Water Europe

Technology & Innovation

TOWARDS A ZERO-POLLUTION STRATEGY FOR CONTAMINANTS OF EMERGING CONCERN IN THE URBAN WATER CYCLE

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Prologue

Water Europe (WE) is the recognized voice and promotor of water-related innovation and RTD in Europe. WE is a value-based multi-stakeholder association that represents the whole diversity of the innovative water ecosystem. WE was initiated by the European Commission as a European Technology Platform in 2004. All WE activities are guided by its Water Vision and the ambition to achieve a Water-Smart Society.

The Water Europe White Papers are aimed at informing readers about complex water-related topics in a concise and targeted way, and presenting WE's vision and philosophy on the matter. They present evidence-based opinions on multiple water-related challenges and on ways to overcome them.

WE White Papers are produced as part of the WE Collaboration Programme by the WE Vision Leadership Teams and the WE Working Groups. They target a wide variety of potential audiences, including the EU institutions, international organisations, the water industry, water users and water-related strategic stakeholders, the economic sectors, as well as media, analysts, regulatory and governing bodies, citizens and society at large.

Durk Krol
Water Europe Executive director

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Abreviations and acronyms

AMR	Anti-microbial resistance	**GW**	Groundwater
AOP	Advanced oxidation processes	**LC-HRMS**	Liquid chromatography – High-resolution mass spectrometry
ARB	Antibiotic resistant bacteria	**NBS**	Nature-based solutions
ARG	Antibiotic resistant genes	**PBT**	Persistent, bioaccumulative and toxic
BAF	Biological activated filtration	**PCR**	Polymerase Chain Reaction, a molecular method to detect genes
CAS	Division of the American Chemical Society, provides a unique, unmistakable identifier for chemical substances: CAS Registry Number	**PFAS**	Perfluoroalkyl chemicals
CECs	Contaminants of Emerging Concern	**PMT**	Persistent, mobile and toxic
CLP	Regulation on Classification, Labelling and Packaging of chemicals	**PPCP**	Pharmaceuticals and personal care products
CMR	Carcinogenic, Mutagenic Reprotoxic	**pZZS**	Dutch abbreviation for compounds of potentially very high concern (potentieel Zeer Zorgwekkende Stoffen)
CSO	Combined Sewer Overflow	**REACH**	Registration, Evaluation, Authorisation and Restriction of Chemicals
CSS	Chemicals Strategy for Sustainability	**SDGs**	Sustainable development goals
CW	Constructed Wetland	**SVHC**	Substances of very high concern
DNA	Deoxyribonucleic acid, carrier of the genetic code in cells	**TRL**	Technology Readiness Level
EBM	Effect-based methods	**UWWTD**	Urban Wastewater Treatment Directive
ED	Endocrine disruptor	**vPvB**	very Persistent and very Bioaccumulative
EQS	Environmental Quality Standard	**WWTP**	Wastewater Treatment Plant
GC-HRMS	Gas chromatography – High resolutions mass spectroscopy	**ZZS**	Dutch abbreviation for compounds of very high concern (Zeer Zorgwekkende Stoffen). Group not identical to SVHC

Executive Summary

Water Europe envisions a Water-Smart Society that recognises and realises the true value of water. For this, we need to avoid pollution of our water sources. The Zero Pollution Action Plan, as part of the European Green Deal [1], clearly expresses the EU's commitment to reducing pollution to levels that are not harmful to human health and ecosystems by 2050. With the present White Paper, the Water Europe Working Group on Zero Pollution presents a collective opinion of stakeholders from the European water sector on achieving zero pollution in water through:

- recommendations for evidence-based policy development to address water pollution;
- an identification of knowledge gaps that hinder achieving a pollutant-free water environment.

The findings are based on a synthesis of the state of the science on chemical and biological pollutants, or Contaminants of Emerging Concern (CECs), in the water cycle.

Our quality of life depends on the use of a wide range of chemical compounds and microbes. However, many of these substances also pose acute health risks to humans and ecosystems, or have adverse effects following long-term exposure. **The EU Action Plan foresees replacing toxic chemicals with inherently safe substances, but persistent and mobile chemicals will remain in the environment from their use in the past.** Achieving the zero pollution ambitions by 2050 therefore requires a detailed and comprehensive understanding of the sources, pathways and fate of pollutants in water environments over long periods. We need this knowledge to develop appropriate actions to prevent further pollution and protect people and ecosystems.

Summary of policy recommendations

Implementation of European policies in the areas of wastewater treatment, marine and freshwater habitat protection, drinking water safety and bathing water quality, has led to improved environmental water quality. Moreover, the banning of single-use plastics, and the reduction of industrial emissions and use of dangerous chemicals have brought about significant improvements in water quality over the last decades.

Achieving the EU's ambition of zero pollution requires the elaboration of policies that address the effects of pollution mixtures on public health and ecosystems. These policies should be built on comprehensive data about exposure to pollutants, depending on time and place, and their effects on human and ecosystem health.

Achieving a zero pollution environment calls for a combination of 'at-source' measures and the removal of compounds during water and wastewater treatment. Lower emission at-source can be achieved by reducing the production volume and use of harmful chemicals. This should be enabled by extending the registration of chemicals, including their production volumes. Furthermore, a broader classification into different groups of chemicals, based on their toxicity and use, is needed to support the development of regulations. Environmental quality standards are needed for prioritised pollutants in water bodies. To enforce these, smart monitoring policies must be developed and implemented.

The current Urban Wastewater Treatment Directive (UWWTD) does not cover many urban discharges to receiving waters, including urban stormwater runoff, combined sewer overflows and unplanned discharges, which thus remain unregulated. Incentives for tackling pollution from these unregulated flows are needed and can be created by including them in future regulations.

There is also a need for greater emphasis on governance processes to support and optimise stakeholder activities for achieving a zero pollution environment. Furthermore, the EU should stimulate investments from public and private actors to restore the natural functions of groundwater, surface water, and marine and coastal waters in a systemic way.

Summary of knowledge gaps

Water pollution by chemical and microbial substances presents a significant challenge. In order to effectively meet this challenge, we need to acquire a better understanding with regard to the following:

1. The release of a wide range of substances from point sources and diffuse emissions. This needs data on the amounts of chemicals that are produced, but information on how they are used is essential to identify how compounds find their way into the environment.
2. Only limited data are available on urban stormwater pollution concentrations, and how these vary with catchment types and weather conditions.
3. The mobility and transport of substances in water and the environment. New types of pollutants (nanoparticles, microplastics, cyanotoxins and anti-microbials) require full characterisation in terms of their occurrence, environmental behaviour and fate. Modelling can help to extrapolate new knowledge to a broader set of substances.
4. The long-term (chronic) effects of many CECs and their mixtures on immune and neurological systems, in both humans and other species, remain largely unknown. Methods for monitoring health effects in bio-assays are valuable tools for the assessment of environmental mixture toxicity. However, translating their results to risks for human health and the environment calls for further research. Also, the understanding of chemical emissions in the development of anti-microbial resistance is still limited and needs further investigation.
5. New solutions for reduction of pollutant loads at-source or during wastewater treatment, including advanced oxidation processes and membrane technologies. Research is needed to increase knowledge on the ability of these processes to remove more polar, mobile and persistent contaminants.
6. Demonstrate the efficiency of nature-based solutions for the removal of CECs from urban stormwater discharges to receiving waters.
7. How to improve, develop and communicate available options for remediating contaminated sludges and sediments.

To advance our knowledge and insights into the above areas, it is necessary to develop new sensors and analytical procedures that are able to detect and quantify a wider range of CECs. The deployment of sensors must be accompanied by the development of the necessary infrastructure and quality assurance procedures.

Successful development and innovation to bring about to a pollution-free Water-Smart Society also needs to be accompanied by governance development, which includes the full participation of all stakeholders (public, governmental and private). Together, they need to co-develop and implement action plans that include criteria and benchmarks for measuring progress.

1. Introduction

With the European Green Deal [1], the EU has set itself the ambitious target of becoming the first carbon-neutral continent. As part of this effort, the European Commission has adopted the EU Action Plan 'Towards Zero Pollution for Air, Water and Soil' [2]. This Action Plan envisions a Europe in 2050, where pollution is reduced to concentration levels that are not harmful to human health and ecosystems. The plan also sets out a series of actions required to achieve this objective, with its delivery being supported by the recently established multi-sectoral 'Zero Pollution Stakeholder Platform' [3]. The purpose of the present White Paper is to proactively contribute to the delivery of this Action Plan. It draws on evidence from the state of the science on chemical and biological pollutants, or Contaminants of Emerging Concern (CECs), in the water cycle in order to:

- provide recommendations for evidence-based policy development to address water pollution, and
- identify knowledge gaps that hinder achieving a pollutant-free water environment.

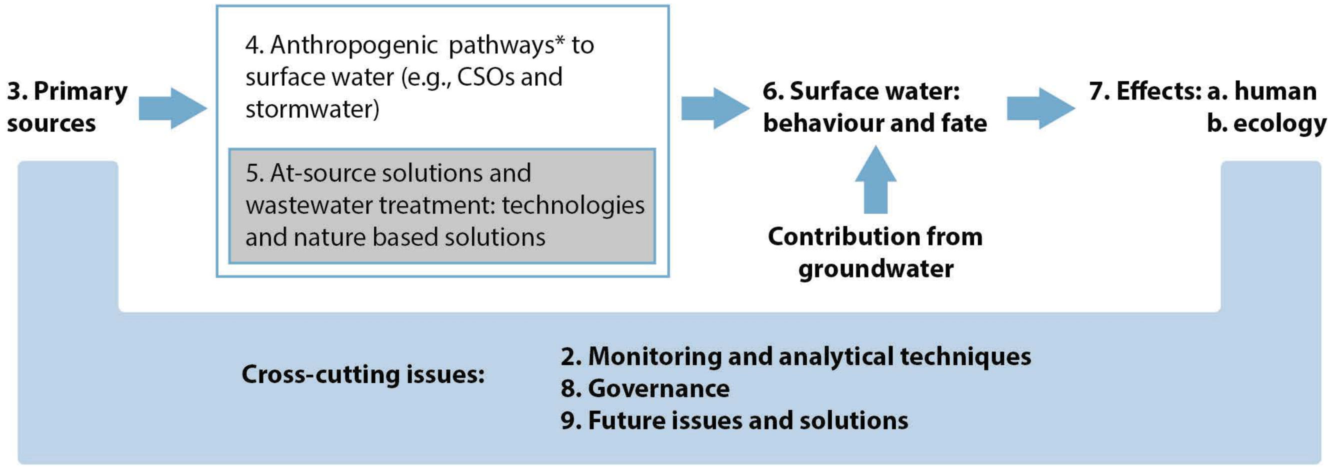
A diversity of chemicals and microbial substances underpin our well-being and ability to deliver the 'high quality-of-life for all' objective identified in the UN Agenda 2030 [4]. However, many substances are also potentially hazardous to human health and the environment. CECs are defined here as chemical and biological substances that are not regulated under existing EU water quality regulations, but that have been identified as having a potential negative impact on human health and/or environmental endpoints. For example, chemicals may promote the emergence and prevalence of antimicrobial resistance (AMR) and cyanobacterial harmful algal blooms [5], with resulting major impacts on human and animal health. With global chemicals production anticipated to double by 2030 [2], Point 34 of the UN Agenda 2030 declaration – which commits all UN members to reduce the impact of urban activities and hazardous chemicals – is undoubtedly ambitious. This commitment is also reflected in three of the UN Agenda 2030's sustainable development goals (SDGs), namely: SDGs 3, 6 and 12. These goals include specific indicators on reducing the impacts of chemicals on human health and the environment (SDG 3), and on minimizing the release of chemicals to water bodies (SDG 6 and 12), and to the air and soil (SDG 12). Likewise, the role of microbials in achieving several SDGs is also highlighted: from healthy lives (SDG 3) and clean water and sanitation (SDG 6), to supporting the transition to a circular economy (e.g., SDGs 9, 12 and 15) [6].

At a European level, significant efforts have already been made to improve water quality, treat wastewater and protect marine and freshwater habitats and species. For example, the implementation of EU Water Framework Directive (WFD) (2000) [7], the Drinking Water Directive (revised in 2021) [8], the Urban Waste Water Treatment Directive (under review) [9], the Bathing Water Directive (under review) [10], the Directive on Single-Use Plastics (2019) [11], the Industrial Emissions Directive (review expected in 2022) [12], and the EU Regulation concerning Registration, Authorisation and Restriction of Chemicals (2006) [13] have led to significant improvements in water quality through the last decades. Nonetheless, only 44% of surface waters in Europe comply with the target of the WFD to achieve 'good ecological status'. For groundwater, 74% complies with the WFD target of 'good chemical status'. When it comes to marine waters, all of the EU's regional seas have large-scale contamination issues, which are mainly associated with the anthropogenic use of these waters, and to the release of synthetic chemicals and metals both on to land and into the sea [14]. Rivers and groundwater provide approximately 88% of Europe's freshwater supply, with reservoirs and lakes accounting for the rest [14]. These resources are unevenly distributed, with water demand exceeding supply in many areas, while their quality is often reduced by pollution. An evaluation of key elements of EU water legislation (EU Water Framework Directive [7], Environmental Quality Standards Directive [15], Groundwater Directive [16] and Floods Directive [17]) with regard to their 'fitness for purpose' was recently completed [18]. While the evaluation broadly concludes that the implementation of these Directives has had positive impacts, chemicals are identified as a key area where results need to be improved [18]. In particular, the approach of the Environmental Quality Standards and the Groundwater Directives to managing risk on the basis of exposure to single or categories of substances, as opposed to real environmental mixtures, is identified as sub-optimal; moreover, the limited information on the types and quantities of substances present in the environment is also highlighted as problematic [18]. Evaluating the substances (and their interactions), with a view to identifying opportunities to reduce human and environmental exposure to their hazardous properties, is therefore a current policy and practice priority. This is central, for example, to the EU's zero pollution ambition (a key commitment of the European Green Deal [1]) and its delivery by the EU Chemical Strategy for Sustainability [2].

Urban wastewater and stormwater runoff – together, as combined sewer overflows (CSOs), or as separate flows – represent an unintentional mix of chemicals and microbial substances, originating from a variety of sources, which end up in surface waters as treated (municipal wastewater) or untreated (CSOs and stormwater) discharges. They can include a mix of both permitted and unpermitted (i.e., illegal) discharges, as well as accidental spills. Within the current policy development and implementation context, there is an urgent need to better understand:

- the sources of point and diffuse urban pollutants (i.e., which substances from which materials/sources and their temporal patterns of release);
- the processes affecting urban pollutant mobilisation, transportation and discharge to receiving waters (e.g., hydraulic and water quality modelling, including 'in pipe' transformations);
- the opportunities to further reduce pollutant loads associated with the discharge of treated effluents (e.g., at-source structural / non-structural methods, tertiary treatment);
- the opportunities to mitigate urban runoff discharge to receiving waters (e.g., performance and maintenance of stormwater blue-green infrastructure);
- the opportunities to remediate contaminated sludges and sediments (e.g., management of gully pot and stormwater pond sediments).

As a contribution to addressing these identified needs within a European context, this White Paper adopts a source-pathway-receptor approach to review the current state of the art in the assessment of point and diffuse urban water pollution, its impacts and opportunities for its mitigation (see Figure 1). Through a series of cross-cutting issues, we cross-match open challenges to current policies. Where research and/or policy gaps are identified, we set out a series of recommendations for research and policy development, which – if addressed – will significantly contribute to achieving the EU's zero pollution objectives and support UN SDG compliance.



* Pre-treatment of industrial effluent is mentioned, but beyond the paper´s scope.

Figure 1. Schematic of this White Paper's structure (numbers correspond to the chapters).

Each chapter starts with a summary box that identifies the key question addressed in the respective chapter, followed by recommendations for policy development and the knowledge gaps identified. Following the box, further details, and underpinning evidence from literature are presented.

2. Monitoring, analytical techniques and databases

Question: How can we develop a robust evidence base on the sources, behaviour and impact of CECs in the urban water cycle?

Recommendations for policy development: Urban wastewater and stormwater runoff – together as CSOs, or as separate flows – represent an unintentional mix of chemicals and microbial substances. Hence, delivery of the EU's zero pollution ambition requires a holistic policy approach, which addresses urban water pollution from chemical and toxicity perspectives. Developments in online sensing technologies and high-throughput analytical instrumentation in environmental chemistry (wide-scope screening of substances) and metagenomics [e.g., (sub-) population level effects] offer an opportunity to provide early warnings and rapid assessments of CECs in the environment. An integrated open-access platform for the systematic collection, assessment and sharing of chemical effects and exposure data (spatial and temporal coverage) would facilitate the identification of priority pollutant groups and their sources, as a step towards mitigating their discharge.

Knowledge gaps: In response to the complex unintentional urban water pollution mixture, the development of sensors, able to detect and quantify a wider range of CECs, and their reliable deployment in critical points of the water cycle, is an urgent research and practice need, which requires substantial investment. Inter-comparison studies between types of sensor technologies (and the development of procedures for sensor validation) will directly advance sensor technology readiness levels (TRLs). The development of standard analytical methods is an open challenge for many CECs, together with the development of harmonised non-target screening protocols and minimum quality requirements. Further research to link genetic functions of interest (e.g., antibiotic resistance marker genes) with taxonomic identities (e.g., phylogenetic marker genes) and/or pathogenicity factors is also required, with a common challenge being the need for mechanisms to enable the use of these approaches/derived datasets to support regulatory monitoring.

The urban water cycle is complex. Pollution sources, drainage network dynamics and climatic conditions vary on a catchment-by-catchment basis, and the development of a systematic universal approach to monitoring and analysis of discharges remains an open challenge. The development of in situ sensing technologies and their application within standardized monitoring strategies has the potential to revolutionize our knowledge of the occurrence, fate and distribution of CECs in a range of aquatic environments. However, to-date, few sensors for CECs have reached a TRL>7. The only commercially available systems are for pathogens; a situation probably driven by regulatory pressures and the risks associated with human toxicity or infection. However, all such sensors are currently associated with high operational and maintenance costs [19,20]. There are several challenges to overcome in the development and deployment of new online sensors for water monitoring. For example, when there is a need to detect chemical compounds and discriminate between their analogues (e.g., microcystins or perfluoroalkylated compounds) [8], the selectivity of the sensor requires several layers of complexity [21]. Only spectroscopic techniques with fingerprinting capabilities, such as nuclear magnetic resonance, infra-red or Raman, have the potential to achieve this required level of selectivity, without using selective receptors or indirect measurements [22]. In the case of fingerprinting techniques, the capital costs involved are usually high (in contrast to receptor-based or indirect measurements, which are characterised by high operating costs). The high costs of online sensors currently means that their implementation is limited to critical points of the water cycle (e.g., influents and effluents of drinking water and wastewater treatment plants, and drinking water source areas), where real-time monitoring provides early warnings of illegal discharges, for instance. Based on their impact on ecology and animal and human health, the CECs that should be prioritised for the development and implementation of online sensors at those critical points would be the following: the priority substances already identified in EU legislation for surface waters, drinking water and treated wastewater; other emerging pathogens or their indicators (bacteriophages); antimicrobials; cyanotoxins; engineered nanoparticles; micro/nanoplastics; and persistent, bioaccumulative and toxic (PBT) substances already identified – for example, in NORMAN (2021) [23] and EU IPCHEM (2020) [24] priority lists – with particular focus on highly mobile substances.

In terms of laboratory-based analysis, high-throughput analytical instrumentation, such as liquid chromatography high-resolution mass spectrometry (LC-HRMS) and gas chromatography high-resolution mass spectrometry (GC-HRMS), have revolutionized environmental chemistry [25,26]. The use of LC- and GC-HRMS can capture polar and non-polar emerging substances, respectively, providing data on thousands of substances at a high level of sensitivity [27]. The three main workflows applied for chemicals screening are target screening (i.e., analytical standards are available), suspect screening (i.e., prior structural information of the substances is available, but analytical standards are lacking), and non-target screening (i.e., no prior information and no analytical standards are available) [28]. Target and suspect screening have gained increasing attention [23,29], and today represent the state of the art for investigating the occurrence of a large number of chemicals in a range of aquatic (and non-aquatic) environments [30]. LC- and GC- HRMS can efficiently support early warning and rapid assessment of CECs in the environment [31]. However, standard analytical techniques are not yet available for all CECs, and the development of harmonised non-target screening protocols and minimum quality requirements is underway to enable their routine implementation in support of regulatory monitoring. In addition to standard analytical techniques, effect-based analysis is increasingly utilised to understand the biological effects of CECs on humans and wildlife [32]. This approach is particularly vital for CECs prioritised for regulation (including polychlorinated biphenyls, phthalates, bisphenols and cyanotoxins) with regard to clarifying their effects in complex mixtures. While cell-based assays have to-date played a key role in this area of research, the recent development of 3D cell models provides a new bioanalytical tool to obtain predictive information about the toxicology and mode of action of chemicals [33]. These in vitro models, together with in silico models, are opening new avenues to identify, evaluate and screen chemicals, in agreement with replacement, reduction and refinement principles. However, a mechanism to enable the use of data derived using predictive models in an enforcement context has yet to be fully developed.

Several CECs have been linked with the evolution of microbial traits (e.g., antimicrobial resistance) that can contribute to the increase of microbial/pathogen loads in environmental reservoirs [34-36]. Therefore, monitoring the microbial load and its diversity, antibiotic resistance genes (ARGs), virulence factors, mechanisms of gene mobility, ecological control agents and microbial functions in environmental settings should be a part of integrated environmental and health risk assessment strategies [37]. Established methods for screening include culture-based approaches [38,39]; however, these are time-consuming and several relevant microorganisms are known to be recalcitrant to cultivation [40,41]. Metagenomic deoxyribonucleic acid (DNA) screening approaches address these limitations, providing faster and more comprehensive data on the presence and abundance of microbes of interest [41,42]. Polymerase chain reaction (PCR)-based methods are routinely used for quantitative [43] or compositional screening of single phylogenetic markers [44], with parallelized open quantitative PCR platforms used for the simultaneous counting of multiple marker genes [45]. Shotgun metagenomic DNA sequencing can provide the complete range of taxonomic and functional gene information of a sample [41,46,47]. Nucleic acids are directly extracted, fragmented and sequenced, and sequenced reads mapped against, for example, databases or assembled into larger contiguous sequences which are annotated and grouped into putative genomes (i.e., a segment of DNA considered to be a gene) [46,48]. Although this approach provides a large amount of information, it lacks the sensitivity of the target sequence amplification methods, while its ability to connect function and identity relies on statistical tests rather than physical evidence. The latter is a limitation, as many CECs are expected to promote horizontal gene transfer mediated microbial selection, which interferes with the linking of critical functions with taxonomy. The need for linking of functions of interest (e.g., antibiotic resistance marker genes) with taxonomic identities (phylogenetic marker genes) has recently led to the employment of methods such as epic PCR (Emulsion, Paired Isolation and Concatenation PCR; looks to fuse and sequence screening of selected functional and phylogenetic markers), Hi-C (Chromatin Conformation Capture protocol; random fusion and sequence screening of functional with phylogenetic markers), and single cell analysis (random or selection-based whole genome or marker screening of single cells) [49-55]. Hence, a wide array of state-of-the-art diagnostic tools are now available to support environmental microbiology-based CEC risk assessment.

Under EU regulation, all monitoring data should be readily available to EU citizens, and data sharing is fundamental to research and its translation into policy and practice. Several initiatives have the common objective of facilitating rapid access to chemical and biological monitoring data from a range of environmental compartments in comparable, quality assured formats. At an EU level, the Information Platform for Chemical Monitoring facilitates access to chemical occurrence datasets collected by Member States, national and international organisations [24]. Containing monitoring data on both conventional pollutants and CECs, it promotes a co-ordinated approach to data collection and storage, supporting identification of links between exposure and human health data as well as facilitating data access by policy-makers. A complementary data-sharing initiative is the NORMAN Database System (NDS) [23]. Developed by the NORMAN network of research organisations, it supports the validation and harmonisation of measurement methods and monitoring tools, and currently hosts 13 inter-linked databases; these include the NORMAN (a compound database of environmentally relevant contaminants), the NORMAN Ecotoxicology Database (containing ecotoxicological threshold values), and the NORMAN Digital Sample Freezing Platform (a virtual platform to exchange HRMS data and enable retrospective screening of suspect chemicals in 'digitally frozen' environmental samples). Recent additions include platforms to share data on antibiotic resistant bacteria and genes in environmental matrices, and a database to facilitate rapid access to data on the occurrence of SARS-CoV-2 in wastewater, together with wastewater characteristics and clinical case numbers [56]. An ongoing challenge in database development is how to promote and better manage linkages between activities to optimise spatial and temporal coverage of CEC occurrence, exposure and effects data.

3. Contribution of various sources of pollution

Question: What are the main sources of pollution in the aquatic environment?

Recommendations for policy development: Tackling pollution should start at the source, since all chemicals produced and used will reach the environment. Registration of chemicals and their use is already in place through the EU REACH (2006) and CLP regulations (2008). The EC Chemicals Strategy under the European Green Deal is now focusing on creating a toxic-free environment (EU CSS, 2021). This requires banning harmful chemicals from consumer products and boosting the use of chemicals that are safe and sustainable by design. For further policy development we recommend that:

- registration processes be extended to include chemical production volumes;
- a broader classification scheme be created for different groups of chemicals, based on their toxicity and use;
- awareness be raised about the presence, and incentives for reducing the use of chemicals in consumer products (see for example https://waarzitwatin.nl/).

Knowledge gaps: The most important knowledge gap that needs addressing relates to the volume of chemicals produced for specific purposes. Databases should be created that register chemical production and use volumes for different applications. Effective source control can only be successful if we understand the mass loads early on in the supply chain.

Many CECs are used in the production of the multiplicity of goods and materials in everyday use, and the parent compound or transformation products are inevitably – directly or indirectly – discharged to receiving urban water bodies. The main urban water pollution sources of chemical and microbial CECs can be broadly categorised into the following groups:

- industrial effluents.
- agricultural effluents and runoff.
- accidental spills.
- illicit disposals.

Municipal wastewater and urban stormwater runoff are also important pathways for pollutants to enter the water environment (Chapter 4). Municipal wastewater contains bulk organics, nutrients and pathogens, but also a range of CECs, such as pharmaceuticals and personal care products (PPCPs), detergents and cleaning agents, sweeteners, fragrances, preservatives, naturally-occurring toxins and illicit drugs (both direct-to-drain and via landfill leachate), as both parent compounds and their metabolites [57,58]. Unlike domestic wastewater, which is typically of a predictable quantity and quality at a sewer-shed scale, urban stormwater runoff is episodic in nature (driven by storm events), and hence characteristically highly variable in terms of both quantity and quality. Important compounds present in urban stormwater runoff are road and vehicle wear pollutants (e.g., a range of metals, tyre particles, hydrocarbons), together with a diversity of substances that leach from building materials (e.g., phthalates) and/or runoff from green spaces (e.g., pesticides and fertilisers) [59]. Industrial effluents can be very specific in terms of their bio-chemical composition, depending on the manufactured products. If the effluent originates from larger industry or business parks, it can contain a broader spectrum of pollutants in varying quantities. Agricultural wastewater and runoff typically contain nutrients, crop protection agents and pesticides, and veterinary pharmaceuticals and hormones [60]. Finally, accidental spills and illicit disposals may contain any type of CECs, with the latter category increasingly connected to illicit drugs production [61]. Figure 2 illustrates the estimated numbers of compounds registered globally in the Chemical Abstracts Service (CAS) Registry as of 2021 [62]. The CAS Registry is the largest authoritative database and covers all chemicals described in publications since the early 1800s. A CAS Registry Number is a unique identifier for a specific substance that links to data and research available on the compound, and is used by many government bodies for substance identification.

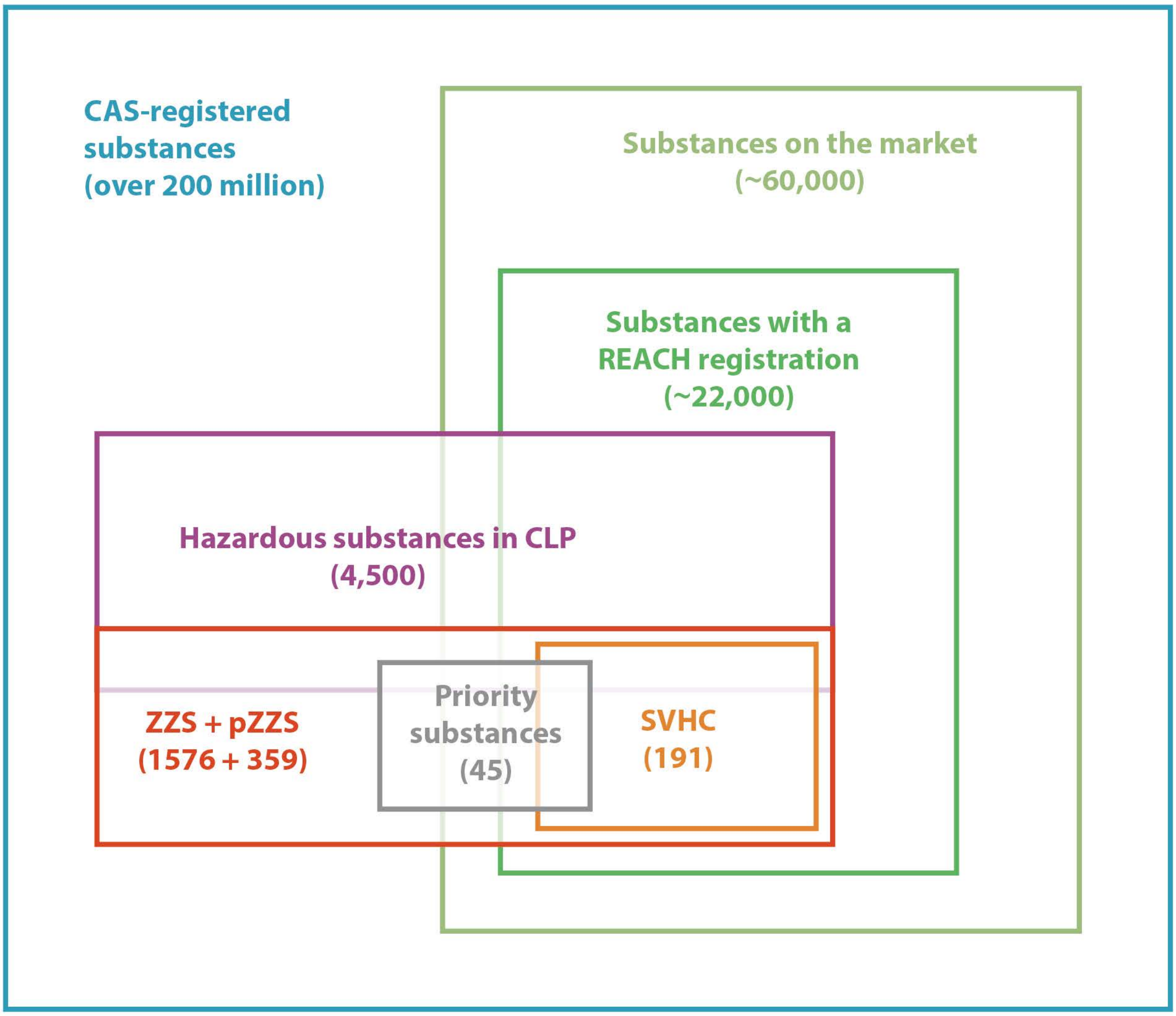


Figure 2. Estimated number of chemicals in different categories [63].

Not all compounds in the CAS Registry are substances that can be purchased on the market or are used for production of goods. It is estimated that globally around 60,000 compounds are available on the market. Industrial substances manufactured or imported in the EU in quantities over one tonne per year, need to be registered under the EU REACH regulations [64]. The purpose of REACH is to manage risks and protect human health and the environment with regard to the manufacturing, formulation and use of chemicals. The REACH regulation processes provide safety information on substances and conditions for their use across the supply chain. In 2020 approximately 22,000 compounds were registered under REACH (see Figure 2); a number that rose to almost 26,000 compounds in 2021 [65]. Among the registered compounds, hazardous compounds are managed according to the Classification, Labelling and Packaging (CLP) Regulations [13], with substances of very high concern (SVHC) identified and submitted to the European Chemicals Agency (ECHA) for restriction or authorisation of their use. When no safer alternative can be found, ECHA may authorise their use for a limited period of time, on the condition that risk mitigation measures are respected. SVHC are compounds with Carcinogenic, Mutagenic Reprotoxic (CMR), persistent, bioaccumulative and toxic (PBT), or very Persistent and very Bioaccumulative (vPvB) substances. The categories ZZS and pZZS in Figure 2 are Dutch categories of very hazardous or potentially very hazardous compounds for humans and the environment [66], which comprise a broader range of chemicals than SVHC under EU REACH (2006) and EU CLP (2008). To preserve this distinction we have retained the Dutch abbreviations for these categories. Figure 2 also shows a group of chemicals that are mentioned as priority substances in the Priority Substances Directive [67].

In October 2020, the EC accepted the Chemicals Strategy for Sustainability (EU CSS) [2], which focuses on banning harmful chemicals from consumer products and phasing out per- and polyfluoroalkyl substances (PFAS). While criteria in the CLP regulation address toxicity, persistency, mobility and bioaccumulation, endocrine disruptors (ED) and persistent mobile and toxic substances (PMT) are specifically targeted in the EU CSS, as well as chemical mixtures. The EC has published roadmaps for updating both the CLP and REACH regulations in light of the EU CSS, with over 80 actions already defined for the implementation of the CSS strategy [2].

Considering the vast number of CECs currently in use, source apportionment between the different sectors, products and users of goods is a complex task requiring a full assessment of all supply chains. An example from a national level is a collaboration between the Netherlands Injury Prevention Institute and the Dutch government to develop a bespoke website (see https://waarzitwatin.nl/), which enables Dutch manufacturers and consumers to connect registered chemicals to specific consumer products. The website gives an overview of the likelihood that a specific compound is present in a product and provides information about the health risks, but there is no quantitative information on use volumes of these compounds. The development and implementation of a zero pollution strategy requires full knowledge of the use (type and volume) of registered chemicals within entire supply chains on a product-by-product basis.

Delivery of a toxic-free environment requires the development of a full supply chain register, which keeps track of how much registered chemicals are used and which products they end up in. REACH registration has qualitative data on different uses, that is, life-cycle descriptions, but quantitative data are not disclosed due to commercial confidentiality. Also, while production tonnages are in the database (presented within tonnage bands), specific tonnages are not disclosed, again for commercial reasons. Registration tonnage and use category data are useful information to prioritise substances for further evaluation. However, without detailed quantitative information, it is difficult to develop and evaluate the efficacy of emission prevention strategies. In addition, quantitative supply chain information on the use of chemicals and materials is key to developing circular economy principles. As a contribution to systematically addressing this data need, we recommend that:

- a database be established to collect quantitative data on mass flows of chemicals in different supply chains;
- the supply chain information be analysed in relation to emission risks to the aquatic environment.

4. Pathways from primary sources to receiving surface waters (including treated effluents, CSOs and stormwater runoff)

Question: What are the principal pathways of pollution into urban water bodies and how can their pollution loads be quantified?

Recommendations for policy development: The EU Urban Wastewater Treatment Directive focuses on point sources discharging to and from wastewater treatment plants. However, the current scope excludes (or only indirectly addresses) many pathways that discharge to receiving waters, including urban stormwater runoff, CSOs and unplanned discharges, which thus remain unregulated. If a zero pollution environment is to be achieved, this regulatory 'loophole' needs to be closed.

Knowledge gaps: Key knowledge gaps in this area relate to urban stormwater pollution concentrations and volumes, and how these vary in relation to catchment type/activities and weather conditions. Opportunities to implement the use of smart modelling and sensors to generate real-time data should be exploited with a view to reducing and preventing CSO discharges. Such datasets would also increase the reliability of urban water pollution models applied at a catchment scale, supporting the implementation of 'whole system thinking'.

The pathways through which urban pollutants can transfer from primary sources to ground- and surface waters are well established. These include pollutant deposition, mobilisation, and wash-off from impermeable and, to a lesser degree, permeable surfaces following rainfall and snowmelt events. Such flows can be discharged untreated to receiving waters (separate piped systems), or be pre-treated, for example, using nature-based solutions (NBS; passive blue-green treatment systems, which can also facilitate infiltration to groundwater and surface water recharge processes). If stormwater flows are discharged to combined piped drainage systems, they are transferred to wastewater treatment plants (WWTPs) and contribute to treated effluent discharges, or are released as untreated discharges from combined sewer overflows (CSOs). However, there are also a variety of 'unplanned pathways', created for instance by illicit misconnections between sewage and stormwater systems (where foul pipes are knowingly or unknowingly connected to the stormwater system), sewer leakages (a function of ageing infrastructure), leachate (from landfill sites for example), and emergency wastewater discharges due to equipment damage. Current key activities aimed at quantifying and characterising urban water pollution pathways focus on point source pollution (i.e., continuous discharges from municipal WWTPs), enhancing treatment efficiencies and promoting the use of advanced treatment technologies (see Chapter 5). This focus is legislatively driven, with the need to satisfy the requirements of the EU Urban Wastewater Treatment Directive (EU UWWTD) [9] – which does not consider diffuse pollution or its treatment – being the motivation behind much of the activity to date. The EU UWWTD is currently under revision, with discussions on extending its scope to encompass CSOs and stormwater issues ongoing. This reflects the increased level of risk of urban pollutants discharging into surface waters during wet weather, as a result of surface runoff, CSOs and the erosion of contaminated land [68]. Discussions on extending the scope of the EU Water Framework Directive [10] concerning the quality of bathing water to also include recreational waters are also ongoing. If supported, this wider scope will also require a significant increase in the control of diffuse pollution discharges to receiving waters.

Several hydrological and hydrodynamic models are available (commercially and as freeware), to support the evaluation of urban drainage pathways, especially for the estimation of flows (e.g., Infoworks, Mike Urban). Selected NBS components have also been included in some of these models, both for hydrological and for water quality issues (e.g., US SWMM). Hydrodynamic models are powerful for discharge estimations and also enable quantification of water quality, but with high uncertainties due to a lack of data and understanding of within-pipe processes – for example, the role of sediments as both pollutant sinks and sources, since flows deposit and remobilise sediments. While some models have the ambition to consider diffuse pollution on a regional scale (e.g., the MoRE model [69]), robust approaches that can comprehensively integrate multiple pollutant sources and their varying patterns of release – both spatially and temporally – remain a challenge. Further open challenges include the integrated modelling of urban drainage systems, which include WWTP, NBS and receiving waters, with weather forecasting systems to support, for example, water quality management of beaches and other surface waters during wet weather or pollution accidents [70]. Runoff from rural and industrial areas can also be an important source of diffuse pollution, contributing to urban water body loads of both conventional pollutants and CECs. For example, the use of treated WWTP effluents as agricultural and/or municipal irrigation waters (as well as the application of manure and/or biosolids, as in agriculture fertilisers) can result in an increased presence of chemical and microbial CECs in soil and aquatic environments, since not all pollutants are removed by conventional wastewater treatment plant processes [71].

Current knowledge gaps include a lack of data on urban water pollution concentrations and volumes in different environmental compartments, as well as the prevalence and impact of unplanned discharges associated for instance with misconnections and pipe infiltration/exfiltration events. Misconnections (i.e., where foul sewers are incorrectly connected to the surface water system) remain a poorly understood issue in many cities with separated foul and surface water piped systems; their identification remains challenging in terms of determining where they occur, and who is responsible for their identification and mitigation. There is also an urgent need for the development and deployment of smart technologies and methodologies to monitor diffuse pollution. The goal being to both enlarge the current evidence base (to directly inform diffuse pollution mitigation strategies), and to improve the use of predictive quality models (to reduce current high levels of uncertainties associated with their use).

5. Treatment technologies

Question: How to engage stakeholders in holistic decision-making processes, which draw on bottom-up technological solutions to facilitate the use of treated wastewater as an alternative water source?

Recommendations for policy development: Stricter regulations, on the quality of discharged wastewater for example, would incentivise upstream polluters to reduce their waste discharges under the 'polluter pays principle'. The recently published EU Regulation 2020/741 on minimum requirements for the reuse of water defines values for target indicators, which focus primarily on physicochemical and microbial parameters. Further specific attention also needs to be directed to the potential presence of a wider range of CECs and more polar, persistent compounds such as PFAS, and to developing an evidence base on the damage that their presence and accumulation could cause to human health and in environmental compartments. Antibiotic resistant genes must be also considered in future policy recommendations.

Knowledge gaps: There are many advanced oxidation process-based and membrane technologies available at TRL 7-8 which target the removal of CECs from the urban water cycle, but their final market introduction has yet to occur. The efficiency of such technologies (as well as more mature ones, such as activated carbon and ozonation) in removing more polar, mobile and persistent contaminants such as PFAS still needs to be demonstrated. Further research on NBS is also required to demonstrate their efficiency as sustainable (i.e., low-cost and low carbon-footprint) alternatives, and their potential contribution to achieving the EU's net-zero carbon ambition by 2050.

There is concern about the discharge of CECs into the environment, which is currently unregulated given the absence of receiving water environmental quality standards [72]. Moreover, the concentration of many CECs in receiving waters is unknown. The implementation of targeted, decentralised, treatment at-source (e.g., substance elimination or substitution) is increasingly recognised as being a more appropriate and cost-effective approach to pollution mitigation, compared to downstream mitigation measures. However, until such options are implemented, attention must be directed further along the source-pathway-receptor chain to identify opportunities to reduce pollutant emissions to receiving waters. This is particularly an issue in southern European countries, where water scarcity is driving the demand for the use of treated effluents in irrigation [73]. The quality of treated effluents and opportunities for their improvement have therefore become a critical area of research and development [74]. While the treatment of wastewater to reduce its pathogen https://www.infomil.nl/onderwerpen/lucht-water/zeer-zorgwekkende/, which have been identified in treated wastewaters (e.g., antibiotic resistance bacteria and genes) present a new challenge for WWTP managers, policy-makers and society in general. The emergence and spread of antibiotic resistance has been identified as a high priority threat [75], but the contribution of urban water pollutants to this phenomena (in terms of sources, pathways, management practices and substance fate) is – at present – poorly understood [76]. In addition, eutrophication of surface waters, caused by phenomena, such as CSOs and the overuse of fertilisers, can lead to the formation of cyanobacterial harmful algal blooms. These can release toxic metabolites (cyanotoxins) into untreated and treated effluent, excluding its further application in crop irrigation and other uses such as gardening [5,58].

Partly as a function of the increasing number of chemicals detected in treated effluents (and knowledge gaps on interactions between CECs), research on the impacts of wastewaters discharged directly from WWTPs, and indirectly after their use in urban/rural irrigation applications, on human and environmental health is a rapidly developing area of research [72,73]. An additional important research activity concerns the innovation and increased implementation of advanced tertiary treatments in WWTPs. Legislation is a significant driver in this context, with for example the recent publication of EU Regulation 2020/741 regarding the minimum quality requirements of water used in reuse applications [77]. In this context, the scientific community and related water management and technology developers are focusing their efforts on identifying new treatment options to address these environmental challenges. The effectiveness of the removal of many CECs by conventional biological treatments is limited by the inherently low biodegradability of many CECs [78]. This means that 'more active' technologies are required, such as advanced oxidation processes (AOPs), enzymatic processes, membrane filtration and activated carbon, as post-treatments, as single processes or in combination with other processes [79]. The current trend therefore involves combining/integrating technologies to maximise opportunities for the removal of the widest possible range of CECs, by exploiting the advantages while overcoming the weaknesses of the different approaches. In this context, the simultaneous application of AOPs (e.g., H_2O_2/UV, O_3/UV, O_3/H_2O_2, UV/H_2O_2/O_3, UV/H_2O_2/TiO_2, persulfate AOPs, ultrasounds/Fenton, photo-Fenton, electrolysis/Fenton, electro-oxidation, non-thermal plasma) has been proven effective against toxic and persistent organic compounds, bacteria and other microorganisms [80-83]. Currently the most commonly integrated/combined technical approaches for CEC abatement at full/commercial scale are: ozone and granular activated carbon; ozone/AOP and biological active filters (BAF); membranes (microfiltration, ultrafiltration, nanofiltration, reverse osmosis, membrane distillation) [84], and activated carbon or ion exchange resins. However, while these approaches succeed in eliminating (removal or degradation) many CECs, the production, behaviour and fate of the (sometimes multiple) by-products generated during advanced oxidation processes have also to be dealt with; this is usually done by means of biological processes [85,86]. Membrane technology is efficient for CEC removal, but its operation is energy intensive (1 kWh/m^3) and comes with high costs (€0.50-€1.00 per m^3). Moreover, the pollutants are con centrated in the retentate stream, which then itself requires treatment. New innovative and cost-effective treatment train strategies and technologies are therefore required to remove these often polar, mobile and persistent compounds, such as PFAS, in an effective manner, that is, with low carbon and energy costs and without generating by-products of concern [87].

Considerable research efforts have also focused on the development and implementation of passive, low-cost urban water pollution treatment solutions that harness natural systems/processes. Growing interest focuses on the use of NBS for decentralised wastewater treatment, the polishing of treated effluents prior to discharge, and on opportunities to mitigate stormwater runoff quantity and improve its quality [88-91]. Internationally, constructed wetlands (CW) are the most extensively used NBS technology for the treatment of wastewater generated in small urban agglomerations [92], and could play a significant role in sustainable sanitation and resource-oriented circular economies [93]. CWs are also capable of removing several CECs, such as pharmaceuticals, hormones or personal care products [78,91,94,95], and have moreover been shown to remove microbial CECs (e.g., ARB and ARGs) [78,96]. However, the evidence on their level of effectiveness is still scarce. NBS can play an important part of the 'multi-barrier' treatment approach, and their use in combination with other types of treatment system (both conventional and/or proprietary) is feasible [97]. Key features of NBS are their multi-functionality and their potential to contribute to meeting several sustainability objectives simultaneously – e.g., climate change mitigation, reduction of noise and air pollution, thermal cooling and ecosystem restoration – contributing to delivering circularity to cities, while also promoting well-being objectives through the provision of well managed urban green spaces [91,98,99]. Further NBS research is needed to increase understanding of the processes delivering ecosystem services, and of their treatment performance with regard to a wider range of CECs, and to evaluate the use of combinations of NBS (e.g., treatment trains) for improved CEC removal at full-scale.

6. Surface water

Question: How can surface waters be effectively protected against mixtures of CECs?

Recommendations for policy development: Regulations and environmental quality standards are required for prioritised CECs in surface waters. Protection mechanisms for surface waters, which specifically include regulations for point and diffuse discharges, and unintended and currently unregulated discharges, are required, and should be supported by the development and implementation of smart monitoring policies.

Knowledge gaps: A better understanding is needed about the presence of new pollutant types in the environment (e.g., nanoparticles, microplastics, pathogens). For chemicals, there is a need for a more reliable prioritisation by means of (i) smart monitoring schemes (including reliable environmental sensors), and (ii) modelling of the transport, fate and toxicity of the chemical mixtures for which complete experimental datasets are lacking. There is also a need for a systematic evaluation of the use of effect-based assays, to support the development of an integrated understanding of the effects of CEC mixtures at environmental concentrations.

The development of a circular economy and progress towards a zero pollution environment require an integrated water quality management, where the focus is on the integration of multiple sources and uses of water, based on fit-for-purpose criteria [100]. Linking the release and fate of CECs within the planned and unplanned use and reuse of water sources – and their interactions within and between further environmental compartments (i.e., soil, air and biota) – is therefore a crucial step in achieving these ambitious policy objectives. In terms of assessments of CECs within integrated urban water management approaches, open access databases, for example on the occurrence, hazardous properties and toxicity of many CECs are expanding, accompanying both developments in analytical techniques and the drive to make datasets available to all users (see Chapter 2). There is also a need to take into consideration new types of CECs, such as biological toxins (e.g., cyanotoxins released from toxic cyanobacteria [101]), nanoparticles and microplastics, as well as new kinds of effects, including infection (for pathogens) and the stimulation of antimicrobial resistance in environmental contexts.

As these datasets grow and multiple users feed into their development, key challenges include how to assure/assess the reliability of reported analytical measurements and datasets pertaining to multiple parameters – e.g., substance partitioning behaviour and microbial degradation time – for the thousands of CECs currently available on the market (see Chapter 3). The analysis of emerging contaminants is really challenging for analytical chemists, because of the diversity in the chemical properties involved, the complexity of matrices and toxic effects exerted at very low concentrations (ng/L or even lower) [102,103] Additional open questions relate to the need to develop a full understanding of the processes and conditions that lead to the degradation of parent components into metabolites with varying levels of toxicity, together with the need to develop robust approaches for the risk assessment of mixtures with a variety of modes of actions and endpoints (see Chapter 7).

As a contributor to surface water quality and quantity, the occurrence of a range of CECs in groundwater (e.g., pharmaceuticals, PFAS, pesticides) has been reported for many years [104-111]. But it is only over the last ten years that advances in this area of scientific research have facilitated the routine detection and reporting of CECs [112-119]. As with surface water bodies, the detection of a wider range of substances is a function of improved analytical technologies that allow both the detection and quantification of CECs at very low concentration levels. Currently, hundreds of substances are routinely quantified in European groundwater [120], and their number is increasing with the development of new monitoring methods, such as integrative passive sampling and the increased use of non-target screening analysis [74] (see Chapter 2). There are multiple pathways from point and non-point sources to surface and groundwaters and associated receptors [102,114]. While processes occurring in WWTPs, surface waters, soils and saturated/unsaturated groundwater zones can lower contaminant mass and/or concentrations, such breakdown processes can also generate metabolites (which may be of more concern in relation to PBT criteria for example). Pollutants that reach groundwater are generally the more persistent and mobile chemicals [121,122]. Groundwater renewal time, which can take hundreds to thousands of years, far exceeds that of surface water, which is in order of days [123]. The concentrations of many substances (including those now banned) and their metabolites therefore continue to show increases in groundwater [111], since their input from surface sources continues (e.g., historic contaminated sediments/already-released substances move from the surface to the subsurface), posing a threat to the health of both current and future generations and ecosystems [124].

In terms of specific open challenges, the current increase in studies on the occurrence and fate of CECs in receiving waters research offers policy advisors and legislators a stronger evidence base on a rapidly expanding list of CECs. However, due to the sheer number of substances, it is no longer possible (or even desirable) to monitor, regulate and formulate mitigation measures on a per CEC basis [125]. The most important challenge is to prioritise the most relevant compounds. This has led to a series of initiatives to prioritise substances in relation to a range of criteria – for example, the NORMAN prioritisation list for all environmental compartments and the development of the first voluntary groundwater watch list [123]. A number of tools can be used to support the prioritisation of CECs, such as smart monitoring to characterise the frequency of occurrence and concentrations, and modelling the effects of chemical mixtures in receiving urban waters, using effect-based assays as a safety net approach to detecting the effects of unknown substances [126-128].

7. Effects of CECs on human health and the environment

Question: What are the effects of exposure to CECs on human health and the environment? How can we develop a robust evidence base on these effects?

Recommendations for policy development: Urban wastewaters represent a complex and variable mixture of CECs, which are being constantly released into the environment and could be hazardous to ecosystems and human health. Firstly, the prevention of exposure needs to be investigated through both at-source and end-of-pipe technological solutions. Secondly, delivery of the EU's zero pollution ambition requires a more targeted policy approach, which addresses the risk that urban mixtures present to the receiving environment, including sensitive areas and/or for specific water reuses (e.g., reclaimed water for agricultural irrigation), and complements current legislation. The development of whole mixture testing, and the definition of benchmark values relevant to assess the impact on the environment and human health, offer an opportunity to provide early warnings and assess the effectiveness of risk mitigation measures already in place. Investment in research is also required to provide evidence for new policy actions, as well as establish a new policy framework for a 'toxic-free environment'.

Knowledge gaps: The long-term (chronic) effects of chemicals (e.g., on immune and neurological systems) and their mixtures on both humans and other species remain largely unknown. Although effect-based methods have demonstrated their utility in the assessment of environmental mixture toxicity, water treatment efficacy and in the identification of unknown toxic entities in combination with chemical analysis (effect-directed analysis), the need to link their results with the risk to human health and the environment remains an open challenge. There is a critical need to fully characterise the effects of cyanotoxins, microplastics and nanoparticles, and to consolidate the list of wider chemical groups impacting microbial resistance (e.g., pharmaceuticals, and chemicals used in biocidal and personal care products). Understanding of AMR environmental hotspots and chemical pressure on AMR dissemination is still limited and requires further investigation. Finally, the development of indicators of impact, distinguishing the different types of pressure on human health and the environment, are urgently needed in order to monitor the drivers and the effectiveness of policy decisions.

The effects of CECs on human health and the environment include toxicity and the non-toxic effects of chemicals and biological pollutants (e.g., bacteria, viruses). Toxic effects of chemical substances marketed in the EU are mostly assessed during their registration process under the legal framework corresponding to their uses. However, data requirements vary in the different pieces of legislation and are not always appropriately addressed by industry, especially for substances regulated under REACH. For example, Oertel, et al. [129] observed that the submitted datasets addressing reproductive toxicity and developmental toxicity for substances manufactured at ≥1000 tons/year were 'non-compliant' in 23% and 32% of the registered dossiers, respectively. Furthermore, the need to submit ecotoxicity data on sediment and soil have been largely waived by applicants [130,131]. There are also data requirements which are not well defined within the relevant legal frameworks, providing room for interpretation by the applicant, as in the case of metabolites and endocrine disrupting effects.

Currently, new concerns are emerging on the long-term effects of chemicals once released within the environment – e.g., effects on the immune and the neurological systems – but also the mixture effects resulting from cumulative exposure to several chemicals. The implementation of a Mixture Assessment Factor is proposed in the EU Chemicals Strategy for Sustainability [2]. However, even if it is accepted that additivity is the main mechanism controlling mixture effects, there is little evidence of mixture effects at environmental concentrations that can be considered relevant at a population level [132], nor on the number of compounds driving toxicity. Further, even though effect-based methods (EBM) have demonstrated their utility in the assessment of environmental mixture toxicity, water treatment efficacy and in the identification of unknown toxic entities in combination with chemical analysis (effect-directed analysis), the need to link their results with the risk to human health and the environment remains an open challenge [74]. Additionally, in silico methods, such as quantitative structure-activity relationship (QSAR) models that are currently promoted by legislation to avoid testing on vertebrates, need to be further developed for specific groups of chemicals and more complex effects.

Among substance effects that are not directly related to toxicity is the capacity of anti-microbials to select resistant microbes in the environment (e.g., antibiotic resistant bacteria). While this is an active research area, to-date only a limited number of antibiotics and environmental compartments have been assessed. There is a critical need to fully understand the effects of antibiotics in all receiving environments, including hotspots, and to consolidate the list of wider chemical groups impacting microbial resistance (e.g., pharmaceuticals, chemicals used in biocidal and personal care products). This concerns CECs such as nanoparticles and microplastics, the effects of emerging pathogens like SARS-CoV-2 and its variants, and the effects of mixtures of cyanotoxins stemming from the same group based on their structure or impact on mammalian health. Finally, the development of indicators of impact of the different types of CECs on human health and the environment are urgently needed, as stressed by the EU Chemicals Strategy for Sustainability, to monitor the drivers and measure the effectiveness of the legislations. The difficulty lies in the concomitance of effects from various types of CECs of anthropogenic and natural origin (such as cyanotoxins) in real situations, and the existence of confounding factors for human health (e.g., dietary habits) and the environment (e.g., climate change).

8. Governance

Question: How can CECs be governed under the umbrella of European legislation and the European Green Deal?

Recommendations for policy development: The use of end-of-pipe solutions alone is not sufficient to achieve a zero pollution environment. The systematic application of a range of at-source solutions, such as reduced CEC production, use and release, will also be required. However, such actions cannot be implemented in isolation and require the co-development and implementation of location-specific and cross-sectoral actions by key stakeholders with the knowledge bases, capacities and incentives to act. A focus on governance processes and mechanisms (involving all sectors and levels, corporate and sub-national actors alike) within regulatory developments will support and optimise stakeholder activities.

Knowledge gaps: Actions to achieve zero pollution can only be effective if developed with a full understanding of the situation in which the company or sub-national government operates. Hence, there is a need for companies, sub-national actors and researchers to work together to co-develop fit-for-purpose methodologies, which systematically and transparently identify impacts of their activities and the actions taken to address these impacts.

Reducing the use and release of CECs to receiving water environments is a pressing, global challenge, which intersects with biodiversity, ecosystem resilience, waste and food issues, and is a key challenge for public policy and governments. At an EU level, the European Zero Pollution Action Plan (2021) and EU Chemical Strategy for Sustainability (2020) are strong drivers for change. Companies and cities should be encouraged by governments to join (EU) initiatives, bringing them into a common sphere of interaction, which amplifies their transformative power by cascading ambitious action and by seizing the collaborative opportunities to set common targets. As an example, the European Commission will be working with the European Committee of the Regions on the Zero Pollution Stakeholder Platform to drive implementation at a local level (EC, 2021b).

In terms of reporting and transparency, European governments should fully implement the Corporate Sustainability Reporting Directive (CSRD) and the sustainability standards as part of measures to motivate companies to reduce their impacts on water and the environment. By leveraging the market power of investors, companies can be encouraged to disclose targets and actions to demonstrate their leadership and accountability to investors, driving ambition among peers and encouraging suppliers to do the same. Reporting carried out by companies and cities should track holistic Key Performance Indicators, such as corporate governance, risk management and value chain engagement, in order to provide consistent, quantifiable and comparable data and insights to stakeholders. A good example of this is the chain approach for reducing pharmaceuticals emissions. In this approach all stakeholders in the supply chain can contribute to reducing the emissions by development and authorisation, prescription and use policies, and waste and sewage treatment, without compromising access to medication for patients [133]. Such insights show that some sectors present a higher risk to water pollution than others. Also, corporate awareness regarding its impact on water pollution along the entire value chain is particularly low in the apparel sector. Working with sector specific data, stakeholders will be able to determine the information gaps and use this knowledge to engage and develop relationships with all suppliers to improve awareness of, and tackle, water pollution [134].

Corporations and sub-national governments can play an essential role in the implementation of European governments' strategies and legislation on water pollution by transitioning their business models to align with a water secure future. Participatory and integrative water governance requires strong leadership skills and expertise in CECs, hence the need for the systematic identification of knowledge gaps and implementation of continuous capacity building measures to address them. This begins by ensuring a common information baseline among sectors with regard to understanding what CECs are and the reasons they should be controlled. This should ensure that all relevant stakeholders are sufficiently knowledgeable to start planning and implementing concrete actions. Capacity building activities should be based on dialogue between jurisdictional levels and different sectors, to make sure that they correspond to each stakeholder's needs and realities. Specifically, an approach that includes the most impacted stakeholders at an early stage in an open and transparent process, that meaningfully considers their viewpoints and data, while ensuring effective communication throughout, is more likely to produce a greater acceptance of the future policies and a stronger commitment to materialize them. Strategic planning, including a set of measurable CEC targets combined with a clear roadmap for achieving and measuring progress against them, are indispensable to good water governance. The co-development of coordination mechanisms and meaningful collaboration across all jurisdictional levels are therefore essential to overcoming current gaps and barriers, which, if not addressed, could weaken the implementation of upcoming policies on CECs. Implementation of the following actions by the different actors are recommended to support delivery of these objectives:

1. **Companies:**
    - Improve the coherence and efficiency of actions by integrating water management and governance in the business model.
    - Implement strategies for the reduction of pollutants in operations, to reduce levels of water pollution discharged to the environment.
    - Implement internal monitoring processes to ensure reduction of, and improve external reporting on, pollutants to allow for accountability and learning.
2. **Sub-national governments.**
    - Improve public disclosure of water management and governance to facilitate learnings, collaboration and accountability.
    - Invest in building the capacity of local level actors to create commitment and solutions with a solid basis on practical action, as well as participate in collaboration opportunities, such as through the European Climate Pact (ECP, 2020) and non-state actor initiatives.
3. **EU governments.**
    - Improve disclosure requirements for companies and sub-national governments to increase transparency of the impacts and actions on (urban) water quality.
    - Establish ways for feeding business and local level experiences back to EU level policy development through initiatives such as the European Climate Pact, the Zero Pollution Stakeholder Platform (EC, 2021b) or the Green City Accord.

9. Future issues and solutions

Question: How can we ensure a zero pollution environment is 'future-proof'?

Recommendations for policy development: Achieving a zero pollution environment is a major component of the European Green Deal's Zero Pollution Action Plan, the EU 2030 Biodiversity Strategy and the EU Urban Agenda. However, the EU should also consider the progressive adaptation of existing policies and the challenge of mobilising adequate investments from a combination of public and private actors to restore the natural functions of groundwater, surface water, marine and coastal waters in a systematic way.

Knowledge gaps: Implementation of new and emerging zero pollution strategies may have significant impacts on supply chains. For example, a move to a low carbon economy is predicted to significantly increase both the water footprint and pollution discharged to receiving urban water compartments (among others) in mining countries, many of which are located in already water scarce areas. Further research on the life-cycle implications of zero pollution strategies should therefore be a key component of policy development and implementation measures.

Europe's level of urbanisation is expected to increase to approximately 84% by 2050, up from the 2021 level of 75% [135]. Without the introduction of new effective measures, this growth will boost water demand in terms of both quantity and quality, while increased concentration of pollution is expected. The efforts to move towards zero pollution therefore require a strong focus on water as part of the European Green Deal's Zero Pollution Action Plan [136], the EU 2030 Biodiversity Strategy [137] and the EU Urban Agenda [138,139]. But the EU should also consider the progressive adaptation of existing policies and strategies, in a context of rapid climate change, with the further aim of addressing the challenge of mobilising adequate investments from a combination of public and private actors for the water sector, with a particular focus on tackling pollution. Actions in the near future must aim at restoring the natural functions of groundwater, surface water, marine and coastal waters in a systemic way. Tackling pollution from urban runoff, and addressing new concerns, such as plastics (including plastic littering and uncontrolled release of microplastics), hazardous chemicals, microorganisms, pathogens, viruses and other CECs, is the way forward to protecting our water resources. This requires a systemic view that leads towards the establishment of long-lasting initiatives to re-design the whole of society in a circular and resilient mode, while gradually phasing out the linear approach. This involves the development of new technologies, solutions, and business and governance models. Such transformations can significantly affect supply chains and therefore also have a global impact. For instance, shifting to a low/carbon neutral economy will increase the need for certain metals and minerals. The International Energy Agency is indeed predicting a 40-fold increase in lithium demand and a 20-fold increase in the demand for cobalt and nickel by 2040 (compared to 2020). These demand increases cannot be met by recycling and will thus significantly increase the water footprint and pollution in mining countries (often located in water scarce areas) [140].

Prevention remains the cheapest and most effective way to secure water quality and quantity in the long term, and to preserve the environment and biodiversity. Only initiatives aimed at preventing and reducing pollution, with the common commitment of authorities, business, research, and citizens to jointly design, co-implement and co-monitor effective measures, will contribute to alleviating pressures on the water ecosystems, towards the achievement of a Water-Smart Society. The above example regarding minerals shows how important it is to think out of the box. Reaching out to other sectors and areas is essential to realising a Water-Smart Society. Moreover, developing a zero-pollution strategy and transitioning to a Water-Smart Society, including circular solutions, require a continuous monitoring strategy to determine progress. Without monitoring, we are travelling blind towards an unknown destination and have no means for creating incentives for improvement and supporting policy development.

10. Conclusions

This paper brings together international expertise from a range of disciplines to review the current state of the art concerning the assessment of sources of urban water pollution, its impacts, and opportunities for mitigation. By posing a series of key questions on different topics around pollution in water, recommendations for policymakers are made and knowledge gaps identified. An overview of the collected information is shown in Table 1. We anticipate that these policy recommendations can significantly contribute to achieving the EU's zero pollution objectives and UN Sustainable Development Goals.

Table 1. Overview of the key questions, recommendations for policy development, and identified knowledge gaps for achieving zero pollution in a Water-Smart Society.

Key Question	Recommendation for policy development	Knowledge gaps
How can we develop a robust evidence base on the sources, behaviour and impact of CECs in the urban water cycle?	● Deployment of early-warning and rapid assessment sensor technologies. ● Provide data on exposure and effects via open-data platforms to identify priority chemicals.	● Sensor development and deployment infrastructure. ● Analytical platforms with non-target screening protocols. ● Link genetic functions to taxonomic identities.
What are the main sources of pollution in the aquatic environment?	● Extend registration processes to include chemical production volumes. ● Create a broader classification scheme for different groups of chemicals, based on their toxicity and use. ● Raise awareness about the presence and incentives for reducing the use of chemicals in consumer products.	● The volume of chemicals produced for specific purposes.
What are the principal pathways of pollution into urban water bodies and how can their pollution loads be quantified?	● Develop discharging regulations for all discharge streams including the currently unregulated streams such as urban stormwater runoff, CSOs and unplanned discharges.	● Urban stormwater pollution concentrations and volumes. ● Data collection via smart modelling and online sensors.
How to engage stakeholders in holistic decision-making processes, which draw on bottom-up technological solutions to facilitate the use of treated wastewater as an alternative water source?	● Specific attention must also be paid to the potential presence of a wider range of CECs and more polar, persistent compounds such as PFAS, as well as developing an evidence base on the damage that their presence and accumulation could cause to human health and in environmental compartments. ● Antibiotic resistant genes must be also considered in future policy recommendations.	● Bringing advanced technologies such as advanced oxidation or membranes to full market development (TRL9). ● Efficiency of such technology for removal of more polar, mobile and persistent compounds. ● Demonstration efficiency and sustainability of Nature-Based Solutions for pollutant removal.

Key Question	Recommendation for policy development	Knowledge gaps
How can surface waters be effectively protected against mixtures of CECs?	• Regulations and environmental quality standards are required for prioritised CECs in surface waters. • Protection mechanisms for surface waters, which specifically include regulations for point and diffuse discharges, and unintended and currently unregulated discharges, are required, and should be supported by the development and implementation of smart monitoring policies.	• A better understanding of new pollutant types in the environment (e.g., nanoparticles, microplastics, pathogens). • For chemicals, a more reliable prioritisation by means of (i) smart monitoring schemes (including reliable environmental sensors), and (ii) modelling of transport, fate and toxicity of the chemical mixtures for which complete experimental datasets are lacking. • Systematic evaluation of the use of effect-based assays, to support development of an integrated understanding of the effects of CEC mixtures at environmental concentrations.
What are the effects of exposure to CECs on human health and the environment? How can we develop a robust evidence base on these effects?	• Prevention of exposure needs to be investigated via both at- source and end-of-pipe technological solutions. • Targeted policy approach which addresses the risk that urban mixtures present to the receiving environment.	• Long-term (chronic) effects of chemicals (e.g., on immune and neurological systems) and their mixtures in both humans and other species remain largely unknown. • Fully characterise the effects of cyanotoxins, microplastics and nanoparticles, and to consolidate the list of the effects of wider chemical groups impacting microbial resistance. • The development of indicators of impact, distinguishing the different types of pressure on human health and the environment, are urgently needed to monitor the drivers and the effectiveness of policy decisions.
How can CECs be governed under the umbrella of European legislation and the European Green Deal?	• Mitigation actions cannot be implemented in isolation and require the co-development and implementation by key stakeholders, and with integration of the knowledge bases, capacities and incentives to act.	• There is need for companies, sub-national actors and researchers to work together to co-develop fit-for-purpose methodologies, which systematically and transparently identify impacts of their activities and the actions taken to address these impacts.
How can we ensure a zero pollution environment is 'future-proof'?	• The EU should consider the progressive adaptation of existing policies and the challenge of mobilising adequate investments from a combination of public and private actors to restore the natural functions of groundwater, surface water, marine and coastal waters in a systematic way.	• Implementation of new and emerging zero pollution strategies may have significant impacts on supply chains. • Further research on the life-cycle implications of zero pollution strategies should be a key component of policy development and implementation measures.

Establishing a zero-pollution strategy for CECs represents a cross-cutting challenge. It requires a shift towards a multi-level and polycentric form of water governance, and the active involvement of civil society, the private sector and other stakeholders in an open and transparent process from an early stage. Water policies require strategic planning, implementation at different jurisdictional levels, and the taking into account of additional cross-sectoral policies. Adequate coordination mechanisms and meaningful collaboration across all jurisdictional levels are essential to overcome current capacity gaps in CEC knowledge bases; moreover, there is an identified need for continuous training at all jurisdictional levels. Effective communication between jurisdictional levels and different sectors is fundamental for stakeholder capacity building and could promote a greater acceptance of upcoming policies on CECs, and a stronger commitment by all actors to their own role and responsibilities in the process. Lastly, market dialogue during the preparation of public tenders can play a key role in boosting environmental action in companies, and in striking an appropriate balance between zero pollution targets and technical and economic feasibility.

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Notes

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TOWARDS A ZERO-POLLUTION STRATEGY FOR CONTAMINANTS OF EMERGING CONCERN IN THE URBAN WATER CYCLE

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