking water distribution networks

Alzamora F.M., Conejos P., Castro-Gama M., Vertommen I. (2021). Digital Twins-A new paradigm for water supply. HydroLink 2021-2 https://api.kwrwater.nl/uploads/2021/08/Alzamora-Conejos-Castro-Gama-Vertommen-Digital-Twins-A-new-paradigm-for-water-supply-and-distribution-networks-Hydrolink-(2021)2-p.48-54.pdf

Cantoni B., Cappello, A., Turolla, A., Antoneill, M. (2021). Bisphenol A leaching from epoxy resins in the drinking water distribution networks as human health risk determinant. Science of The Total Environment, Volume 783, 146908, ISSN 0048-9697. https://doi.org/10.1016/j.scitotenv.2021.146908

Conejos Fuertes, P., Martínez Alzamora, F., Hervás Carot, M., and Alonso Campos, J. (2020). Building and exploiting a Digital Twin for the management of drinking water distribution networks. Urban Water Journal, 17(8):704–713. https://doi.org/10.1080/1573062X.2020.1771382

Gabrielli et al. (2023). Source to tap investigation of natural organic matter in non-disinfected drinking water distribution systems. doi: 10.1039/d3ew00280b

Gabrielli et al. (2023). Identifying Eukaryotes and Factors Influencing Their Biogeography in Drinking Water Metagenomes. doi: 10.1021/acs.est.2c09010

Li Z., Ma W., Zhong D., Ma J., Zhang Q., Yuan Y., Liu X., Wang X., Zou K. (2024). Applications of machine learning in drinking water quality management: A critical review on water distribution system. Journal of Cleaner Production. Volume 481, 2024, 144171, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2024.144171

Shi Z., Chow C.W.K., Fabris R., Liu J., Jin B. (2022). Applications of Online UV-Vis Spectrophotometer for Drinking Water Quality Monitoring and Process Control: A Review. Sensors, 2022 (22) 2987. https://doi.org/10.3390/s22082987

WFD 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy

Zechman Berglund E., Shafiee E.M., Xing L., WEn J. (2020). Digital Twins for Water Distribution Systems. Journal of Water Resources Planning and Management, 149 (3) https://doi.org/10.1061/JWRMD5.WRENG-5786

Human health risk assessment

Bil W, Zeilmaker M, Fragki S, Lijzen J, Verbruggen E, Bokkers B. (2021) Risk Assessment of Per- and Polyfluoroalkyl Substance Mixtures: A Relative Potency Factor Approach. Environ Toxicol Chem. Mar;40(3):859-870. doi: 10.1002/etc.4835. Epub 2020 Sep 8. PMID: 32729940

Cantoni B., Cappello, A., Turolla, A., Antoneill, M. (2021). Bisphenol A leaching from epoxy resins in the drinking water distribution networks as human health risk determinant. Science of The Total Environment, Volume 783, 146908, ISSN 0048-9697. https://doi.org/10.1016/j.scitotenv.2021.146908

Cantoni, B., Penserini L., Vries D., Dingemans M.M.L., Bokkers B.G.H., Turolla A., Smeets P.W.M.H., Antonelli M (2021). Development of a quantitative chemical risk assessment (QCRA) procedure for contaminants of emerging concern in drinking water supply, Water Research, Volume 194, 116911, ISSN 0043-1354, https://doi.org/10.1016/j.watres.2021.116911

Havelaar A.H., De Hollander A. E., Teunis P.F, Evers E.G., Van Kranen H. J., Versteegh J.F., Van Koten J. E., and Slob W. (2000). Balancing the risks and benefits of drinking water disinfection: disability adjusted life-years on the scale. Environmental Health Perspectives. Volume 108, Issue 4. Pages 315 – 321. https://doi.org/10.1289/ehp.00108315

Kirsten A. Baken, Rosa M.A. Sjerps, Merijn Schriks, Annemarie P. van Wezel (2018). Toxicological risk assessment and prioritization of drinking water relevant contaminants of emerging concern, Environment International, Volume 118, Pages 293-303, ISSN 0160-4120, https://doi.org/10.1016/j.envint.2018.05.006

Rana, R.; Kalia, A.; Boora, A.; Alfaisal, F.M.; Alharbi, R.S.; Berwal, P.; Alam, S.; Khan, M.A.; Qamar, O. (2023). Artificial Intelligence for Surface Water Quality Evaluation, Monitoring and Assessment. *Water* **2023**, *15*, 3919. https://doi.org/10.3390/w15223919

Zeilmaker M.J., Fragki S., Verbruggen E.M.J. Bokkers B.G.H., Lijzen J.P.A. (2018). Mixture exposure to PFAS: A Relative Potency Factor approach RIVM Report 2018-0070. DOI 10.21945/RIVM-2018-0070

Adaptation strategies

Interstate Technology and Regulatory Council (ITRC) (2023). Managed Aquifer Recharge Overview. Retrieved from https://mar-1.itrcweb.org/managed-aquifer-recharge-overview/

Grazia Martelli, M., Teatini, P., Cherubini, C., Goi, D. (2024). Managed Aquifer Recharge for Sustainable Groundwater Management: New Developments, Challenges, and Future Prospects. Water 2024, 16 (22), Water 2024, 16(22), 3216; https://doi.org/10.3390/w16223216

Zhang, H; Xu, Y., Kanyerere, T. (2020). A review of the managed aquifer recharge: Historical development, current situation and perspectives. Physics and Chemistry of the Earth, Parts A/B/C, Volumes 118–119, October 2020, 102887. https://doi.org/10.1016/j.pce.2020.102887