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Risk-based prioritisation of WWTPs for quaternary treatment: a practical workflow informed by Swedish experience

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The recently revised European Urban Wastewater Treatment Directive (Directive (EU) 2024/3019) requires Member States to identify where organic micropollutants (OMPs) pose risks and to prioritize wastewater treatment plants (WWTPs) for advanced (quaternary) treatment. Micropollutant-related obligations are thereafter phased in over time. In this perspective, we propose a cost-effective three-phase workflow to prioritize WWTPs for quaternary treatment, grounded in two decades of Swedish experience from monitoring, environmental risk assessments, pilot trials, and full-scale implementation. We argue that harmonized minimum data requirements and a structured phased approach are essential to implement risk-based prioritization efficiently. Phase 1 screens WWTP-recipients using harmonized chemical and system data to model predicted environmental concentrations (PEC) and compare them with predicted no-effect concentrations (PNEC) and environmental quality standards (EQS). Phase 2 validates identified risks through targeted chemical analysis and, where relevant, effect-based monitoring to capture mixture and seasonal variability. Phase 3 supports implementation and follow-up of quaternary treatment focusing on high-risk OMPs and performance verification. Our intention is that the proposed workflow will help authorities and utilities allocate investments where environmental benefits are largest relative to costs and to support harmonized implementation across Sweden and the EU.

KEYWORDS

environmental risk assessment, organic micropollutants, prioritisation, quaternary treatment, Sweden, Urban Wastewater Treatment Directive, wastewater treatment plants

1 Introduction

Wastewater treatment plants (WWTPs) play a crucial role in society by eliminating nutrients and organic materials from sewage prior to discharge to the aquatic environment. However, conventional treatment processes are not designed to remove persistent organic micropollutants (OMPs) such as pharmaceuticals and per- and polyfluorinated substances (PFAS) (Falås et al., 2016; Hollender et al., 2009; Schaefer et al., 2023). The discharge of individual OMPs and their mixtures from WWTPs can impair water quality and can lead to adverse ecological effects (Kidd et al., 2024). Importantly, with complementary treatment techniques for OMPs removal at WWTPs, also known as quaternary treatment, emissions can be substantially reduced (Pistocchi et al., 2022a), with ozonation and activated carbon frequently highlighted as feasible options for broad micropollutant reduction (Joss et al., 2008). A remaining key challenge is, however, how to prioritize which WWTPs should be upgraded first to maximize environmental benefits relative to costs.

Switzerland introduced national legislation in 2016 to achieve 80% removal of selected OMPs by implementing quaternary treatment at prioritized WWTPs (UVEK, 2016). There, selection was based on criteria related to high loads, drinking-water relevant catchments, and low dilution in receiving waters (Eggen et al., 2014). The Swiss approach illustrates that clear prioritisation criteria can target a limited subset of WWTPs while delivering substantial reductions in risk and loads. This is supported by evidence from Switzerland showing reduced ecotoxicological effects in effluents after ozonation with post-treatment (Kienle et al., 2023).

The revised European Urban Wastewater Treatment Directive (UWWTD) (Directive (EU) 2024/3019) introduces phased requirements to address OMPs, including implementation of quaternary treatment at WWTPs larger than 150,000 p.e. and, where indicated by environmental risk assessments (ERAs), also at other WWTPs. As an EU Member State, Sweden will be significantly affected during implementation. Sweden's long-running efforts to assess and reduce OMP emissions provide an informative case for implementation (Undeman et al., 2022).

In this perspective, we synthesize two decades of Swedish experiences from authorities, municipalities, researchers and consultants to propose a practical three-phase workflow (screening, validation and implementation) for prioritizing WWTPs for quaternary treatment under the revised UWWTD. The workflow is intended to support cost-effective, risk-based decision-making and can be adapted to prioritise additional measures for other harmful OMPs beyond the minimum regulatory scope.

2 The need for a harmonised prioritisation framework

Sweden has accumulated two decades of experience in monitoring, risk assessments, pilot trials and full-scale implementation of OMP removal at WWTPs (Björklund and Svahn, 2022), providing a basis for proposing a practical three-phase prioritization workflow.

2.1 Early quaternary treatment projects 2005–2015

Early Swedish pilot and research programs demonstrated that ozone and activated carbon can substantially reduce OMP emissions from WWTPs (Wahlberg et al., 2010; MistraPharma, 2016). These efforts also highlighted methodological inconsistencies in chemical-by-chemical risk assessment and the need for periodic updates as toxicity data evolve, including consideration of mixture toxicity for substances with similar modes of action (Ågerstrand et al., 2015). The systematic compilation and subsequent updating of predicted no-effect concentrations (PNEC) values (Ågerstrand, 2019) enabled more structured screening, but their application across WWTPs remained inconsistent. Together, these early experiences demonstrated that while technical feasibility was established early on, the lack of harmonised assessment criteria limited comparability across sites and over time.

2.2 Strategic projects financed by the Swedish government 2014–2023

Projects funded by the Swedish Agency for Marine and Water Management (SwAM) between 2014 and 2017 evaluated multiple technologies and again identified ozone and activated carbon as the most suitable options for substantial OMP removal. However, these projects applied no harmonized approach for environmental risk assessments (ERAs); when performed, assessments were often limited to comparing measured or estimated concentrations with PNECs (Cimbritz and Mattsson, 2018).

In 2015, The Swedish Environmental Protection Agency (SEPA) was tasked with determining whether quaternary treatment should and could be introduced at Swedish WWTPs. The need for quaternary treatment and potential technical solutions have been assessed in several nationally funded Swedish projects, and summarized in two national reports (Wallberg et al., 2016; Baresel et al., 2017). These studies identified ozonation and granular activated carbon (GAC) as the most viable treatment technologies at a reasonable cost (Sundin et al., 2017). This reinforced the need for a structured decision framework alongside continued technical development.

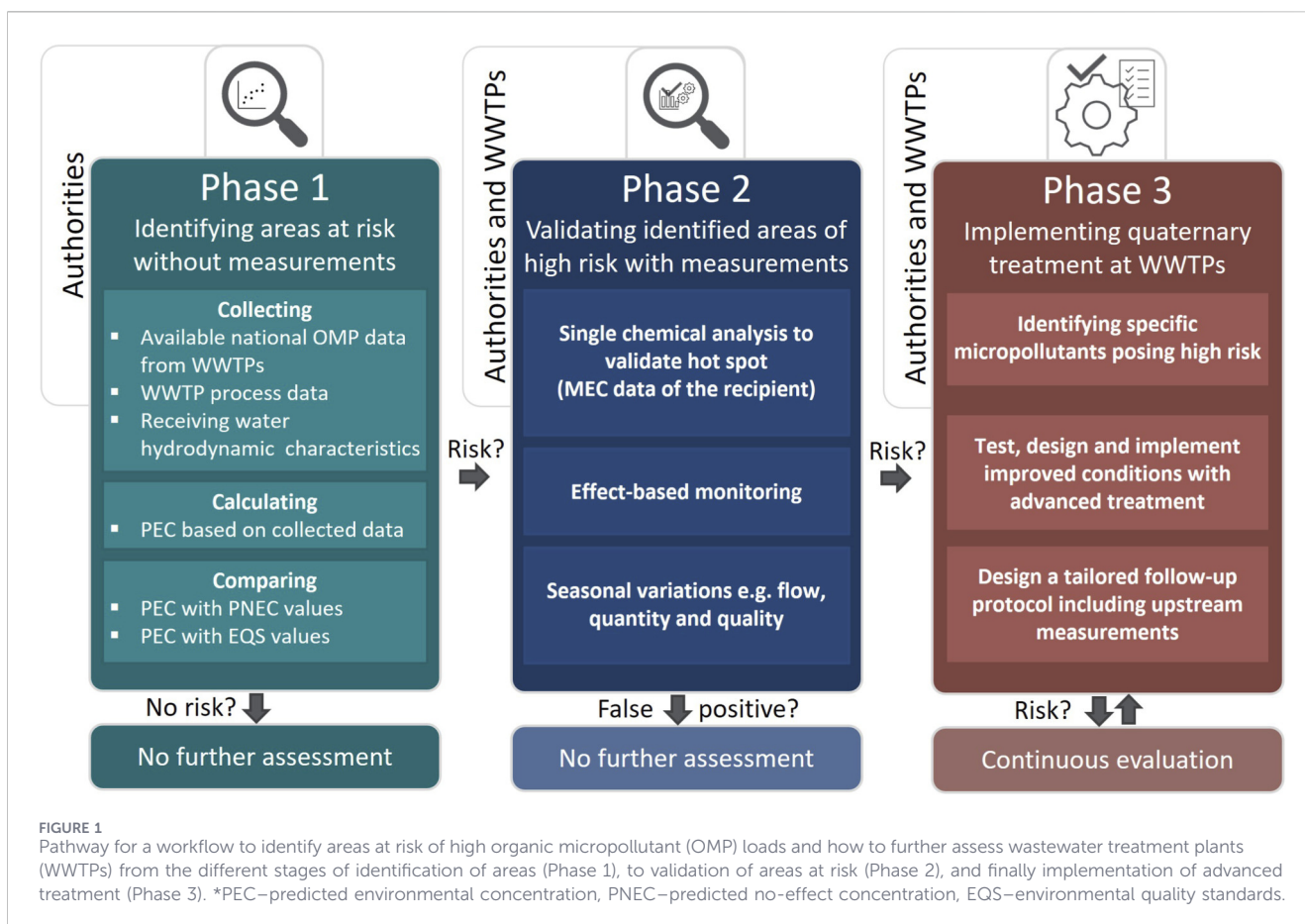
SEPA's €21M program (2018–2023) resulted in more than 65 projects spanning theoretical investigations, pilot trials, and full-scale installations (Svenskt Vatten, 2023). Despite substantial investments since 2018, a consistent ERA approach has not been applied across projects, and many studies and installations have been conducted at WWTPs below 150,000 p.e. without establishing whether quaternary treatment is environmentally warranted. European overviews similarly emphasise that implementation of quaternary treatment requires structured, risk-based approaches to ensure cost-effective deployment (Kosek et al., 2020).

2.3 Why a phased workflow is needed: uncertainties and decision criteria

Already in 2017, SEPA concluded that existing data were insufficient to determine where and to what extent quaternary treatment should be implemented (Sundin et al., 2017). At that time, several factors were identified as crucial screening criteria for local prioritisation:

- i. the magnitude of the OMPs discharged into the receiving water,
- ii. the retention time and dilution factor in the receiving water,
- iii. the presence of several WWTPs discharging into the same water body,
- iv. the vulnerability of the receiving water body.

SEPA did not actively allocate funds to address identified knowledge gaps, nor did it harmonize methods for performing ERAs or selecting OMPs for assessment in projects over the past 20 years. Some internal harmonization efforts were made, and a recommended list of OMPs was released after initial projects were completed. As a result, there is still no unified Swedish strategy for identifying and prioritizing WWTPs for quaternary treatment. This motivates a phased workflow that combines screening, targeted



validation, and implementation with follow-up, presented in Section 3.

3 Evidence and lessons learned from Sweden (2005–2023)

Based on the decision criteria and uncertainties outlined above, we propose a three-phase workflow (Figure 1) as a structured approach to prioritize WWTPs for quaternary treatment. Phase 1 screens WWTP–recipient settings using harmonized chemical and system data; Phase 2 validates identified risks through targeted monitoring and, where relevant, effect-based methods; Phase 3 supports implementation and follow-up to verify emission reductions and treatment performance.

A conservative trigger to proceed from Phase 1 to Phase 2 is a risk quotient $RQ = PEC/PNEC \geq 1$ for one or more indicator substances, consistent with standard screening practice in environmental risk assessment (ECHA, 2008). Because PECs are sensitive to dilution assumptions and PNECs/EQS are periodically updated, Phase 1 screening should be run using conservative dilution scenarios (e.g., low-flow conditions) and sites with RQ close to unity should be treated as uncertain and prioritized for Phase 2 validation.

A conservative trigger to proceed from Phase 1 to Phase 2 can be $PEC/PNEC \geq 1$ for one or more priority and indicator substances, repeated exceedance of an EQS, or high vulnerability or low dilution

dilution combined with elevated predicted loads. Progression from Phase 2 to Phase 3 can be triggered by confirmed exceedance frequency such as repeated measured environmental concentration (MEC)/PNEC ≥ 1 or EQS exceedance under relevant conditions, and/or consistent signals in effect-based methods indicating biological concern. Thresholds should be set by authorities to balance sensitivity and feasibility and can be updated as benchmarks evolve.

The revised UWWT D emphasizes the need to identify areas at risk of micropollutant impacts and to apply risk-based decision-making as requirements are introduced progressively. Swedish quaternary treatment projects since 2005 provide clear and transferable lessons on how risk has been assessed in practice and where uncertainties and inconsistencies have arisen. Below, we summarize key experiences that inform each phase of the proposed workflow.

3.1 Phase 1: screening

3.1.1 OMP loads at Swedish WWTPs

Across Swedish projects, estimation of OMP loads at WWTPs has relied on a wide range of data sources and sampling strategies. The first step in the projects was often to define the OMP load that the WWTP exerts on the recipient. This has been done in a few different ways in the various projects. A vast majority of the projects performed new sampling campaigns and analysed OMPs in the

effluent wastewater, but in many cases also in the incoming wastewater. In some cases, a wider range of OMPs beyond pharmaceuticals was included such as PFAS or bisphenol A.

Several studies compared their site-specific WWTP concentrations with data from other WWTPs or historical measurements from the same plant, and concentrations often agreed well with previous studies. Many projects also sampled the receiving water body upstream and downstream of the discharge point (or in surrounding areas for wetlands, lakes and coastal zones). This enabled comparisons between MEC and PEC, where PECs were calculated by dividing effluent concentrations by a recipient-specific dilution factor (see [Section 3.1.2](#)).

Only a few projects relied on previously published chemical monitoring data for their ERA, and only one project used regional survey averages to estimate WWTP-loads. Taken together, these approaches provide inputs for Phase 1 screening but also illustrate the need for harmonized minimum datasets and comparable sampling strategies.

Proposed minimum dataset for Phase 1 screening:

- i. Effluent concentrations for a harmonised set of indicator OMPs: at least one campaign representative for the site; ideally complemented with existing national or regional data where available.
- ii. WWTP system data: average and seasonal effluent flow, population equivalent, major treatment configuration, and industrial contribution where relevant.
- iii. Receiving-water hydrology: dilution factor or its range, low-flow conditions, and where relevant exchange rates or retention times for lakes and coastal waters.
- iv. Context and vulnerability: protected status and sensitive uses (e.g., drinking-water abstraction, Natura 2000), and presence of multiple WWTP discharges to the same water body.
- v. Benchmark values: PNECs and EQS should be referenced to a defined source and version or date (e.g., specific guideline/report and year, or the date the benchmark list was extracted), to ensure reproducibility and facilitate future updates.

3.1.2 Recipient characteristics - exchange rates and dilution factors

To determine the OMP dilution factor essential for ERA, it is crucial to consider WWTP effluent flows and the hydrodynamic characteristics of the recipient, such as stream flows and exchange rates in lakes and coastal zones. While continuous flow data are typically available for Swedish WWTPs, recipient characteristics are less frequently monitored and can vary substantially over time. Dilution-based PEC calculations often assume conservative behavior of OMPs, thereby ignoring transformation or degradation processes. In protected areas (e.g., Natura 2000) stricter requirements may apply, increasing the need for representative data to assess compliance with EQS ([EC, 2022](#)).

For streams, dilution factors are often estimated using models such as the S-Hype model ([SMHL, 2023](#)), although overestimation has been reported ([Pirzadeh et al., 2021](#)). Alternative approaches include using daily flow monitoring or pre-existing dilution factors (e.g., [Karlsson et al., 2023](#); [Chen et al., 2019](#); [Baresel et al., 2019](#)). Seasonal variability can be large ([Önnby et al., 2023](#)), which is

particularly important for WWTPs discharging to vulnerable or protected waters ([Baresel et al., 2024](#)).

To mitigate model uncertainty during screening, authorities can apply a conservative dilution range (e.g., using low-flow percentiles or seasonal minima where available) and flag sites as uncertain when dilution estimates are highly sensitive to model choice. Such sites can be prioritised for targeted hydrological verification in Phase 2, reducing the risk of false reassurance based on optimistic dilution estimates.

For lakes and coastal zones, studies have used expert judgement and hydrodynamic dispersion models to estimate dilution and exchange rates (cf. [Baresel et al., 2021a; 2023](#); [Chen et al., 2022](#)), again highlighting strong variability with season and weather. Overall, these experiences underline that robust Phase 1 screening should explicitly account for dilution uncertainty and seasonal variability.

[Pistocchi et al. \(2022b\)](#) similarly argue for selective application of quaternary treatment, particularly for larger WWTPs and smaller WWTPs with dilution factors of ten or less, to balance toxicity reduction with manageable costs. This supports screening approaches that prioritize large WWTPs and low-dilution settings.

3.1.3 Predicted no-effect concentration (PNEC) and environmental quality standards (EQS) benchmarks

The establishment of realistic and harmonized PNEC values is crucial when performing comparative ERAs. PNEC values relevant to Swedish wastewater have been compiled and later re-derived in Swedish work ([Ågerstrand, 2019](#)), illustrating that values may change as new data and assessments become available. When PNEC values are absent, they can be estimated based on general guidelines published by, for example, [ECHA \(2008\)](#), provided that toxicological data exist.

Across Swedish projects, different strategies were used to identify or apply PNEC values. These included using compiled PNEC values from other projects (cf. [Baresel et al., 2024](#); [Habagail et al., 2020](#); [Hey et al., 2022a](#)), using PNECs reported in single studies ([Chen et al., 2019](#)), calculating PNEC according to guidance ([ECHA, 2008](#)), and performing new toxicity studies ([Hoyer et al., 2022](#)).

In ERAs, derived PEC values have been compared with available PNEC values. The selection of OMPs included in the evaluation became partly harmonized during later stages of the national program when SEPA recommended a set of OMPs to be included. In addition to PEC/PNEC comparisons, compliance has been evaluated within many ERAs ([SwAM, 2013](#); [SwAM, 2019](#)), either as part of broader assessment (cf. [Chen et al., 2022](#); [Baresel et al., 2019](#)) or in EQS-focused studies (cf. [Pirzadeh et al., 2021](#)).

In recent years, it has become evident that the concentrations of the PFAS substances PFOS and PFOA, for which EQS exist, are often exceeded in receiving waters ([Önnby et al., 2023](#); [Hey et al., 2022b](#)). However, assessment of mixture-oriented PFAS standards have been less consistently implemented in performed ERAs. In the 2025 provisional agreement on updating EU water pollutant standards, TFA is added to the initially proposed sum of 24 PFAS for surface waters, effectively moving toward a sum of

25 PFAS (expressed as PFOA equivalents) (Council of the European Union, 2025). Scientific advice to the Commission has also recommended including TFA in the PFAS24 approach (SCHEER, 2025). Together, these developments underscore an urgent need to harmonize and regularly update ERAs to ensure consistent implementation and inclusion of essential substances across sites and over time.

3.2 Phase 2: validation (targeted monitoring and effect-based methods)

Following Phase 1 screening, Phase 2 validates whether identified WWTP-recipient settings represent a consistent environmental risk and reduces key uncertainties before implementation decisions are made. Validation needs to combine targeted chemical monitoring in effluent with upstream-downstream sampling in the receiving water to confirm predicted exposure levels (Sweco, 2021), distinguish WWTP contributions from background sources (Pirzadeh et al., 2021; Önnby et al., 2024), and capture temporal variability such as low-flow periods and seasonal changes in dilution (Lindbäck et al., 2023; Pirzadeh et al., 2021). A key purpose of this step is to determine whether the WWTP is a dominant source for the substances of concern; for some pollutants, background levels or upstream sources may contribute substantially, implying that end-of-pipe measures would yield limited environmental benefit. Where mixtures and unknown contributors are likely to drive risk, effect-based methods (EBMs) can complement chemical analysis by integrating mixture effects and supporting prioritization of substance groups or endpoints (Brack et al., 2019; Escher et al., 2018; Holm and Önnby, 2022; Lavonen, 2025). In practice, this can be done by applying a small bioassay battery (e.g., *in vitro* reporter-gene assays for estrogenicity and AhR-mediated activity, plus assays for oxidative stress or baseline toxicity) to solid-phase extracts from effluent and upstream/downstream recipient water. Responses can be benchmarked against effect-based trigger values (EBTs) to support a transparent “go/no-go” decision for Phase 3 and to guide targeted follow-up chemical screening. The outcome of Phase 2 is a decision gate: sites with confirmed risks proceed to Phase 3, while sites without consistent evidence of risk can be deprioritized or returned to Phase 1 with refined data needs. Key outputs include a refined list of high-risk OMPs (and/or effect endpoints), uncertainty bounds for exposure or risk, and a monitoring baseline enabling post-implementation verification.

3.3 Phase 3: implementation and follow-up (verification of performance)

Phase 3 covers implementation of quaternary treatment at prioritized WWTPs and verification that the intended risk reduction is achieved under real operating conditions. Phase 3 also includes source-control actions where end-of-pipe measures are unlikely to deliver sufficient benefit, e.g., when upstream or background dominates, such as targeted industrial pretreatment, product substitution, or catchment-level interventions. Technology selection and design are guided by the validated risk profile from Phase 2 such as dominant OMP groups and expected removal needs, while considering site-specific

constraints such as hydraulics, existing process configuration, and costs (Sundin et al., 2017). To operationalize “cost-effectiveness”, implementation decisions should combine validated risk (e.g., RQ/EQS exceedance frequency and/or EBM responses), expected removal performance, and CAPEX/OPEX to prioritize sites where the expected reduction in risk per invested euro is greatest (Kosek et al., 2020; Pistocchi et al., 2022b). Follow-up requires a fit-for-purpose monitoring program that verifies emission reductions for the prioritized OMPs and/or relevant effect-based endpoints, and that documents operational robustness, e.g., performance across seasons and varying loads. As a pragmatic example, utilities can combine routine operational monitoring with 2–4 targeted performance campaigns per year capturing contrasting flow or dilution conditions and include upstream measurements where relevant to separate WWTP effects from background. Because PNECs, EQS and priority substance lists evolve over time, implementation plans need to include periodic review of target compounds and assessment criteria. For example, under the Water Framework Directive, the EU Surface Water Watch List is periodically updated through implementing decisions to generate monitoring data that can inform future prioritization and regulatory updates (European Commission, 2025). In parallel, EU processes to update pollutant standards further underline the need for regular revision of targets and benchmarks (Council of the European Union, 2025). This allows monitoring and treatment objectives to be updated without restarting the full process and helps keep investments aligned with the current policy landscape (European Commission, 2025). In this way, Phase 3 closes the loop by linking investments to documented environmental benefit and by providing feedback to refine Phase 1 screening criteria and Phase 2 validation needs.

4 Practical implications for implementing the revised UWWTD and risk-based ERAs

The revised UWWTD requires Member States to identify areas where micropollutant pollution may threaten human health or the environment and to review these assessments periodically. In countries with many receiving waters, broad area-based classifications are associated with a risk of overlooking site-specific conditions which can lead to inefficient prioritization. Building on Swedish experiences, we propose that implementation is complemented with a WWTP-recipient screening perspective using the three-phase workflow shown in Figure 1. A key implication is to establish harmonized minimum datasets in Phase 1 (effluent concentrations, WWTP process and flow data, and recipient hydrology) enabling comparable PEC calculations against regularly updated PNECs and EQS. Targeted validation in Phase 2 is essential to reduce uncertainty and avoid false negatives, especially where dilution is highly seasonal or where mixture effects may dominate. If risks are confirmed, implementation and follow-up in Phase 3 need to verify emission reductions for the prioritized OMPs and/or effect-based endpoints and allow periodic updates as assessment criteria evolve. Harmonized screening and reporting across

WWTPs would support transparent, cost-effective investment decisions and facilitate comparability across Member States. At the same time, upstream measures remain essential for substances that are not reliably reduced by typical quaternary treatment configurations (e.g., ozonation), including many PFAS, which may require dedicated treatment approaches. A coordinated strategy therefore needs to combine risk-based end-of-pipe prioritisation with source control and targeted upstream interventions to manage future OMP loads, including mixture effects and emerging pollutants.

5 Conclusion and key messages

- Two decades of Swedish monitoring, ERAs, pilot trials and full-scale experience provide a strong basis for implementing quaternary treatment under the revised UWWTD; however, despite substantial investments, Sweden still lacks a harmonized and consistently applied approach to determine which WWTPs require quaternary treatment based on risk.
- Key screening determinants include WWTP OMP loads and receiving-water characteristics, especially dilution and exchange rates, with particular attention to vulnerable and protected waters.
- We propose a cost-effective three-phase workflow: Phase 1 screening using harmonized data and modeled PECs against PNECs/EQS; Phase 2 targeted validation, including effect-based methods where relevant; Phase 3 implementation with follow-up to verify emission reductions and updated targets over time.
- Applying this workflow can support transparent, comparable prioritization across WWTPs and help allocate investments where environmental benefits are largest relative to costs.

Data availability statement

The publicly available dataset can be found at: <https://www.smed.se/vatten/5843> - the Swedish Environmental Emission Data.

Author contributions

LO: Conceptualization, Investigation, Methodology, Project administration, Writing – original draft, Writing – review and editing, Resources. CB: Investigation, Visualization, Writing – original draft, Writing – review and editing. EB:

Conceptualization, Supervision, Writing – original draft, Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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