



# Future-proofing the mixing zone concept in water resources management: an industrial perspective

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## Abstract

Mixing zones allow limited exceedances of Environmental Quality Standards within defined areas of receiving waters, yet their implementation across Europe remains uneven and increasingly scrutinised. This study evaluates how environmental change, regulatory evolution, and industrial water-use practices may influence the future viability of mixing zones. A cross-European assessment was conducted using (i) regulatory and technical guidance, (ii) a survey of 22 fuel manufacturing facilities in 14 countries, and (iii) CORMIX near-field modelling to test sensitivity to effluent and ambient parameters. Results revealed substantial variability in permitting conditions, discharge limits, and review frequencies. Only four facilities used mixing zones, though several anticipated future reliance as concentration-based criteria tighten. Modelling demonstrated that effluent density, ambient density, flow regimes, and temperature strongly affected mixing zone dimensions and dilution, with climate change and water reuse practices requiring careful considerations. These findings highlight the need for harmonised guidance, incorporation of mass-loading considerations, and climate-resilient assessment methods to ensure the long-term applicability of mixing zones in (industrial) wastewater management.

**Keywords** Wastewater · Refinery · CORMIX · Surface water · Effluent · Fuel manufacturing

## Abbreviations

AA	Annual average	EHS	Environmental, health and safety
AEL	Associated emission level	EPA	Environmental Protection Agency
ANZECC	Australian and New Zealand Environment and Conservation Council	EQS	Environmental quality standard
BAT	Best available technique	EU	European Union
BTEX	Benzene, toluene, ethylbenzene, and xylenes	IFC	International Finance Corporation
CIS	Common implementation strategy	MAC	Maximum allowable concentration
COD	Chemical oxygen demand	PFAS	Per- and polyfluoroalkyl substances
CORMIX	Cornell Mixing Zone Expert System	TN	Total nitrogen
		TSS	Total suspended solids
		USA	United States of America
		WFD	Water Framework Directive
		WWTP	Wastewater treatment plant

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## Introduction

Industrial wastewater management is a critical component of sustainable water resource protection and environmental compliance. Within this context, mixing zones—designated areas within receiving water bodies where pollutant concentrations may exceed Environmental Quality Standards (EQS), provided compliance is achieved at the boundary—remain an important regulatory instrument. The concept is recognised under the European Union (EU) Water

Framework Directive (WFD, 2000/60/EC) and the EQS Directive (2008/105/EC). Current guidance spans from preliminary screening approaches to advanced modelling and investigative assessments, employing tools such as the Cornell Mixing Zone Expert System (CORMIX) and PLUMES for simulation and analysis (European Commission 2010; CIS-WFD 2010). Despite this, the interpretation and implementation of mixing zones across Europe remain inconsistent, reflecting the absence of harmonised definitions and diverse national regulatory traditions (Romero et al. 2023).

These inconsistencies pose particular challenges for industrial sectors with complex effluent profiles such as petroleum refining. Although refinery wastewater typically contains low concentrations of hydrocarbons, ammonia, metals, sulphides, and phenols after treatment (Hjort et al. 2021), and current evidence suggests refineries are not major contributors to ecological toxicity compared to other wastewater sources (Wang et al. 2023), the viability of mixing zones is increasingly debated in Europe. Regulatory scrutiny has intensified, as recent WFD assessments reveal that only 39.5% of EU surface waters attain good ecological status and just 26.8% achieve good chemical status (European Commission, 2025), while public expectations for environmental accountability continue to rise (Okeke 2021).

Against this backdrop, several studies have highlighted that even treated and highly diluted effluents from wastewater treatment plants (WWTPs) can produce measurable ecological effects. For instance, De Guzman et al. (2023), through a large-scale ecosystem manipulation experiment, demonstrated that effluents from a well-treated WWTP reduced invertebrate diversity. Similarly, chronic effluent discharges from WWTPs have been linked to changes in fish community structure (Di Prinzio et al. 2024). Moreover, studies addressing chemical pollutants showed that mixtures released in effluents may remain of concern even after treatment and dilution. A risk assessment on 56 European WWTP effluents found that many compounds (pharmaceuticals, personal care products, industrial chemicals) exceeded risk thresholds when considering mixture toxicity (algae, crustaceans, fish), underscoring that effluent composition—not just concentration—matters for ecological risk (Finckh et al. 2022).

At the same time, industrial water stewardship initiatives promote water reuse and efficiency (Concawe 2024). While beneficial in reducing freshwater demand, these practices may result in more concentrated effluents, increasing reliance on the assimilative capacity of the receiving water body (Karkou et al. 2024), thereby intensifying the uncertainties around mixing-zone reliability under variable hydrological and ecological conditions. Furthermore, this may be further exacerbated by climate change through altered hydrological regimes and rising baseline water temperatures (Rodríguez Benítez et al. 2016).

In addition to ecological concerns, hydrodynamic complexity introduces further uncertainty: modelling studies have demonstrated that near-field mixing and far-field dispersion—especially for buoyant or dense plumes—are sensitive to ambient conditions (e.g. stratification, crossflow, density gradients), discharge design, and diffuser configuration (Robinson et al. 2016). This implies that a “one-size-fits-all” regulatory mixing zone approach may not safeguard ecosystem integrity under all conditions, particularly when background conditions or discharge profiles change (e.g. due to climate change altering flow regimes).

Given these scientific, regulatory, and societal developments, there is a need to critically evaluate the current and future role of mixing zones in industrial water management. This study therefore addressed this gap by combining:

- (i) A comprehensive review of European and international mixing-zone regulations and guidance
- (ii) Survey data from 22 European fuel manufacturing facilities across 14 countries
- (iii) CORMIX modelling analyses examining sensitivity to key parameters under realistic and climate-related scenarios

By integrating regulatory, empirical, and modelling perspectives, the study provided the first cross-European assessment of how mixing zones are currently applied at industrial sites, the challenges and inconsistencies encountered, and how future regulatory or environmental changes may influence their feasibility. The findings contributed to the broader discussion on future-proofing industrial wastewater management, highlighting opportunities for harmonisation, improved technical guidance, and adaptive strategies that enhance environmental protection while enabling sustainable industrial operations.

## Methodology

### Regulatory framework

A targeted scoping review of regulatory and technical guidance on surface-water mixing zones was undertaken to characterise definitions, acceptability criteria, sizing methods, and assessment tools used in permitting. Searches were conducted in ScienceDirect, Scopus, and Google Scholar, complemented by primary regulatory repositories. Search strings combined controlled and free-text terms. Inclusion criteria comprised (i) binding legislation and competent-authority guidance defining or operationalising mixing zones, (ii) international lender standards applicable to industrial discharges, and (iii) peer-reviewed methods papers directly informing mixing-zone assessment and design.

**Table 1** Overview of discharges with mixing zones

Parameter	Discharge #1	Discharge #2	Discharge #3	Discharge #4
Location	UK	The Netherlands	Sweden	France
Effluent type	Industrial	Industrial	Industrial	Industrial
Number of mixing zones	1	2	1	1
Receiving waterbody	Coastal estuary	Estuary	Estuary	River
Mixing zone constituent #1	Temperature increase $\leq 1.5$ °C	Temperature limit of 28 °C	Chemical of concern	Chemical of concern
Mixing zone constituent #2	Not applicable	Chemical of concern	Not applicable	Not applicable

## Survey

A digital structured questionnaire was designed to collect information on how surface water mixing zones are applied for fuel manufacturing effluent discharges across Europe. The questionnaire elicited responses across various topics including (i) characteristics of the site discharge permit, (ii) characteristics of the mixing zone, (iii) challenges faced by the facility with regard to mixing zone(s), and (iv) characteristics of the discharged effluent (Table A in Supplementary Material).

The survey was distributed electronically amongst operators of European refineries jointly organised in Concawe (scientific division of the European Fuel Manufacturers Association), and being cascaded to the site-level individuals with the most understanding of their site's effluent discharge permit. As with most social enquiry research, the survey was dependent on respondents being truthful and accurate to ensure that collected data are credible. Respondents were advised that the survey was for research purposes and would protect the anonymity of facilities.

## CORMIX modelling

CORMIX v12.0 was applied as a United States of America (USA) Environmental Protection Agency (EPA)-approved near-field modelling tool, using its hydrodynamic classification scheme and scenario-specific elements for single-port, multipoint, and surface discharges (Jirka et al. 1991). Inputs comprised discharge characteristics (flow, temperature, density), outlet geometry, and ambient properties (depth, current, temperature).

## CORMIX input data

The data used to set up the CORMIX simulations were primarily obtained from the survey responses. However, data provided by three out of the four facilities (i.e. facilities relying on a mixing zone) were insufficient to undertake the simulations (Table B in Supplementary Material). To address this, a supplemental data request was issued to the

three facilities (Discharges #2–4) to obtain the necessary inputs for CORMIX. Additional data was only received from Discharge #2.

For Discharges #3 and #4, assumed values were used to create generic base cases that complemented the available data. For instance, ambient river discharges were not provided for company #3; since the facility discharge flowed into an estuary, low flow conditions were assumed for those simulations. Additional ambient data was sourced from C-Map, a digital mapping and navigation tool for marine and coastal environments.

## Scenarios tested

To assess the sensitivity of the mixing zone dimensions under a variety of parameters, a modelling assessment was undertaken using data from the survey responses focusing on four refineries that utilised mixing zones as part of their permit requirements (Table 1). Amongst the four fuel manufacturing facilities, one monitored both thermal discharges and chemicals of concern (Discharge #2), one monitored only thermal discharges (Discharge #1), and two monitored only chemicals of concern (Discharges #3 and #4).

Modelling scenarios were developed for the two types of discharges identified in the survey, namely (i) thermal discharges and (ii) discharges containing chemicals of concern (i.e. non-thermal discharges thereafter). For each discharge, a baseline scenario was developed from the data obtained from the survey responses to represent the effluent characteristics and ambient conditions specific to each site. Since the ambient data was either assumed, inferred from available information or obtained from global datasets, an exact replication of regulatory mixing zone was not achieved (nor was it required to analyse the sensitivities of the inputs). Tailored CORMIX model parameter modifications were then applied to account for the unique features of each type of mixing zone.

Starting from the baseline case, individual parameters were systematically adjusted, one per scenario run, to assess their isolated effects on mixing zone dimensions and dilution values. These scenarios were designed to reflect real-world

**Table 2** Summary of the modelling parameters and variables considered for each discharge type

Discharge type	Parameter	Variable
Thermal discharge	Effluent characteristics (flowrate, density, temperature, concentrations)	<ul style="list-style-type: none"> <li>• Effluent flowrate increase (by 10%): represents a proxy for enhanced operational throughput or production scale-up, leading to higher volumetric charges without altering thermal or chemical characteristics</li> <li>• Effluent flowrate reduction with constant thermal load (flow reduced by 10% and 20%): represents the implementation of water conservation strategies</li> <li>• Effluent temperature variation (<math>\pm 10\%</math>): represents modifications in cooling system efficiency or operational regime</li> <li>• Effluent density increase (salinity increased by 1–2 g/L): reflects industrial blending with saline streams</li> </ul>
	Receiving waterbody's flow	<ul style="list-style-type: none"> <li>• Ambient velocity variation (<math>\pm 10\%</math>, <math>\pm 20\%</math>): represents hydrodynamic shifts in receiving waters, driven by climate-induced flow variability or tidal regime changes, influencing dilution and dispersion patterns</li> </ul>
	Background temperature	<ul style="list-style-type: none"> <li>• Ambient temperature variation (<math>\pm 5\%</math>, <math>\pm 10\%</math>, and <math>\pm 20\%</math>): serves as an indicator of climate-driven thermal trends in the receiving environment, affecting stratification and mixing dynamics</li> </ul>
Discharges monitoring chemicals of concern (non-thermal)	Effluent characteristics (flowrate, density, temperature, concentrations)	<ul style="list-style-type: none"> <li>• Effluent flowrate increase (by 10%): represents a proxy for enhanced operational throughput or production scale-up, leading to higher volumetric charges without altering thermal or chemical characteristics</li> <li>• Effluent flowrate variation with constant concentration (<math>\pm 10\%</math>, <math>\pm 20\%</math>): represents operational adjustments or intake restrictions during drought conditions</li> <li>• Effluent density variation (<math>\pm 5\%</math>, <math>\pm 10\%</math>): reflects changes in discharge composition due to industrial blending practices</li> </ul>
	Receiving waterbody's flow	<ul style="list-style-type: none"> <li>• Ambient velocity variation (<math>\pm 10\%</math>, <math>\pm 20\%</math>): indicates seasonal or climate-driven alterations in riverine or estuarine flow regimes, affecting effluent dispersion</li> </ul>
	Background concentrations	<ul style="list-style-type: none"> <li>• Ambient density variation (<math>\pm 5\%</math>, <math>\pm 10\%</math>, <math>\pm 20\%</math>): represents fluctuations in background water quality, potentially linked to catchment-scale inputs or episodic pollution events</li> </ul>

challenges, such as reduced river flows and increased water temperatures driven by climate change, more concentrated effluents resulting from water circularity practices, stricter EQS, and the impact of background contamination. Dilution values refer to the ratio of the concentration of a substance in the effluent to its concentration in the receiving ambient waterbody after mixing. These values illustrated the extent to which substances disperse and dilute in natural waterbodies. In the absence of concentrations for substances of concern, dilution value analysis was performed as a surrogate for these values. In total, 20 simulations were performed for each of the four discharges to ensure a comprehensive evaluation (Table 2).

## Results and discussion

### Regulatory framework

#### National transposition of EU legislation

EU Member States have incorporated the WFD and the EQS Directive into their national legal frameworks, resulting in notable variation in the implementation of mixing zones (Table 3). In Flanders and the Netherlands, the regulatory

approaches appeared comparatively mature and supported by detailed technical methodologies. In Flanders, the Integrated Water Policy provides the legal basis for mixing zones and ensures alignment with the WFD and EQS Directive requirements (Flemish Government 2003). Assessment is supported by tools such as the Wezertool (Flemish Environment Agency 2025), which operationalises a structured seven-step procedure designed to size mixing zones, prevent ecological barriers, and maintain waterbody objectives (Flemish Environment Agency 2023). Both chronic and acute mixing zones are distinctly defined, and their extent is evaluated in proportion to chemical concentration gradients.

Similarly, the Netherlands applies a robust framework that integrates the General Assessment Methodology, the Immission Test, and Best Available Techniques (BAT) standards. The procedural steps outlined in the national Guidance Immission Assessment ensure that mixing zones comply with environmental quality requirements (Ministry of Infrastructure and Water Management 2019). Specific provisions apply to cooling water discharges, and mixing zone dimensions are tightly regulated, particularly within protected areas.

In contrast, although countries such as France, Italy, Spain, and the UK (which retains WFD-compliant legislation due to its past EU membership) have adopted the mixing

**Table 3** Summary of mixing zone framework for selected European countries

Country	Maturity level	Complexity	Sizing
Belgium, Flanders	Detailed guidelines developed	Complex, but logical, process in place	<p><b>Chronic mixing zone</b> The maximum length is determined as the minimum value of one of the following criteria:</p> <ul style="list-style-type: none"> <li>• 10 times the width of the watercourse being assessed</li> <li>• 1000 m in length</li> <li>• 1/10 of the length of the water body into which the discharge occurs</li> </ul> <p>The maximum width corresponding to 1/3 of the width of the watercourse being assessed</p> <p><b>Acute mixing zone</b> The maximum length is determined as the minimum value of one of the following criteria:</p> <ul style="list-style-type: none"> <li>• 100 m</li> <li>• 1/100 of the length of the water body into which the discharge occurs</li> </ul> <p>The maximum width is determined as 1/3 of the width of the watercourse being assessed</p>
France	Some guidelines developed	Relatively simple design recommendations provided, mostly relying on empirical formulas	<p>Cannot exceed:</p> <ol style="list-style-type: none"> <li>10 times the width of the watercourse downstream of the discharge point</li> <li>10% of the length of the body of water into which the discharge takes place</li> <li>1 km</li> </ol> <p>At the discharge point No sizing guidelines provided</p> <p>Limited to the proximity of the discharge point Shall be calibrated on the basis of the pollutant concentrations at the point of discharge, the application of the discharge regulation provisions of current regulations, and the adoption of best available techniques, depending on the achievement or maintenance of environmental objectives</p>
Germany	No technical guideline developed		
Italy	No technical guideline developed		
The Netherlands	Detailed guidelines developed	Complex, but logical, process in place	<p><b>AA-mixing zone</b></p> <ul style="list-style-type: none"> <li>• Linear water systems: the AA mixing zone may not exceed a length of 10 times the width of the water system with a maximum of 1000 m</li> <li>• Lakes: the AA mixing zone may not exceed 0.25 times the diameter of the lake with a maximum of 1000 m</li> </ul> <p><b>MAC mixing zone</b></p> <ul style="list-style-type: none"> <li>• Linear water systems: the MAC zone may never exceed 0.25 times the width of the water system with a maximum of 25 m</li> <li>• Lakes: may not exceed 0.0065 times the diameter of the lake, also with a maximum of 25 m</li> </ul> <p>Sizing considerations are provided for water bodies in Norway including rivers, lakes, fjords, archipelagos and coastal waters Defined as a zone adjacent to a point of discharge Limited to 10× the river width or 1 km but always considering that 10% of the length of the water body is not exceeded</p> <p>The Scottish Environment Protection Agency sets a maximum distance of 100 m in any direction; in Northern Ireland, it is restricted to the proximity of the point of discharge</p>
Norway	Some guidelines developed		
Spain	No guidelines developed		
UK	Some guidelines developed, with complexity varying on the country		

AA annual average, MAC maximum allowable concentration

zone concept, they generally lack the comprehensive guidance available in the Flemish or Dutch system. As a minimum, mixing zone dimensions are commonly capped at ten times the watercourse width, 10% of the waterbody length, or 1 km (Ministry of Ecology, Sustainable Development, and Energy 2012). Germany applies a different approach, with discharge permitting based on combined emissions and immission principles; permits are issued only after detailed analyses confirming that water quality deterioration will not occur.

Although not an EU Member State, Norway voluntarily aligns with EU water regulations and has implemented the principles of the WFD through its Water Regulation (Vannportalen 2024). Mixing zones in Norway are assessed using a tiered approach that incorporates advanced modelling and accounts for local hydrological conditions such as tidal dynamics and fjord systems (Norwegian Climate and Pollution Agency 2010).

### Other international regulatory frameworks

Countries outside Europe, as well as international organisations, have developed frameworks for the management of mixing zones in surface waters. In the USA, the EPA provides detailed guidance for mixing zone assessments, emphasising compliance with water quality standards at the mixing zone boundary (US EPA 2014). The USA framework additionally underscores ecological protection and public transparency in permitting and monitoring processes. Computational tools, such as CORMIX, are routinely employed to evaluate pollutant dispersion and assess compliance with regulatory thresholds (Jirka et al. 1991).

The Australian and New Zealand Environment and Conservation Council (ANZECC) National Water Quality Management Strategy provides the primary guidance for mixing zones. Key principles include mixing zones are not suitable for nutrients, bioaccumulative, or particulate discharges; they are prohibited in waters with high ecological, recreational, or water supply value; and hydrodynamic models should account for stratification (ANZECC 2000). Mixing zones, if applied, should be as small as practicable, avoiding full-width waterway coverage or interference with biota migration. State- and regional-level guidelines further specify local requirements, e.g. in Northern Territory (Northern Territory Environment Protection Agency 2013), Queensland (Queensland Government 2025), Victoria (Environment Protection Authority Victoria 2010), and the Auckland Regional Council (Cooke et al. 2010).

At the international level, the International Finance Corporation (IFC) incorporates mixing zones within its Environmental, Health, and Safety (EHS) Guidelines. For example, the IFC recommends that the temperature of wastewater discharges should not increase ambient water temperatures

by more than 3 °C at the edge of a scientifically established mixing zone, taking into account ambient water quality, receiving water use, and assimilative capacity (IFC 2007a). Sector-specific guidance, such as that developed for onshore oil and gas operations, further specifies that cooling water discharges should be released in locations allowing maximal mixing and cooling, ensuring compliance with the 3 °C criterion at the edge of the defined mixing zone or within 100 m of the discharge point (IFC 2007b).

These observations illustrated the complexities and heterogeneity of mixing zone regulations across jurisdictions. Variations in regulatory approaches influence how industrial facilities, including refineries, manage effluent discharges, shape compliance strategies, and guide technological investments. Increasing regulatory scrutiny and stakeholder expectations underscore the need for standardised guidelines and advanced modelling techniques. This review established a foundation for the subsequent analysis, in which empirical survey data and CORMIX modelling were applied to evaluate the effectiveness and adaptability of mixing zones under evolving environmental and regulatory conditions.

### Survey

The use of structured surveys to collect site-level data at European refineries is well established with previously studies reporting response rates of 73% (Concawe 2020) and 56% (Concawe 2025). In total, 22 responses (i.e. 22 facilities responded) were received for this study which covered 25% of the 86 currently operating European refineries (Concawe 2023). As such, the dataset reflected only a subset of the targeted population, which introduced potential limitations regarding representativeness and generalisability. The coverage of 25% of operating European refineries may not fully capture the diversity of effluent management practices across different geographic regions, refinery configurations, and operational scales. Consequently, findings should be interpreted with caution, recognising that site-specific variability and unreported practices could influence broader conclusions.

Questions 1.1 and 1.2 requested the facility name and operator; these identifiers were subsequently anonymised. The responding facilities were distributed across 14 European countries (Question 1.3), with Germany providing the largest number of responses ( $n = 4$ ).

### Environmental permits

Environmental permits were issued by the competent national or regional authorities (Question 2.1). Survey respondents were asked to report the issuance date of their current permit (Question 2.2) and its review frequency (Question 2.3). Nearly half of the facilities ( $n = 10$ ) indicated

**Table 4** Review frequency of environmental permits presented by country

Country	Review frequency (years)							Facilities with a mixing zone	
	1	2	2–3	5	> 5	Irreg	Never		n/d
North	1	1	2		2				2
Central		1	1		4	1	1		1
South				1	3			1	1
East				2	1				0
<b>Total</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>3</b>	<b>10</b>	<b>1</b>	<b>1</b>	<b>1</b>	<b>4</b>

n/d indicates that no data was provided; *Irreg.* irregular. North includes Norway, Sweden, and the UK; South: France, Italy, Portugal and Spain; Central: Austria, Belgium, Czech Republic, Germany, the Netherlands; East: Poland, Czech Republic, and Slovakia

a review interval exceeding 5 years (Table 4), and one facility reported that no formal review frequency was established. Notably, the data revealed intra-country variability in permit review practices, including in Germany, Sweden, and the Netherlands. In Germany, such differences may reflect the federal governance structure, whereby permitting approaches vary amongst states. In Sweden, reported review frequencies ranged from annual to greater than 5-year intervals. These findings indicate that variability in permitting processes exists not only across Europe but also within individual countries.

For 19 of the respondents (86% of the sample), there had been changes to the permit conditions in the last ten years highlighting the dynamic nature of environmental permitting (Question 2.4). Critically, these changes reflected ongoing adjustments to regulatory requirements and technological advancements (e.g. application of Refining of Mineral Oil and Gas BAT conclusions (Barthe et al. 2015)). All the survey respondents indicated that their environmental permits included end-of-pipe limits for effluent discharges which are consistent with the EU's ambition to minimise the release of pollutants into water bodies (Question 2.5). In addition, four respondents (18% of the sample) indicated that there was a point of compliance not located at the end of pipe (Question 2.6). Within the responding facilities, the environmental department generally lead compliance monitoring (Question 2.7). Effluent discharge points were all reported to be subject to monitoring and reporting to the regulator, with the reporting requirements to the regulator ranging from monthly to annually (Question 2.8). Finally, in some cases, exceedances of the discharge limits prohibited effluent discharge into the receiving water body (Question 2.9).

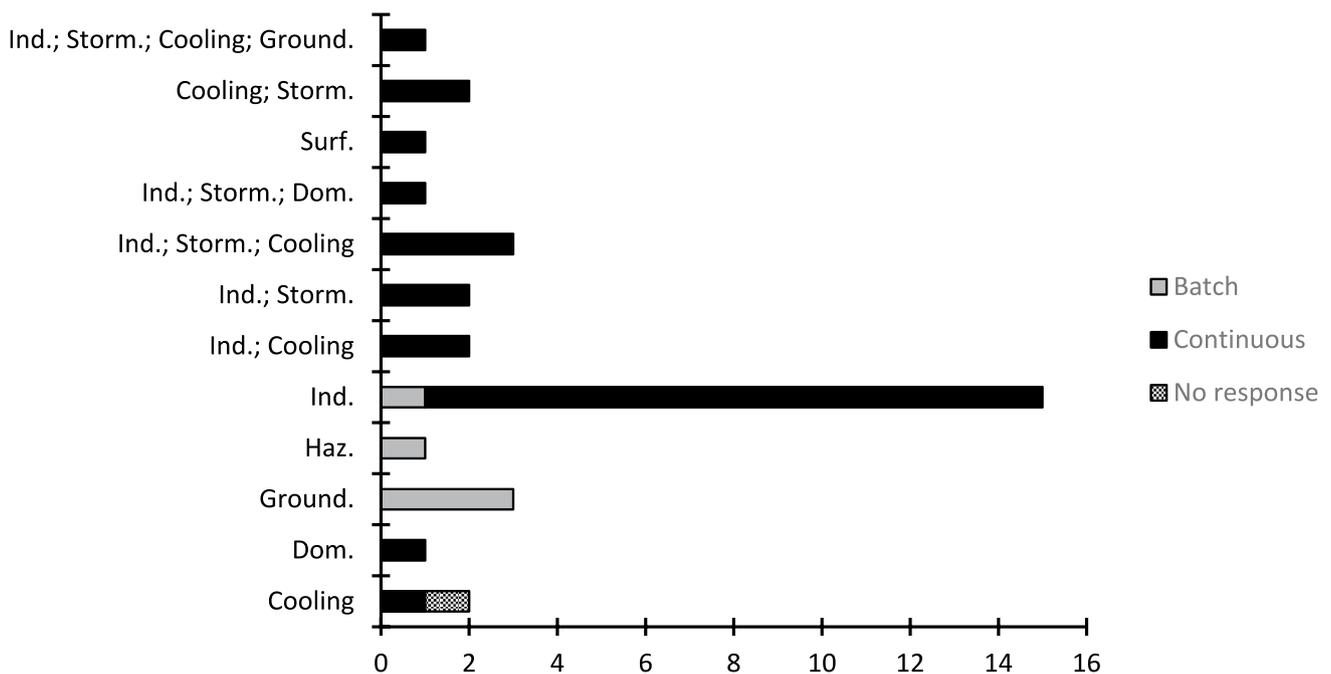
## Discharges

Wastewater discharges at refineries are a result of sanitary wastewater, process, and utilities. Previous surveys conducted across European refineries have classified 14 broad water uses, with cooling processes representing the largest user (Concawe 2025). Amongst the 20 facilities that

disclosed information on their discharge permits, 45% reported having more than one discharge point. Most permits specified requirements for industrial wastewater, but several facilities also discharged sanitary wastewater, cooling water, and stormwater or surface runoff (Fig. 1). The predominance of continuous discharge regimes (Fig. 1) had implications for mixing zone design, as continuous flows interact differently with ambient hydrodynamics compared to episodic releases, potentially affecting dilution rates and ecological risk (Finckh et al. 2022). Ultimately, this diversity in effluent types and discharge regimes reflects the operational complexity of European refineries, being consistent with recent work (Hjort et al. 2021; Concawe 2025).

Rivers and seas emerged as the predominant receiving water bodies for effluent discharges, accounting for 59% ( $n = 13$ ) and 23% ( $n = 5$ ) of responses, respectively. In contrast, one facility reported routing its wastewater to an external treatment plant, while three others discharged into estuaries (14%). The prevalence of river systems is particularly noteworthy because implementing a mixing zone in such environments requires addressing complex factors, including flow variability, seasonal fluctuations, and potential downstream impacts. These challenges reinforce findings from recent hydrological studies, which highlight the need for site-specific modelling and adaptive management strategies in riverine mixing zone design (Rodríguez Benítez et al. 2016).

Analysis of reported flowrates indicated that average discharge volumes were typically below the consented limits, often in the range of 10–50% of the maximum allowed (Fig. 2). This pattern suggested operational flexibility; however, the total mass of discharged substances generally remains constant, irrespective of water volume. Notably, only three permits included explicit mass load restrictions, specified in kilograms per year, suggesting that environmental regulators mostly focus on concentrations which indirectly encourages dilution (Schellenberg et al. 2020). As noted in previous studies, reductions in water use can lead to higher concentrations of pollutants in effluents, even if the overall chemical mass remains unchanged (Concawe



**Fig. 1** Discharge regime reported by discharge type. Notes: Ind., industrial wastewater; surf., surface runoff; storm., stormwater; ground., groundwater; dom., domestic; haz., hazardous. To note,

groundwater and hazardous are not considered to be associated with industrial effluent discharges

2024a). This dynamic creates a regulatory paradox: facilities may increase discharge volumes within permitted limits, but without sufficient dilution, concentration-based thresholds could be exceeded, undermining compliance. Such circumstances may inadvertently incentivise dilution rather than genuine reductions in water use and chemical loads, unless regulatory frameworks balance both concentration and total mass limits.

Reported discharge limits varied across facilities and countries, reflecting a site-specific approach rather than a uniform European standard (Fig. 3). Facilities relying on a mixing zone had often higher permitted discharge limits than those discharging directly to the environment (Fig. 3). Specifically, discharge limits for facilities with mixing zones often exceeded the BAT-Associated Emission Levels (BAT-AELs) established for direct discharges from the refining of mineral oil and gas. For example, the BAT-AELs for substances such as cadmium, lead, mercury, and nickel were lower than the discharge limits allowed for facilities using mixing zones (Barthe et al. 2015).

This difference arose because the limits applied to discharges that relied on mixing zones were typically based on the concept that the environmental standard (e.g. EQS) would be met after mixing, at the edge of the mixing zone. It is assumed that, if the discharge meets these higher limits at the point of discharge, the concentration of chemicals will be sufficiently diluted by the time it reaches the edge of the

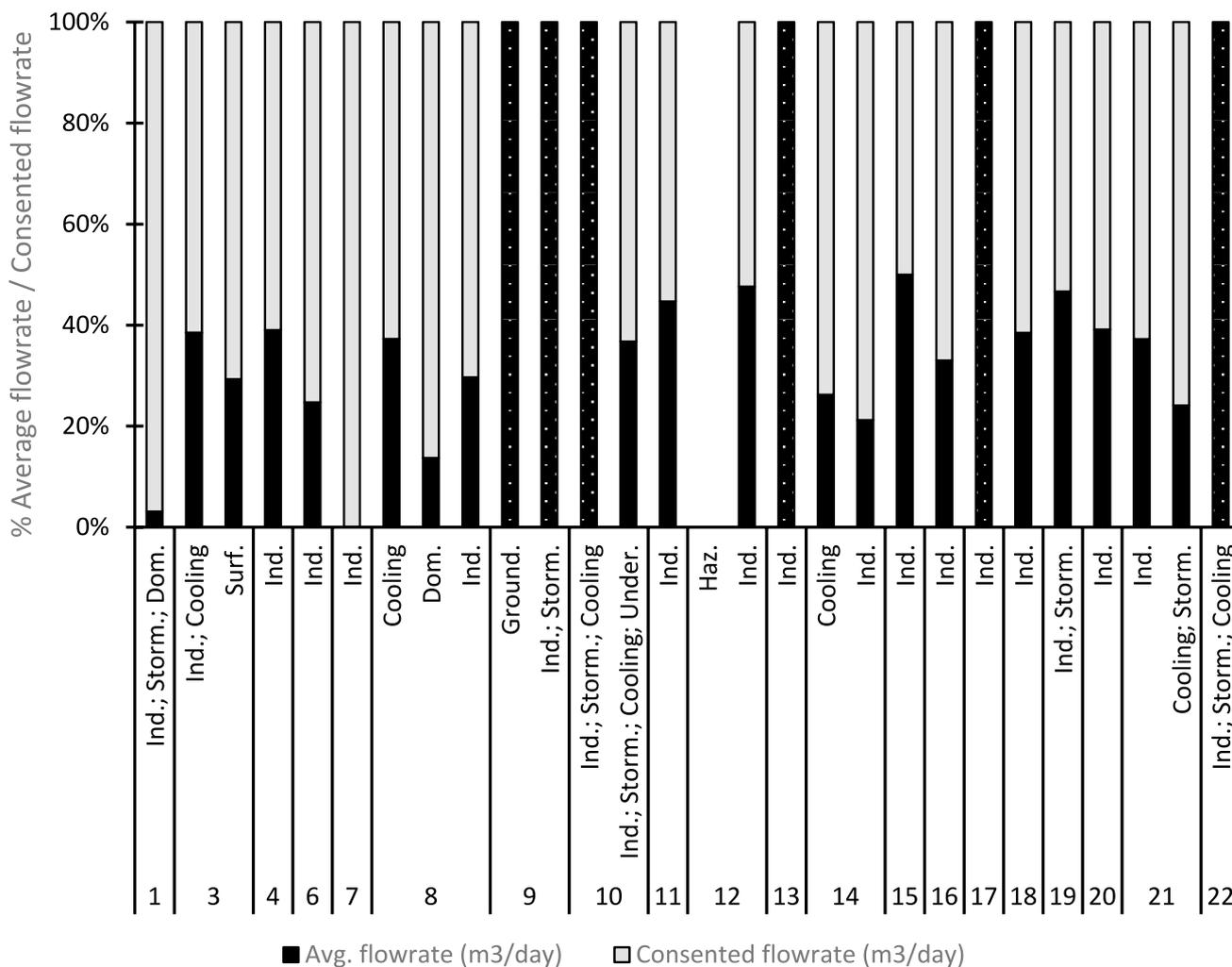
mixing zone, thus complying with the BAT-AELs. Consequently, higher discharge limits were permitted for mixing zones, provided that the final effluent quality meets regulatory standards after mixing has taken place.

In addition to the core parameters discussed, several discharge permits also included limits for a broader suite of substances, including phenols, vanadium, per- and poly-fluoroalkyl substances (PFAS), and other trace metals such as copper, zinc, and chromium, as well as operational parameters like pH, temperature, and flow rate.

A comparison of discharge limits across facilities with no mixing zone within the same country, namely Germany and Sweden, showed that discharge limits were mostly consistent within the two countries (Table C in Supplementary Material). In Germany, this was consistent with the discharge limits proposed in Annex 45 (petroleum processing) of the Wastewater Ordinance for petroleum processing plants (Federal Ministry of Justice and Consumer Protection 2004). For Swedish facilities, observed differences in discharge limits were likely attributable to variations in receiving water bodies, with facility 13 discharging into a river and facility 14 into the sea.

### Application of mixing zones

Four facilities reported relying on a mixing zone for effluent discharge. These mixing zones were primarily designed



**Fig. 2** Average and consented discharge flowrates. Notes: facilities having not disclosed their consented flowrate are represented with a dotted pattern. Ind., industrial wastewater; surf., surface runoff;

storm., stormwater; ground., groundwater; dom., domestic; haz., hazardous. To note, ground. and haz. are not believed to relate to industrial discharges

for industrial wastewater, with two facilities incorporating stormwater and one managing all effluent streams, including “all waters” (Questions 3.1–3.3).

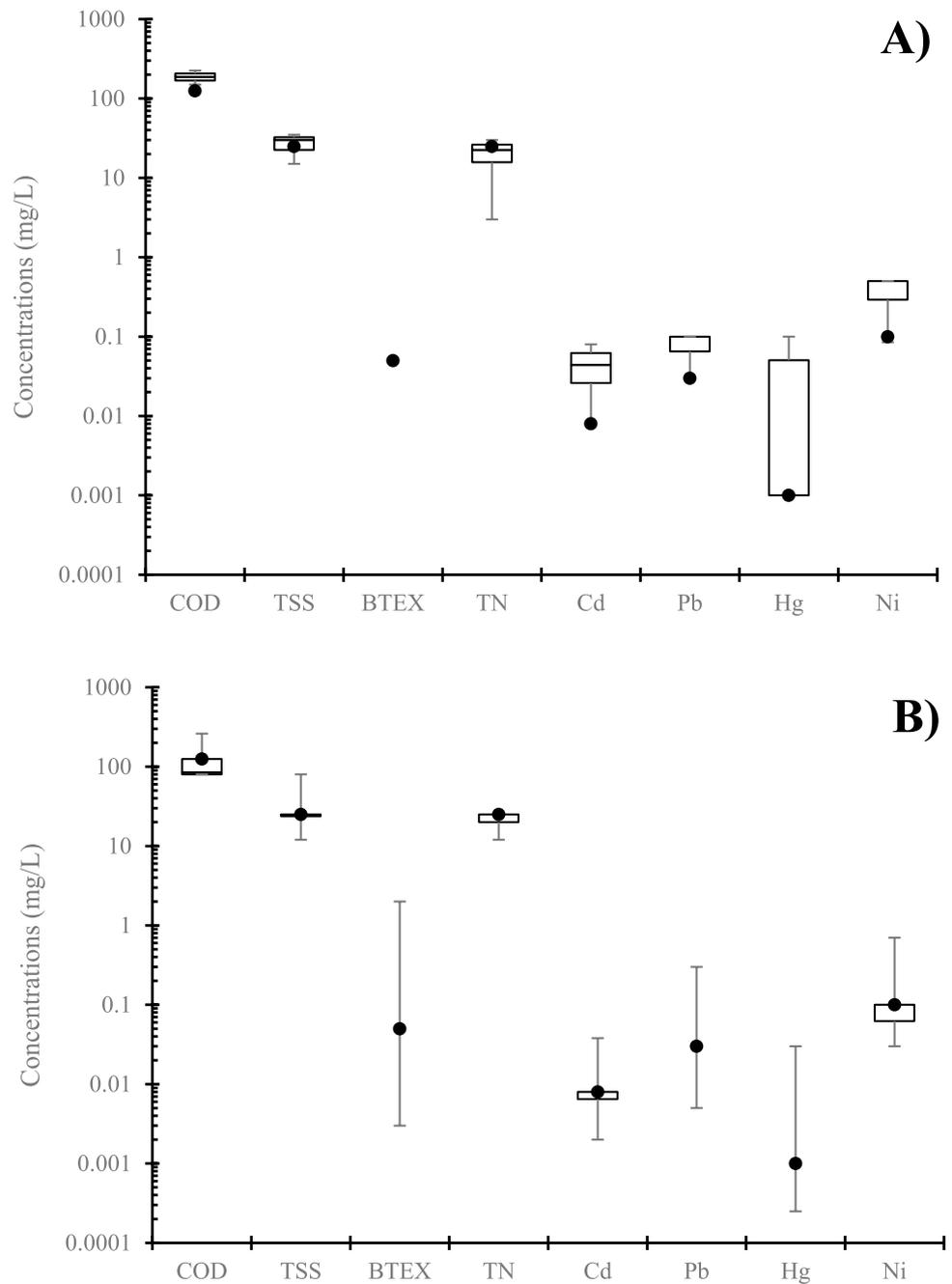
The survey highlighted geographic disparities: none of the responding facilities in Eastern Europe utilised mixing zones. In contrast, two out of six (33%) facilities in Northern Europe relied on mixing zones, as well as one for both Central (13%) and Southern Europe (20%; Table 4). This aligned with the comparatively mature mixing zone frameworks in Northern Europe versus the more conservative policies in other parts of Europe.

Three out of the four mixing zones assessed in this study were designed for discharges into coastal or estuarine environments, while the remaining site relied on a river system (Table 5). In other words, out of the eight surveyed facilities that discharged into marine or estuarine environments, three utilised mixing zones (38%). In contrast, of the 13 sites

discharging into rivers, only one had a mixing zone (8%). Although coastal and estuarine mixing zones are subject to complex tidal dynamics which can significantly influence plume dispersion (Heidari et al. 2025), the data suggested that regulators were far less inclined to allow mixing zones in inland rivers, likely due to seasonal flow variability, potential low-flow conditions, and longitudinal transport, all of which affect the spatial extent and effectiveness of mixing (Rodríguez Benítez et al. 2016). Interestingly, no seasonal considerations were reported by the facilities in the design of these mixing zones (Question 3.4).

Three respondents provided further insight into the design of their mixing zones. Two facilities reported that their mixing zones were delineated using the CORMIX hydrodynamic modelling system. A third facility indicated that its mixing zone configuration accounted for effluent flow, river hydrodynamics, and the spatial relationship between legacy

**Fig. 3** Discharge limits for key substances with BAT-AELs, for permits with a mixing zone (A) and without a mixing zone (B). Note: the circles represent the BAT-AEL's upper limits for direct wastewater discharges from the refining of mineral oil and gas (Barthe et al. 2015). COD, chemical oxygen demand; TSS, total suspended solids; BTEX, benzene, toluene, ethylbenzene, and xylenes; TN, total nitrogen; Cd, cadmium; Pb, lead; Hg, mercury; Ni, nickel



**Table 5** Reliance on mixing zones in relation to receiving water bodies

Receiving water body	Rely on a mixing zone	Do not rely on a mixing zone	Total
Estuary	2	1	3
External facility	0	1	1
River	1	12	13
Sea	1	4	5
Total	4	18	22

and newly constructed treatment infrastructure. However, detailed technical specifications were not disclosed in the survey response (Question 3.5). Notably, one facility located in the Netherlands (representing a jurisdiction with one of the most advanced regulatory frameworks for mixing zones in the European Union) subsequently clarified that its mixing zone was dimensioned based on a maximum allowable length of 1000 m, consistent with national regulatory guidance (Table 3).

In terms of responsibility for design, one facility developed its mixing zone internally, while another used a

consultancy. The remaining two respondents did not provide information about the design process (Question 3.6). Drivers for implementation varied, with one facility citing compliance with the WFD and another referencing WWTP optimisation. Implementation drivers for the remaining two facilities were not disclosed (Question 3.7).

Three facilities reported that their mixing zones required routine updates, with one respondent highlighting the need for effluent studies every 5 years and temperature studies as mandated by regulators (Question 3.8). This aligned with permit review frequencies: three reported occurrence on a 2–3-year basis, and one over 5 years. This hinted that authorities tend to review mixing-zone permits more frequently, perhaps due to the additional scrutiny such permits entail.

One facility reported occasional exceedances of discharge limits due to internal and external factors (Question 3.9). Although submerged multiport diffusers have been proposed as a solution to optimise mixing conditions (Bleninger and Jirka 2011), none of the respondents had diffusers installed (Question 3.11).

### Future outlook at industrial sites

In response to Question 4.1, which invited participants to describe anticipated challenges related to mixing zones or effluent management, several key themes emerged. The most frequently cited concern was the prospect of heightened regulatory scrutiny, mentioned by three facilities. One respondent also highlighted increasing public awareness as a potential driver of future compliance pressures. Climate change was explicitly referenced by one facility, while two others identified deteriorating upstream water quality as a growing issue that could compromise the effectiveness of existing discharge strategies.

Of particular note, two facilities flagged the emergence of substances of very high concern, including PFAS, as likely to attract intensified regulatory attention. These substances, due to their persistence and potential ecological impacts, are expected to feature more prominently in future permitting requirements and compliance frameworks. This point was also highlighted by a recent study that underscored this urgency with above half of the refineries surveyed indicating being in the process of developing PFAS management plans, primarily focused on the management of wastewater (Concawe 2024b).

Regarding the potential need for mixing zones in the future (Question 4.2), one facility (representing 6% of respondents currently without a mixing zone) indicated that re-permitting pressures from regulators and non-governmental organisations would likely necessitate the implementation of a mixing zone. A further four respondents (22%) anticipated that future permit renewals could introduce such

requirements. In contrast, nine facilities (50%) did not foresee any need for a mixing zone, while four (22%) did not provide a response.

These evolving environmental conditions underscored the need for more robust and adaptive design approaches. In particular, the use of simplified empirical equations for mixing zone modeling may prove inadequate under future scenarios. Instead, more sophisticated modeling techniques—capable of accounting for variable and extreme conditions—may be required. This shift would necessitate enhanced technical expertise and potentially greater regulatory engagement during the permitting process, to ensure that mixing zones remain both effective and compliant in a changing climate. This observation formed the basis for the CORMIX modeling approach.

## CORMIX modelling

### Thermal discharges

For each scenario, variations in mixing zone dimensions were evaluated, and the percent change in volume from the base case was calculated. Expectedly, an increase in mixing zone size may violate permit conditions and pose compliance risks. Modelling showed that a decrease in effluent flowrate while maintaining thermal load (proxy for the implementation of water conservation strategies) led to substantial increases in mixing zone size for both Discharges #1 and #2. For example, a 20% reduction in effluent flowrate while maintaining thermal load increased mixing zone volume by 182.6% and 984.1% for Discharges #1 and #2, respectively (Table 6).

A variation in effluent temperature (proxy for changes in cooling system efficiency) exerted a strong configuration-dependent influence on mixing zone dimensions. A 10% decrease in effluent temperature reduced the mixing zone size by 85.6% at Discharge #1 and 61.8% at Discharge #2 (Table 6). By contrast, a 10% increase had only a marginal effect at Discharge #1 but expanded Discharge #2's mixing zone by 115.1%. This divergence reflected differences in jet design and ambient advection: Discharge #1's multi-slot, horizontal outfall in a bounded estuary (ambient velocity 0.05 m/s) achieved substantial initial dilution. Discharge #2's single-port, vertical release into an unbounded, low-flow setting (ambient velocity 0.01 m/s) is buoyancy-dominated, so warming increased the buoyancy flux and surface spreading, substantially enlarging the thermal footprint. Additionally, a larger baseline  $\Delta T$  at Discharge #2 ( $\approx 16.5$  °C vs  $\approx 14.2$  °C at Discharge #1) and the interplay of temperature with effluent salinity (26.8 g/L vs ambient 10 g/L) further modulated plume density and rise behaviour.

Modelling results showed that decreasing ambient velocity (proxy for hydrodynamic shifts in receiving waters)

**Table 6** Variations of the mixing zone dimensions from the CORMIX modelling for non-thermal discharges

Parameter	Discharge #1					Discharge #2						
	Results at excess temperature of 1.5 °C (regulatory limit)					Results at temperature of 28 °C (regulatory limit)						
Tested scenarios	-20%	-10%	-5%	+5%	+10%	+20%	-20%	-10%	-5%	+5%	+10%	+20%
Effluent flow					1.33×0.69×8.42 -7.5%						0.30×3.48 -9.1%	
Effluent flow and thermal load	3.24×0.87×8.48 182.6%	2.69×0.82×8.48 120.4%					1.97×6.32 984.1%	1.07×5.18 363.6%				
Effluent temperature		1.36×0.67×1.34 -85.6%			1.40×0.70×8.40 -3.0%			0.16×2.74 -61.8%			0.58×4.26 115.1%	
Ambient velocity	0.90×0.66×8.42 -36.5%	1.19×0.6×8.42 -19.7%			1.71×0.72×8.42 22.1%	2.02×0.75×8.42 50.3%	0.30×3.50 -20.8%	0.30×3.48 -9.1%			0.37×3.48 12.1%	0.41×3.48 24.2%
Ambient density	1.42×0.70×8.42 -1.4%	1.43×0.70×8.42 -0.7%	1.43×0.70×8.42 -0.7%	1.44×0.70×8.42 0%	1.44×0.70×8.42 0.7%	1.38×0.68×1.36 -84.9%	0.19×2.88 -52.3%	0.24×3.12 -24.8%	0.28×3.30 -19.5%	0.41×3.74 33.5%	0.52×2.04 -7.6%	1.00×5.28 359.8%
Tested scenarios	-3 ppt	-2 ppt	-1 ppt	+1 ppt	+2 ppt	+3 ppt	-3 ppt	-2 ppt	-1 ppt	+1 ppt	+2 ppt	+3 ppt
Effluent density				1.46×0.7×8.42 1.4%	1.49×0.7×8.42 3.5%					0.33×3.48 0%	0.33×3.48 0%	

Mixing zone size is provided as length×width×depth; percentages represent the difference in volume from the baseline scenario. Dimensions for the baseline scenario for discharge #1 were 1.44×0.70×8.42 for a volume of 8.49 m<sup>3</sup>; dimensions for the baseline scenario for discharge #2 were 0.33×3.48 (length×width/depth) for a volume of 1.15 m<sup>3</sup>. For discharge #2, CORMIX computed width and depth as a ratio in the near-field due to the dominance of effluent momentum and salinity

consistently reduced the size of the mixing zone, while increases in ambient velocity led to expansions in mixing zone volume (Table 6). Lower ambient velocities reduced the advective transport and lateral dispersion of the thermal plume, causing the heated effluent to remain more concentrated and confined near the discharge point. This resulted in a larger area where temperature exceeded the regulatory thresholds. In contrast, higher ambient velocities enhanced cross-stream mixing and dilution, rapidly dispersing the thermal load and thereby reducing the spatial footprint of the mixing zone.

These findings are consistent with recent studies on thermal plume behaviour, which demonstrate that local morphology (e.g. spits, constrictions) and flow reductions can amplify near-field confinement, elevating temperature footprints unless diffuser placement and angles are optimised (Heidari et al. 2025). Their field-validated modelling at power plant outfalls demonstrated that small geometric changes and seasonal ambient variations materially alter plume size and compliance distances (Heidari et al. 2025).

### Non-thermal discharges

Mixing zones for chemicals of concern are typically designed to meet water quality standards for all regulated substances, often using the largest required distance. To avoid complexities arising from varying standards, dilution was used as a direct metric. Dilution values at 100 m were modelled for each discharge, and scenarios were assessed to ensure regulatory criteria were met. The distance required to reach the baseline dilution value at 100 m was calculated for Discharges #2, #3, and #4. These calculations illustrated how parameter changes can extend or reduce the mixing zone length. For scenarios modifying effluent flowrate while maintaining concentration balance, the distance was determined at the target concentration rather than the baseline dilution factor.

Across all sites, ambient velocity emerged as a primary control on dilution and compliance distance, but the magnitude and direction of its effect varied. For Discharge #3 (bounded estuary), a 20% decrease in ambient velocity increased the distance required to reach the baseline dilution value to 157.7 m (a 57.7% increase), while for Discharge #4 (river), the same reduction led to a distance of 230.3 m (a 130.3% increase). Conversely, a 20% increase in ambient velocity reduced the compliance distance by 71.2% for Discharge #3, but unexpectedly increased it by 13.2% for Discharge #4 (Table 7). This divergence highlights the importance of site-specific hydrodynamics: in confined riverine systems, higher velocities may advect the plume downstream more rapidly, reducing the time available for lateral mixing and, in some cases, increasing the distance required to achieve regulatory dilution.

Ambient density (proxy for background concentrations) also exerted a strong, site-dependent influence. In bounded estuarine and riverine systems (Discharges #3 and #4), variations in ambient density substantially reduced dilution capacity and expanded the mixing zone. For example, a 10% decrease in ambient density reduced dilution values by up to 69.4% for riverine discharges, with the compliance distance increasing by up to 257.1% (Table 7). In contrast, in unbounded estuarine environments (e.g. Discharge #2), changes in ambient density had a negligible effect on dilution and compliance distance, reflecting the buffering effect of high assimilative capacity and open geometry.

The modelling results indicate that reductions in effluent flowrate while maintaining a constant contaminant mass load (an operational scenario often motivated by water reuse and efficiency strategies) can have a counter-intuitive impact on mixing zone behaviour, particularly in bounded and riverine systems (e.g. Discharge #4). Specifically, decreasing the effluent flowrate without reducing the total contaminant mass led to a more concentrated discharge. This, in turn, resulted in a shorter distance required to achieve the baseline dilution value, effectively reducing the spatial extent of the mixing zone. Interestingly, a similar pattern was observed when increasing the effluent flowrate while maintaining the mass load. In both scenarios, whether flowrate is reduced or increased at constant mass, the distance to reach the baseline dilution value was affected, underscoring the complex interplay between flow dynamics, concentration, and mixing efficiency in confined waterbodies.

Increased effluent density may happen as a result of more cycles of concentration in cooling towers (Rahmani 2017), or reduced blending due to water use restrictions. In all tested conditions, higher effluent density resulted in increased dilution values at 100 m (Table 7), indicating enhanced mixing efficiency in the near field. However, this effect was often accompanied by an increase in the distance required to reach the baseline dilution value, effectively extending the spatial footprint of the mixing zone. This outcome reflects the complex interplay between plume buoyancy, ambient hydrodynamics, and waterbody geometry. Denser effluents tend to sink and spread laterally along the bed, promoting mixing with ambient water but also causing the plume to persist over longer distances before achieving regulatory dilution thresholds.

Overall, the CORMIX modelling for non-thermal discharges demonstrates that the distance over which effluent dilutes to reach a specific concentration is heavily influenced by both effluent and ambient density. These results aligned with previous research on brine discharges comparing the sensitivity of four near-field

**Table 7** Variations of the dilution values and distances to dilution values from the CORMIX modelling of concentration-based (non-thermal) discharges

Parameters	Discharge #2					Discharge #3					Discharge #4				
	-20%	-10%	+5%	+10%	+20%	-20%	-10%	+5%	+10%	+20%	-20%	-10%	+5%	+10%	+20%
Tested scenarios	-20%	-10%	+5%	+10%	+20%	-20%	-10%	+5%	+10%	+20%	-20%	-10%	+5%	+10%	+20%
Effluent flow	13.8	13.9	16.8	16.8	16.4	37.4	38.2	36.4	40.0	38.2	16.0	25.4	27.9	28.6	25.1
Effluent flow and constant thermal load	-15.8%	-15.2%	2.4%	2.4%	0%	-2.4%	-4.2%	-6.9%	2.3%	-2.4%	-39.5%	-4.0%	5.1%	8.1%	-5.3%
Effluent flow and constant concentration*	16.3	16.3	16.4	16.4	16.4	37.4	38.2	36.4	40.0	38.2	16.0	25.4	27.9	28.6	25.1
Effluent temperature	-0.6%	-0.6%	0%	0%	0%	-2.4%	-4.2%	-6.9%	2.3%	-2.4%	-39.5%	-4.0%	5.1%	8.1%	-5.3%
Ambient velocity	17.4	16.8	15.2	15.2	15.2	29.6	34.0	30.2	50.9	56.6	22.4	24.9	28.0	20.5	20.5
Ambient density	6.1%	2.4%	-7.3%	-7.3%	-7.3%	-24.3%	-13.0%	30.2%	30.2%	44.8%	-15.5%	-6.0%	5.7%	5.7%	-22.6%
Tested scenarios	-3 ppt	-2 ppt	+1 ppt	+2 ppt	+3 ppt	-20%	-10%	+5%	+10%	+20%	-20%	-10%	+5%	+10%	+20%
Effluent density	16.4	16.4	16.4	16.4	16.4	31.2	30.4	18.8	15.6	10.3	9.6	8.1	8.4	8.4	8.4
Test	Distance to dilution value of 16.4	Distance to dilution value of 39.1	Distance to dilution value of 39.1	Distance to dilution value of 39.1	Distance to dilution value of 26.4										
Tested scenarios	-20%	-10%	+5%	+10%	+20%	-20%	-10%	+5%	+10%	+20%	-20%	-10%	+5%	+10%	+20%
Effluent flow	614.5	280.0	92.5	92.5	92.5	114.7	143.7	114.7	143.7	143.7	143.7	143.7	143.7	143.7	143.7
Effluent flow and constant thermal load	515%	180%	-7.5%	-7.5%	-7.5%	14.7%	43.7%	14.7%	43.7%	43.7%	43.7%	43.7%	43.7%	43.7%	43.7%

**Table 7** (continued)

Parameters	Discharge #2					Discharge #3					Discharge #4				
	-20%	-10%	+5%	+10%	+20%	-20%	-10%	+5%	+10%	+20%	-20%	-10%	+5%	+10%	+20%
Tested scenarios	-20%	-10%	+5%	+10%	+20%	-20%	-10%	+5%	+10%	+20%	-20%	-10%	+5%	+10%	+20%
Dilution values at 100 m															
Effluent flow and constant concentration*	100.0	100.0	100.0	100.0	100.0	107.7	105.0	105.6	95.3	105.6	43.1	32.7	20.7	17.8	
Effluent temperature	-0.02%	-0.02%	100.0	-0.02%		7.7%	5.0%	5.6%	-4.7%	5.6%	-56.9%	-67.3%	-79.3%	-82.2%	
Ambient velocity	83.1	91.7	262.2	162.2%	448.0	157.7	127.7	28.8	44.3	28.8	230.3	142.5	92.9	113.2	
Ambient density	-16.9%	-8.3%	100.0	100.0	348.0%	57.7%	27.7%	-71.2%	-55.7%	-71.2%	130.3%	42.5%	-7.1%	13.2%	
Effluent density	100.0	100.0	100.0	100.0	100.0	499.1	477.3	156.8	162.5	142.6	357.1	87.4	229.3	144.7	91.1
	-0.02%	-0.02%	-0.02%	-0.02%	-0.02%	399.1%	377.3%	56.8%	62.5%	42.6%	257.1%	-12.6%	129.3%	44.7%	-8.9%
	100.0	100.0	100.0	100.0	100.0	161.2	158.7	312.5	432.8	124.8	227.4	77.3	309.7	309.7	
	-0.02%	-0.02%	-0.02%	-0.02%	-0.02%	61.2%	58.7%	212.5%	332.8%	24.8%	127.4%	-22.7%	209.7%	209.7%	

The current mixing zone (baseline case) dilution value at 100 m equals 16.4, 39.1, and 26.4 for discharges #2, #3, and #4, respectively. \*Concentration was used (equation: 100 mg/L divided by the dilution at 100 m) for these scenarios

modelling tools, including CORMIX (Loya-Fernández et al. 2012).

## Practical implications and recommendations for the mixing zone concept

### Inadequate technical guidelines

Discrepancies in technical guidelines emerged as one of the most critical challenges, consistent with comparative analyses (Campos et al. 2022; Romero et al. 2023) that highlighted substantial variation in mixing-zone design methodologies across jurisdictions. These differences result in outcomes that are highly sensitive to the quality of input data and the selection of modelling tools. Compounding this issue, the survey revealed that permit review frequencies vary considerably between and within countries, with some facilities reporting intervals exceeding 5 years or lacking formal review schedules altogether (Table 4). This variability undermined the consistency of regulatory oversight and may delay the integration of updated scientific understanding or environmental conditions into permit conditions. Collectively, the lack of harmonised technical guidance and irregular permit reviews contributes to regulatory uncertainty and may compromise the effectiveness of mixing zones.

### Optimising mixing zones

Optimising mixing zone design presents a cost-effective alternative to extensive end-of-pipe treatment, potentially reducing operational expenditure. Well-engineered mixing zones—particularly those incorporating multiport diffusers and informed by site-specific hydrodynamic modelling—can achieve regulatory compliance with lower treatment intensity (Bleninger and Jirka 2011). However, it is notable that only one of the facilities surveyed in this study reported the use of engineered diffusers (i.e. six slots cut in 16" diameter pipe, Table B in Supplementary Material), suggesting an underutilisation of available technologies that could enhance initial dilution and minimise spatial impacts. Expanding mixing zones without such safeguards may increase the area of pollutant dispersion, thereby elevating risks to sensitive aquatic habitats. It should also be acknowledged that the effective design and implementation of such systems often require specialised hydrodynamic expertise and access to high-quality site-specific data (i.e. resources that may not be readily available at all facilities) potentially limiting the feasibility or consistency of such approaches.

### Site-specific conditions

The results from the CORMIX modelling enabled the identification of key factors that may have an impact on the

physical footprint of a mixing zone, when considering thermal or non-thermal discharges. Mixing zone performance is inherently site-specific, governed by a complex interplay of effluent characteristics, discharge configurations, and receiving waterbody conditions. For instance, a 20% reduction in ambient flow velocity led to a 6.1% increase of the dilution value at 100 m for Discharge #2, while the same change had a 24.3% decrease effect on Discharge #3. Such disparities underscore the limitations of applying uniform regulatory thresholds or design assumptions across diverse hydrological and operational contexts. Instead, site-specific assessments are essential to ensure that mixing zones are appropriately sized and managed to protect local ecological conditions.

While the primary emphasis of this study is on the risks associated with effluent discharges and the regulatory frameworks governing mixing zones, it is important to acknowledge that not all discharged substances exert uniformly negative effects on aquatic ecosystems. Certain chemical species, particularly trace metals such as zinc and copper, while potentially toxic at elevated concentrations, also serve as essential micronutrients for aquatic organisms. Notably, recent research has demonstrated that higher concentrations of these metals can inhibit the growth of toxin-producing cyanobacteria, which are responsible for harmful algal blooms in nutrient-enriched waters (Facey et al. 2019). This dual role underscores the complexity of assessing ecological risk in the context of industrial discharges: while regulatory frameworks appropriately prioritise the prevention of harmful exposures, there may be circumstances where specific constituents contribute to ecosystem resilience or mitigate other environmental stressors. Several surveyed facilities reported discharge limits for metals such as zinc and copper that, while subject to regulatory control, may also interact with receiving water chemistry in ecologically nuanced ways. These considerations highlight the need for a more holistic, context-sensitive approach to mixing zone assessment—one that accounts not only for pollutant concentrations but also for their ecological function and interactions within dynamic aquatic systems.

### Upstream water quality

Changes in ambient density—used here as a proxy for changes in background concentrations—also marked effects on mixing zone behaviour. As expected, Discharges #1 and #2, located in coastal and estuarine settings, exhibited limited sensitivity to variations in ambient density, with negligible changes in dilution values across the tested scenarios (Table 6). This relative stability is attributable to the higher assimilative capacity and dynamic hydrodynamics of marine and estuarine systems, which buffer against shifts in background conditions. In contrast, Discharges #3 and #4 demonstrated pronounced sensitivity: a 10% increase in

ambient density led increased distances to reach the dilution values (Table 7). This suggests that elevated background concentrations (e.g. upstream pollution) can significantly constrain the effectiveness of mixing zones in freshwater systems. These findings are particularly salient given that two facilities explicitly identified deteriorating upstream water quality as a growing concern in their survey responses. It underscores the importance of accounting for spatial and temporal variability in background water quality during mixing zone assessments, particularly in rivers where dilution capacity is inherently limited and more susceptible to external pressures.

The challenge is compounded by the proliferation of emerging substances, which can interact synergistically and exacerbate mixture toxicity. For example, a wide-scope screening of 499 emerging chemicals across 52 WWTP effluents in Europe found 366 compounds with mixture risks exceeding thresholds for algae, crustaceans, and fish in numerous outfalls (Finckh et al. 2022), indicating that compliance at the mixing-zone edge for a small set of regulated analytes may not capture mixture toxic pressure.

### Water efficiency and reuse practices

The modelling results underscored the nuanced and site-specific impacts of water efficiency and reuse strategies on mixing zone behaviour. A decrease in effluent flow while maintaining concentration balance (serving as a proxy for more concentrated discharges, such as those arising from brine management or circular water practices) has become increasingly relevant as industrial facilities seek to reduce freshwater abstraction and enhance sustainability. However, the simulations reveal that such operational changes do not yield uniform outcomes across all receiving environments. For instance, a 20% reduction in effluent flowrate, while maintaining the same contaminant load, led to a 2.4% and 39.5% decrease in dilution values at 100 m for Discharges #3 (bounded estuary) and #4 (bounded riverine system), respectively (Table 7). In the estuarine setting, this reduction in dilution resulted in increased distances required to reach the baseline value, effectively expanding the mixing zone. Conversely, in the riverine system, the same scenario led to a shorter distance to compliance, thereby reducing the mixing zone size. This outcome was consistent with research by Wolfand et al. (2022, 2023) which demonstrated that increased wastewater reuse can have unintended consequences for water quality, including elevated concentrations of certain pollutants and changes in mixing zone dynamics. For example, in their study, a 50% increase in reuse was associated with a 33% rise in total suspended solids, while concurrent reductions in mass loading under higher reuse scenarios led to decreased concentrations of emerging contaminants. Crucially, these results highlighted that

operational changes aimed at improving water efficiency did not always result in an expanded mixing zone. Under certain hydrodynamic and geometric conditions, a more concentrated discharge can achieve the required dilution over a shorter distance, potentially simplifying regulatory compliance.

Similarly, the modelling results showed that higher effluent density consistently led to increased dilution values at 100 m, reflecting enhanced initial mixing. However, this benefit was frequently offset by a concurrent increase in the distance required to reach the baseline dilution value, effectively extending the spatial footprint of the mixing zone. Survey responses highlighted that discharges often consist of a blend of effluents (Fig. 1). Consequently, this study prompts careful consideration over operational measures intended to improve water efficiency or sustainability as they have complex, and sometimes counterintuitive effects on regulatory compliance and environmental protection.

### Climate change

The simulations highlighted the potential implications of climate change. Scenarios incorporating changes in ambient velocity (i.e. river flows) produced larger mixing zones for Discharges #3 and #4 (Table 7). Ambient velocity serves as a useful indicator for assessing the impact of flow variations in receiving water bodies, particularly in the context of climate change. Hydrological projections (Abily et al. 2021; Sepp et al. 2025) suggest that climate-driven changes—such as increased storm severity and altered flow regimes—could result in more pronounced short-term fluctuations than those tested in this study. To put this into perspective, Abily et al. (2021) modelled a decrease in dilution factor for 11% of the EU surface water bodies receiving urban WWTP discharges by 2040. While these events may temporarily intensify mixing zone impacts, their brief duration relative to compliance monitoring intervals means the overall risk from ambient velocity changes remains lower than that posed by ambient and effluent density variations. These results reinforced the need for adaptive permitting strategies that account for hydrological variability and thermal constraints, as also advocated by recent work on climate-resilient water quality management (Van Vliet et al. 2023).

### Conclusions

This study presented the first cross-European assessment of how mixing zones are applied in industrial water management, with a focus on the fuel manufacturing sector. It revealed substantial variability in regulatory frameworks, permitting conditions, and site-level practices. Although only a minority of surveyed facilities operated with mixing

zones at the time of the study, several anticipated future reliance as concentration-based discharge requirements become more stringent.

CORMIX modelling confirmed that mixing zone performance was highly sensitive to effluent and ambient parameters. Climate change, water reuse, and upstream water quality deterioration emerged as critical stressors that could compromise the reliability of mixing zones under future conditions.

These findings highlighted the urgent need for more harmonised, technically robust, and adaptive approaches to mixing zone design. In particular, the near-absence of engineered dispersion systems such as multiport diffusers across surveyed sites represented a missed opportunity to enhance dilution efficiency and minimise spatial impacts. However, the implementation of such systems requires specialised hydrodynamic expertise and high-quality site data—resources that are not universally available and could limit uptake.

Several priorities for future action emerged. Research should focus on integrating climate resilience into mixing zone assessments, including the development of modeling frameworks that account for non-stationary hydrological conditions and evolving effluent characteristics. The observed variability in permit review frequencies and the limited public disclosure of mixing zone characteristics pointed to a broader governance gap. Establishing a cross-European transparency framework—capturing the location, extent, and performance of mixing zones—would support regulatory consistency, improve public trust, and enable more comprehensive assessments of cumulative impacts on aquatic ecosystems.

Ultimately, future-proofing the mixing zone concept would require a shift from static, one-size-fits-all approaches to dynamic, site-specific, and ecologically informed strategies. This includes not only technical innovation, but also regulatory alignment, improved data transparency, and sustained investment in capacity-building. Stakeholders—regulators, industry, and researchers—would need to collaborate to implement these adaptive strategies, ensuring that mixing zones remain a viable and protective tool in industrial water management without compromising environmental integrity.

While the findings were based on a limited sample of facilities and included some assumed input data, they remained indicative of broader trends. Further research across additional sectors and geographies would be warranted to validate and expand upon these insights. Nonetheless, this study provided a critical foundation for updating guidance and practices, enabling policy-makers and industry to act promptly in safeguarding the future effectiveness and legitimacy of mixing zones in a changing environmental and regulatory landscape.

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**Data availability** The data supporting the findings of this study are not publicly available due to the confidential nature of effluent permitting and industrial site-specific information.

## Declarations

**Ethics approval** This study did not involve any procedures requiring formal ethical review. The survey was designed to collect anonymised operational information related to effluent discharge permits and mixing zones. All participants were informed of the purpose and voluntary nature of the study. Clinical trial number: not applicable.

**Consent to participate** Receivers of the survey were informed about the purpose of the survey, and that participation was voluntary. Completion of the survey was taken as implied consent to participate.

**Consent for publication** Participants were made aware that the anonymised results of the survey would be used for publication. No personally identifiable information has been collected or disclosed.

**Competing interests** The authors declare no competing interests.

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## References

- Abily M, Acuña V, Gernjak W, Rodríguez-Roda I, Poch M, Corominas L (2021) Climate change impact on EU rivers' dilution capacity

- and ecological status. *Water Res* 199:117166. <https://doi.org/10.1016/j.watres.2021.117166>
- Australian and New Zealand Environment and Conservation Council (ANZECC) (2010) Australian and New Zealand guidelines for fresh and marine water quality. <https://www.waterquality.gov.au/sites/default/files/documents/anzecc-armcanz-2000-guidelines-voll.pdf>. Accessed 09 December 2025
- Barthe P, Chaugny M, Roudier S, Delgado Sancho L (2015) Best available techniques (BAT) reference document for the refining of mineral oil and gas. Publications Office of the European Union. [https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/REF\\_BREF\\_2015.pdf](https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/REF_BREF_2015.pdf). Accessed 30 April 2024
- Bleninger T, Jirka GH (2011) Mixing zone regulation for effluent discharges into EU waters. *Water Manag* 164:387–396. <https://doi.org/10.1680/wama.900037>
- Campos CJA, Morrissey DJ, Paul B (2022) Principles and technical application of mixing zones for wastewater discharges to freshwater and marine environments. *Water* 14:1201. <https://doi.org/10.3390/w14081201>
- CIS-WFD (2010) Technical background document on identification of mixing zones. <https://circabc.europa.eu/sd/a/78ce94bb-6f1c-4379-87ac-88a18967c4c3/Technical%20Background%20Document%20on%20the%20Identification%20of%20Mixing%20Zones.doc>. Accessed 30 April 2024
- Concawe (2020) 2016 survey of effluent quality and water use at European refineries. Concawe. [https://www.concawe.eu/wp-content/uploads/Rpt\\_20-10.pdf](https://www.concawe.eu/wp-content/uploads/Rpt_20-10.pdf). Accessed 05 December 2025
- Concawe (2023) Refinery and biorefinery sites in Europe. Concawe. <https://www.concawe.eu/refineries-map/>. Accessed 30 April 2024
- Concawe (2024a) Water use and efficiencies in refineries. Concawe. <https://www.concawe.eu/publication/water-use-and-efficiencies-in-refineries/>. Accessed 30 April 2024
- Concawe (2024b) Review of end-of-life management options for refinery equipment and lubricants/greases potentially containing PFAS. [https://www.concawe.eu/wp-content/uploads/Rpt\\_24-12.pdf](https://www.concawe.eu/wp-content/uploads/Rpt_24-12.pdf). Accessed 09 December 2025
- Concawe (2025) 2022 survey of effluent quality and water use at European refineries. Concawe. <https://www.concawe.eu/wp-content/uploads/2022-Survey-of-Effluent-Quality-and-Water-Use-at-European-Refineries-2.pdf>. Accessed 05 December 2025
- Cooke J, Milne P, Rutherford K (2010) A review of definitions of “mixing zones” and “reasonable mixing” in receiving waters. Auckland Regional Council. <https://knowledgeauckland.org.nz/media/1786/tr2010-045-review-of-definitions-of-mixing-zones-and-reasonable-mixing-in-receiving-waters.pdf>. Accessed 09 December 2025
- De Guzman I, Elozegi A, von Schiller D, González JM, Paz LE, Gauzens B, Brose U, Antón A, Olarte N, Montoya JM, Larrañaga A (2023) Treated and highly diluted, but wastewater still impacts diversity and energy fluxes of freshwater food webs. *J Environ Manage* 345:118510. <https://doi.org/10.1016/j.jenvman.2023.118510>
- Di Prinzio CY, Andrade-Muñoz AS, Assef YA, Dromaz WM, Quinteros P, Miserendino ML (2024) Impact of treated effluent discharges on fish communities: evaluating the effects of pollution on fish distribution, abundance and environmental integrity. *Sci Total Environ* 917:170237. <https://doi.org/10.1016/j.scitotenv.2024.170237>
- Environment Protection Authority Victoria (2010) Guidance for the determination and assessment of mixing zones. <https://vgl.sdp.sirsidydney.net.au/client/search/asset/1159449>. Accessed 09 December 2025
- European Commission (2010) Technical guidelines for the identification of mixing zones pursuant to Art. 4(4) of the directive 2008/105/EC. European Commission, Brussels
- European Parliament (2024) Directive (EU) 2024/1203 of 11 April 2024 on the protection of the environment through criminal law and replacing Directives 2008/99/EC and 2009/123/EC. [https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L\\_2024\\_1203](https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_2024_1203). Accessed 09 December 2025
- European Commission (2025) Report from the Commission to the Council and the European Parliament on the implementation of the Water Framework Directive (2000/60/EC) and the Floods Directive (2007/60/EC): Third river basin management plans, Second flood risk management plans. European Commission. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52025DC0002>. Accessed 09 December 2025
- Facey JA, Apte SC, Mitrovic SM (2019) A review of the effect of trace metals on freshwater cyanobacterial growth and toxin production. *Toxins* 11:643. <https://doi.org/10.3390/toxins11110643>
- Federal Ministry of Justice and Consumer Protection (2004) Ordinance on requirements for the discharge of wastewater into waters (Wastewater Ordinance – AbwV), Annex 45: Petroleum Processing. [https://www.gesetze-im-internet.de/abwv/anhang\\_45.html](https://www.gesetze-im-internet.de/abwv/anhang_45.html). Accessed on 09 December 2025 (in German)
- Finckh S, Beckers LM, Busch W, Caroma E, Dulio V, Kramer L, Krauss M, Posthuma L, Schulze T, Slootweg J, Von der Ohe P, Brack W (2022) *Environ Int* 164:107234. <https://doi.org/10.1016/j.envint.2022.107234>
- Flemish Government (2003) Integrated water policy decree. <https://www.integraalwaterbeleid.be/nl/regelgeving/decreet-integraal-waterbeleid>. Accessed 9 December 2025 (in Dutch)
- Flemish Environment Agency (2023) Impact assessment of industrial wastewater discharge - step-by-step plan. <https://www.vmm.be/water/afvalwater/impactbeoordeling-bedrijfsafvalwater/uitgebreid-stappenplan-impactbeoordeling-bedrijfsafvalwater.pdf>. Accessed 15 April 2025 (in Dutch)
- Flemish Environment Agency (2025) Industrial wastewater impact assessment (from 1 June 2025). <https://vmm.vlaanderen.be/diensten-producten/impactbeoordeling-bedrijfsafvalwater>. Accessed 09 December 2025 (in Dutch)
- Heidari N, Aksel M, Yagci O, Erbisim MY, Cokgor S, Valyrakis M (2025) Morphodynamic Controls on Thermal Plume Dispersion at River Mouths: Insights from Field Data and Numerical Modeling. *Water*. 17(18):2721. <https://doi.org/10.3390/w17182721>
- Hjort M, den Haan KH, Whale G, Koekkoek J, Leonards PEG, Redman AD, Vaiopoulou E (2021) Conventional and high resolution chemical characterization to assess refinery effluent treatment performance. *Chemosphere* 278:130383. <https://doi.org/10.1016/j.chemosphere.2021.130383>
- IFC (2007a) Environmental, health, and safety (EHS) guidelines: environmental, wastewater and ambient water quality. World Bank Group. <https://www.ifc.org/content/dam/ifc/doc/2000/2007-general-ehs-guidelines-wastewater-and-ambient-water-quality-en.pdf>. Accessed 14 Apr 2024
- IFC (2007b) Environmental, health, and safety guidelines for onshore oil and gas development. World Bank Group. <https://documents1.worldbank.org/curated/en/858751486372860509/pdf/112103-ENGLISH-Onshore-Oil-and-Gas-Development-PUBLIC-LIC.pdf>. Accessed 09 December 2025
- Jirka GH, Doneker RL, Barnwell TO (1991) CORMIX: a comprehensive expert system for mixing zone analysis of aqueous pollutant discharges. *Water Sci Technol* 24(6):267–274
- Karkou E, Papadaki A, Angelis-Dimakis A, Arnaldos AN, Arampatzis G (2024) Water efficiency solutions for the oil refinery industry. *J Environ Manag* 391:126343
- Loya-Fernández A, Ferrero-Vicente LM, Marco-Méndez C, Martínez-García E, Zubcoff J, Sánchez-Lizaso JL (2012) Comparing four mixing zone models with brine discharge measurements from a reverse osmosis desalination plant in Spain. *Desalination* 286:217–224. <https://doi.org/10.1016/j.desal.2011.11.026>

- Ministry of Ecology, Sustainable Development, and Energy (2012) Technical guide on the methods for taking into account the objectives of the Water Framework Directive (WFD) in water regulation for IOTA/ICPE. [https://aida.ineris.fr/sites/default/files/guides/guide\\_DCE\\_version\\_2\(13\).pdf](https://aida.ineris.fr/sites/default/files/guides/guide_DCE_version_2(13).pdf). Accessed on 09 December 2025 (in French)
- Ministry of Infrastructure and Water Management (2019) Imission assessment handbook. [https://iplo.nl/publish/pages/180794/handboek\\_immissietoets\\_oktober2019t.pdf](https://iplo.nl/publish/pages/180794/handboek_immissietoets_oktober2019t.pdf). Accessed 30 April 2025 (in Dutch)
- Norwegian Climate and Pollution Agency (2010) Common implementation strategy – guidance on setting mixing zones under the EQS-directive (2008/105/EC). <https://www.miljodirektoratet.no/globalassets/publikasjoner/klifst/publikasjoner/2724/ta2724.pdf>. Accessed 09 December 2025 (in Norwegian)
- Northern Territory Environment Protection Agency (2013) Guidelines on mixing zones. [https://ntepa.nt.gov.au/\\_media/waste-and-pollution/pdf/guidelines/guidelines\\_mixing\\_zones.pdf](https://ntepa.nt.gov.au/_media/waste-and-pollution/pdf/guidelines/guidelines_mixing_zones.pdf). Accessed 09 December 2025
- Okeke A (2021) Towards sustainability in the global oil and gas industry: identifying where the emphasis lies. *Environ Sustain Indic* 12:100145. <https://doi.org/10.1016/j.indic.2021.100145>
- Queensland Government (2025) Technical guideline: wastewater release to Queensland waters. [https://www.detsi.qld.gov.au/\\_global/policy-register/policy-register-pdf?getdoc=1654&name=pr-gl-wastewater-to-waters.pdf](https://www.detsi.qld.gov.au/_global/policy-register/policy-register-pdf?getdoc=1654&name=pr-gl-wastewater-to-waters.pdf). Accessed 09 December 2025
- Rahmani K (2017) Reducing water consumption by increasing the cycles of concentration and considerations of corrosion and scaling in a cooling system. *Appl Therm Eng* 114:849–856. <https://doi.org/10.1016/j.applthermaleng.2016.12.075>
- Robinson D, Wood M, Piggott M, Gorman G (2016) Cfd modelling of marine discharge mixing and dispersion. *J Appl Water Eng Res* 4:152–162. <https://doi.org/10.1080/23249676.2015.1105157>
- Rodríguez Benítez AJ, García Gómez A, Álvarez Díaz C (2016) Definition of mixing zones in rivers. *Environ Fluid Mech* 16:209–244. <https://doi.org/10.1007/s10652-015-9425-0>
- Romero I, Martínez-Guijarro R, Pachés M (2023) Methodology for the definition of the mixing zones of punctual discharges in coastal waters. *Limnol Oceanogr Methods* 21(5):267–278. <https://doi.org/10.1002/lom3.10544>
- Schellenberg T, Subramanian V, Ganeshan G, Tompkins D, Pradeep R (2020) Wastewater discharge standards in the evolving context of urban sustainability—The case of India. *Frontiers in Environmental Science*. 17(8):30. <https://doi.org/10.3389/fenvs.2020.00030>
- Sepp M, Abbasi M, Döll P, Freixa A, Marcé R, Sabater S (2025) Impacts of climate change on the dilution capacity of perennial and non-perennial European rivers. *Water Res* 287:124499. <https://doi.org/10.1016/j.watres.2025.124499>
- US EPA (2014) Water quality standards handbook, Chapter 5: General policies. <https://www.epa.gov/sites/default/files/2014-09/documents/handbook-chapter5.pdf>. Accessed 09 December 2025
- Vannportalen (2024) The water regulations. <https://www.vannportalen.no/regelverk-og-foringer/lover-og-forskrifter-av-betydning-for-forvaltningen-av-vann/vannforskriften/>. Accessed 09 December 2025 (in Norwegian)
- Van Vliet MTH, Thorslund J, Strokal M, Hofstra N, Flörke M, Macedo HE, Nkwasa A, Tang T, Kaushal SS, Kumar R, van Griensven A, Bouwman L, Mosley LM (2023) Global river water quality under climate change and hydroclimatic extremes. *Nat Rev Earth Environ* 4:687–702. <https://doi.org/10.1038/s43017-023-00472-3>
- Wang J, Smit MGD, Verhaegen Y, Nolte TM, Redman AD, Hendriks AJ, Hjort M (2023) Petroleum refinery effluent contribution to chemical mixture toxic pressure in the environment. *Chemosphere* 311:137127. <https://doi.org/10.1016/j.chemosphere.2022.137127>
- Wolfand JM, Sytsma A, Hennon VL, Stein ED, Hogue TS (2022) Dilution and pollution: assessing the impacts of water reuse and flow reduction on water quality in the Los Angeles river basin. *ACS ES&T Water* 2:1309–1319. <https://doi.org/10.1021/acsestwater.2c00005>
- Wolfand JM, Sytsma A, Taniguchi-Quan KT, Stein ED, Hogue TS (2023) Impact of wastewater reuse on contaminants of emerging concern in an effluent-dominated river. *Front Environ Sci* 11:1091229. <https://doi.org/10.3389/fenvs.2023.1091229>

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