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Future-Proofing the Mixing Zone Concept

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Future-Proofing the Mixing Zone Concept

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ABSTRACT

This report describes an assessment of the evolving role of mixing zones in European water protection management, including the potential impacts on regulated industry such as fuel manufacturing operations. Mixing zones are designated areas within receiving surface water bodies where wastewater effluents may cause localised exceedances of regulatory criteria, provided that water quality standards are met at the boundary of the mixing zone. They allow in-waterbody mixing and dilution to ensure protection of the quality of the wider aquatic environment. However, the concept faces increasing scrutiny due to regulatory focus, public environmental concerns, and climate change related impacts on water systems. The work employed a comprehensive literature review, a survey of 22 refineries across 14 countries, and advanced modelling using the CORMIX tool. Findings revealed significant regulatory variation across Europe, with some countries providing detailed guidelines while others lack clear frameworks, resulting in operational uncertainty, and potentially hindering efforts to achieve the Water Framework Directive's water quality goals. Survey data showed limited current use of mixing zones but anticipated growing reliance due to evolving standards. Climate change-induced variability in water systems and the detection of emerging contaminants highlight the need for adaptive management and advanced treatment technologies. This study concludes that harmonised European-wide regulations or guidance would be beneficial to futureproof the mixing zone concept.

KEYWORDS

Mixing Zone, Wastewater, Discharge, Fuel Manufacturing, Oil and Gas, Modelling, Climate Change.

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SUMMARY

This report examines the current status and future applicability of the "mixing zone" concept in managing refinery effluent discharges in Europe. Mixing zones are designated areas within receiving water bodies where pollutant concentrations are allowed to exceed environmental quality standards temporarily, providing necessary dispersion for compliance without immediate impacts on overall water quality. However, as regulatory pressures increase and climate-related changes affect water systems, the use of these zones may come under greater scrutiny from both regulators and the public. The research approach encompassed a comprehensive review of scientific literature, a survey of Concawe European fuel manufacturing sites, and detailed modelling assessments of mixing zone dynamics.

This research highlighted the following key findings:

- **Regulatory Inconsistencies:** There was significant variability across European countries in how mixing zones are regulated, leading to inconsistent environmental protections and uncertainty for operators.
- **Survey Insights:** Only 18% of respondents currently relied on a mixing zone to manage their effluent discharges. However, an additional 18% of facilities expected a mixing zone requirement in the future. The survey also revealed that existing regulations often do not address total mass loading, limiting incentives for water reuse or reducing effluent volumes.
- **Climate and Environmental Challenges:** Rising temperatures and altered water flows due to climate change presented new obstacles for effective pollutant dilution in water bodies, potentially impacting the compliance of mixing zones.
- **Emerging Contaminants and Technological Needs:** Increasing detection of new pollutants (perfluorinated compounds, endocrine-disrupting chemicals) in European waters may necessitate updates to treatment technologies and modelling practices. Regulatory shifts toward more stringent pollutant limits were likely, requiring facilities to adopt advanced treatment methods and more robust dilution models.

To futureproof the mixing zone concept, the report recommends the following:

- **Regulatory Harmonisation:** Establish EU-wide guidelines for mixing zone design and implementation to ensure consistent environmental protections and operational clarity across Member States.
- **Adaptive and Climate-Resilient Management:** Develop adaptive strategies that account for climate change impacts on water systems, such as temperature increases, altered flow patterns, and shifts in rainfall distribution, to support long-term regulatory compliance. Additionally, consider potential changes in land use and infrastructure, such as new industrial discharges, upstream and downstream flow modifications, etc that may influence water quality and hydrodynamics.
- **Technological Advancements:** Invest in advanced treatment technologies and monitoring systems to address emerging contaminants and respond effectively to evolving environmental standards. By reducing pollutant loads and improving effluent quality, these technologies directly influence the size and impact of mixing zones, ensuring compliance with regulatory limits and minimising environmental harm within the recipient ecosystem.

- **Enhanced Stakeholder Engagement:** Proactively engage regulators, industry stakeholders, and the public to build transparency around mixing zone management practices. Ensure that the harmonised mixing zone concept reflects robustness in protecting the recipient ecosystem, demonstrating a commitment to environmental stewardship and sustainable resource management.

1. INTRODUCTION

The EU water legislation shares an overarching objective of protecting human health and the environment from the combined effects of toxic and/or persistent pollutants. This concerns Directive 2000/60/EC (Water Framework Directive, WFD) which requires European Union (EU) Member States to achieve good chemical and ecological status in all water bodies by 2027 [1].

Two 'daughter' directives, namely Directive 2006/118/EC (Groundwater Directive) and Directive 2008/105/EC (Environmental Quality Standards (EQS) Directive) put further emphasis on the protection of groundwater and surface waters respectively. Directive 2008/105/EC lays down EQS for priority substances and certain other pollutants with the aim of achieving good surface water chemical status. Article 4, of the present Directive, introduces the concept of mixing zones, granting Member States the discretion to establish these zones near discharge points into surface waters.

In addition, Emission Limit Values (ELV) may be set by local Competent Authorities in permits based on (i) the Industrial Emissions Directive (IED), the IED Best Available Techniques (BAT) concept, and (iii) the WFD.

Best practice guidance on wastewater management identifies options to improve treatment and effluent quality through the application of BAT, and in some cases promote the re-use and recycling of treated effluents. Competent Authorities, when identifying locally appropriate management options, may also consider factors such as technological and engineering constraints, the characteristics of the effluent, the hydrological context, and environmental protection areas [2].

Yet, the original WFD did not include provisions or recommendations as to where in the water body the EQS should apply and which procedures shall be used for compliance of discharges [3]. Thus, amendments to the EQS Directive (2013/39/EU) were made defining mixing zones as the area of a receiving water body expected to contain concentrations of pollutants above the relevant EQS and Predicted No-Effect Concentration (PNEC) value as a result of the discharge. As such these 'zones' can also be considered by discharge consenting authorities for discharges.

Fuel manufacturing effluents, which are wastewaters generated from the extraction and processing of crude oil and petroleum-based products, potentially contain various pollutants such as hydrocarbons, ammonia, heavy metals, sulphides and phenols [4]. Although these effluents are not believed to be major contributor to the toxic pressure in the environment [5], increased focus on chemical discharges and scrutiny from both the public and regulators, as well as uncertainties relating to climate change, are putting the mixing zone concept under pressure. While Concawe[1] has previously collated information and performance data regarding fuel manufacturing effluents, the mixing zone concept was not the focus of previous research.

[1] Concawe was established in 1963 by a small group of leading oil companies to carry out research on environmental issues relevant to the oil industry. Its membership has broadened, and currently includes most fuel manufacturing operating in EU-27, Norway, Switzerland and the United Kingdom, representing approximatively 95% of petroleum refining capacity in those countries.

1.1. AIMS AND OBJECTIVES

Thus, the overall aim of this project is to understand how current trends and developments in regulations may influence the mixing zone concept.

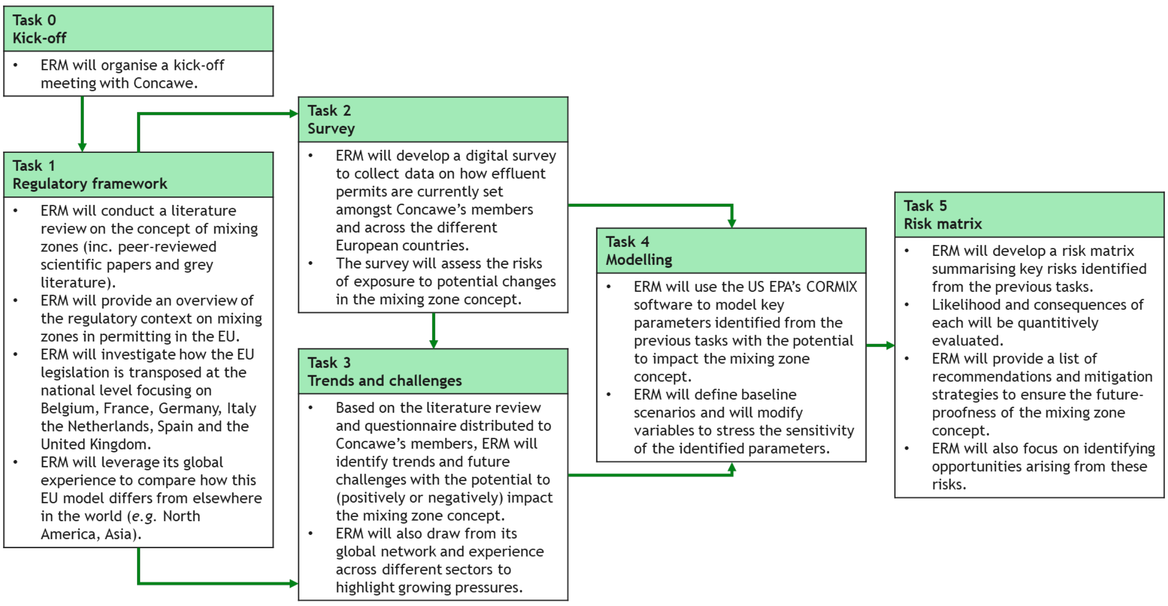
The specific project objectives are summarised below:

- Undertake a review of the scientific literature on the concept of mixing zones;
- Review the regulatory context on mixing zones in the EU, and investigate their transposition at the national level for selected countries;
- Determine the trends and challenges with the potential to impact the mixing zone concept;
- Investigate how these processes numerically impact the concept through discharge modelling; and
- Develop a risk matrix summarizing key findings.

1.2. METHODOLOGY

To address the project aims and objectives, a methodology was developed by Environmental Resources Management (ERM), and further delivered by a global team of experts from the UK, Europe and the US. The project methodology is outlined in Figure 1.

Figure 1. Overview of the project methodology



1.2.1. Regulatory framework

A literature search was performed using scientific databases, including ScienceDirect, Scopus and Google Scholar. Keywords covering the topic of the review were inserted and combined.

The regulatory framework on mixing zone was analysed at the EU level, and extended to the selected countries (United States and Australia/New Zealand) to gather insights on the application of the mixing zone concept outside of the EU. International guidelines were also studied to understand how they might relate to mixing zones and refineries. Publicly available sources were consulted to gather this data.

1.2.2. Survey

A structured questionnaire was developed in a digital format to gather information on the application of mixing zones for fuel manufacturing effluent discharges. 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 (see Appendix A for the topics covered by the survey) amongst operators of European refineries jointly organised in Concawe (scientific division of European Fuel Manufacturers Association), and being cascaded to the site-level individuals with the most understanding of their site's discharge permit. As with most social enquiry research, the survey is 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.

1.2.3. Trends and Challenges

Drawing on the literature review and feedback from Concawe's members gathered through the survey, as well as leveraging its global network and cross-sector experience, ERM listed trends and challenges in water management with a focus on the mixing zone.

It was originally anticipated that these factors relate to:

- Climate change presents a significant challenge as the expected increase in extreme weather events, such as prolonged droughts, intense rainfall, and higher temperatures, may necessitate a more dynamic approach to managing discharges and mixing zones. These climatic changes could complicate the prediction and management of dilution in receiving waters, potentially leading to stricter ELVs to ensure compliance with EQS.
- Societal pressure, arising from public concern over environmental issues, particularly water pollution, is on the rise. This societal pressure is likely to result in increased scrutiny from stakeholders, including regulatory bodies and non-governmental organizations. The public's growing interest in environmental protection could drive stricter regulations and enforcement, further tightening the constraints on mixing zone management and potentially lowering acceptable ELVs to align with public expectations.
- Advancements in technology and knowledge are continually refining the understanding of environmental pollutants and their impacts. For instance, emerging contaminants (e.g. perfluorinated compounds, endocrine-disrupting chemicals), are being identified at an increasing rate, necessitating updates to monitoring and assessment protocols. Additionally, enhanced toxicity data and knowledge of mixture effects—whereby the interaction of multiple compounds can exacerbate toxicity—may lead regulators to impose more stringent limits on pollutants. This evolving knowledge base will likely push for the development of more sophisticated dilution models and potentially advocate for end-of-pipe solutions, further challenging the management of mixing zones.

1.2.4. Modelling

To evaluate the behaviour of effluent discharges into the receiving water body, the US Environmental Protection Agency (EPA)-approved near-field Cornell Mixing Zone Expert System (CORMIX) modelling tool was employed (CORMIX; Version 12.0)[2] [6].

1.2.4.1. Scenarios considered

To determine 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 the four refineries that utilised mixing zones as part of their permit requirements (Table 1). Amongst the four refineries, one monitored both thermal discharges and pollutants of concern (discharge #2), one monitored only thermal discharges (discharge #1), and two monitored only pollutants of concern (discharges #3 and #4).

Table 1. Overview of discharges with mixing zones

Parameter	Discharge #1	Discharge #2	Discharge #3	Discharge #4
Location	United Kingdom	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	Excess temp. of 1.5°C	Thermal limit of 28°C	POC	POC
Mixing zone constituent #2	N/A	POC	N/A	N/A

Notes: POC= pollutant of concern; temp.=temperature

The sensitivity analysis was thus conducted for the two types of discharges identified in the survey, namely (i) thermal discharges and (ii) discharges containing pollutants 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. However, the approximate replication was sufficient for the purposes of this study. Tailored CORMIX model parameter modifications were then applied to account for the unique features of each type of mixing zone.

[2] CORMIX is a robust hydrodynamic simulation model designed to predict the mixing, dispersion, and dilution of pollutants from point-source discharges, such as industrial effluents. It considers various environmental and discharge parameters, including effluent flow rates, ambient water velocities, temperature differentials, and receiving water characteristics (*e.g.* depth, width, and flow regime). A typical CORMIX application requires three types of data as inputs: (i) description of the discharge stream (i.e. flowrate, temperature, and water quality concentrations); (ii) dimensions, location, and configuration of the discharge structure; and (iii) properties and characteristics of the receiving waterbody (*i.e.* depth, current speed, salinity, and temperature).

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 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. By modelling these scenarios, the work provides insights into how these evolving conditions influence mixing zones, offering guidance for adapting management practices. 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 illustrate 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 those values. In total, 20 simulations were performed for each of the four discharges to ensure a comprehensive evaluation (Table 2).

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)	• Increase in effluent flowrate only (by 10%) • Decrease in effluent flowrate while maintaining the same thermal load (flow reduced by 10% and 20%) • Increase/decrease in effluent temperature only (by 10%) • Increased in effluent density (discharge salinity increased by 1 ppt and 2 ppt)
	Receiving waterbody's flow	• Increase/ decrease in ambient velocity only (by 10% and 20%)
	Background concentrations	• Increase/decrease in ambient temperature only (by 5%, 10%, and 20%)
Discharges monitoring pollutants of concern (non-thermal)	Effluent characteristics (flowrate, density, temperature, concentrations)	• Increase in effluent flowrate only (by 10%) • Increase/decrease in effluent flowrate while maintaining concentration balance (flow increased/decreased by 10% and 20%) • Increase/decrease in effluent density only (by 5%, 10%)
	Receiving waterbody's flow	• Increase/decrease in ambient velocity only (by 10%, 20%)
	Background concentrations	• Increase/decrease by ambient density only (5%, 10%, 20%)

1.2.4.2. 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 3). To address this, a supplemental data request was issued to the three facilities (facilities #2-4) to obtain the necessary inputs for CORMIX. Additional data was only received from facility #2.

For facilities #3 and #4, assumed values were used to create generic base cases that complemented the available data. For instance, ambient currents were not provided for company #3; since the facility discharge flows 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.

Table 3. Simulation parameters for CORMIX sensitivity analysis modelling

Parameter	Facility #1	Facility #2	Facility #3	Facility #4
Diffuser/pipe design	6 slots cut in a 16" diameter pipe	Single Port	Single Port	Single Port
Discharge Location	Subsurface	Subsurface	Subsurface	Subsurface
Port diameter (m)	0.17	1.0	0.34	1.09
Port centre height above channel bottom (m)	0.945	0.5	0.172	0.545
Port orientation	Theta: 180 Gamma: 0	Theta: 0 Gamma: 90	Theta: 0 Gamma: 90	Theta: 0 Gamma: 90
Port distance from shoreline	340	15	115	218
Flow rate (m^3/s)	12,300	0.36	0.0461	0.4631
Effluent Temperature	29.4	36.5	20	20
Effluent Salinity (ppt)	0	26.8	0	0
Waterbody type (bounded/unbounded)	Bounded	Unbounded	Bounded	Bounded
Bounded width (m)	1650	N/A	818	439
Bed roughness (Manning n coefficient)	0.03	0.03	0.03	0.03
Ambient current velocity (m/s)	0.72	0.01	0.1	0.1
Ambient temperature (°C)	15.2	20	20	20
Ambient salinity (ppt)	33.7	10	15	0
Ambient density (kg/m^3)	1,024.84	1,005.81	1,009.58	998.21
Wind speed (m/s)	3.1	0	0	0

Note: N/A = Not applicable.

1.2.5. Risk matrix

Drawing on insights from the literature review, survey data, and CORMIX modelling outputs, the study identified a range of risks and opportunities that could influence the future viability of the mixing zone concept, with both positive and negative potential impacts.

2. LITERATURE REVIEW

2.1. DEFINITIONS

A mixing zone is a designated area within a water body where a permitted discharge of pollutants is allowed to mix with the receiving water. In this zone, water quality standards may be exceeded while the effluent are diluted and dispersed to meet these standards at the edge. The purpose of a mixing zone is to provide a controlled area where the immediate effects of the discharge can be managed, with the expectation that outside this zone, the concentration of pollutants will be reduced to levels that meet EQS [6].

Whilst this definition is generally agreed upon, there is much terminology associated with wastewater mixing processes with a lack of universal definitions of such terms [7] (Table 4).

Table 4. Mixing zone terminology [7] [8]

Term	Definitions
Mixing zone or Allocated impact zone	Limited area where rapid mixing takes place and where numeric water quality criteria can be exceeded but acutely toxic conditions must be prevented. Specified dilution factors and water quality requirements must be met at the edge of the mixing zone.
Regulatory mixing zone or Legal mixing zone	As defined by the appropriate regulatory authority.
Near-field or Hydrodynamic mixing zone	Region where mixing is caused by turbulence and other processes generated by the discharge itself.
Far-field	Region where mixing is due to ambient environmental conditions.
Toxic dilution zone	A more restrictive mixing zone within the usual mixing zone.
Initial dilution	A general term for the rapid dilution that occurs near the outlet.
Zone of initial dilution	A region extending over the water column and extending up to one water depth around the outlet.

2.2. IMPACTING FACTORS

In Europe, industrial wastewater, while historically perceived as a significant environmental challenge due to its high pollutant load, is now managed through wastewater treatment processes where contaminants are substantially reduced prior to discharge to the environment It is generally appreciated that although industrial discharge may undergo diurnal and seasonal variations these discharges are controllable [8]; thus concentration profiles in the water body will be less dynamic and dominated by the river flow rate dynamics, for instance [9].

Nevertheless, there is no substitute for the estimation of the extents of the mixing zone for each application case due to the multitude of factors occurring in the vicinity of a mixing zone [10]. These factors may include:

- Hydrodynamic conditions of the receiving water body: for instance, estuaries and coastal areas are mostly influenced by waves and tides, while in rivers flow regimes (low and high flows dictated by the prevailing climate) have the main influence. Conditions in lakes and lagoons, hydrodynamic conditions can be dominated by flow currents and the wind [11].
- Geomorphology: for instance, the presence of curves in a river generates circulation phenomena in a section transverse to the flow [11].
- Density: differences between the effluent and receiving water body can generate buoyancy or sinking effects [12].
- Background concentrations: in certain cases, the receiving water body can have an existing background concentration for a pollutant under study.

2.3. DESIGN CONSIDERATIONS

To optimise mixing, it has been recommended that the discharge outlet should be: (i) oriented into the open water body and not against the bed or the water surface, (ii) not cause strong bed or surface interactions, (iii) and not be concentrated at one single point. As such, submerged multiport diffusers have been proposed as a solution to address these objectives [3].

Several diagnostic and predictive methodologies can be used for mixing assessment such as (i), field experiments, (ii) analytical equations, (iii) mixing zone models, and (iv) multi-dimensional water quality models [3]. The following sections briefly describe some of the methodologies reported in the literature. To note, mixing zone techniques can be equally applied in canals and lakes, however, for the fuel manufacturing sector, there appears to be few or no cases where industrial discharges occur into these types of water body. Thus, the following sub-sections focus on rivers and coastal waters.

2.3.1. Streams and rivers

The size of the mixing zone can be determined through one-dimensional models using general empirical formulas as described in Table 5.

Table 5. Empirical formulas used to calculate the distance of the full mixing path in rivers [13]

Horizontal direction	Vertical direction
$L_X = \alpha_X . \frac{V_p . S^2}{D_y}$ Where: L_x - distance of the discharge point from the cross-section of the total cross-sectional mixing [m] α_x - experimentally determined coefficient, V_p - average flow rate of water in cross-section of the watercourse [m/s] s - linear transverse scale, for regulated rivers to be adopted s ≈ 0.7b; for symmetrical channels - s ≈ 0.5b, where: b - width of the water surface [m] D_y - transverse dispersion coefficient [m^2/s]	$L_y = \alpha_y . \frac{V_p . S^2}{D_z}$ Where: L_y - distance of wastewater discharge point from the cross-section of total mixing in vertical direction [m] α_y - experimentally determined coefficient s - linear vertical scale [m] D_z - vertical dispersion coefficient [m^2/s]

Horizontal direction	Vertical direction
$D_y = \beta_1 . h . v_*$ Where: β_1 - coefficient dependent on the riverbed regularity, β_1 = 0.4 (for rivers with meanders and isles), β_1 = 0.6 (for regulated riverbeds) h - average depth of the watercourse [m] v_* - dynamic flow rate [m/s]	$D_y = \beta_2 . h . v_*$ Where: β_2 - coefficient equals to 0.07 [14]

Skorbilowicz et al. (2017) provided a comparison of several empirical formulas for calculating the full mixing path of sewage in surface waters. The authors reported that calculation methods based on computational designs differed from each other, and concluded that there was no one-size-fits-all approach to characterise the multiple and complex factors affecting the mixing of treated wastewater with receiving waters [13].

The location of the discharge, and the coefficients used for modelling may result in significant differences in terms of outputs. To illustrate, mixing in the horizontal direction on the bank of the watercourse using the Fischer formula considers an α value of 0.12, while the Rutherford formula considers an α value of 0.536, which will result in a 4.5 times difference [13, 14, 15].

More complex approaches involve the use of models ranging from simple mass balance and dilution calculation spreadsheets to complex hydrodynamic and water quality models. No single model is appropriate for all types of discharges, and a combination of models to simulate far field and near field conditions is often appropriate [6]. Yet, the research available tends to agree on the importance to consider both 'best-case' and 'worst-case' modelling outputs [16, 6]. Similarly, the analysis of historical monitoring data (or field studies should monitoring data not be available) are recommended to inform mixing zones assessments [6], i.e. the results of modelling need to be demonstrably proven to be accurate and/or conservative for the given realities of a specific discharge.

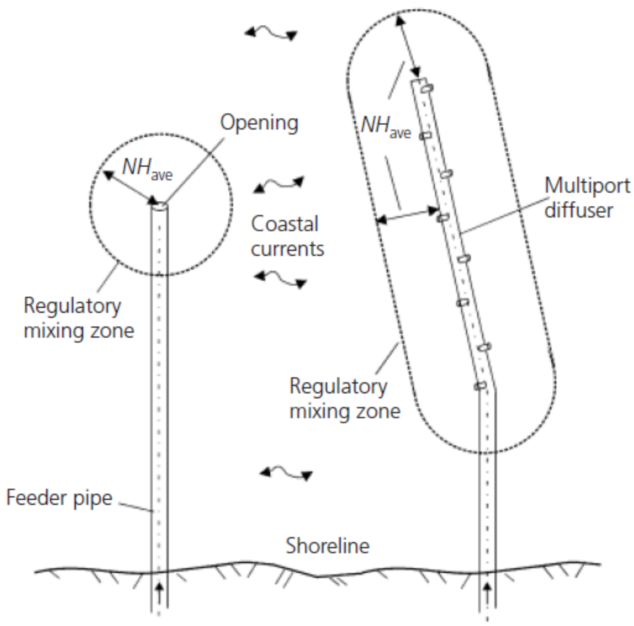
Interestingly, recent research conducted by Khandelwal et al. (2024) has called for a review of the use of empirical mixing lengths in streams and rivers after their research demonstrated discrepancies between experimental and empirical equations [17]. The authors further posited that these may be relating to threshold processes defining mixing at different flow regimes such as jet diffusion at low flows, the Coanda effect (which describes the tendency of a fluid to adhere to a curved surface) at intermediate flows, and turbulent mixing at higher flows [17].

Critically, the available literature suggests that modelling mixing zones for effluent discharges is inherently complex due to the multitude of factors that vary across water bodies and conditions. While empirical formulas and models provide valuable insights, they must be applied with caution and verified through field data when possible. The variability in flow regimes and water body characteristics makes it critical to adopt a site-specific approach rather than relying on a one-size-fits-all formula.

2.3.2. Coastal waters

For coastal waters, the mixing zone is defined as "a volume with vertical boundaries in the coastal water body that is limited in its horizontal extent to a distance equal to N multiples of the average water depth H_{ave} at the outfall location and measured in any direction from the outfall structure" (Figure 2) [3]. For a single port outfall, this would be a cylindrical volume centred on the port. For multiport diffusers, it would be a rectangular prism with semicircular cylinders at the ends. The value of N, typically between 1 and 10, should be set by regulatory authorities based on local conditions, with N=1 for highly sensitive waters and N=2 to 3 for most coastal waters [18].

Figure 2. Examples of regulatory mixing zone specifications for offshore submerged coastal discharges where the horizontal extent of the mixing zone is defined by some multiple N of the average water depth Have at the sea outfall: (left) single port outfall; (right) multiport diffuser sea outfall [3]



3. REGULATORY FRAMEWORK

3.1. EU LEGISLATION

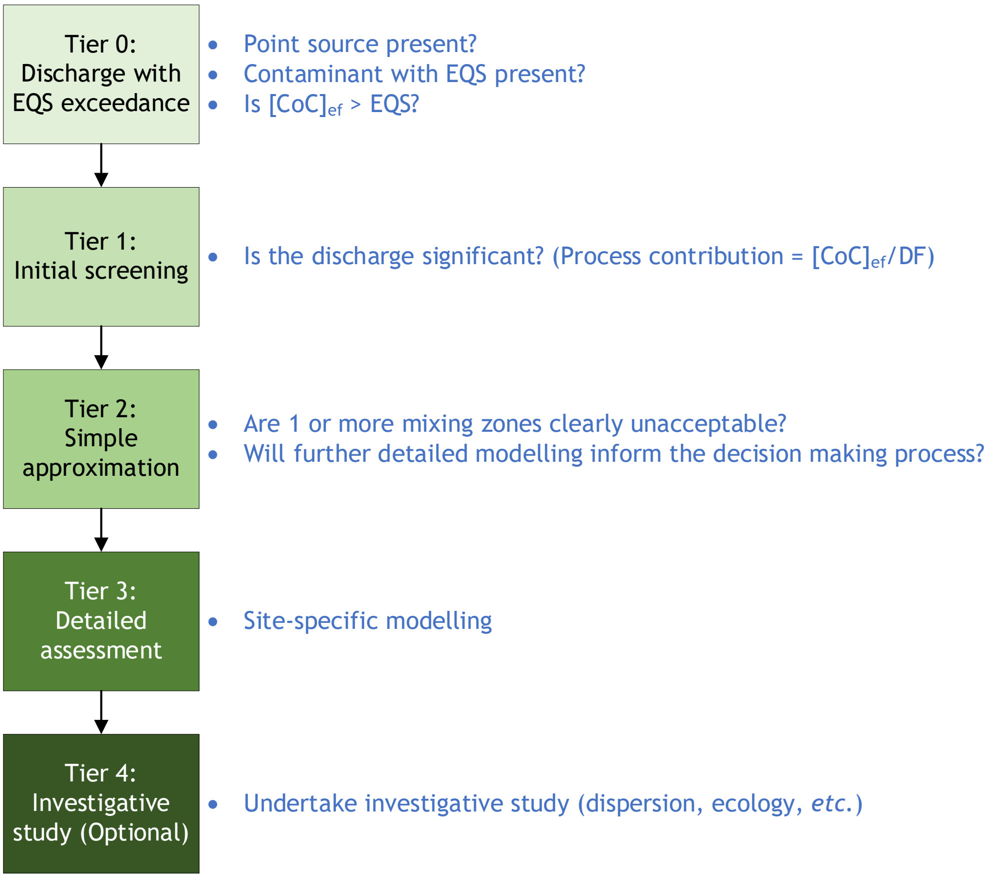
The EU water legislation shares an overarching objective of protecting human health and the environment from the combined effects of toxic and/or persistent pollutants. This concerns Directive 2000/60/EC (Water Framework Directive, WFD), and its two 'daughter' directives, namely Directive 2006/118/EC (Groundwater Directive) and Directive 2008/105/EC (Environmental Quality Standards Directive) which focus on the protection of groundwater and surface waters respectively.

Directive 2008/105/EC lays down EQS for priority substances and certain other pollutants with the aim of achieving good surface water chemical status. Article 4, of the present Directive, introduces the concept of mixing zones, granting Member States the discretion to establish these zones near discharge points into surface waters.

In these designated areas, concentrations of priority substances may surpass relevant EQS, provided they do not impede overall compliance of the water body with those standards. Member States opting for mixing zones must incorporate in their River Basin Management Plans an account of the methods used to delineate these zones and the measures enacted to decrease their extent in the future.

Technical guidelines have been produced to assist member state authorities to establish mixing zones in rivers, canals, lakes, and transitional waters and to determine the size and acceptability of the zones based on a tiered approach [19, 20], as described in Figure 3.

Figure 3. Tiered approach for determining the size and acceptability of mixing zones recommended by the European Commission [19]



Notes: CoC: Contaminant of Concern; DF: Dilution Factor

The European Commission technical guidelines introduce different cases for Tier 1 depending on the receiving water body (*i.e.* rivers and canals, lakes, transitional and coastal; Table 6).

Tier 2 consists in a "simple approximation" of the mixing zone concept that can be achieved using tools such as the Discharge Test (an auxiliary tool for these guidelines provided in Microsoft Excel workbook format) and commercially available software such as CORMIX and PLUMES analysis [20, 21, 22]. Furthermore, to assess the possibility of acute toxic effects in the mixing zone, it recommends using the Maximum Allowable Concentration (MAC)-EQS; while the Annual Average (AA)-EQS is proposed as sufficiently protective against short-term toxicity (i.e. used to address acute or episodic pollution scenarios leading to immediate ecological damage).

Table 6. Comparison of Tiers 1 and 2 guidelines [19]

Receiving water body	Tier 1	Tier 2
1a, Inland - Rivers and canals	• Calculate the Process Contribution (PC) • Express the PC as a % of the EQS • Compare the value to proposed allowable increase in concentration	The extent of EQS exceedance should be restricted to the lesser of 10 times the river width or 1 kilometre provided that this does not exceed 10% of water body length overall.
1b, Inland - Lakes	the Discharge Test in Tier 2	
1c, Transitional	• If the scenario tends towards a riverine water body, then apply Tier 1a. • If the estuary is not sufficiently 'riverine', Tier 1d is applied.	
1d, Coastal	• Check the discharge is well covered at all stages of the tide and is 'offshore' • Check the discharge is buoyant • Calculate the Effective Volume Flux (m^3/s) • Check if EQS is exceeded after initial dilution	Special considerations may be required if stratification occurs in deep waters.

Tier 3 requires a detailed modelling-based approach - it requires more complexity than in Tiers 1 and 2 (*e.g.* modelling based on worst-case assumptions, dynamic approach considering variability of discharges).

Tier 4 describes the use of investigative studies which is applied at the Member State discretion. It references a wide range of activities including: chemical concentrations of Priority Substances/Priority Hazardous Substances or other parameters under consideration, receptor characterisation, evidence of impairment of receptors, and literature reviews or new laboratory-based ecotoxicity studies.

3.2. EU NATIONAL TRANSPOSITIONS

Some countries have developed their own methodology based on the guidelines of the European Commission to facilitate the designation of mixing zones to the competent authorities [21]. The following section details the transposition of the relevant EU legislation at the national level.

3.2.1. Belgium

Belgium's three regions, namely Flanders, Wallonia and Brussels-Capital, have their own environmental legislation and regulations. The present section focuses on Flanders as it is the only region with active refineries. Additionally, Flanders has a more conservative legislation than the two other regions. Flanders is increasingly focusing on improving water quality to meet the WFD 'good status' objectives by

2027 to both chemical and ecological status. This may mean that discharge standards are becoming stricter and that there is less room for deviations in mixing zones.

3.2.1.1. Legislations

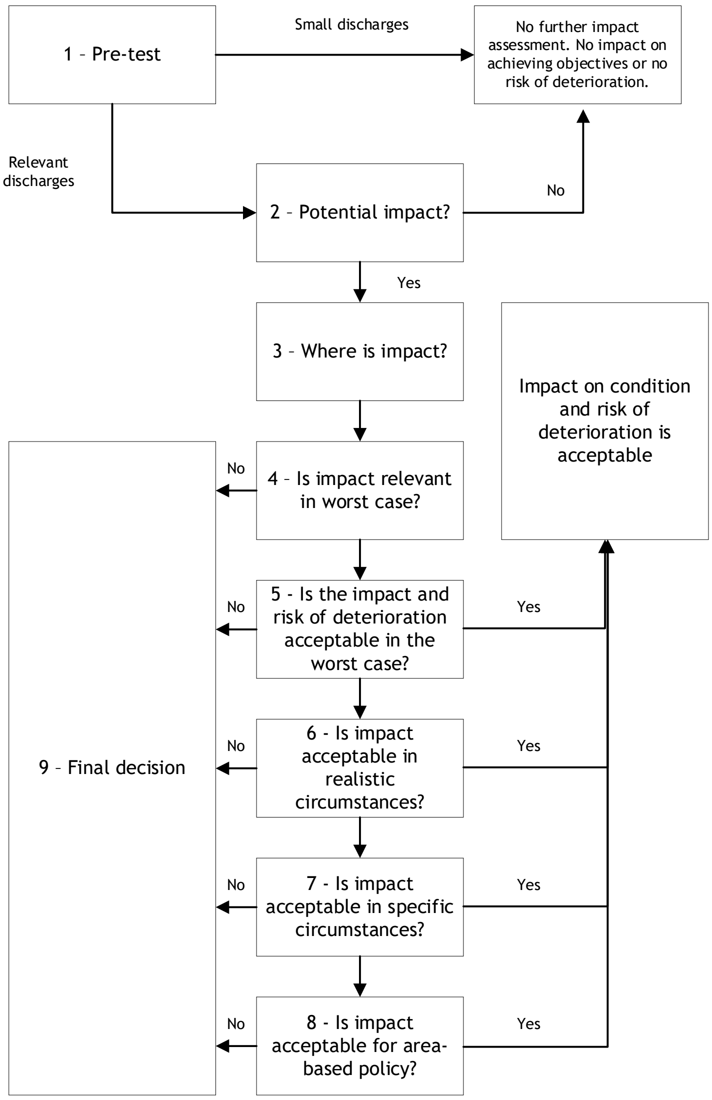
The *Decreet Integraal Waterbeleid* (Flemish Decree on Integrated Water Policy) is the juridical implementation of the WFD, the Groundwater Directive and Floods Directive in Flemish Law. It determines that the Flemish Government can designate mixing zones adjacent to discharge points. In these mixing zones, the concentrations of priority substances and pollutants designated by the Flemish Government may exceed the relevant environmental objectives, if this has no consequences for compliance with these standards in the rest of the surface water body in question. The overall management of water quality and the application of mixing zones is regulated and monitored by the *Vlaamse Milieumaatschappij* (VMM, Flemish Environment Agency).

The Decree defines the boundaries of the mixing zone as (i) limited to the vicinity of the discharge point, and (ii) to be proportional to the concentrations of the pollutants at the discharge point and the applicable conditions for the discharge of pollutants.

3.2.1.2. Design specifications

For new industrial wastewater discharges and adjustment/extensions of existing ones, an impact assessment must be carried out as part of the environmental permit application. This assessment is added as an appendix to the permit application. As presented in Figure 4, a 9-step plan has been developed with the final step being the final assessment of the discharge by the Flemish Environment Agency [22].

Figure 4. Nine-step assessment – adapted from VMM



An Excel calculation tool (*Wezertool*) has been developed to estimate the impact of a wastewater discharge [23]. The initial steps, 1 to 2, act as a screen to assess any potential impacts. Step 3 considers the receiving water body and its associated flowrate, while Step 4 involves upstream concentration data. The Step 5 of this assessment focuses on mixing zones, and generates automated outputs based on the inputted data. The purpose of Step 5 is to identify those discharges where the risk of not meeting the objectives, and the risk of quality deterioration are clearly acceptable or unacceptable. To investigate the risk of not meeting the objectives, it is considered whether the relevant test values are met downstream after complete dilution. In addition, it is examined whether the mixing zone is not too large relative to the dimensions of the receiving water body.

The determination of the mixing zone is considered necessary when the upstream concentration is lower than the test value and when the downstream concentration is also even lower than the test value. In all other cases, no mixing zones can be calculated because the mixing zone is considered infinite if it is exceeded. The calculated mixing zone is subsequently tested with respect to the dimensions of the receiving water body, so that no chemical barrier is formed in the watercourse that hinders or makes the migration of organisms impossible.

Within the *Wezertool*, depending on the pollutants discharged, a distinction is made between chronic and acute mixing zones. Chronic mixing zones are areas in a water body where long-term discharges of pollutants occur. The concentrations of these substances are such that under normal circumstances they do not cause direct, acute harmful effects on the environment, but they do have a long-term presence. Acute mixing zones, on the other hand, are areas in a water body where short-term discharges of high concentrations of pollutants occur. These substances can cause harmful effects upon direct exposure, but the discharge is of short duration.

The mixing zones are determined as follows:

<u>Chronic mixing zone</u>
The maximum length is determined as the minimum value of one of the following criteria:

- 10 times the width of the watercourse being assessed,
- 1,000 meters in length, or
- 1/10 of the length of the water body into which the discharge occurs.

The maximum width corresponding to 1/3 of the width of the watercourse being assessed.

<u>Acute mixing zone</u>
The maximum length is determined as the minimum value of one of the following criteria:

- 100
- 0 of the length of the water body into which the discharge occurs.

The maximum width is determined as 1/3 of the width of the watercourse being assessed.

3.2.2. France

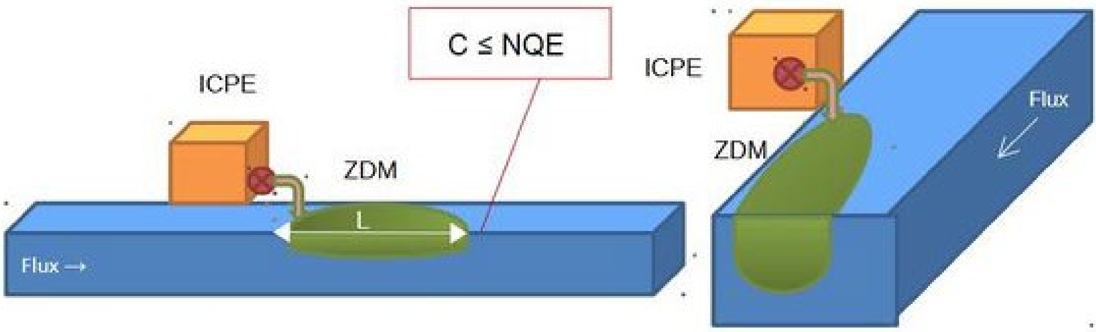
3.2.2.1. Relevant regulations

France transposed the Directive 2008/105/EC setting EQS in the field of water policy into their national legislation via the Ministerial Decree dated from 25th January 2010. This Decree introduces a definition of mixing zone as "*zone adjacente au point de rejet où les concentrations d'un ou plusieurs polluants peuvent dépasser les normes de qualité environnementales. Cette zone est proportionnée et limitée à la proximité du point de rejet et ne compromet pas le respect des normes de qualité environnementales sur le reste de la masse d'eau*" [Area adjacent to the discharge point where concentrations of one or more pollutants may exceed environmental quality standards. This area is proportionate and limited to the proximity of the discharge point and does not compromise compliance with environmental quality standards on the rest of the water body].

The Decree also requires the length (L in Figure 5) of a mixing zone (ZDM in Figure 5) to be proportionate to the width of the body of water and not to exceed:

- 10 times the width of the watercourse downstream of the discharge point;
- 10 percent of the length of the body of water into which the discharge takes place;
- 1 kilometre.

Figure 5. Schematic of a mixing zone [24]



Notes: ICPE: Installations Classified for the Protection of the Environment; NQE: EQS; ZDM: mixing zone

3.2.2.2. Mixing zone design

Prefectoral Orders, issued by Prefects, determine the discharge limits, and if required the length and width of the mixing zone.

The approach for a mixing zone in France [25] is based on technical guidelines provided by the European Commission [19]. If the conditions of Tiers 0 and 1 are not met (Table 6), then the modelling of a mixing zone is required.

For narrow surface watercourses, an empirical formula can be used as follows [26]:

$$L_m = \frac{K.V.B^2}{H}$$

Where:
L_m: mixing length (m)
K: constant varying from 2.6 if the discharge point is lateral to 1.6 if it is located in the middle of the watercourse
V: mean flowrate (m/s)
B: width (m)
H: mean depth (m/m)

For detailed approaches and cases involving coastal, estuary and “internal” (*e.g.* lakes) surface waters, the guideline refers to software packages developed by Deltares, including Delft3D which is a 2D/3D modelling system to investigate hydrodynamics, sediment transport and morphology and water quality [25].

3.2.3. Germany

3.2.3.1. Relevant regulations

In Germany, the WFD and the EQS Directive in accordance with Directive 2000/60/EC and 2008/105/EC are embedded in the *Wasserhaushaltsgesetz* (WHG, Water Resources Act), the *Oberflächengewässerverordnung* (OGewV, Ordinance on the Protection of Surface Waters) and the *Grundwasserverordnung* (GrWV, Groundwater Ordinance). These specify the requirements for emission analyses. Regarding emissions, the requirements of the *Abwasserverordnung* (AbwV, Wastewater Ordinance), Annex 1 must be complied with [27] [28] [29].

According to § 8 in conjunction with § 9 Para. 1 No. 4 of the WHG, the discharge of wastewater into a waterbody is subject to authorisation. This requires a water law (discharge) licence in accordance with § 8 WHG. It is determined whether the discharge complies with the state of the art according to § 57 WHG [30]. This means that the quantity and toxicity of the wastewater must be minimised to the extent possible using the relevant state-of-the-art processes (wastewater treatment, retention).

The impact that the discharge may have on the water body itself is also considered. To assess the potential impact on protected areas or objects, a dispersion calculation of discharge plumes may be required in the course of an impact assessment as part of the discharge permit application under water law.

When deciding on the discharge of treated or untreated mixed water and precipitation water into water bodies, the preservation and guarantee of the good status of the water body is decisive. The prohibition of deterioration applies (§ 27 para. 1 sentence 1 WHG).

For discharges from facilities that are subject to the areas of origin specified in the AbwV, minimum requirements for the discharge of wastewater are specified in the annexes to the AbwV. In all other cases, the minimum requirements (emission values) must be specified by the pertinent authority in the discharge permit [31].

The annexes to the AbwV, which are structured based on areas of origin, contain specific prevention and treatment measures as minimum requirements for the discharge of wastewater into surface water bodies. Since the amendment to the AbwV of 2 September 2014 (and most recently by the 10th amendment to the AbwV of 10 June 2020), the updated annexes to the AbwV also contain all the requirements for the (waste)water-related BAT published by the EU Commission [31] [32].

<u>AbwV § 3 General requirements</u>

(4) If requirements are specified prior to blending, blending for the purpose of joint treatment is permitted if at least the same overall reduction in pollutant load per parameter is achieved as if the respective requirements were met separately.

(5) If requirements are specified for the place where wastewater is produced, mixing shall only be permitted if these requirements are met.

(6) If wastewater streams to which different requirements apply are discharged together, the relevant requirement for each parameter shall be determined by means of a mixing calculation and specified in the authorisation under water law.

Paragraphs 4 and 5 shall remain unaffected if the applicable Annexes stipulate requirements for the place where the wastewater is produced or before mixing.

Section 5 (1) of the AbwV 'Reference point of the requirements' describes that the requirements relate to the point at which the wastewater is discharged into the water body and, if specified in the annexes to this ordinance, also to the point at which the wastewater arises or the point before it is mixed [32].

According to paragraph 2 of Annex 8 'Environmental quality standards for the assessment of chemical status of the OGewV, compliance with the environmental quality standards [...] must be monitored if there are discharges or inputs of these substances in the catchment area of the representative monitoring point for the surface water body.

If necessary, a technical report in accordance with the WFD may be required for a project to discharge wastewater into a water body to demonstrate that the discharge is compatible with the objectives of the WFD (*e.g.* EQSs are not exceeded by the discharge and whether deterioration of the water body is ruled out) [33].

3.2.3.2. Mixing zone design

Although Germany has integrated the European directives (2000/60/EC and 2008/105/EC) in the WHG, in the OGewV and in the GrwV, and the combined approach of analysing immissions (WHG, OGewV, GrwV) and emissions (AbwV) is applied, the concept of the mixing zone has not been included in the implementation of the WFD in German law. Furthermore, there is no definition of where exactly the EQS apply in the water body.

3.2.4. Italy

3.2.4.1. Relevant legislations

Italy transposed the Directive 2008/105/EC into their national legislation via the Legislative Decree n.219 dated from 10th December 2010 [34], which introduced the concept of *mixing zone* in the article 78-bis of the Legislative Decree 152/2006 (*Testo Unico dell'Ambiente*) [35].

The Decree establishes that the regions and autonomous provinces can designate mixing zones adjacent to points of discharge of wastewater. In these zones, the concentration of one or more substances in the priority list may exceed the applicable EQS, but in the meantime the exceedance shall not affect compliance with the EQS for the rest of the surface water body. It is worth noting that protected areas (defined according to Part three - Annex 9 of the Decree 152/2006) are excluded from the application of these dispositions.

The mixing zones can be established by the regions and autonomous provinces of Trento and Bolzano ensuring that the extension of each one is:

- Limited to the proximity of the discharge point,
- 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.

Moreover, the management of mixing zones shall be implemented through regional Water Protection Plans (*Piani di Tutela delle Acque*), in which they are designated by indicating:

- Location and extension;
- The approaches and methodologies applied to define these zones;
- The measures taken for the purpose of limiting the extent of mixing zones in the future.

3.2.4.2. Design specifications

It is worth noting that for Italy the designation and the calculation of mixing zones is not linked to specific national/international guidelines, for that reason this type of assessment should be carried out on the basis of the current state of art and/or known best practices [36].

To verify the achievement of EQS that identify the good chemical status of surface water, the regions and autonomous provinces of Trento and Bolzano shall compile and transmit to the National Institute for Environmental Protection and Research (*Istituto superiore per la protezione e ricerca ambientale – ISPRA*) a standard inventory of the release points in order to track all possible releases from diffuse sources, discharges, and leaks.

An example for the control of the mixing zone is defined by the IRSA-APAT 2003 method, which defines how to calculate the thermal increase due to the discharge of industrial water (typically cooling water) into the sea (or a water body), preserving the water quality status. The method explains how to estimate the water temperature reference and the thermal increase of water due to discharge, in order to verify that there is no increase of more than +3°C. Generally, propagation effects are assessed at 1,000 m from the discharge point, whereas for the Venetian Lagoon it is assessed at 100 m.

3.2.5. The Netherlands

3.2.5.1. Relevant legislations

The European Directive is implemented in Dutch legislation as '*Kaderrichtlijn Water (KRW)*', Water Framework Directive [37].

In the Netherlands, companies are required to obtain government permits that set the concentrations they are allowed to discharge at. Permit issuers often assess risks on a per-substance basis rather than considering the entire mixture [38]. Permit applications for discharges into surface waters must be assessed via the *Algemene beoordelingsmethodiek* (ABM, General Assessment Methodology), *immissietoets* (Immission Test) and *beste beschikbare technieken* (best available techniques). First it is determined if the concerning party that is requesting the permit is adhering to the best available techniques, then the ABM is applied. This tool classifies substances into categories of '*waterbezwaarlijkheid*', the extent to which there is a potential for adverse effects on the aquatic environment. The level of potential adverse effects determines the treatment intensity the requesting party must perform.

The *immissietoets* (Immission Test) is the final step in assessing a discharge, discussed after the ABM has been completed. This test assesses whether a discharge is acceptable from a water quality point of view. It is used to test whether the applicable water quality objectives are met at the edge of the mixing zone. The discharge is measured with *milieukwaliteitseisen* (MKE, environmental quality requirements). These determine the MAC of specific substances in the receiving surface water body. Besides the MKE's, there are also remaining substance concentrations that are used to measure the discharge.

Guidelines for the Immission Test, published by the Ministry of Infrastructure and Water Management, in the *Handboek Immissietoets*, includes information on testing mixing zones [39].

There are seven measuring steps to test at the edge of the mixing zone, considering the MKEs.

These steps are based on the technical guidelines for the identification of mixing zones, pursuant to article 4(4) of the Directive 2008/105/EC:

- Step 1 – Effluent test: testing if the planned discharge water concentration is lower than the desired environmental quality. If it is the case, the water quality cannot be influenced negatively, and no more testing is required.
- Step 2 - Trivial test: Screening the planned discharge water can be considered trivial (insignificant), purely based on the number of substances to be discharged in relation to the concentration already present in the receiving surface water (maximum increase in percentage). If this step is passed, step 7 must be done as well.
- Step 3 - Significance test: Testing the increase of concentration at the edge of the mixing zone. This cannot be more than 10% of the applicable AA-MKE. If this test is passed successfully, step 4 must be done.
- Step 4 - Norm test: Consider if the increase of concentration in addition to the background value does not lead to exceeding the desired water quality. If this test is passed successfully, step 7 must be done. If it does not pass the test, step 5 must be done.
- Step 5 - Water body level assessment: If the to be discharged water cannot adhere to the norm test, it goes against the European Directive 2000/60/EC and is therefore not allowed. Additional measures are required to minimize pollution and/or step 6 is applied.
- Step 6 - Testing the plan: assessing if in the future there will be 'space' based on estimated developments of the quality of a surface body.
- Step 7 - (Additional) Assessment impact on protected areas: if the discharged water has influence on a downstream protected area, the distance from the discharge point must be at least equal to the size of the AA-mixing zone and must adhere to the applicable MKE's.

The MKE are based on the requirements noted in the *Besluit kwaliteit leefomgeving* (Environment Quality Decree) and *Omgevingswet* (Environment and Planning Act) and are often measured at the edge of the mixing zone, so called *schadedrempel* (damage threshold) [40]. The following types of substances are being measured [39]:

- **Substances of priority according to the Directive 2008/105/EC regarding priority substances in the field of water policy [41]**

For this category of substances, there are two different MKEs:

- MKE expressed as an annual average (AA-MKE): at every representative measuring point in the water body, the arithmetic mean of all the measured total concentrations in the whole water sample of all isomers (if applicable) of that substance cannot exceed the MKE.
- MKE expressed as the MAC (MAC-MKE): none of the total measured concentration in the full water sample is allowed to exceed the MKE at every representative measuring point in the waterbody.

If the concentration of a MAC-MKE is higher, it can lead to acute effects and above the AA-MKE can lead to chronic effects. To prevent acute effects, the size of the MAC-mixing zone has to be smaller than the AA-MKE. This means that:

- AA-mixing zone:
  - 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 1,000 meters.
  - Lakes: the AA-mixing zone may not exceed 0.25 times the diameter of the lake with a maximum of 1,000 meters.
- MAC-mixing zone:
  - Linear water systems: the MAC-zone may never exceed 0.25 times the width of the water system with a maximum of 25 meters.
  - Lakes: may not exceed 0.0065 times the diameter of the lake, also with a maximum of 25 meters.

- **Substances relevant for the ecological conditions and ecological potential of the waterbody**

These substances are called *specifieke verontreinigende stoffen* (specific pollutants). To maintain good ecological conditions in natural waterbodies, these substances cannot exceed the listed maximum concentration per annum (listed in the Environment Quality Decree, annex IIIa). This is also valid for rapidly changing and artificial water bodies. The measuring point is again at the edge of the mixing zone.

- **Assessment of other (standardized) substances**

For other substances besides the substances of priority and specific pollutants, there are indicative norms. These can be found on the website of www.rivm.nl at 'Risico's van stoffen' (risks of substances).

The testing on these substances is also done at the edge of the mixing zone, which is allowed to be the same size as mixing zones for priority substances.

For the substances without indicative norms (with a potential chemical or negative effect on the water quality or the societal functions of the concerning water systems), an Immission Test must be performed. In order to do this, one must determine a 'norm', this can be done based on toxicity level data and considering safety factors.

- **Requirements arising from protected areas**

Certain waterbodies could have additional functions that bring additional or stricter requirements, such as the water body functioning for drink water, swimming water, water for shellfish and bodies of water part of Natura-2000. For these areas, there will be additional measuring requirements.

3.2.5.2. Design specifications

Mixing zones have been designated in all River Basin Districts in the Netherlands. The Netherlands reports that the methodology for the designation of Mixing Zones in these River Basin Districts follows the tiered approach as laid down in the 'Technical Background Document on Identification of Mixing Zones' [19].

The River Basin Management Plan refer to the methodology from the "Guidance Immission assessment" which comprises four tiers: Tier 0 (Is pollution present?), Tier 1 (An initial screening if emission is trivial), Tier 2 (simple dilution calculations), Tier 3 (Detailed modelling), and Tier 4 (Research and validation of models). The Netherlands clarified that an assessment of fictive discharges in different types of water bodies was carried out with the above methodology. In each case, the distance where the Environmental Quality Standards were met was significantly smaller than the maximal size of the mixing zone mentioned in the CIS Guidance Document. The Netherlands also mentioned that the implementation of new Best Available Techniques should further reduce the extent of the mixing zones in the future [42].

Testing of mixing zones for cooling water:

The mixing zone is one of three criteria to test cooling waters. The mixing zone-test is based on the mixing of cooling water with the receiving surface water until the temperature is equal to the *ernstig risico niveau (*severe risk level). Concerning cooling waters, a maximum percentage of the hydraulic cross-section and maximum volume in which the temperature is higher than the severe risk level. The severe risk level is 30 degrees Celsius for fresh water and 25 degrees for saline water. With the mixing zone-test it is assumed that there is complete mixture within the mixing zone, so a worst-case scenario regarding the magnitude of the mixing zone. The formula to calculate its magnitude is as follows:

$$Mixing\ zone = \frac{Qcoolingwater}{Qflowrate\ waterbody} * (1 + \frac{Tdischarge - severe\ risk\ level}{severe\ risk\ level - Tbackground}$$

In this formula, the Q is concerned with flowrate in cubic metre per second (m3/s) of the cooling water being discharged, and the flowrate of the receiving waterbody. T relates to the temperature in Celsius ($^{\circ}$C), so the temperature of the discharged water and the temperature upstream the receiving waterbody at the edge of the zone to be maintained (background) [43].

In summary, the Netherlands integrates the European Directives (2000/60/EC and 2008/105/EC) as *Kaderrichtlijn Water*, Environment and Planning Act and in the Environment Quality Decree to establish the ways and norms to measure mixing zones. There are several aspects to consider when setting up a mixing zone, such as the existing water quality, types of substances to be discharged and its maximum acceptable concentration, the established environmental quality requirements and potential for additional measures needed based on the water body's function.

3.2.6. Norway

3.2.6.1. Legislations

The WFD is implemented in Norway through the *Vannforskriften* (Water Regulation) which provides a framework for setting environmental targets that ensure the protection and sustainable use of water resources [44]. Water bodies included are surface water (lakes, reservoirs, rivers, streams, canals, fjords or coastal waters), parts of these, or a limited amount of groundwater within aquifers[3].

The Water Regulation is transposed into national law through the following acts:

- Pollution Act (forurensningsloven)
- Diversity Act (naturmangfoldloven)
- Water Resources Act (vannressursloven)
- Planning and Building Act (*plan-og bygningsloven*)

3.2.6.2. Design specifications

In December 2010, the *Common Implementation Strategy - Guidance on setting mixing zones under the EQS-directive (2008/105/EC)* was prepared for the Climate and Pollution Directorate (*Klima-og forurensningsdirektoratet*) by the Norwegian Institute for Water Research (*Norsk institutt for vannforskning*) [45]. The report assesses the EU Directive 2008/105/EC with regard to Norwegian conditions. It was found that the models and approximations used to determine mixing zones in the Directive largely corresponded to those already used in Norwegian practice. The process of applying these models and approximations apply if concentrations in the effluent water exceed the respective EQS values.

- Level 1: Basic calculations of dilution and concentrations at certain distances away from the point of discharge. If results indicate significant impacts to water quality the evaluation proceeds to Level 2.
- Level 2: The objective here is to provide a basic quantification of the volume of water that exceeds EQS values, preferably by applying a simplistic mathematical model. If there is uncertainty about the representativeness of the calculated results the evaluation proceeds to Level 3.
- Level 3: The objective is to determine the volumes of water that exceed the EQS values during varying discharge volumes, mixing zone size and concentrations using advanced computer modelling. If unacceptable uncertainty remains the evaluation proceeds to Level 4.
- Level 4: Voluntary investigative study to verify or calibrate the results from Level 3. This may include sampling of water, sediment, organisms and various hydrographic measurements.

Some considerations need to be made to the guidelines for use in Norway (Table 7). Advice for methodology changes can be found in the guidance document.

[3] There are multiple references to this specific choice of words in the regulatory document. They are clarifying that the regulations do not necessarily apply to an entire watershed area but may only apply to a certain portion of the aquifer.

Table 7. Additional considerations for water bodies in Norway

Water Body	Consideration
Rivers	High and low tides affect the impact of effluent on whether EQS limits have been reached. However, this is not specific to Norway, hence, amendments to the EU Directive methodology are not required.
Lakes	There can be large differences in the mixing zones of lakes depending on the annual cycle. Norwegian climate causes vertical circulation in water bodies of lakes twice a year due to temperature change. EU guidelines do not take into account the two stagnation periods and two circulation periods; hence adaptations must be made to the methodology.
Fjord	There are two types of fjords in Norway: fjords with thresholds and fjords without threshold. Many threshold fjords have cities or industries located at the inner part, and often as the outlet at the waterway. This means that the wastewater can remain near the mouth of the river and that extra care for ecosystems is required when discharge is assessed. Fjords without thresholds often have better capacity to receive effluent. Considerations to be taken include: • **Freshwater supply:** Where there is significant freshwater supply, two conditions arise that are relevant to mixing zones. Firstly, a two-way current system is formed of outward flowing brackish water and a smaller incoming flow of sea water. Wastewater should be avoided in brackish water. It is also important to avoid wastewater being stored in the incoming sea water flow, which can lead the diluted wastewater back to vulnerable ecosystems in the estuary. • **Current:** Tidal flow is a central factor in the spread and dilution of wastewater. In Norway the semi-daily tide dominates the tide, which often means that current direction and current speed varies with a period of 12.4 hours.
Archipelagos and Coastal Waters	Most of what is mentioned for fjords will apply to emissions in archipelagos and coastal waters. However, compared to fjords, the following 3 factors should be taken into account: • Fresh water supply is usually very small • For wastewater stored at depth, it will most often be found that the current strength is larger than inside a fjord • The topography is often more "open" and the volumes of water in which wastewater can be diluted are larger than in the fjords.

As detailed in the guidance document prepared for the Climate and Pollution Directorate, variations in current strength and volume of effluent will impact the size of the mixing zone. This means that to assess the size of a mixing zone, an assessment of combinations of the following factors should be completed:

- Volume or concentration of the effluent
- Vertical layering of the water body
- Current strength

If impacts on surface layers of the water body must be avoided, or there are extra requirements on the extend of the mixing zone which entails the dilution of effluent, the use of a diffuser should be considered A diffuser is a cylindrical attachment mounted on the end of a discharge line with many small holes (typically 8-15 cm in diameter, spaced 2-3 cm apart), which can increase the dilution of the discharge and therefore reduce the extent of the mixing zone.

3.2.7. Spain

3.2.7.1. Legislations

In Spain, the Directive 2008/105/EC was transposed into several national regulations (*Real Decreto*, RD) as follows:

- RD 60/2011 dated from 21st January 2011 on EQS included a mention about the mixing zone at a very high level. It states that if this was defined, then it requires to reflect it in the corresponding Basin Hydrological Plan. In addition, strategies to reduce its surface area in the future must be defined. There was no further reference on how to define a mixing zone or what technical guidance should be considered to do so.
- RD 817/2015 dated from 11th September 2015, on monitoring and assessment criteria for surface water quality and EQS superseded the RD 60/2011 and set the first formal definition of the mixing zone in Article 3.47:
    - *"Zona adyacente a un punto de vertido donde las concentraciones de los diferentes constituyentes del mismo pueden no corresponder al régimen de mezcla completa del efluente y el medio receptor."* [Zone adjacent to a point of discharge where the concentrations of the different constituents may not correspond to the regime of complete mixing of the effluent and the receiving water body]
- The remainder of the text of RD 817/2015 (Article 26) is the same as the abolished RD 60/2011.
- RD 663/2023 dated from 31st August 2023 on the modification of the Public Hydraulic Domain Regulations in Spain includes a reference to the mixing zone as part of the requirements to assess the compliance with the environmental objectives of the overflowing water discharges produced during rainfall events (Article 7.4 of Annex XI)
- "b) La muestra del medio receptor debe ser representativa por lo que son de aplicación las consideraciones sobre zona de mezcla señaladas en el articulo 26 del Real Decreto 817/2015 del 11 de septiembre y desarrolladas en el anexo III sobre Objeto de Inspección 3 – Calidad Medio Receptor del Protocolo de inspección de vertidos de aguas residuales destinado a las entidades colaboradoras de la administración hidráulica." [The sample in the receptor media must be representative and as such considerations about the mixing zone must be made as indicated in the Article 26 of RD 817/2015 and as developed in Annex III about Inspection Object 3 – Quality of the receptor media of the Inspection Protocol for wastewater discharges to be followed by Accredited Inspection Entities from the Hydraulic Authority]

From this last reference included within the RD 663/2023, a brief guidance to set the mixing zone which will allow to place a sampling point is developed (point III.6.4 in Annex III), and must be applied sequentially as follows:

- Mixing zone as defined in the discharge permit or as a condition requested to the discharge subject.
- Mixing zone as defined by the Water Basin Authorities and in accordance with Directive 2008/105/EC and RD 60/2011.
- The Water Basin Authority has established a designated mixing zone or the downstream sampling location along with the direct request for inspection.
- As defined in the document for technical guidance to identify mixing zones in accordance with the Article 4, Section 4 from the Directive 2008/105/EC and with the aim that the excess of contamination does not impact the overall water body quality. From the above, the mixing zone should be limited to the minimum of the values represented by 10xW (river width) or 1 kilometre but always considering that 10% of the length of the water body is not exceeded. This criterion does not apply to stocked waters or groundwaters.

Overall, it can be observed that at a national level regulation about mixing zones is not fully defined and its use has not become normal.

- At a water basin level and regarding points b) and c) above, there are 18 Water Basin Authorities in Spain that should have to deploy a more precise definition of the mixing zone with a description of the approaches and methods applied to define such zones, as well as the measures adopted to reduce the extension of such mixing zone in the future [1]. However, these further developments are very limited and currently only three Plans have introduced this concept:
- The Miño-Sil Hydrological Plan introduces the concept in a theoretical way and, for the moment, does not have any practical application.
- The Guadalquivir Hydrological Plan defines a specific value for the mixing zone without considering any characteristic of the receiving ecosystem: type, width, length, currents, type of priority substance or contaminant, etc. It defines mixing zones for the discharges in a river of wastewater treatment plants (WwTP) as 100 m downstream of the point of discharge. It does not define the methodology and focuses on WwTP discharges in a river.
- The Management Plan of the River Basin District of Catalonia defines mixing zones as a fixed value for discharges at the coast (circumference with a radius of 50 m) and for direct discharges into rivers (50 m downstream from the point of discharge).

In summary, these definitions or designations of mixing zones are not adapted to Directive 2008/105/EC. There are not descriptions and/or explanations of the applied approaches and methods to delimit it. Furthermore, the definition of mixing zone with fixed values is inaccurate, and it may not make sense because it may be too large or insufficient [1].

3.2.8. United Kingdom

3.2.8.1. England and Wales

England and Wales follow the EU guidance set out under the WFD and other EU water laws to define mixing zones. Under The Water Environment (Water Framework Directive) (England and Wales) Regulations 2017, Article 4(2) information relating to mixing zones, if the activity releases chemicals listed on the 'EQSD List' and has a mixing zone, like a discharge pipeline or outfall, the Environment Agency's 'Surface water pollution risk assessment guidance' must be followed as part of the Environmental Permitting Regulations guidance [46].

The Surface water pollution risk assessment include a three-step screening process to (i) identify the pollutants released from a plant, (ii) gather data on pollutants, and (iii) carry out the screening tests either for freshwater or estuaries and coastal waters. Should the risk assessment screening tests not screen out pollutants, further modelling is required. Mixing zones are only described for modelling tests to be conducted for transitional and coastal waters for simple modelling and complex hydrodynamic [47]; the purpose of these modelling tests is to determine of the mixing zone is acceptable or not.

Unlike England and Wales, which follow the EU process for defining mixing zones, both Scotland and Northern Ireland have independent regulations for the identification of mixing zones, these are outlined in the following sections (3.2.8.2 and 3.2.8.3).

3.2.8.2. Scotland

According to The Scottish Environmental Protection Agency (SEPA), the mixing zone should meet all of the following criteria that are relevant:

- It is expected that the mixing zone around the effluent surface boil would normally be set at a maximum distance of 100 m in any direction (that the plume may travel) from the centre of the boil, or from the nearest individual diffuser boil where there is a multiport arrangement. The dilution this allows must be calculated for each site.
- The concentration of dispersing effluent must be such that no established relevant UK or SEPA chemical EQS is breached out with the mixing zone. This must take account of the individual standards which may be expressed as annual mean values, or percentile exceedance values, or maximum allowable concentrations.
- Where an effluent requires control through toxicity-based criteria then the concentration of dispersing effluent must be such that there is no residual toxicity out with the defined mixing zone i.e. the residual concentration of the toxic substance shall comply with the PNEC lethal or sub-lethal, acute or chronic, determined from an appropriate SEPA approved toxicity test (see Definitions).
- After initial dilution there should no point within the mixing zone where the residual concentration of effluent exceeds the 3-hour acute No Observed Effects Concentration (NOEC) for any SEPA approved lethal or sub-lethal test. Twenty-four-hour acute tests may be substituted where such test data cannot be obtained.
- Two or more mixing zones from different neighbouring outfalls must not merge or take up all the diluting capacity of any receiving water body. It is recommended that the edges of the mixing zones be at least 100 m apart. If, for any reason, this criterion cannot be met, then the toxicity of the mixed effluents must be considered.
- Normally no mixing zone would be expected to impinge on the MLWS shoreline, although SEPA recognises that this may be varied in narrow estuarine locations.
- A mixing zone should generally not plug an estuary, sea loch or small bay. It is expected that a mixing zone in such a situation should take up no more than a half of the narrowest dimension.
- SEPA has a statutory obligation, under the Conservation Regulations, not to issue a licence for any discharge which has been shown, by an appropriate assessment, to be likely to have an adverse effect on the designated

conservation interests of a Special Area of Conservation (SAC, under the European Habitats Directive) or a Special Protection Area (SPA, under the European Wild Birds Directive). Where a mixing zone may impinge on any SAC or SPA, SEPA has a duty to ensure, before issuing a licence, that the integrity of the site will not be adversely affected. The integrity of a site is defined in the Habitats Directive 92/43/EEC (CELEX: 31992L0043) as the coherence of its ecological structure and function, across its whole area, that enables it to sustain the habitat, complex of habitats and/or levels of populations of the species for which it was classified. SEPA will ensure that no mixing zone will jeopardise the integrity of any designated sites and will apply the same approach to other sites with statutory conservation designation (*e.g.* SSSIs). Consideration will also be given to other areas which have a recognised, but non statutory, conservation interest (egg Marine Consultation Areas).

- The mixing zone should not give rise to any significant visible slicks or other aesthetic problems.
- Where solids are present in the effluent, and where these solids are expected to accumulate on the seabed, a similar approach to that used for the liquid dispersal will be utilised. In this case the 100m mixing zone is retained but the toxicity criteria must recognise the extended exposure times possible for the resident benthic organisms.

The seabed sediment must meet standstill clauses for appropriate EC dangerous substances outside the mixing zone. Build-up of other potentially toxic substances must also be avoided but no formally accepted quantitative standards currently exist.

SEPA will expect that no solids will be permitted to accumulate on the seabed within the identified mixing zone in quantities which would give rise to acute toxicity. However, the science of sediment toxicity is in a developmental stage with no widely agreed protocols for toxicity testing. SEPA will discuss individual cases with each discharger.

3.2.8.3. Northern Ireland

According to the Water Framework Directive (Priority Substances and Classification) Regulations (Northern Ireland) 2011, the Department of the Environment may designate mixing zones adjacent to points of discharge under the following conditions:

- Concentrations of one or more substances listed in Table 38 of Part 2 of Schedule 1 may exceed the relevant standards within mixing zones if they do not affect the compliance of the rest of the body of surface water with those standards.
- The extent of any mixing zone shall be restricted to the proximity of the point of discharge and shall be proportionate, having regard to concentrations of pollutants at the point of discharge and any conditions contained within the discharge consent or permit.
- The Department of Environment shall include information about designated mixing zones in river basin management plans. This information shall include a description of: (i) the approaches and methodologies applied to define mixing zones; and (ii) measures taken with a view to reducing the extent of mixing zones in the future.

3.3. OTHER REGULATORY FRAMEWORKS

Mixing zones, in an international context, are not a new concept, and it can be found in regulations of other countries. These are further discussed in the subsequent sections.

3.3.1. United States

As described in Title 40 Section 131.13 of the Code of Federal Regulations [48], "States may, at their discretion, include in their state standards, policies generally affecting their application and implementation, such as mixing zones, low flows and variances. Such policies are subject to EPA review and approval."

Per the US EPA's Water Quality Standards Handbook, the following specific mixing zone language was identified:

- "*For lakes, estuaries, and coastal waters, dimensions [of the mixing zone] are usually specified by surface area, width, cross-sectional area, and/or volume. The EPA recommends that states and tribes use methods that result in quantitative measures sufficient for permitting authorities to develop Water Quality-based Effluent Limitations (WQBELs) in a transparent and straightforward manner*." [49]
- Similar to other regions, the USEPA defines the actual size of the mixing zone for a discharge on a case-by-case basis: "*The EPA recommends that specific characteristics of an individual mixing zone for a specific discharger be defined on a case-by-case basis using the state or tribal mixing zone policy. This site-specific assessment would ideally take into consideration the physical, chemical, and biological characteristics of the discharge (including the type of pollutant discharged) and receiving waterbody; the life history and behavior of organisms in the receiving waterbody; and the designated uses of the waterbody*." [49]

The US EPA's National Pollutant Discharge Elimination System (NPDES) General Permit for offshore oil and gas operations establishes effluent limitations, prohibitions, reporting requirements, and other conditions on discharges. The following mixing zone extents are discussed in the NPDES General Permit for offshore dischargers in the western Gulf of Mexico for different discharges: produced water, hydrate control fluids and pipeline brines:

- Produced Water – "*Permittees discharging Produced Water at a rate greater than 75,000 bbl/day shall determine the critical dilution using CORMIX version 7.0 (or higher). In order to be in compliance with a WET limit, the No Observable Effect Concentration (NOEC) must be equal to or greater than the critical dilution concentration specified in Appendix D, Table 1 (1-A through 1-F) of this permit*." [49]. The permit specifies the critical dilution to be achieved at 100 m.
- Hydrate Control Fluids – "*In case a discharge of hydrate control fluids is not monitored by the toxicity testing of either produced water or miscellaneous discharge, the permittee must conduct a 7-day chronic toxicity test for that specific hydrate control fluid prior to the discharge, and demonstrate that the final critical dilution at the edge of the 100 meters from the point discharge must not exceed its No Observable Effect Concentration (NOEC). The discharger shall present the modelling result using CORMIX 7.0 or later version and the toxicity testing result in the Discharge Monitoring Reports (DMR).*" [50]

- Pipeline Brines – "*The Operator must control the discharge rate to ensure the applicable critical dilution at the edge of 100 meters from the point of discharge (using CORMIX or other dispersion modelling) will not exceed its NOEC*." [50]

3.3.2. Australia and New Zealand

Technical information is provided in the ANZECC and ARMCANZ's National Water Quality Management Strategy document [51]. These guidelines state that:

- Mixing zones are not considered appropriate for managing the discharge of nutrients, bioaccumulatory or particulate substances.
- Mixing zones are not applicable to waters which "have values or characteristics which are not compatible with the existence of a plume of water which does not meet ambient management goals" (e.g. waters which either: (a) receive significant and regular use for primary; contact recreation; (b) are recognised as of significant value as spawning or nursery areas; (c) are close to areas used for aquaculture; (d) are close to potable water supply intakes; (e) are of outstanding ecological or scientific importance; (f) have high conservation ecosystem values; or (g) where the mixing zone plume is likely to hug the shoreline).
- Models should consider the stratification effect (*e.g.* due to differences in density between the effluent and the receiving water).

As mixing zones are regulated at the state or territory level in Australia, and the regional council level in New Zealand, local guidelines have also been developed. For instance, these include the Northern Territory [52], Queensland [53], Victoria [54], and the Auckland Regional Council [55].

3.3.2.1. Design specifications

High-level design specifications are provided by the Australian Government Initiative (AGI) stating that: "if mixing zones are to be applied, then they should be as small as practicable". Furthermore, for river or coastal waters, the mixing zone should not extend across the entire width of the waterway and impact on biota migration pathways [56]

The boundary is usually defined in terms of the concentrations of indicator species in the effluent. A standard distance for mixing zone or point of compliance is not specified by the ANZECC; rather, it refers to an "agreed zone" based on site-specific conditions and receptor sensitivities.

In terms of modelling, the guidelines recommend that modelling results should be discussed both in terms of the probabilities of certain outcomes and the range of uncertainty within the model's predictions [51].

Although CORMIX is referenced as one of the existing modelling tools available, others can be considered as long as a good understanding of the assumptions made is provided (with the consequence of these assumptions when interpreting the results), the model has a publication record in relevant applications and has a good technical support.

In addition, local guidelines such as those prepared by the Environment Protection Authority Victoria (2010) contains further recommendations for modelling. The establishment of a mixing zone is analysed on a case-by-case basis but considers:

(a) identifying the beneficial uses and local values of the receiving waters, (b) characterisation of the effluent and receiving waterbody, (c) determining the dilution and dispersion of the effluent, (d) assessing the impact of the effluent discharge to beneficial uses and local values.

The recommendations also include the parameters to be considered based on the receiving water body:

- Rivers and streams: flow regime needs to be characterized; modelling should consider low-flow conditions (determined from long-term data under recent climatic conditions) taking into account seasonal and climatic variability. These flow data are used to identify the month with the lowest average flow over the whole data set. The minimum flow for the mixing zone calculation is the 10th percentile value for all observations for that month.
- Coastal: characteristics such as tidal and current movements, density and temperature differences, depth of water and rate of flow need to be considered, and appropriate modelling conducted to assess the dilution capabilities of the waterbody under various scenarios.

3.4. INTERNATIONAL GUIDELINES

3.4.1. United Nations Environment Programme

The Mediterranean Countries are cooperating under the Mediterranean Action Plan (MAP) to control the inputs of pollutants into the marine ecosystem of the Mediterranean Sea. “Guidelines for authorizations for the discharge of liquid wastes into the Mediterranean Sea” were prepared for the World Health Organization (WHO) to provide national and local authorities with relevant information on requirements and conditions attached to the issue of authorizations for the discharge of liquid wastes into the coastal marine environment in terms of national legislation enacted in conformity with the provisions of the Protocol for the Protection of the Mediterranean Sea against Pollution from Land-based Sources and Activities, and in accordance with measures adopted by Contracting Parties to date for the progressive implementation of the original protocol in question [57].

The mixing zone concept was introduced for Mercury and Mercury Compounds such as “the increase of mercury concentrations in biota and sediments at a radius of 5 km from the outfall structures will not be more than 50% above background levels” [57].

3.4.2. International Finance Corporation

The International Finance Corporation (IFC)’s Environmental, Health and Safety guidelines include general liquid effluent quality. It states that “*discharges of process wastewater, sanitary wastewater, wastewater from utility operations or stormwater to surface water should not result in contaminant concentrations in excess of local ambient water quality criteria or, in the absence of local criteria, other sources of ambient water quality*” [58].

The mixing zone concept is introduced such as the “*temperature of wastewater prior to discharge does not result in an increase greater than 3°C of ambient temperature at the edge of a scientifically established mixing zone which takes into account ambient water quality, receiving water use and assimilative capacity among other considerations*” [58].

Guidelines specific to the Oil and Gas sector include:

- Liquefied Natural Gas (LNG) Facilities
- Offshore Oil and Gas Development: the mixing zone concept is introduced in relation to cooling water discharge such as the "*temperature is within 3 degrees Celsius of ambient seawater temperature at the edge of the defined mixing zone, or if the mixing zone is not defined, within 100 meters of the discharge point*" [59].
- Onshore Oil and Gas Development: recommends that cooling water should "*discharged to surface waters in a location that will allow maximum mixing and cooling of the thermal plume to ensure that the temperature is within 3 degrees Celsius of ambient temperature at the edge of the defined mixing zone or within 100 meters of the discharge point*" [60].

3.5. SUMMARY

Mixing zone regulations vary significantly across different regions, reflecting diverse environmental priorities, legal frameworks and industrial practices; summary of which is provided for the studied European countries in Table 8.

Table 8. Summary of mixing zone framework across selected European Countries

Country	Maturity level	Complexity	Sizing	
Belgium, Flanders	Detailed guidelines developed.	Complex, but logical, process in place.	<u>Chronic mixing zone</u> The maximum length is determined as the minimum value of one of the following criteria: • 10 times the width of the watercourse being assessed, • 1,000 meters in length, or • 1/10 of the length of the water body into which the discharge occurs. The maximum width corresponding to 1/3 of the width of the watercourse being assessed.	<u>Acute mixing zone</u> The maximum length is determined as the minimum value of one of the following criteria: • 100 meters, or • 1/100 of the length of the water body into which the discharge occurs. The maximum width is determined as 1/3 of the width of the watercourse being assessed.
France	Some guidelines developed.	Relatively simple design recommendations provided, mostly relying on empirical formulas.	Cannot exceed: (i) 10 times the width of the watercourse downstream of the discharge point (ii) 10% of the length of the body of water into which the discharge takes place (iii) 1 kilometre.	
Germany	No technical guideline developed.		At the discharge point. No sizing guidelines provided.	
Italy	No technical guideline developed.		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.	

Country	Maturity level	Complexity	Sizing	
The Netherlands	Detailed guidelines developed.	Complex, but logical, process in place.	**AA-mixing zone:** • 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 1,000 meters. • Lakes: the AA mixing zone may not exceed 0.25 times the diameter of the lake with a maximum of 1,000 meters.	**MAC mixing zone:** • Linear water systems: the MAC zone may never exceed 0.25 times the width of the water system with a maximum of 25 meters. • Lakes: may not exceed 0.0065 times the diameter of the lake, also with a maximum of 25 meters.
Norway	Some guidelines developed.		Sizing considerations are provided for water bodies in Norway including rivers, lakes, fjords, archipelagos and coastal waters.	
Spain	No guidelines developed.		Defined as a zone adjacent to a point of discharge. Limited to 10x the river width or 1 kilometre but always considering that 10% of the length of the water body is not exceeded.	
United Kingdom	Some guidelines developed, with complexity varying on the country.		SEPA sets a maximum distance of 100 m in any direction; in Northern Ireland, it is restricted to the proximity of the point of discharge.	

Although the mixing zone concept has been incorporated into the national legislations of EU Member States, and EU-wide design guidance has been developed, its application varies significantly from one country to another (Table 8). For instance, the Netherlands and Belgium (Flanders) scored the highest in terms of maturity and complexity, providing a detailed methodology as part of the environmental permitting process, with the mixing zone being an integral component. In contrast, other countries offer little to no design guidance (Table 8).

This inconsistency highlights the need for more harmonised practices and robust frameworks that account for regional variations such as hydrology and geography. Although achieving uniform application of environmental standards across Member States will be a complex and challenging task, this effort is essential for better environmental protection and regulatory efficiency.

However, considering a scenario where mixing zones are phased out, industries may need to prepare for a future where mixing zones are less tolerated, potentially replaced by more advanced, in-plant treatment technologies. This would mean retrofitting existing facilities or investing in new treatment infrastructure, which could lead to significant costs, particularly for industries already facing reduced demand in the transition to a low-carbon economy.

The subsequent section explores the practical application of mixing zones within European refineries through a survey.

4. SURVEY

A digital questionnaire was developed to collect data in relation to effluent discharge approaches across European refineries belonging to Concawe members. The survey covered four main topics, namely details on the facility, the discharge permit, the mixing zone (if applicable) and the future outlook. The questions covered in the survey are presented in Appendix A.

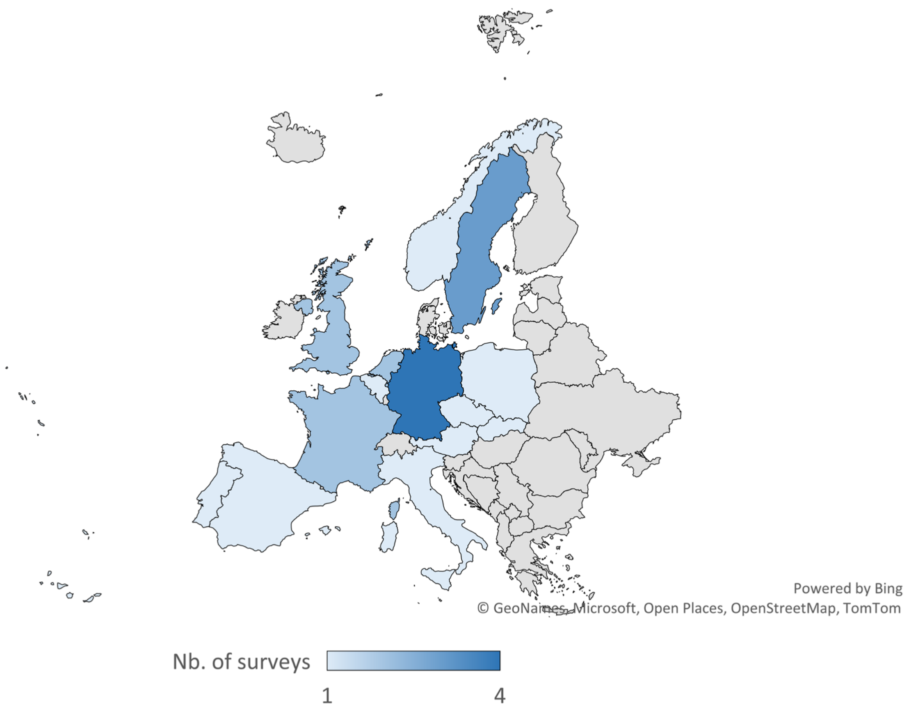
This questionnaire was shared amongst the Concawe members; the completed questionnaires were then returned via email, and data was extracted to be analysed.

4.1. RESPONDENTS

In total, 22 responses (*i.e.* 22 facilities responded) were received which covered approximately 25% of an estimated 86 current operating European refineries [61]. Questions 1.1 and 1.2 covered the name of the facility and their respective operator which have been anonymised.

The responding facilities were located in 14 European countries (Question 1.3), with Germany being the country with the highest number of respondents with four surveys received (Figure 6).

Figure 6. Number of surveys elicited for each country



4.2. ENVIRONMENTAL PERMITS

Environmental permits are set by the competent environmental authorities in each country (Question 2.1). Respondents were then asked about the issuance date of their environmental permit (Question 2.2), and its associated review frequency

(Question 2.3). Nearly half of the sample (10 respondents) reported a review frequency higher than five years (Table 9). Furthermore, one respondent highlighted no review frequency was in place for their facility in Central Europe. Interestingly, the data shows discrepancies in terms of review frequency within a same country, for instance with Germany, Sweden and the Netherlands. These differences in Germany are posited to relate to the federal structure in place where approaches may differ depending on the location. The three facilities in Sweden, for example, reported a review frequency ranging from yearly to higher than five years. Critically, not only differences in permitting processes exist between European countries, but also within a same country.

Table 9. Review frequency of environmental permits presented by country

Country	Review frequency (years)							
	1	2	2-3	5	> 5	Irreg.	Never	n/d
North	1	1	2		2			
Central		1	1		4	1	1	
South				1	3			1
East				2	1			
Total	**1**	**2**	**3**	**3**	**10**	**1**	**1**	**1**

Notes: 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.

For 19 of the respondents (86% of the sample), there had been changes to the permitting conditions in the last ten years highlighting the dynamic nature of environmental permitting (Question 2.4). Critically, these changes reflect on-going adjustments to regulatory requirements and technological advancements (*e.g.* application of Refining of Mineral Oil and Gas BAT conclusions).

All the survey respondents indicated that their environmental permits included end-of-pipe limits for effluent discharges which is consistent with the EU ambitions 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 is generally the leading structure for 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).

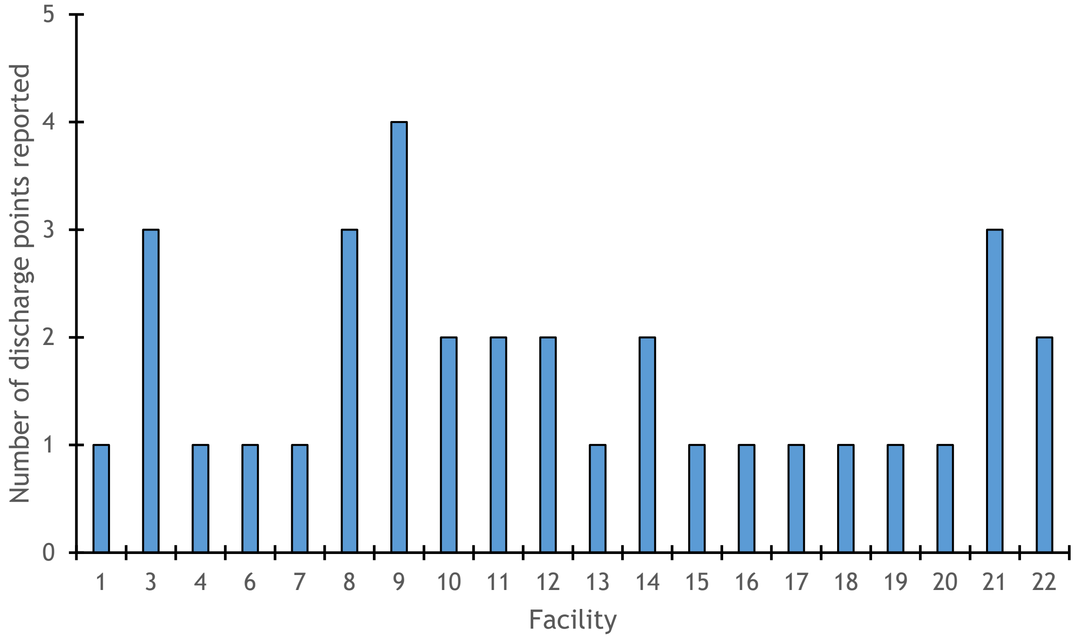
Finally, in some cases, exceedances of the discharge limits prohibit effluent discharge into the receiving water body (Question 2.9).

4.3. DISCHARGE

4.3.1. Discharge type

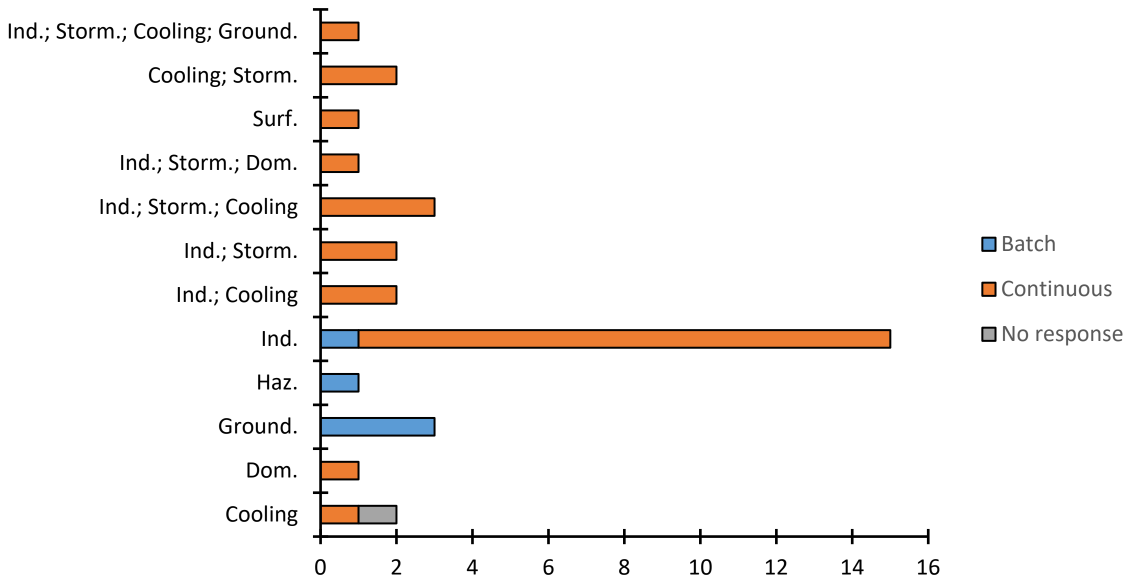
Data was collected on the nature of the discharged effluents. Nine out of the 20 facilities having disclosed information on their discharge permit (45% of the sample) had more than one discharge point (Figure 7).

Figure 7. Number of discharge points for each facility



Most of the discharge permits have specific requirements for industrial wastewater; however, some of the discharges were reported to receive other effluent streams such as sanitary wastewater, cooling water, and stormwater/surface runoff (Figure 8). All the industrial discharges but one were reported to be undertaken on the basis of a continuous discharge regime (Figure 8).

Figure 8. Discharge regime reported by discharge type



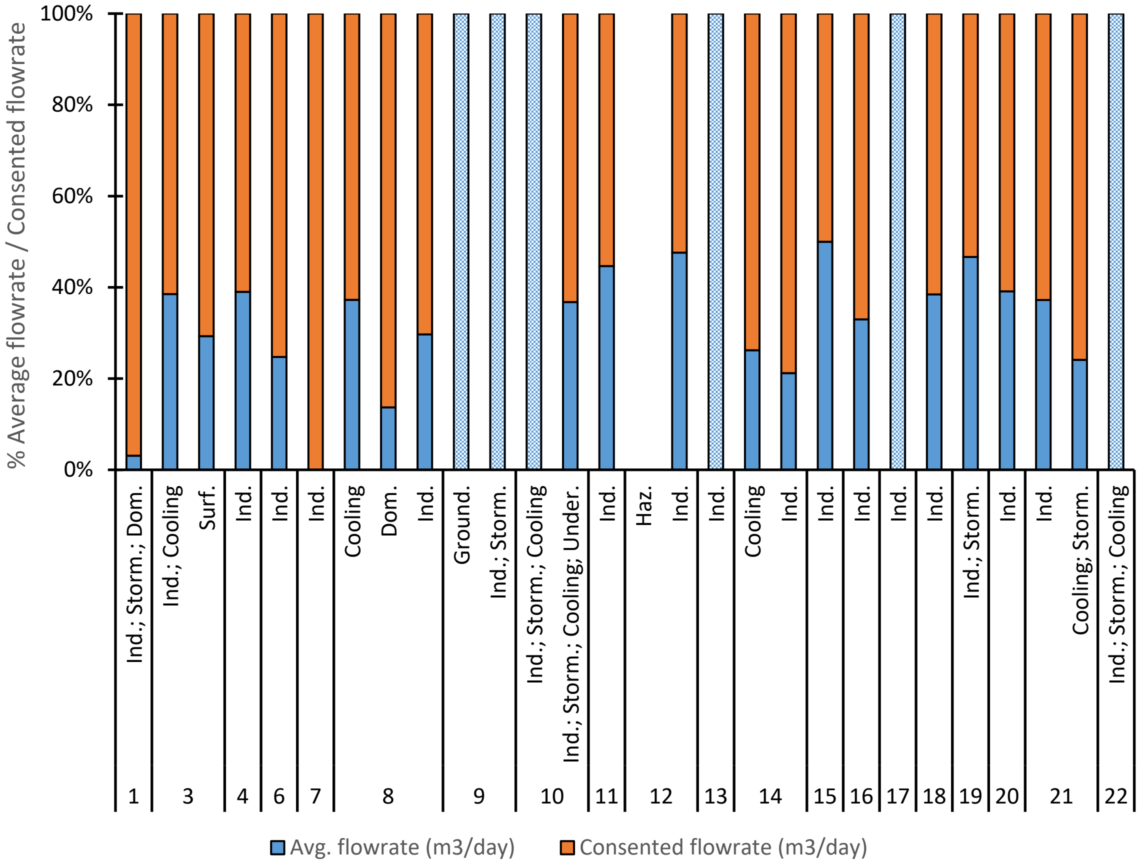
Notes: Ind.: industrial wastewater, surf.: surface runoff, storm.: stormwater, ground.: groundwater, dom.: domestic; ground.: groundwater; haz.: hazardous. To note, ground. and haz. are not believed to relate to industrial discharges.

The respondents also disclosed data on the average and consented flowrates of their discharged effluents (*i.e.* the maximum allowed discharge as per the discharge permits; Figure 9). This data shows that the reported average flowrates are well below the consented flowrates. Although it may seem that there is potential capacity for these facilities to increase their discharge volumes while remaining compliant with their permit, it is important to consider the implications of this in terms of total contaminant mass. Only three permits included some considerations for mass loads (set in kg/year).

While average flowrates are lower than the consented flow limits, the total mass of pollutants being discharged remains constant, regardless of the water volumes used for dilution. In line with the findings from the previous Concawe study, which emphasised the EU's imperative to reduce water consumption, a decrease in water usage could lead to higher pollutant concentrations in effluents, even if the overall mass of contaminants remains unchanged [62].

This presents a paradox: facilities have the potential to discharge more effluent within their permitted flowrates, but without dilution, the concentration-based limits could be exceeded, undermining environmental compliance. In this scenario, there is little incentive for facilities to save water, as doing so would likely result in higher concentrations of pollutants, potentially pushing them beyond regulatory limits. This highlights a counterproductive situation where the focus may shift towards diluting effluents rather than genuinely reducing water usage and contamination. Without regulatory adjustments that balance both concentration and total mass limits, the drive to conserve water could be compromised by the need to dilute effluents before release, defeating the purpose of water-saving initiatives.

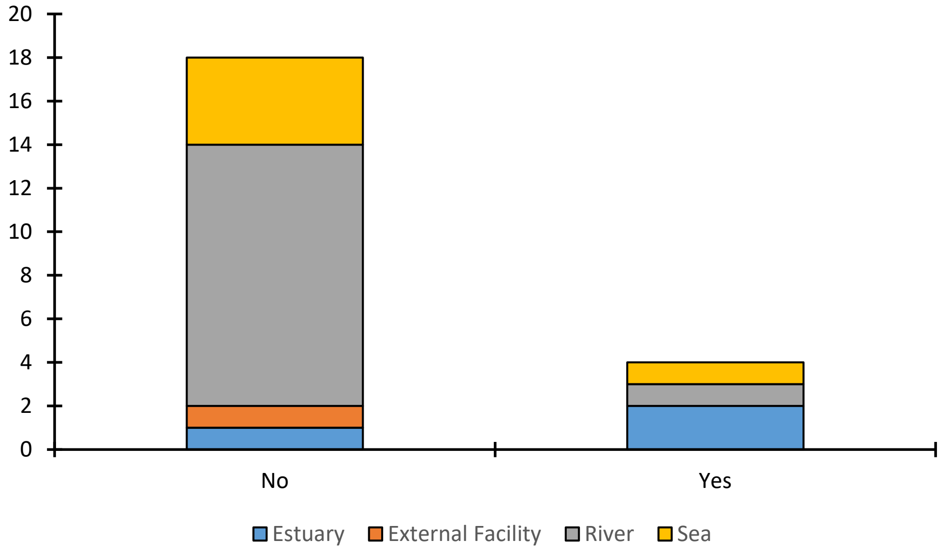
Figure 9. Average and consented discharge flowrates



Notes: facilities 8, 13, 17 and 22 have not disclosed their consented flowrate; these are represented with a dotted pattern. Ind.= industrial wastewater, surf.= surface runoff, storm.= stormwater, ground.= groundwater, dom.= domestic; ground.= groundwater; haz.= hazardous. To note, ground. and haz. are not believed to relate to industrial discharges.

Rivers and seas were identified as the most common receiving water bodies for effluent discharges representing 59% and 23% respectively of the total responses (Figure 10). The regulatory process for implementing a mixing zone is more complex in a river system as it involves addressing concerns related to flow variations, seasonal changes and potential downstream impacts. In rivers, mixing zones may need to be designed to account for narrower, linear dispersion along the flow path. In contrast, in seas, mixing zones might be broader but could require more complex modelling to understand how tides, currents, and other factors affect pollutant dispersion.

Figure 10. Reliance on mixing zone and receiving water body type



Notes: Yes: Site is requiting/utilising a mixing zone; No: Site does not require a mixing zone or is not permitted to have a mixing zone currently.

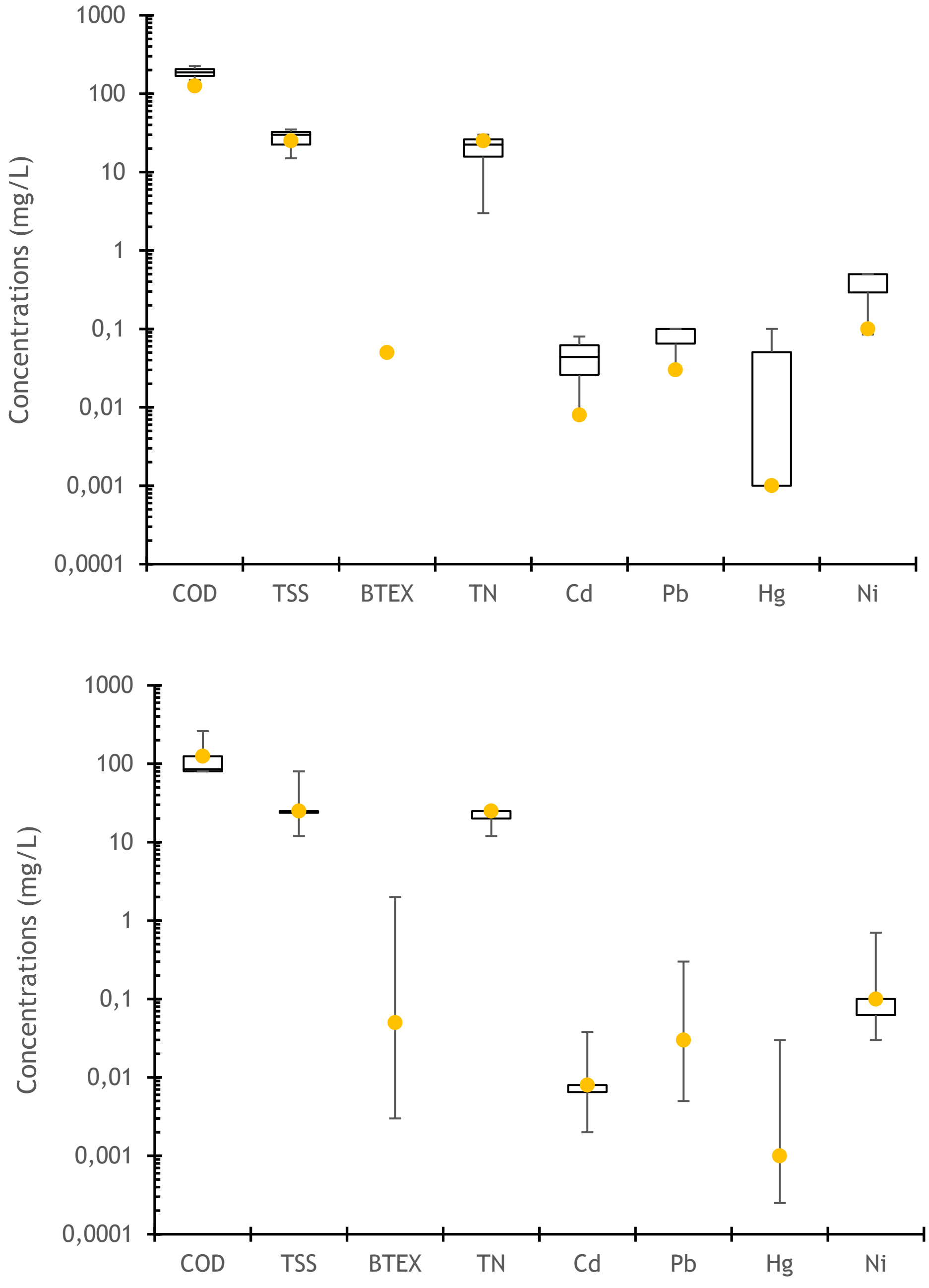
4.3.2. Discharge limits

The respondents provided the acceptable discharge limits set out in their respective permits (Figure 11). These discharge limits are set out as concentration limits. Only three permits included an element of mass load (in kg/year). The data shows that these discharge limits vary on a facility basis across the European Union (Figure 11), stressing a lack of a uniform approach across the EU for determining discharge limits.

Facilities that rely on a mixing zone have different discharge limits compared to those that discharge wastewater directly into the environment (Figure 11). Specifically, the discharge limits for facilities with mixing zones are often higher than the Best Available Techniques—Associated Environmental Levels (BAT-AELs) set for direct discharges from the refining of mineral oil and gas. For example, the BAT-AELs for pollutants such as cadmium, lead, mercury, and nickel are lower than the discharge limits allowed for facilities using mixing zones [2].

This difference arises because the limits discharges that rely on mixing zones are typically based on the concept that the limits would be met after mixing, and 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 pollutants will be sufficiently diluted by the time it reaches the edge of the mixing zone, thus complying with the BAT-AELs. Therefore, the higher limits for mixing zones are intended to ensure that, even with greater pollutant concentrations at the discharge point, the final effluent quality meets regulatory standards once dilution has occurred.

Figure 11. Discharge limits for key substances with BAT-AELs, for permits with a mixing zone (top) and without a mixing zone (bottom)



Note: the circles represent the BAT-AEL's upper limits for direct wastewater discharges from the refining of mineral oil and gas [2].

A comparison of discharge limits across facilities with no mixing zone within a same country, namely Germany and Sweden, shows that discharge limits are mostly consistent within the two countries (Table 10). For Germany, this is consistent with the discharge limits proposed in Annex 45 ("*Anhang 45 Erdölverarbeitung*") of the *Abwasserverordnung* for petroleum processing plants. The difference between the two Swedish facilities is posited to be related to differences in the receiving water bodies, with facilities 13 and 14 discharging into a river and the sea respectively.

Table 10. Comparison of discharge limits for facilities with no mixing zone within a same country

Country	Sweden		Germany				
Plant ID	**13**	**14**	**7**	**8**	**11**	**11**	**20**
pH	6 - 9		6 - 8.5	6 - 9			6.5 - 9
Temp.			35				30
COD	90		80	80	80	80	80
BOD			15	15	15	15	15
TOC			25	25	25	25	25
TSS		12		25			25
OiW	2	1	1.5	1.5			1.5
Phenols	0.1	0.05	0.1	0.15			0.1
TN	20	12	25		20	25	25
TP		0.17			1.3	1.3	1.3
Cd					0.008	0.008	0.008
Cu							
Pb					0.03	0.03	0.03
Hg					0.001	0.001	0.001
Ni						0.1	0.1
AOX				0.1	0.1		
Furfurol				1			

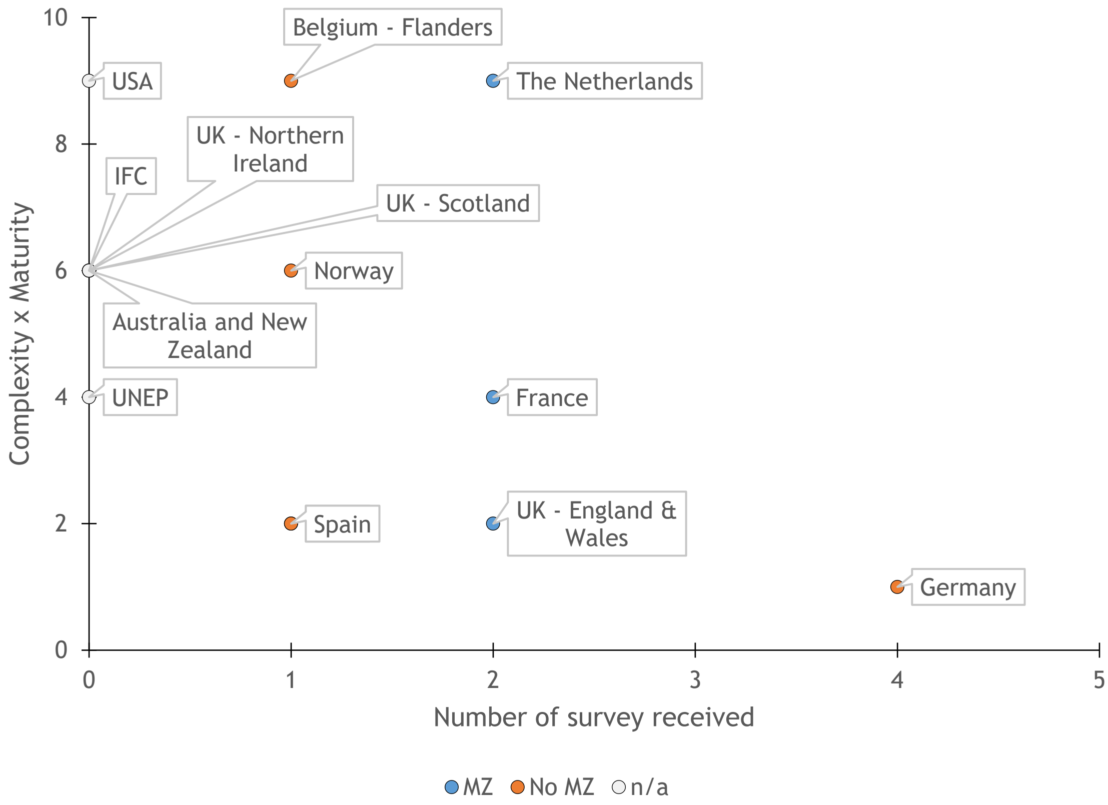
Note: OiW: Oil in Water

4.4. MIXING ZONES

Four of the respondents (~20% of the sample) indicated their effluent discharge point relied on a mixing zone. The four mixing zones have been designed for industrial wastewaters; two of the respondents also mentioned that their mixing zone also included stormwater; one respondent mentioned their mixing zone has been designed for all their effluent (*i.e.* reported as "all waters"; Questions 3.1 to 3.3).

The respondents, currently relying on a mixing zone or without one, were located in countries with various levels of complexity and maturity in terms of guidelines. This was further described in Figure 12 where countries previously studied were represented against the number of surveys elicited in these countries.

Figure 12. Summary of the mixing zone concept across the studied countries and guidelines



Notes: Maturity is defined as: Low (minimal or no framework in place), Medium (framework exists but may lack some elements or enforcement) or High (well-established framework, regularly updated and enforced); Complexity is defined as: Low (simple or minimal guidelines, lack of detail), Medium (guidelines exist but may not cover all scenarios or be very specific) or High (detailed guidelines specifying numerous factors and conditions).

Seasonal requirements were not included in the design of these mixing zones (Question 3.4).

Two of the respondents provided additional data on the dimensioning of their mixing zone which was done using CORMIX (Question 3.5). Another respondent indicated that their mixing zone was designed based on (i) effluent flow, (ii) river flow and (iii) distance between two pipes (*i.e.* new facility connecting two historical treatment plants); however, no further information was provided regarding the design.

In terms of design, one of the mixing zones was designed by the facility. Another respondent mentioned that it was designed by a consultancy. Two of the facilities were not able to provide further information (Question 3.6).

One respondent highlighted the WFD as a driver for the implementation of the mixing zone, while another mentioned change relating to the WWTP optimisation; to note, the implementation drivers for the two other facilities were not known (Question 3.7).

For three respondents, the mixing zone has to go through routine updates (Question 3.8). One respondent further stressed that an effluent study is required every five years, and a temperature study must be performed when required by the regulator.

In terms of compliance, exceedances of discharge limits were reported for one of the respondents, caused by both internal and external factors (Question 3.9).

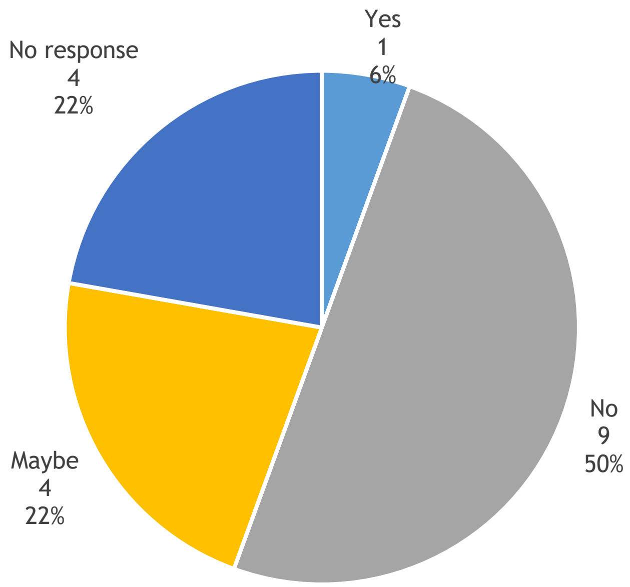
None of the respondents had installed a diffuser to assist with mixing (Question 3.11).

4.5. FUTURE OUTLOOK

Regulatory scrutiny was identified by one of the respondents relying on a mixing zone as a future challenge for their facility. Another respondent also highlighted climate change to be of concern due to uncertainty around temperature and flow at the discharge point and in the receiving water body; the facility also highlighted the existing industrial contamination in the receiving waterbody as one of their potential future challenges. The other two respondents with a mixing zone did not highlight any specific forthcoming issue (Questions 3.12 and 4.1).

When asked about the potential need for a mixing zone in the future (Question 4.2), one facility stressed they will need to implement a mixing zone when they go through re-permitting next due to pressure from the environmental regulator as well as NGOs (Figure 13). Four further respondents (~20% of the sample with no mixing zone currently) considered they *may* need a mixing zone when they go through their permit re-approval process (Figure 13).

Figure 13. Future requirement for a mixing zone



4.6. SUMMARY

From the 22 surveys received the following observations were made:

- Only four refineries (18% of the sample) currently make use of a mixing zone for their industrial discharge(s) (Figure 10).
- Future requirement for mixing zones has been identified by a further 18% of the remaining refineries (Figure 13).
- Inter-country limits appear to be consistent for discharges (Table 10) but limits vary greatly for discharges across the European countries (Figure 11) – to the extent that it is not clear if regulators are implicitly including some degree of dilution/mixing within their permitting process.
- Except for one anomaly the refineries questioned are all compliant with their permitted discharge limits.
- All limits relate to concentrations and in the most part all refineries comfortably operate within the licensed volumetric/concentration-based discharge capacity.
- There is limited recognition in the permitting around total mass loading and therefore currently no incentive for sites to minimise water reuse (since larger volumes accommodated for in their permits would enable easier meeting of concentration-based limits).

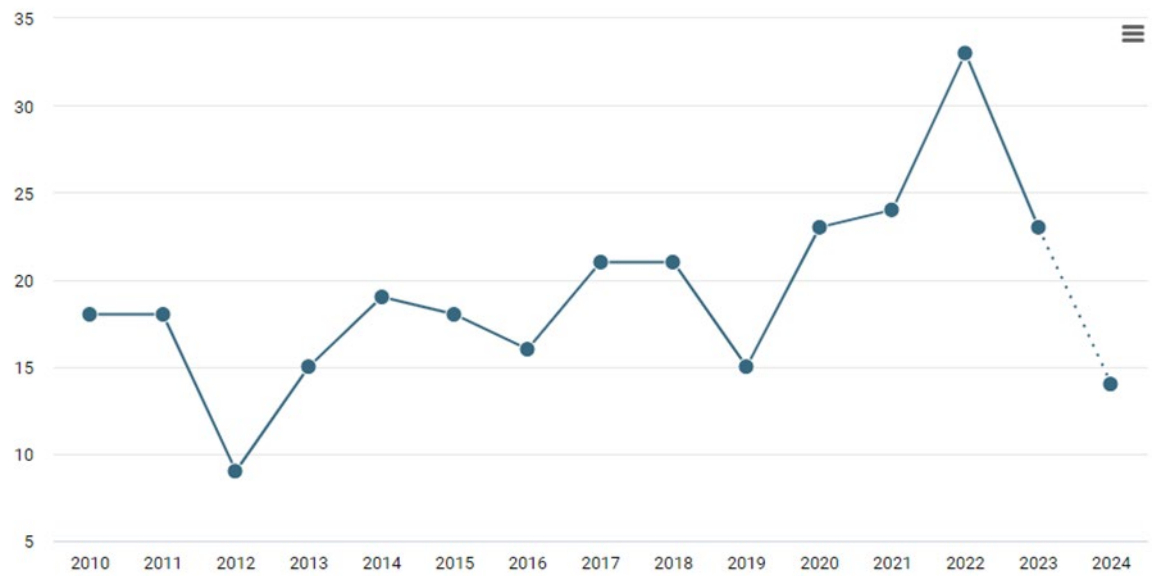
5. TRENDS AND CHALLENGES

Drawing from the literature review and information gathered through the survey of European refineries, the following trends and challenges were identified when considering the futureproofing of the mixing zone concept

5.1. AN OVERLOOKED TOPIC

The design and development of a mixing zone can be complex due to the multitude of factors impacting the mixing processes. As there is no one-size-fits-all, models help in describing some of these factors, and can be supported by experimental data. Nevertheless, mixing zones, in the context of industrial discharges, remain a poorly studied topic (Figure 14).

Figure 14. Number of published publications with keywords “mixing zone” and “discharge” in Title and Abstract fields, generated with Dimensions.ai



5.2. A LACK OF A STRUCTURED APPROACH

The multitude of methodologies available, and the lack of a coherent framework do not readily facilitate the development of the mixing zone concept.

The survey has evidenced differences in approaches undertaken in permitting amongst European countries, for instance with the review frequency (Table 9). Furthermore, discrepancies were also evidenced within a same country, with the case of Germany, the Netherlands and Sweden (Table 9).

Furthermore, although the mixing zone concept is integrated into the national legislation of EU Member States, its application varies widely. The Netherlands and Belgium (Flanders) lead in terms of maturity and complexity, incorporating detailed methodologies in their environmental permitting processes (Table 8). In contrast, other countries offer minimal design guidance, as shown in a survey where only four out of 20 respondents (20%) reported relying on a mixing zone (Figure 10).

These findings highlight significant inconsistencies broadly in environmental permitting, and in turn in how mixing zones are applied across the EU. The disparities, both between and within countries, underscore the need for more harmonised guidelines and frameworks to ensure a level playing field. Without consistent standards, industries and environmental stakeholders may face uncertainty, while ecosystems in less-regulated areas could experience greater degradation. Addressing these gaps in guidance and permitting practices is crucial for fostering both environmental integrity and regulatory fairness across Europe.

5.3. AN INCREASED SCRUTINY AND ACCOUNTABILITY

The survey highlighted that both public awareness and regulatory scrutiny could significantly impact the implementation and management of mixing zones.

As environmental awareness grows, there is a heightened public interest in the environmental impact of industrial activities. This increased awareness can lead to more rigorous scrutiny of industrial practices, with the public demanding greater accountability [63] involving transparency in disclosing environmental performance, taking responsibility for environmental outcomes, and being answerable to stakeholders for environmental decisions.

Recent incidents, such as major oil spills or pollution events, have already led to a shift in public and regulatory attitudes. In response, regulators are not only tightening regulations but also increasing fines and enforcement actions. To illustrate, research has shown that average legal penalties and remediation costs for environmental violations have significantly increased between 1980-2000 and 2001-2016 in the US; respectively from a mean value of 4 million USD to 38 million dollars for fines and damage awards, for water damages [64]. Recently, the EU adopted the new Environmental Crime Directive which introduced criminal or non-criminal penalties (e.g., imprisonment), as well as fines (Directive-EU-2024/1023-EN-EUR-Lex) (e.g., up to 5% of global turnover) [65]. This trend suggests that environmental scrutiny is indeed escalating and is likely to continue, driven by both public demand for greater corporate responsibility and a more assertive regulatory environment. As a result, companies may find themselves under increased pressure to align with evolving expectations and demonstrate a commitment to environmental stewardship.

Accountability for companies under these conditions would likely involve stricter compliance with environmental regulations, more frequent reporting, and potentially higher penalties for non-compliance. Companies might be required to demonstrate more clearly how they are mitigating environmental risks, with a focus on transparency in their operations. For oil and gas companies, this could mean adapting their practices to establish and meet consistent standards that reflect best practices or facing the risk of reputational damage and financial penalties.

Increased scrutiny from European regulators is also anticipated as only 39.5% (EUR-Lex-52025DC0002-EN-EUR-Lex) of surface waters currently achieving good or high ecological status with the 2027 WFD deadline approaching [68].

Ultimately, this heightened scrutiny could manifest in various ways, such as increased demands for detailed environmental assessments, more stringent permitting processes, and closer monitoring of discharges.

5.4. THE REQUIREMENTS FOR EXPERT KNOWLEDGE

Although the complexity of mixing zone guidelines varies greatly across EU Member States, there is currently no one-size-fits-all approach to designing a mixing zone.

Several approaches can be considered when designing a mixing zone, including:

- Analytical equations are relatively easy to use, and can often reliably predict the mixing behaviour of a pollutant plume. Whilst this approach does not require expert knowledge, the careful selection of key parameters is critical as evidenced by Skorbilowicz *et al*. (2017) as it can lead to significant differences in terms of outputs. Ultimately, they provide a first estimate about the discharge conditions informing the discharge design [3].
- Experiments, relying on field measurements or tracer tests can be used for existing discharges in order to verify whether EQS values are met. These can be costly to perform and inefficient for examining a range of possible interactions between the effluent and the receiving water body [3].
- Mixing zone models can detail with a good resolution the characteristics of physical mixing processes. However, these rely on simple exposure based ecological risks for biological interactions, and can be limited in their ability to accurately predict overall risk. Multi-dimensional models are usually suited for more complex situations but require expert knowledge and are time consuming. Critically, this requirement for expert knowledge was evidenced by two of the respondents indicating that modelling was conducted by a consultant using CORMIX.

Critically, the breadth of approaches for design adds more complexity which may refrain the development of a mixing zone and privilege process-focused solution.

5.5. AN EVOLVING REGULATORY LANDSCAPE

Exceedances of discharge limits set by environmental permits may prohibit effluent discharges (Question 2.9), creating real challenges in terms of storage capacity. One respondent noted that exceedances had occurred both internally and externally at their facility (Question 3.9). Such incidents point to the current difficulties' facilities face in maintaining compliance, which can disrupt operations and increase the pressure to manage discharge effectively.

In addition, environmental permits are dynamic and undergo routine reviews by regulators (Table 9). Critically, as more data becomes available on substances of concern and their associated toxicity, more substances can be added to a permit. One respondent highlighted the strong focus of the regulator on hazardous substances and substances of very high concern, while another mentioned PFAS exceedances upstream in the receiving water body as potential future drivers (Question 4.1). This evolving regulatory landscape can significantly impact operations, particularly when new contaminants must be managed.

Finally, with growing pressure to reduce water consumption (and thereby reduce the volumes of water needing to be discharged), it becomes even more critical to understand the mixing of contaminants in water courses. As facilities aim to meet concentration-based discharge limits at the 'end-of-pipe,' this task may become more complex. The challenge of balancing water use reduction while staying within discharge limits emphasises the need for continuous adaptation to regulatory changes and evolving environmental concerns.

5.6. THE IMPACT OF CLIMATE CHANGE

As climate patterns shift, several key factors can either positively or negatively impact the effectiveness of mixing zones.

A prime concern of climate change, possibly negatively affecting the efficiency of a mixing zone, is the expected varying hydrodynamic conditions of a water body resulting in different characteristics [11]. For example, the reduction in water flows (*e.g.* droughts) during critical periods of the year. Lower flow rates mean less dilution capacity, increasing the likelihood that discharges will exceed concentration-based permit limits.

Additionally, rising baseline water temperatures could exacerbate the problem, as higher temperatures can reduce the ability of water bodies to absorb heat from industrial effluents. This may lead to stricter regulatory controls, particularly regarding temperature increase allowances (*e.g.* the current 3°C rise may no longer be acceptable in the future).

These changes highlight the need to consider how climate-related shifts affect the viability of current discharge practices. The following sub-sections explore these elements in more detail, offering insights into potential challenges and mitigation strategies as climatic conditions evolve.

5.6.1. Temperature

As an EQS, the IFC, for example, recommends that the water temperature does not result in an increase greater than 3°C above ambient temperature at the edge of a scientifically established mixing one [58].

Warmer temperatures can influence the solubility and reaction rates of pollutants in wastewater. Higher temperatures may increase the toxicity of certain chemicals, alter the stratification of water bodies, and impact the dilution rates within the mixing zones. This is critical as mixing zones, as reported by one of the survey respondents, may be designed based on thermal plume.

In the context of mixing zones, rising water temperatures can reduce their effectiveness in diluting pollutants due to changed density gradients between ambient and discharge flows, leading to higher concentrations of harmful substances at the discharge point. If mixing zones are primarily designed around thermal dispersion, any increase in ambient water temperature could reduce the capacity for dilution, making it harder to meet regulatory limits. This may necessitate redesigning mixing zones, altering discharge strategies, or investing in advanced treatment technologies - all of which could have substantial operational and financial implications for industries.

5.6.2. Precipitation

Rivers are of the most common type of receiving water body for fuel manufacturing effluents, representing 60% of the surveyed facilities (Figure 10). Furthermore, two out of the five facilities relying on mixing zones also discharge their effluent into rivers. River flow is one of the parameters used for the design of the mixing zone. Critically, altered precipitation patterns, including increased frequency of extreme weather events and changes in seasonal rainfall, affecting the flow rates of rivers and streams will have a direct impact on mixing zones. Increased runoff during heavy rainfall can lead to higher dilution rates in mixing zones, but it can increase the load of contaminants entering water bodies from surface runoff. Conversely, prolonged droughts can reduce water flow, thereby decreasing the dilution capacity of mixing zones and increasing the concentration of pollutants.

The changing flow dynamics of rivers due to climate-related shifts in precipitation can compromise the reliability of mixing zones to adequately dilute pollutants. During periods of extreme rainfall, mixing zones may appear effective due to increased dilution, yet the overall contaminant load can rise, posing risks to water quality. Similarly, during extremely high flow events, river flows can push the discharge plume against a riverbank limiting is ability to mix creating longer mixing zones that may exceed applicable criteria for length. On the other hand, droughts can exacerbate pollution levels by reducing river flow, undermining the intended function of mixing zones and making it harder to meet regulatory standards.

5.6.3. Impact on modelling

Ultimate, the uncertainty of changing climatic conditions underscores the need for additional design considerations to account for extreme cases, and/or adaptive management strategies to ensure that mixing zones remain effective under variable climatic conditions, safeguarding both compliance and ecosystem health.

Critically, more complex modelling may be required when designing a mixing zone, requiring expert knowledge. As such, modelling in its simpler form, using empirical equations, may be ineffective in exploring changing climatic conditions.

6. MODELLING

CORMIX was used to explore the sensitivity of the approved mixing zone dimensions under a variety of changing parameters. This assessment used data gathered by the survey from the four refineries currently relying on a mixing zone. Where data were not available, assumptions were made to develop representative baselines. The simulations considered two discharge types: (i) thermal discharges and (ii) discharges of pollutants of concern *(i.e.* non-thermal discharges). The following sections describe the results of this modelling exercise.

The purpose of this modelling study was to assess how the regulatory approved mixing zones under the existing operations at these sites would change as various parameters are modified. Variations in mixing zone sizes will indicate what parameters would have influence on how the facility mixes in the ambient environment, and whether these variations could make compliance with the approved mixing zone size challenging in the future. It should be noted that the mixing dynamics of a discharge is highly site-specific as it depends on effluent characteristics (flow, density, concentrations, etc.), discharge characteristics (pipe/diffuser design, location, angle of discharge, etc.) and ambient conditions (flow, density, background concentrations, depth, etc.). Furthermore, facility effluents may employ diffuser designs that are optimized for existing conditions. As a result, the outcomes of this modelling study should be used for more general understanding, and it should also be noted that with changing conditions in the future, the diffuser may not represent the most optimized configuration.

For each of the discharges considered here, facility data and relevant assumptions were used to develop a base case. The CORMIX results from this base case represented, for this study, the existing regulatory approved mixing zone. CORMIX model was then run with modifications to a variety of parameters to obtain a range of dimensions of the mixing zone. Increases in mixing zone dimensions would indicate that the facility may not be able to comply with the existing approved mixing zone, and decreases in these dimensions would indicate that the facility would continue to be able to comply.

Parameters were selected such that insights can be drawn on the sensitivity (how influential) and directionality (increases denote and increase in result) to the mixing zone dimensions. Individual values for model runs were selected to be realistic (potential degree of change in the future) and targeted (minimum number of model runs needed to determine sensitivity and directionality). Key changes that were anticipated to be relevant for future were:

- Effluent characteristics (flowrate, density, temperature, concentrations);
- Effect of more stringent discharge limits: no tests were necessary as reduced discharge limits will likely result in improved compliance (i.e. a lower target concentration would result in the need for a smaller mixing zone by definition (with all things being equal. Changes in target criteria may also lead to sites employing greater degrees of treatment before discharge which would also result in a decrease in the size of the mixing zone in comparison to the base case);
- Decrease in the receiving waterbody's flow (e.g. from climate change);
- Increases in background concentrations: increase/decrease in ambient temperature only; and

- The impact of more concentrated effluent streams (*e.g.* from membrane filtration): no separate test was necessary as it is represented in concept by decrease in flowrate while maintaining the heat load.

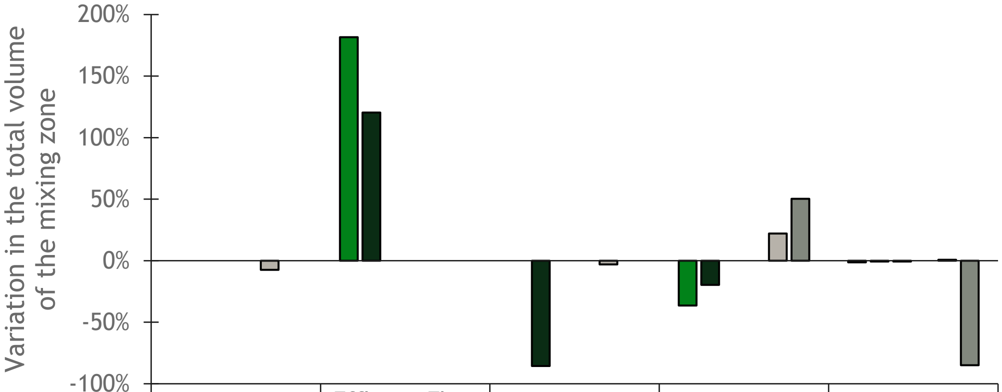
6.1. THERMAL DISCHARGES

For each scenario considered, the variations in the dimensions of the mixing zone were evaluated, and the percent change of the volume from the base case were derived. Ultimately, an increase in the mixing zone dimensions translated into a negative impact as it may violate the terms of the permit. Further details from the modelling outputs for thermal discharges are provided in Appendix C.

The modelling results showed that a decrease in effluent flowrate while maintaining effluent thermal load, and an increase in ambient density both lead to an increase in the size of the mixing zone for both discharge #1 and #2 simulations. To illustrate, a decrease of 20% in effluent flowrate while maintaining thermal load increased the total volume of the mixing zone by 182% (Figure 15). In the case of discharge #2, the overall largest impact on the volume of the mixing zone was shown when decreasing the effluent flowrate by 20% while maintaining effluent thermal load which contributed to an increase by 984% compared to the base case (Figure 17).

By contrast, an increase of the effluent density by +1 ppt or +2 ppt only contributed to a limited increase of the total volume of the mixing zone for discharge #1 (Figure 16). Density increases could be due to several potential factors such as increase in salinity intrusion that would result in an increase in source water salinity or an increased number of cycle of concentrations for a cooling tower, or a decrease in cycled water due to use restrictions that could result in higher total dissolved solids concentrations (reduced blending), etc. To note, an increase in effluent density, tested at +1 ppt and +2 ppt (*Table 16* in Appendix C) did not impact the size of the mixing zone.

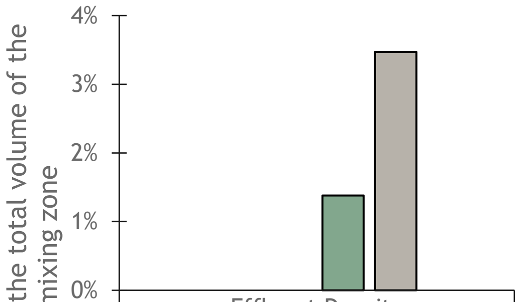
Figure 15. Discharge #1: Results at excess temperature of 1.5°C (regulatory limit)



	Effluent Flow	Effluent Flow & Thermal Load	Effluent Temp.	Ambient Velocity	Ambient Density
-20%		182%		-36%	-1%
-10%		120%	-86%	-20%	-1%
-5%					-1%
+5%					0%
+10%	-8%		-3%	22%	1%
+20%				50%	-85%

-20% -10% -5% +5% +10% +20%

Figure 16. Discharge #1: Results at excess temperature of 1.5°C (regulatory limit)

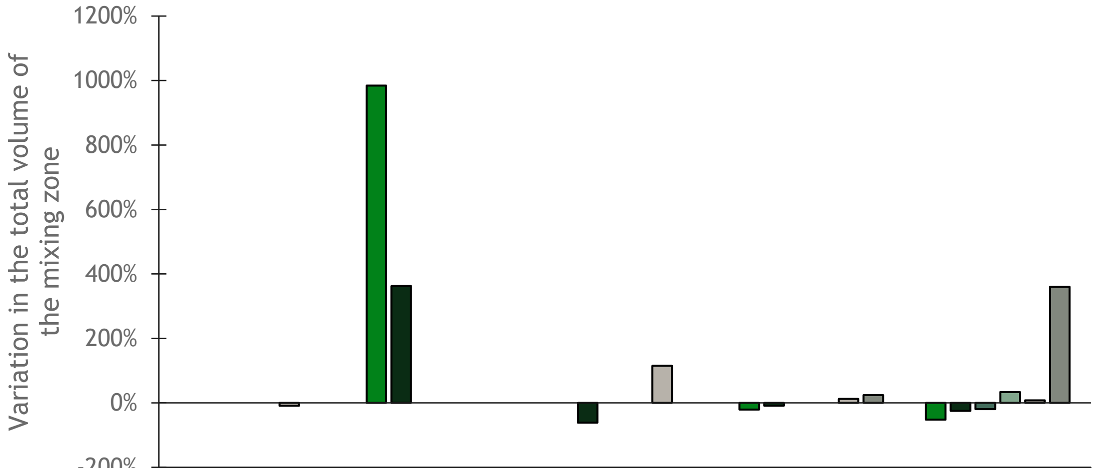


	Effluent Density
-3	
-2	
-1	
+1	1%
+2	3%
+3	

-3 -2 -1 +1 +2 +3

Note: the effluent density variations are represented in ppt.

Figure 17. Discharge #2: Results at temperature of 28°C (regulatory limit)



	Effluent Flow	Effluent Flow & Thermal Load	Effluent Temp.	Ambient Velocity	Ambient Density
-20%		984%		-21%	-52%
-10%		363%	-62%	-9%	-25%
-5%					-20%
+5%					34%
+10%	-9%		115%	12%	8%
+20%				24%	360%

Figure 18 illustrates the sensitivity of key parameters influencing thermal discharge mixing zone volume. A decrease in effluent flow while maintaining thermal load had the most significant effect in increasing mixing zone volume, followed by decreases in effluent temperature, ambient velocity, and ambient density. Conversely, an increase in ambient velocity led to the greatest expansion of the mixing zone, with increases in effluent temperature and ambient density also contributing to a lesser extent. The size of the arrows is proportional to the level of change in the selected parameters. However, the exact percentage of these changes are intentionally not reported in this table. This was done to ensure that the reader does not consider percentage increases as an exact representation of quantitative sensitivity if a different thermal discharge in being considered. Mixing zones are highly site-specific and results from one site should not be considered as an exact representation of another site (*e.g.* assuming a 10% change in flows resulting in 15% increase in mixing zone at Site A would not be representative of same level of increase at Site B). Rather, the directionality and the qualitative sensitivity (extent of change denoted by the relative size of the arrows) should be sufficient to understand the importance of different parameters on the facility's ability to continue to comply in the future.

Figure 18. Summary of main impacts for thermal discharges

Notes: The size of the arrow is relative to its overall impact. When several modelled simulations effected the mixing zone volume in the same manner, however, at varying degrees (*e.g.* both 10% and 20% increase to ambient density increase the volume of the mixing zone), these values were averaged and represented as a single arrow. The above values are based on discharges that were the most sensitive (*e.g.* had the greatest percent change comparatively).

6.2. NON-THERMAL DISCHARGES

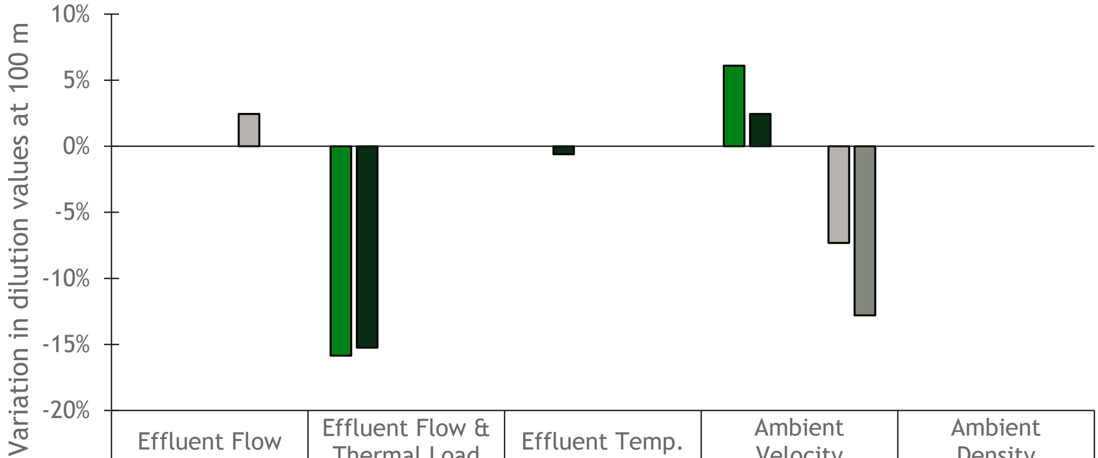
The approved mixing zones for pollutants of concern are more complex as they typically consider the distance necessary to meet water quality standards for all pollutants and uses the largest distance. To avoid any nuances due to the variations in water quality standards and how they could change amongst different pollutants in the future, a more direct metric (dilution) was used. The dilution values at a distance of 100 m were modelled for discharges. However, the assessment for all scenarios were done to ensure that the regulatory criteria (concentrations instead of dilution) were used as mixing zones always rely on meeting the concentration criteria. The resulting outcomes should be interpreted in the same way as the thermal discharges.

The distance required for the modified scenarios to reach the base case dilution value at 100 meters was calculated for discharges #2, #3 and #4. Further details are available in Appendix D; these illustrate how each modified parameter negatively or positively effects the length of the original mixing zone by extending or decreasing distance. For the scenarios that modified the effluent flowrate while maintaining the concentration balance, the distance was found at the target concentration (discharge concentrations/dilution) instead of the base case dilution factor at 100 m. There could be potential factors that lead to increase effluent flowrates such as an increased demand for other facility processes that introduce additional waste streams, need for additional blending of the effluent waste streams due to the need to comply with certain end of pipe limits or facility expansions. Concentration were calculated in those instances to account for the base change in concentration. Percent changes from the baseline scenario were reported such as an increase in distance to reach the base case dilution value negatively effects the mixing zone as the facility is not able to meeting the current permitted limits (larger distance to achieve the same level of dilution).

For discharge #2, a 20% decrease in effluent flow while maintaining effluent thermal load was the largest impact identified, representing a 16% decrease in the dilution value at 100 m from the baseline scenario. A similar value was obtained with a 10% decrease in effluent flow while maintaining effluent thermal load (Figure 19). To note, an increase in effluent density, by 1 ppt and 2 ppt, had no impact on dilution values for discharge #2 (Table 18 Discharge #2: Dilution Values at 100 m in Appendix D).

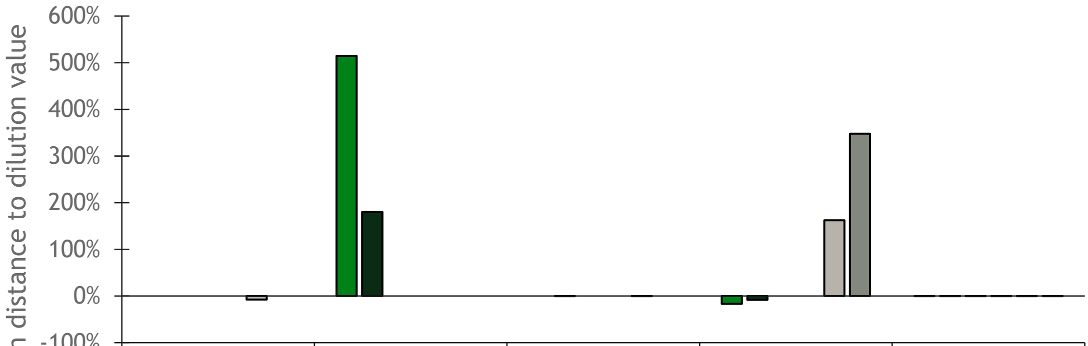
Ultimately, the distance to reach a dilution value of 16.4 (dilution at 100 m for base case) was increased by 515% when considering the most impactful scenario, namely a 20% decrease in effluent flow while maintaining effluent thermal load. While a 20% increase in ambient velocity decrease the dilution value at 100 m by 13%, the distance to reach the dilution value of 16.4 was increased by 348% (Figure 19).

Figure 19. Discharge #2: Dilution values at 100 m



	Effluent Flow	Effluent Flow & Thermal Load	Effluent Temp.	Ambient Velocity	Ambient Density
-20%		-16%		6%	0%
-10%		-15%	-1%	2%	0%
-5%					
+5%					
+10%	2%		0%	-7%	0%
+20%				-13%	0%

Figure 20. Discharge #2: Distance to dilution value of 16.4 (corresponds do the dilution at 100 m in base case)

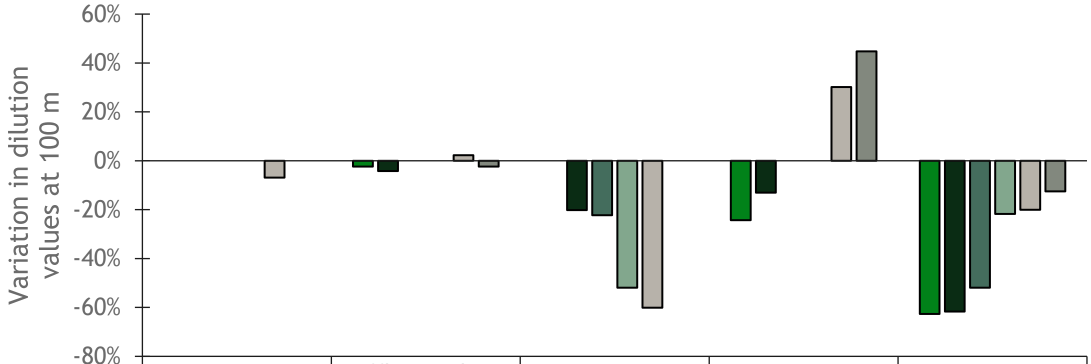


	Effluent Flow	Effluent Flow & Thermal Load	Effluent Temp.	Ambient Velocity	Ambient Density
-20%		515%		-17%	0%
-10%		180%	0%	-8%	0%
-5%					0%
+5%					0%
+10%	-8%		0%	162%	0%
+20%				348%	0%

Note: Current mixing zone (base case) dilution value at 100 m equals 16.4 m.

The modelling of dilution values at 100 m for discharge #3 showed that effluent density and ambient density were the most impactful parameters. To illustrate, a 10% decrease in effluent density and ambient density contributed to a 20% and 62% decrease in the dilution values at 100 m respectively (Figure 21). Interestingly, the largest variations in the distance to reach a dilution value of 39.1 (dilution at 100 m for base case) were observed for a 20% decrease in ambient density (399% increase in distance) and a 10% increase in effluent density (333% increase in distance; Figure 22).

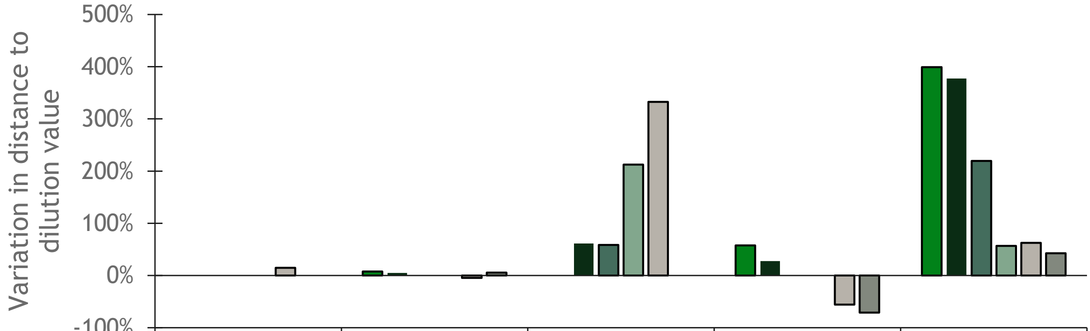
Figure 21. Discharge #3: Dilution values at 100 m



	Effluent Flow	Effluent Flow & Concentration*	Effluent Density	Ambient Velocity	Ambient Density
-20%		-2%		-24%	-63%
-10%		-4%	-20%	-13%	-62%
-5%			-22%		-52%
+5%			-52%		-22%
+10%	-7%	2%	-60%	30%	-20%
+20%		-2%		45%	-13%

-20% -10% -5% +5% +10% +20%

Figure 22. Discharge #3: Distance to dilution value of 39.1 (corresponds do the dilution at 100 m in base case)



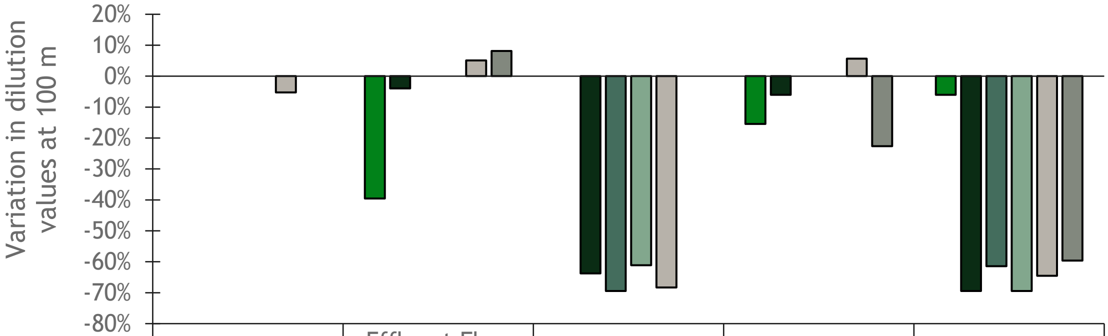
	Effluent Flow	Effluent Flow & Concentration*	Effluent Density	Ambient Velocity	Ambient Density
-20%		8%		58%	399%
-10%		5%	61%	28%	377%
-5%			59%		220%
+5%			213%		57%
+10%	15%	-5%	333%	-56%	62%
+20%		6%		-71%	43%

-20% -10% -5% +5% +10% +20%

Notes: Current mixing zone (base case) dilution value at 100 m equals 39.1. *Concentration was used (equation: 100 mg/L divided by the dilution at 100 m) for these scenarios

A relatively similar pattern to discharge #3 was observed when modelling the dilution values at 100 m for discharge #4. Indeed, variations of effluent density and ambient density were the most impactful parameters (Figure 23). More variabilities were reported in the distances to reach a dilution value of 26.4 (dilution at 100 m for base case) for discharge #4; nevertheless, a 10% decrease in ambient density contributed to a 257% increase in the distance to reach this dilution value, while the second most impactful scenario was a 10% increase in effluent density contributing to a 210% increase in this distance (Figure 24).

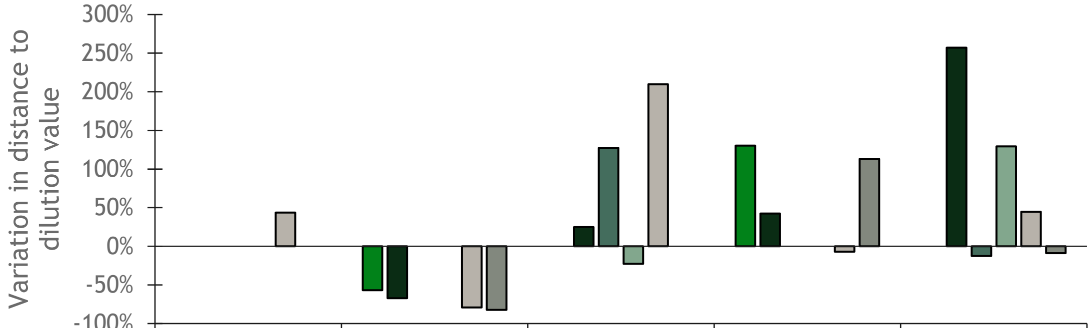
Figure 23. Discharge #4: Dilution values at 100 m



	Effluent Flow	Effluent Flow & Concentration*	Effluent Density	Ambient Velocity	Ambient Density
-20%		-40%		-15%	-6%
-10%		-4%	-64%	-6%	-69%
-5%			-69%		-61%
+5%			-61%		-69%
+10%	-5%	5%	-68%	6%	-65%
+20%		8%		-23%	-60%

-20% -10% -5% +5% +10% +20%

Figure 24. Discharge #4: Distance to dilution value of 26.4 (corresponds to the dilution at 100 m in base case)



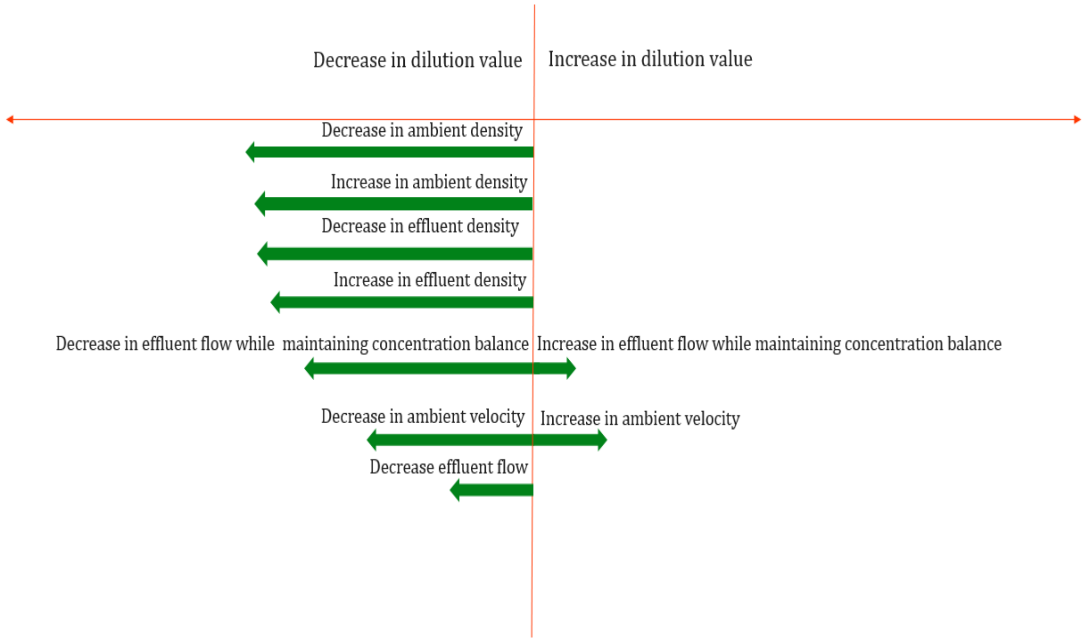
	Effluent Flow	Effluent Flow & Concentration*	Effluent Density	Ambient Velocity	Ambient Density
-20%		-57%		130%	
-10%		-67%	25%	43%	257%
-5%			127%		-13%
+5%			-23%		129%
+10%	44%	-79%	210%	-7%	45%
+20%		-82%		113%	-9%

-20% -10% -5% +5% +10% +20%

Notes: Current mixing zone (base case) dilution value at 100 m equals 26.4. *Concentration factor was used (equation: 100 mg/L divided by the dilution at 100 m) for these scenarios.

Ultimately, whilst the CORMIX modelling for non-thermal discharges show some differences between the scenarios considered, the distance over which the effluent dilutes to reach a specific concentration (or dilution ratio) is heavily influenced by both the density of the effluent and the density of the ambient water (Figure 25).

Figure 25. Summary of main impacts for non-thermal discharges (decrease in dilution value represents an eventual increase in mixing zone dimensions)



Notes: The size of the arrow is relative to its overall impact to the mixing zone volume. When several modelled simulations effected the dilution in the same manner, however, at varying degrees (*e.g.* both 10% and 20% increase in ambient density increase the volume of the mixing zone), these values were averaged and represented as a single arrow sized. The above values are based on discharges that were the most sensitive (*e.g.* had the greatest percent change comparatively).

6.3. SUMMARY OF MODELLING

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. These are summarised in Table 11, and practical recommendations are proposed to help address these challenges.

Table 11. Summary of modelling assessment

Parameters	Risk		Consequences	Recommendations
	Thermal discharges	Non-thermal discharges		
Effluent characteristics: Effluent flow	• Increase in effluent flow created a decrease (<10% change) in volume. • Decreases were not applied to this scenario.	• Increase in effluent flow decreased dilution value by approximately 7% change from base case. • Decreases were not applied to this scenario.	• In scenarios where the dilution value decreased, it will take a greater distance for the pollutants of concern to mix in the receiving waterbody making it harder to maintain the mixing zone.	• Facility may benefit from a more optimized diffuser design or a more optimized discharge placement.
Effluent characteristics: Effluent density	• Increase in effluent density created an increase (up to 3.47% change) in mixing zone volume. • Decreases were not applied to this scenario.	• Increase and decrease in effluent density decreased the dilution value by over 60% change from base case.	• In scenarios when the mixing zone volume was increased, the mixing zone will be harder to maintain. • In scenarios where the dilution value decreased, it will take a greater distance for the pollutants of concern to mix in ambient water making it harder to maintain the mixing zone.	• Higher levels of industrial wastewater treatment prior to discharge to reduce loadings. • Facility may benefit from a more optimized diffuser design or a more optimized discharge placement.
Effluent characteristics: Effluent flow & Thermal load *Total thermal load was maintained*	• Increases were not applied to this scenario. • Decrease in effluent flow and thermal load created an increase in volume (up to 985%) resulting in a highly sensitive scenario.	• Not applicable for non-thermal discharges.	• In scenarios when the mixing zone volume was increased, the mixing zone will be harder to maintain.	• Use of diffusers to enhance mixing or supplemental options for additional cooling prior to discharge.

Parameters	Risk		Consequences	Recommendations
	Thermal discharges	Non-thermal discharges		
Effluent characteristics: Effluent flow & Concentration *Total pollutant load was maintained*	• Not applicable for thermal discharges.	• Increase in effluent flow and concentration both increased (2.4% change) and decreased (-2.4% change) dilution value. • Decrease in effluent flow and concentration decreased the dilution value by over 15%.	• In scenarios when the dilution value was decreased. It will take a greater distance for the pollutants of concern to mix in ambient water making it harder to maintain the mixing zone.	• Use of diffusers to maximize mixing and higher levels of industrial wastewater treatment prior to discharge to reduce loadings.
Effluent characteristics: Effluent temperature	• Increase in effluent temperature created increase in volume (115% change). • Decrease in effluent temperature created decrease in volume (62% change).	• Not applicable to non-thermal discharges.	• In scenarios when the mixing zone volume is increased, the mixing zone will be harder to maintain.	• Use of diffusers to enhance mixing or supplemental options for additional cooling.
Receiving waterbody's flow: Ambient velocity	• Increase in ambient velocity created increase in volume (up to 50% change). • Decrease in ambient velocity created decrease in volume (up to 20%).	• Increase in ambient velocity both increased (6%) and decreased (-23%) the dilution value. • Decrease in ambient velocity decreased (up to 24%) the dilution value.	• In scenarios when the mixing zone volume is increased, the mixing zone will be harder to maintain.	• Work with regulators and appropriate water management agencies to develop a climate resilient management plan addressing flow regulation.
Background concentrations: Ambient density	• Increase in ambient density increased in volume (up to 359% change) resulting in a highly sensitive scenario.	• Increase and decrease in ambient density decreased the dilution value (up to -69% change).	• In scenarios when the mixing zone volume is increased, the mixing zone will be harder to maintain. • When the dilution value decreases, it takes a greater	• Work within the basin to identify the root cause and work collaboratively with regulatory agencies. responsible for managing the health of the basin.

Parameters	Risk		Consequences	Recommendations
	Thermal discharges	Non-thermal discharges		
	• Decrease in ambient density created decrease in volume (up to 1.4% change).		distance for pollutants of concern to mix making it harder to maintain the mixing zone.	• Work with other industrial discharges to collectively improve the water quality conditions. • Invest in other engineering interventions that could help alleviate the issue.

7. RISK MATRIX

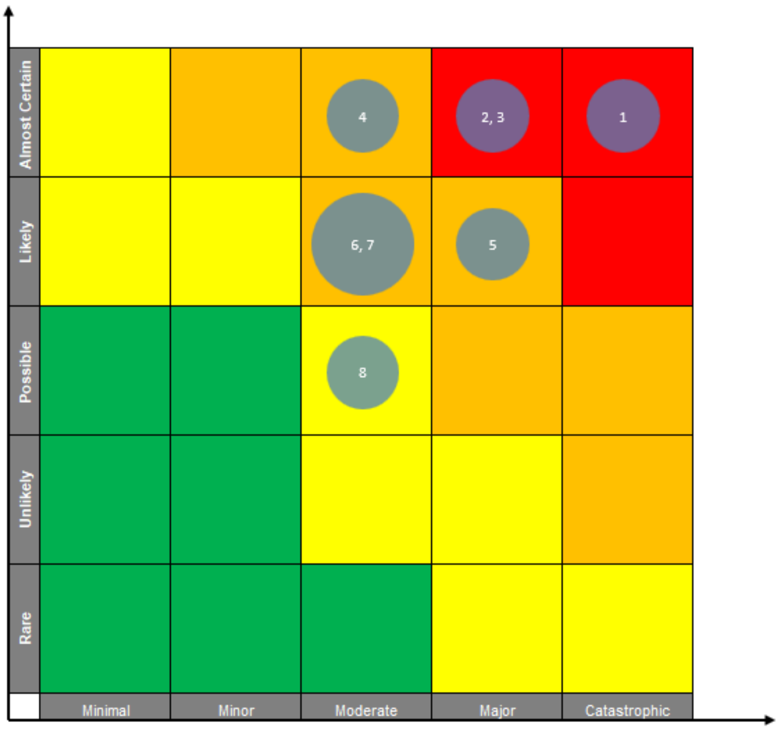
Leveraging information gathered during the literature review, data from the survey, and outputs from the CORMIX modelling assessment, a set of risks (Table 12) and opportunities were identified with the potential to impact, either negatively or positively, the mixing zone concept.

Based on this assessment, the highest risk identified, in terms of consequence and likelihood, was the discrepancy in mixing zone guidelines provided (Figure 26). Indeed, the design of a mixing zone can be performed through several methodologies, however, the final design will be highly dependent on the input data and considered modelling tools.

Inadequate mixing, and emerging pollutants were identified as the second highest risks for the mixing zone concept (Figure 26). Results from the modelling have indicated that variations in ambient density, used as a proxy for background concentrations, were one of the most sensitive scenarios tested.

Ambient velocity can be considered as a proxy to investigate flow variations in the receiving waterbody, and in turn reflects on variations due to climate change. Whilst the mixing zone dimensions will be impacted by flow variations, these were not as sensitive as ambient density and effluent density.

Figure 26. Risk matrix for the mixing zone concept



Notes: Rare will probably never happen; Unlikely is not expected to happen but it is possible it may so; Possible might happen or recur occasionally; Likely will probably happen, but it is not a persisting issue; Almost certain will undoubtedly happen.

Two opportunities were identified for the mixing zone. This included potential cost savings from optimised mixing zone design which can reduce the need for extensive end-of-pipe treatment, lowering operational costs. However, larger mixing zones could pose risks to ecosystems by increasing pollutant dispersion over a wider area. Thus, it is crucial to balance economic benefits with environmental protection. The second opportunity resides in optimising mixing zones for changing climatic conditions to ensure long-term compliance and environmental resilience. To achieve this, adaptive design in mixing zones should be considered to prepare for future shifts in hydrology due to climate change.

Table 12. Risks identified for the mixing zone concept

ID	Risk	Likelihood	Consequence	Description and Impact	Recommendations
1	**Inadequate mixing zone guidelines**	Almost certain	Catastrophic	Although the definition of a mixing zone has been transposed into the national legislation of the studied European countries, there are discrepancies between countries in terms of technical guidelines. Furthermore, even in its simplest form (*i.e.* empirical formulas), the selection of variables can lead to significant differences in terms of outputs, and in turn for the mixing zone design.	• Harmonise EU technical guidelines to standardise methodologies to account for key parameters affecting mixing dynamics. • Refine modelling protocols to accommodate complex waterbody dynamics.
2	**Inadequate mixing**	Almost certain	Major	The modelling highlighted the sensitivity of mixing zones to density parameters. Although diffusion systems reduce acute impacts in the near-field discharge region [3], none of the surveyed facilities currently relying on a mixing zone had this system in place.	• Integrate diffusion systems to optimise mixing.
3	**Uncertain impact of emerging contaminants on mixing zone effectiveness**	Almost certain	Major	Emerging contaminants ay require tighter regulations in mixing zones. This is also true for contaminants found in the receiving water body whose background concentrations may interact with the discharged effluent. Results from the modelling have indicated that variations in ambient density, used as a proxy for background concentrations, were one of the most sensitive scenarios tested.	• Invest in advanced treatment systems to reduce emerging pollutants and research their behaviour in mixing zones for better regulatory alignment. By reducing pollutant loads and improving effluent quality, these technologies directly influence the size and impact of mixing zones, ensuring compliance with regulatory limits and minimising environmental harm within the recipient ecosystem. • Water basin discovery studies can support identifying the sources of pollution to work towards addressing these.
4	**Inconsistent permit review frequency**	Almost certain	Moderate	Variations in permit review schedules across EU countries, and regions lead to inconsistencies in compliance monitoring.	• Establish a harmonised schedule for environmental permit review across EU Member States to maintain consistency, considering the existing Industrial Emissions Directive requirement for permit reviews.

ID	Risk	Likelihood	Consequence	Description and Impact	Recommendations
5	**Climate change impact on receiving water bodies**	Likely	Major	Climate variability can change water flow and temperature, impacting the effectiveness of mixing zones and pollutant dispersion. Specifically, river systems are more susceptible to changing conditions. As more than half of the surveyed facilities rely on rivers for their discharges, this can have a major impact on how mixing zones are applied. The modelling of ambient velocity through CORMIX tested flow variations in the receiving water body. Interestingly, based on the studied cases, this scenario had a relatively low impact on the dilution values.	• Implement climate resilience strategies in mixing zone design to adapt to changing hydrodynamic conditions (*e.g.* low flows, increased precipitation). • Consider potential changes in land use and infrastructure, such as new industrial discharges, upstream and downstream flow modifications, and construction projects (*e.g.* bridges) that may influence water quality and hydrodynamics, ensuring the mixing zone management remains effective and robust under evolving conditions.
6	**Stricter regulatory scrutiny on mixing zones**	Likely	High	Increasing public pressure and environmental concerns may lead regulators to reduce the allowable size of mixing zones or not adopting mixing zones, resulting in higher emission limits	• Engage with regulators proactively to influence the adoption of adaptive governance frameworks focused on mixing zone flexibility and mass loading-based permitting. • Enhance corporate transparency and establish clear protocols for environmental performance.
7	**Technical complexity and knowledge gaps**	Likely	Moderate	Complex mixing dynamics and regulatory variability increase the need for specialised knowledge.	• Strengthen and harmonise EU technical guidelines on mixing zones.
8	**Inadequate stakeholder engagement on mixing zones**	Possible	Moderate	Limited transparency about how mixing zones are managed can erode stakeholder trust and increase public pressure.	• Promote public engagement and transparency about mixing zone management to build trust and demonstrate environmental stewardship.

8. CONCLUSIONS

The present research underscored several critical findings about the future of the mixing zone concept, particularly within the context of European fuel manufacturing effluent management:

- The evolving regulatory landscape, driven by environmental concerns and public scrutiny, is placing increased pressure on industries to ensure compliance with EQS within water bodies.
- There is also a dichotomy with the drive to reduce the use of water resulting in higher discharge concentrations requiring greater use of mixing zones to attain prescribed limits. This in effect reduces the imperative for lower water use. It also suggests that total mass loading needs to be considered to enable the optimum approach around water, energy, waste and cost to be achieved.
- The effects of climate change, emerging contaminants, and inconsistent regulatory frameworks across European countries introduce significant challenges for the management and optimization of mixing zones.
- A major takeaway from the study is that although the mixing zone concept has been incorporated into EU legislation, the application of these zones varies considerably between and within countries. The lack of standardised technical guidelines and differences in regulatory interpretations highlight the need for more harmonised approaches to managing mixing zones. The study reveals that in certain regions, the regulatory framework is more mature, incorporating sophisticated methodologies into environmental permits, while other regions offer minimal design guidance. This disparity creates uncertainty and may result in uneven environmental protection.
- Furthermore, the report emphasises the increasing complexity of managing discharges in the context of climate change. Rising temperatures and changing water flows are expected to exacerbate the challenges of pollutant dilution, particularly for facilities discharging into river systems. Therefore, adopting climate-resilient strategies and adaptive designs for mixing zones will be crucial for maintaining compliance in the long term.
- Technological advancements and the identification of new contaminants, such as perfluorinated compounds and endocrine-disrupting chemicals, further complicate the regulatory environment. The need for improved treatment systems and more robust dilution models is becoming apparent, especially as more stringent pollutant limits are likely to be introduced.
- Finally, the study calls for proactive stakeholder engagement, particularly with regulators and the public, to foster transparency and trust in how mixing zones are managed. This engagement, alongside the development of cost-effective and climate-resilient solutions, will be vital for ensuring sustainable industrial practices and environmental protection.

In summary, the future-proofing of the mixing zone concept will require harmonized regulatory guidelines, adaptive management strategies in the face of climate change, and the integration of emerging technological solutions to address both existing and novel pollutants. Furthermore, it is suggested that more routine consideration of modelling approaches should be adopted to recognise the high variability in factors that impact the success of mixing and mixing zone extents and the added value and certainty that such studies provide sites and regulators in terms of where individual site risks lie. A drive to accommodate total mass as a measure of compliance alongside a more detailed analysis of mixing zone dynamics should be an objective for the industry so that the parallel needs or reducing emissions and lowering water demand can be factored into the overall decision-making process.

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APPENDIX A - SURVEY

Topic	#	Question	Guidance information provided
1- Facility	1.1	Name of the facility	
	1.2	Company name operating the facility	
	1.3	Location (town, country)	Provide the locality and country where the facility is located.
2- Discharge permit	2.1	What is the name of the authority/body issuing the sites environmental/discharge permit?	This may be a local or national regulator.
	2.2	When was the environmental/discharge permit issued?	Date format DD/MM/YYYY or MM/YYYY or YYYY
	2.3	How often is the permit reviewed?	Frequency of permit review/renewal/resubmission in Years or NEVER
	2.4	Have there been any recent (< 10 years) changes to the permit/permit conditions?	If so, what were the reasons? Were there any changes in effluent water quality and/or processes? Free text field.
	2.5	Does the environmental/discharge permit include specific end-of-pipe limits? If so, please fill in the 'Discharge permit' tab	If the permit is publicly available, please attach a copy (either as attachment or the URL from where it can be accessed) or email directly to XXX@XXX.com.
	2.6	Is there a point of compliance that is not located at the end-of-pipe?	This could be downstream in the receiving water body. Please either provide coordinates or an indication of the distance downstream from the point of discharge.
	2.7	Who is in charge of compliance monitoring?	Provide the Position and Department of the person in charge.
	2.8	Are there monitoring reports that are routinely submitted? If YES, is data from these reports available?	What does the monitoring include (e.g. effluent discharged, downstream in the receiving water body)?
	2.9	Are there any specific permit conditions that prohibit effluent discharge under certain conditions? (e.g. internal monitoring/exceedance, external factor such as river flow, background monitoring data)	

Topic	#	Question	Guidance information provided
3- Mixing zone	3.1	How many discharges and mixing zones are permitted by the facility?	Indicate if these are covered in separate permits or a permit covering multiple discharge types/locations.
	3.2	If more than 1, are there individual or combined mixing zones?	
	3.3	What types of effluents are of concern?	These effluents can be industrial wastewater, stormwater, cooling water, etc.
	3.4	Is there any seasonality requirement to the compliance? (e.g. mixing zone dimensions are different or different thermal limits during different seasons)	For instance, is the mixing zone required all the time or adjust for occasional discharges (that otherwise would not meet the permit limits)?
	3.5	In dimensioning the mixing zone, what are the parameters considered (ambient flow, effluent flow, etc.) and what statistical values are used for these parameters?	Please detail the factors considered in the design of the mixing zone (e.g. river flow considered, effluent flow, worst-case scenario, pollutants and associated concentrations, cut-off values). If possible, append the mixing zone definition report or email it to XXX@XXX.com.
	3.6	Who designed the mixing zone?	The mixing zone may have been designed by your facility, the regulator or a sub-contractor for instance.
	3.7	What were the main drivers for the implementation?	Is it due to technology not being able to meet discharge limits at the end of the pipe, the need for cooling effects, etc?
	3.8	Are mixing zones required to go through routine updates and re-approval?	If yes, how often and who undertakes the review?
	3.9	Has the facility faced any exceedances beyond the approved mixing zone? If YES, were those exceedances a result of external factors (e.g. flows, weather conditions) or facility operations?	Indicate what were the consequences of these exceedances? (e.g. fine, warning). Indicate the reason (e.g. operational issue, external factor such as drought

Topic	#	Question	Guidance information provided
			reducing the flow in the receiving environment)
	3.10	What type of surface water body does the facility discharge to? (e.g. lake, river, estuary, coastal, offshore)	Provide the name of the water body where the effluent is discharged to.
	3.11	Has the facility designed and implemented a diffuser to assist with mixing?	If so, please provide any technical data.
	3.12	Is the facility facing any pressures from external stakeholders? (e.g. public, regulator)	Consider both the pressures associated with mixing zones and the quality of receiving water bodies.
	3.13	Has the mixing zone requirement led to conflicting decision (positive or negative) about water treatment?	For instance, does it provide the opportunity to treat less due to relaxed discharge capability or is there a drive to improve water treatment to remove reliance on the mixing zone?
4 - Future outlook	4.1	What are the future challenges/concerns you foresee for your mixing zone?	Consider upstream contributions from other industrial establishments, emerging substances, climate change, etc.
	4.2	If you do not currently rely on a mixing zone, are you expecting to need one in the future? For what reason?	

APPENDIX B – ADDITIONAL MODELLING INFORMATION

Descriptive information	Notes
Overview of facilities	facility location (coordinates or Google Earth .kmz), facility description, project status (proposed or existing), photos
Regulatory environment	agency name, regulatory requirements, permit language, etc.
Previous studies	list w/dates, e.g., dye studies, modeling
Areas of special interest	e.g., sensitive receptors; other dischargers in the region
Discharge Design	
Discharge structure plan and elevation	engineering drawings
Discharge location	coordinates and depth
Effluent Characteristics	
Flow rate, with units	
Duration (continuous or intermittent)	
If thermal: temperature rise or heat load; if other constituents of concern, concentration	
Salinity or density (for marine or brine discharges only)	
For each constituent of concern other than temperature: concentration, decay rate if non-conservative	
Risk thresholds for each constituent	
Waterbody Characteristics	
Region of interest (horizontal and vertical extent)	e.g. identify ecologically sensitive areas, downstream water intakes, public use areas
Waterbody type	river, lake, estuary, coastal or ocean?
Waterbody flow rate	if river; typically cfs or $m^3\ s^{-1}$
Water depth at discharge structure	depth likely shown on engineering drawings
Stream or river width at discharge structure	for streams/rivers only
Average water depth in the region of interest	if available, otherwise ERM will source
Ambient velocity	if available, otherwise ERM will source
Wind speed	if available, otherwise ERM will source

APPENDIX C – MODELLING OUTPUTS FOR THERMAL DISCHARGES

The following tables show the dimensions of the mixing zone, volume, and percent change from the base case for mixing zones with thermal discharges. Values in red indicate an increase to the select mixing zone dimension and percent increase by volume compared to the original scenario analysed. An increase to the mixing zone dimensions is a negative impact as it may violate the terms of their permit.

Table 13 Discharge #1: Results at excess temperature of 1.5˚C

Parameter	Decrease (%)			Increase (%)		
	20	10	5	5	10	20
Effluent Flow					1.33x0.69x 8.42 -7.5%	
Effluent Flow & Thermal Load	3.24x0.87x 8.48 181.63%	2.69x0.82x 8.48 120.38%				
Effluent Temp.		1.36x0.67x 1.34 -85.6%			1.4x0.7x 8.4 -3.0%	
Ambient Velocity	0.9x0.66x 8.42 -36.48%	1.19x0.6x 8.42 -19.72%			1.71x0.72x8.42 22.12%	2.02x0.75x8.4 2 50.29%
Ambient Density	1.42x0.7x 8.42 -1.38%	1.43x0.7x 8.42 -0.69%	1.43x0.7x 8.42 -0.69%	1.44x0.7x 8.42 0%	1.44x0.7x 8.42 0.69%	1.38x0.68x 1.36 -84.9%

Notes: Current mixing zone (base case) size (L x W x D): 1.44 x 0.7 x 8.42. Current mixing zone (base case) volume: 8.49 m^3. temp.=temperature

Table 14 Discharge #1: Results at excess temperature of 1.5˚C

Parameter	Decrease (ppt)			Increase (ppt)		
	3	2	1	1	2	3
Effluent Density				1.46x0.7x 8.42 1.38%	1.49x0.7x 8.42 3.47%	

Notes: Current mixing zone (base case) size (L x W x D): 1.44 x 0.7 x 8.42; Current mixing zone (base case) volume: 8.49 m^3.

Table 15 Discharge #2: Results at temperature of 28°C

Parameter	Decrease (%)			Increase (%)		
	20	10	5	5	10	20
Effluent Flow					0.3x3.48 -9.09%	
Effluent Flow and Thermal Load	1.97x6.32 984.15%	1.07x5.18 382.63%				
Effluent Temp.		0.16x2.74 -61.82%			0.58x4.26 115.15%	
Ambient Velocity	0.3x3.5 -20.76%	0.3x3.48 -9.09%			0.37x3.48 12.13%	0.41x3.48 24.24%
Ambient Density	0.19x2.88 - 52.35%	0.24x3.12 -24.79%	0.28x3.3 -19.54%	0.41x3.74 33.52%	0.52x2.04 - 7.63%	1.0x5.28 359.77%

Notes: Current mixing zone (base case) size (L x W/ D): 0.33 x 3.48. Current mixing zone (base case) volume: 1.15 m^3. For Discharge #2, COMIX computed width and depth as a ratio in the nearfield due to the dominance of the effluent momentum and salinity. Temp. = Temperature

Table 16 Discharge #2: Results at temperature of 28°C

Parameter	Decrease (ppt)			Increase (ppt)		
	3	2	1	1	2	3
Effluent Density				0.33x3.48 0%	0.33x3.48 0%	

Notes: Current mixing zone (base case) size (L x W/ D): 0.33 x 3.48; Current mixing zone (base case) volume: 1.15 m^3. For Discharge #2, CORMIX computed width and depth as a ratio in the nearfield due to the dominance of the effluent momentum and salinity.

APPENDIX D – MODELLING OUTPUTS FOR NON-THERMAL DISCHARGES

When assessing the impact of varying factors on the mixing zones, dilution values at a distance of 100 m were modelled for discharges monitoring pollutants of concern. A concentration factor was calculated in lieu of a dilution value at 100 m for the scenarios modifying flowrate while maintaining the concentration balance. Concentration factors were calculated in those instances to account for the base change in concentration.

The distances required for the modified scenarios to reach the base case dilution value at 100 m were evaluated in the following tables. These tables illustrate how each modified parameter negative or positively effects the length of the original mixing zone by extending or decreasing distance. For the scenarios that modified the flowrate while maintaining the concentration balance, the distance was found at a concentration factor instead of the base case dilution factor at 100 m. Concentration factors were calculated in those instances to account for the base change in concentration. Values in red indicate an increase in distance and an increase in percent change compared to the original scenario analysed. An increase in distance to reach the base case dilution value negatively effects the mixing zone as it is potentially violating the current permitted limits.

Table 17 Discharge #2: Dilution Values at 100 m

Parameter	Decrease (%)			Increase (%)		
	20	10	5	5	10	20
Effluent Flow					16.8 2.44%	
Effluent Flow & Thermal Load	13.8 -15.85%	13.9 -15.24%				
Effluent Temp.		16.3 -0.61%			16.4 0%	
Ambient Velocity	17.4 6.10%	16.8 2.44%			15.2 -7.32%	14.3 -12.80%
Ambient Density	16.4 0%	16.4 0%	16.4 0%	16.4 0%	16.4 0%	16.4 0%

Notes: Current mixing zone (base case) dilution value at 100 m equals 16.4. temp=temperature

Table 18 Discharge #2: Dilution Values at 100 m

	Decrease (ppt)			Increase (ppt)		
Parameter	3	2	1	1	2	3
Effluent Density				16.4 0%	16.4 0%	

Note: Current mixing zone (base case) dilution value at 100 m equals 16.4m.

Table 19 Discharge #2: Distance to Dilution Value of 16.4

Parameter	Decrease (%)			Increase (%)		
	20	10	5	5	10	20
Effluent Flow					92.49 -7.51%	
Effluent Flow & Thermal Load	614.53 514.53%	280 180%				
Effluent Temp.		99.98 -0.02%			99.98 -0.02%	
Ambient Velocity	83.06 -16.94%	91.74 -8.26%			262.16 162.16%	448.04 348.04%
Ambient Density	99.98 -0.02%	99.98 -0.02%	99.98 -0.02%	99.98 -0.02%	99.98 -0.02%	99.98 -0.02%

Table 20 Discharge #2: Distance to Dilution Value of 16.4

Parameter	Decrease (ppt)			Increase (ppt)		
	3	2	1	1	2	3
Effluent Density				99.98 -0.02%	99.98 -0.02%	

Table 21 Discharge #3: Dilution Values at 100 m

Parameter	Decrease (%)			Increase (%)		
	20	10	5	5	10	20
Effluent Flow					36.4 -6.91%	
Effluent Flow & Concentration*	37.45 -2.38%	38.2 -4.21			40 2.30%	38.17 -2.38%
Effluent Density		31.2 -20.20	30.4 -22.25	18.8 -51.92	15.6 -60.10%	
Ambient Velocity	29.6 -24.30%	34 -13.04%			50.9 30.18	56.6 44.76
Ambient Density	14.6 -62.66	15 -61.64	18.8 -51.92	30.6 -21.74%	30.9 -20.97	34.2 -12.53

Notes: Current mixing zone (base case) dilution value at 100m equals 39.1. *A concentration factor was calculated (equation: 100 mg/l divided by the concentration at 100m) for these scenarios.

Table 22 Discharge #3: Distance to Dilution Value of 39.1

Parameter	Decrease (%)			Increase (%)		
	20	10	5	5	10	20
Effluent Flow					114.66 14.66%	
Effluent Flow & Concentration*	107.66 7.66%	105.00 5%			95.29 - 4.71%	105.62 5.62%
Effluent Density		161.18 61.18%	158.69 58.69%	312.53 212.53%	432.77 332.77%	
Ambient Velocity	157.71 57.71%	127.68 27.68%			44.34 - 55.66%	28.8 - 71.20%
Ambient Density	499.12 399.12%	477.29 377.29%	319.66 219.66%	156.83 56.83%	162.47 62.47%	142.61 42.61%

Notes: Current mixing zone (base case) dilution value at 100 m equals 39.1. *A concentration factor was calculated (equation: 100 mg/l divided by the concentration at 100 m) for these scenarios.

Table 23 Discharge #4: Dilution Values at 100 m

Parameter	Decrease (%)			Increase (%)		
	20	10	5	5	10	20
Effluent Flow					25.1 -5.28%	
Effluent Flow & Concentration*	16.03 -39.53%	25.45 -3.98%			27.86 5.11%	28.65 8.13%
Effluent Density		9.6 -63.77%	8.1 -69.43%	10.3 -61.13%	8.4 -68.30%	
Ambient Velocity	22.4 -15.47%	24.9 -6.04%			28 5.66%	20.5 -22.64%
Ambient Density	24.9 -6.04%	8.1 -69.43%	10.1 -61.43%	8.1 -69.43%	9.4 -64.53%	10.7 -59.62%

Notes: Current mixing zone (base case) dilution value at 100 m equals 26.4. *A concentration factor was calculated (equation: 100 mg/L divided by the concentration at 100 m) for these scenarios.

Table 24 Discharge #4: Distance to dilution value of 26.4

Parameter	Decrease (%)			Increase (%)		
	20	10	5	5	10	20
Effluent Flow					143.72 43.73%	
Effluent Flow & Concentration*	43.09 -56.91%	32.73 -67.27%			20.74 -79.26%	17.77 -82.23%
Effluent Density		124.84 24.84%	227.43 127.43%	77.3 -22.7%	309.66 209.66%	
Ambient Velocity	230.33 130.33%	142.5 42.5%			92.89 -7.11%	113.19 113.19%
Ambient Density		357.09 257.09%	87.36 -12.64%	229.29 129.29%	144.75 44.75%	91.09 -8.91%

Notes: Current mixing zone (base case) dilution value at 100 m equals 26.4. *A concentration factor was calculated (equation: 100 mg/L divided by the concentration at 100 m) for these scenarios.

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