



**D2.4: Recommendations on the use of the iMERMAID monitoring sensors for the purposes of the WFD and MSFD Directives**

**T2.6: Develop recommendations for the applicability of the iMERMAID monitoring sensors in the monitoring programmes of the WFD and MSFD Directives with focus on the Mediterranean**

**WP2: Screening, mapping and monitoring of chemical pollution**

Authors: Tzempelikou E., Zeri C., Michalopoulos P., Kalantzi I. (HCMR), Loic Charpentier (WE)

Date: 28 February 2026



**Funded by  
the European Union**

GRANT AGREEMENT NUMBER	101112824
ACRONYM/ FULL TITLE	iMERMAID/ Innovative solutions for Mediterranean Ecosystem Remediation via Monitoring and decontamination from Chemical Pollution
START DATE	01 June 2023
END DATE	31 May 2026
PROJECT URL	<a href="http://www.imermaid.eu">www.imermaid.eu</a>
DELIVERABLE TITLE	Deliverable 2.4. Recommendations for the applicability of the iMERMAID monitoring sensors in the monitoring programmes of the WFD and MSFD Directives with focus on the Mediterranean Sea
WORK PACKAGE	2
CONTRACTUAL DATE OF DELIVERY	28/02/2026
ACTUAL DATE OF DELIVERY	M33 (28/02/2026)
NATURE	Report
DISSEMINATION LEVEL	Public
LEAD BENEFICIARY	HCMR
RESPONSIBLE AUTHOR	Eleni Tzempelikou
CONTRIBUTORS	Christina Zeri, Panagiotis Michalopoulos, Ioanna Kalantzi (HCMR), Loic Charpentier (WE)
ABSTRACT	This Deliverable assesses the applicability of iMERMAID's real-time in situ sensors under the WFD, MSFD, and UWWTD frameworks. The sensors enable continuous monitoring, capturing sporadic pollution peaks and generating high-frequency data to support Digital Twins for proactive management. Targeting heavy metals, organic micropollutants, and BTEX compounds, their compliance performance varies across water types. Sensor sensitivity is compared with regulatory limits, Environmental Quality Standards (EQS), and conventional monitoring data from European coastal, freshwater, transitional, and groundwater bodies, with emphasis on the Mediterranean. Results show they are currently best suited for groundwater and highly contaminated "hot spots".

#### Disclaimer

Any dissemination of results reflects only the author's view, and the European Commission is not responsible for any use that may be made of the information it contains.

#### Copyright message

© iMERMAID Consortium, 2023

This deliverable contains original unpublished work except where clearly indicated otherwise. Acknowledgement of previously published material and of the work of others has been made through appropriate citation, quotation, or both. Reproduction is authorised provided the source is acknowledged.

### Document history

Version	Description of changes	Author	Role in the project
0.1	Table of contents	Christina Zeri, HCMR	Beneficiary
0.2	First draft	Eleni Tzempelikou, HCMR	Beneficiary
0.3	Second draft	Eleni Tzempelikou, Christina Zeri, HCMR	Beneficiary
0.4	Final draft for internal review	Eleni Tzempelikou, Christina Zeri, Panagiotis Michalopoulos, Ioanna Kalantzi, HCMR	Beneficiary
0.5	First Internal Review	Loic Charpentier, WE	Beneficiary
0.6	Second Internal Review	Vladan Gligorijevic, CUB	Beneficiary
1.0	Final review and formatting	Rodrigo Sedano, ITCL	Project Coordinator

## EXECUTIVE SUMMARY

The present Deliverable evaluates the applicability of iMERMAID's real-time in situ sensors within the regulatory frameworks of the WFD, MSFD, and UWWTD.

The sensors developed under the iMERMAID project, represent a major shift from traditional site-specific sampling, allowing for the detection of sporadic pollution peaks and providing the high-frequency data necessary to power Digital Twins for proactive environmental management. While the sensors target a broad range of contaminants, including heavy metals, organic micropollutants, and oil compounds (BTEX), their effectiveness for compliance monitoring varies. The Deliverable examines and compares sensors' sensitivity against regulatory limits and established Environmental Quality Standards (EQS) as well as against respective data from conventional monitoring studies in three types of water bodies (coastal/marine, freshwater/transitional, ground waters) in Europe with particular focus in the Mediterranean basin. The analysis showed that currently, iMERMAID sensors are most suitable for monitoring groundwaters and heavily contaminated "hot-spots" where pollutant concentrations align more closely with the sensors' limits of detection. Because the sensors were developed and tested for wastewater applications, effluents are not addressed in this Deliverable, as they are already suitable for that purpose.

## TABLE OF CONTENTS

DOCUMENT HISTORY .....	3
EXECUTIVE SUMMARY .....	4
TABLE OF CONTENTS .....	5
LIST OF TABLES .....	5
ACRONYMS.....	7
1.0 INTRODUCTION/SCOPE OF THE DELIVERABLE .....	8
2.0 MONITORING REQUIREMENTS OF THE EU DIRECTIVES.....	9
2.1 The Water Framework Directive (WFD) .....	9
2.2 The Marine Strategy Framework Directive (MSFD) .....	10
2.3 The Urban Waste Water Treatment Directive (UWWTD) .....	10
2.4. Priority Substances and Environmental Quality Standards (EQS) .....	11
3.0 <i>IN-SITU</i> SENSORS AND THE DIGITAL TWIN.....	13
4.0 THE IMERMAID MONITORING SENSORS.....	15
5.0 APPLICABILITY OF THE IMERMAID SENSORS IN EUROPEAN WATER BODIES.....	17
5.1 Heavy Metals.....	20
5.2 Organic micropollutants .....	21
5.3 Oil compounds.....	22
6.0 CONCLUSION.....	24
REFERENCES.....	26

## List of Tables

Table 1: The iMERMAID sensors targeted contaminants, measurement principles and corresponding limits of detection. ....	15
Table 2: The iMERMAID target contaminants as listed under the relevant EU regulations. ....	18
Table 3: The iMERMAID target contaminants across established EQS values for various water bodies. ....	19
Table 4: Indicate concentration ranges of heavy metals (Cd, Cu, Pb) ( $\mu\text{gL}^{-1}$ ) in European/Mediterranean water bodies.....	20
Table 5: Indicative concentration ranges of pharmaceuticals ( $\text{ngL}^{-1}$ ) in European/Mediterranean water bodies.....	21
Table 6: Indicative concentration ranges of industrial micropollutants ( $\text{ngL}^{-1}$ ) in European/Mediterranean water bodies.....	21
Table 7: Indicative concentration ranges of bentazone ( $\text{ngL}^{-1}$ ) and nitrites ( $\mu\text{gL}^{-1}$ ) in European/Mediterranean water bodies.....	22
Table 8: Indicative concentration ranges of BTEX ( $\mu\text{gL}^{-1}$ ) in European/Mediterranean water bodies.....	22

Table 9: Suitability of iMERMAID sensors for monitoring European water bodies in relation to established EQS according to 2013/39/EU..... 24

## ACRONYMS

AA-EQS	Annual average-Environmental Quality Standard
BPA	Bisphenol A
BTEX	Benzene-Toluene-Ethylbenzene-Xylenes
CV	Cyclic voltammetry
DPV	Differential pulse voltammetry
ECS	Electrochemical sensor
EQS	Environmental quality standards
EU	European Union
IBU	Ibuprofen
KETO	Ketoprofen
LOD	Limit of detection
LSV	Linear sweep voltammetry
MAC-EQS	Maximum Annual Concentration- Environmental Quality Standard
MIMS	Membrane Inlet Mass Spectrometry
MIP	Molecularly Imprinted Polymer
MSFD	Marine strategy framework directive
ND	Not detected
PAP	Para-aminophenol
PFOA	Perfluoro-octanoic acid
PFOS	Perfluoro-sulfonic acid
SPE	Screen printed electrode
SWASV	Square Wave Anodic stripping voltammetry
TBD	To be determined
UWWTD	Urban wastewater treatment directive
VOC	Volatile organic compounds
WFD	Water framework directive

## 1.0 Introduction/Scope of the Deliverable

iMERMAID' project primary goal is to safeguard the Mediterranean Sea basin, an area highly vulnerable to chemical build-up due to intense anthropogenic activities, from Contaminants for Emerging Concern (CoEC). It aims to achieve this by integrating innovative preventive, monitoring, and remediation solutions into a multidimensional framework that supports the EU's Zero Pollution goals.

The scope of this Deliverable is to evaluate how iMERMAID's specialized monitoring sensors can be utilized within the existing regulatory frameworks of several European Union Directives, specifically: The Water Framework Directive (WFD): Focusing on protecting inland, transitional, coastal, and groundwaters; the Marine Strategy Framework Directive (MSFD): Aiming at achieving Good Environmental Status (GES) in marine waters through eleven qualitative descriptors; the Urban Waste Water Treatment Directive (UWWTD), which mandates standards for the collection and treatment of urban and industrial wastewater.

A central theme of the document is the transition from traditional site-specific sampling to the use of real-time in situ sensors. These sensors provide high-frequency data (e.g., measurements every 10 minutes), which is essential for capturing sporadic pollution peaks and informing Digital Twins—virtual models of ecosystems that allow for proactive environmental management and "what if" scenario testing.

Finally, the Deliverable provides a detailed technical assessment of the iMERMAID sensor boxes, which target heavy metals, organic micropollutants (such as pharmaceuticals, industrial chemicals and pesticides), and oil compounds. It compares the Limits of Detection (LOD) of these sensors against Environmental Quality Standards (EQS) to determine their practical applicability in monitoring coastal waters, freshwaters, and groundwaters. Because the sensors were developed and tested for wastewater applications, effluents are not addressed in this discussion, as they are already suitable for that purpose.

## 2.0 Monitoring Requirements of the EU Directives

This section provides an overview of the monitoring requirements arising from key European Union (EU) water-related environmental Directives. These Directives establish harmonized frameworks for the systematic observation, assessment and reporting of water quality and pressures, with the overarching objective of protecting human health and the aquatic environment. The focus is on the Water Framework Directive (WFD) and the monitoring of Priority Substances in relation to Environmental Quality Standards (EQS), the Marine Strategy Framework Directive (MSFD) and the Urban Waste Water Treatment Directive (UWWTD).

### *2.1 The Water Framework Directive (WFD)*

The Water Framework Directive (Directive 2000/60/EC) establishes a comprehensive framework for the protection of inland surface waters, transitional waters, coastal waters and groundwater. The Directive refers to water bodies within River Basins for which specific management plans are required by each of the Member States, in order to achieve and maintain the 'Good ecological status'. A central pillar of the WFD is the establishment of monitoring programmes that enable the assessment of the ecological and chemical water status in all the European aquatic ecosystems and the effectiveness of the management plans implemented to achieve the Directive's objectives.

Under Article 8 of the WFD, Member States are required to implement coordinated monitoring programmes for surface waters and groundwater within each river basin. For surface waters, monitoring must cover three main components: ecological status (or ecological potential for heavily modified and artificial water bodies) chemical status, and hydromorphological supporting elements. Ecological monitoring includes biological quality elements, supported by physico-chemical parameters and hydromorphological characteristics.

Chemical status monitoring focuses on substances listed as Priority Substances under EU legislation, defined by the Directive 2008/105/EC and its revision 2013/39/EU, ensuring compliance with Environmental Quality Standards (EQS). Good chemical status is considered when the levels of priority substances are found below the EQS and is expressed with two quality classes 'Good' / 'not Good'. Groundwater monitoring includes both quantitative status (water levels and removal/pumping pressures) and chemical status, with particular attention to pollutants and trends in concentration increases.

The WFD distinguishes between surveillance monitoring and operational monitoring. The surveillance monitoring provides an overall assessment of water status and long-term trends and results are provided once every six years. The operational monitoring targets water bodies at risk of failing environmental objectives and provides continuous data to assess the impact of pressures. Both networks are crucial for the WFD, ensuring a coherent overview of the ecological and chemical status of water bodies and informing management decisions. In addition, investigative monitoring is carried out where the causes of pollution or deterioration are unknown. Monitoring results are reviewed and updated on a six-year cycle.

Alongside the Water Framework Directive the Groundwater Directive 2006/118/EC refers specifically to quality status of groundwaters. It provides a structured approach for maintaining and improving groundwater chemical quality across the European Union, integrating assessment, monitoring, and management measures to prevent pollution and reverse deteriorating trends. The two Directives, WFD and GFD are closely aligned with coupled monitoring programmes and assessments.

## *2.2 The Marine Strategy Framework Directive (MSFD)*

The Marine Strategy Framework Directive (Directive 2008/56/EC) is a comprehensive and integrated approach to the protection of all European coastal and open marine waters. The Directive aims to achieve or maintain Good Environmental Status (GES) of the EU's marine waters in relation to eleven (11) qualitative Descriptors which include biodiversity (D1), non-indigenous species (D2), commercially exploited fish and shellfish (D3), food webs (D4), eutrophication (D5), sea-floor integrity (D6), hydrographical conditions (D7), contaminants (D8), contaminants in seafood (D9), marine litter (D10) and underwater noise (D11). Achieving GES means that the exploitation of the marine resources is conducted at a sustainable level, ensuring their continuity for future generations. Two pillars of the MSFD are the monitoring programmes, described under Article 11 and the Programmes of Measures under Article 13. Monitoring under the MSFD is designed to support an ecosystem-based approach to the management of human activities affecting the marine environment and to understand the effectiveness of measures taken.

Article 11 of the MSFD requires Member States to establish and implement coordinated monitoring programmes for the ongoing assessment of environmental status in their marine waters. These programmes must be compatible and coherent within marine regions and sub-regions and aligned, where relevant, with monitoring activities under other EU legislation, including the WFD.

Monitoring is structured around the 11 Descriptors and in relation to a number of criteria and methodological standards. For each descriptor, specific criteria and elements guide the selection of parameters, matrices, and monitoring frequencies. Two of the descriptors refer to contaminants. Descriptor 8 focuses on ensuring that contaminant levels in the marine environment remain low enough to prevent pollution-related effects on ecosystems. Descriptor 9 specifically addresses contaminants in fish and seafood intended for human consumption, with the specific scope of safeguarding the marine environment as a source of human food supply.

MSFD monitoring programmes must assess both the state of the marine environment and the pressures and impacts arising from human activities. The results are used to evaluate progress towards GES, to inform the establishment and revision of environmental targets and to assess the effectiveness of measures. Reporting is carried out on a six-year cycle, aligned with the adaptive management approach of the directive.

Considering the announcement of the revision of the directive by the European Commission in 2025 and also the public consultation launched in December 2025, the document will pay particular attention to develop recommendations.

## *2.3 The Urban Waste Water Treatment Directive (UWWTD)*

The Urban Waste Water Treatment Directive (Directive 2024/319/EU) establishes a comprehensive framework to protect the environment and human health from the adverse effects of urban wastewater discharges by mandating collection, treatment and discharge standards for urban wastewater across the EU and waste water from certain industrial sectors.

The Directive strengthens monitoring requirements for wastewater treatment to reduce pollution from nutrients, organic matter and hazardous substances, highlighting the issue of micropollutants (heavy metals, microplastics, pharmaceuticals, micropollutants including per- and polyfluoroalkyl substances (PFAS) that are hazardous for public health and the environment even in low concentrations, ensuring compliance with treatment standards. It further addresses that adequate monitoring is necessary concerning micropollutants, non-domestic pollution, energy neutrality, storm water overflows and urban runoff, supported through the use of digital tools. The monitoring of pollutants shall be carried out at the following frequencies: (a) at least two samples per year, with a maximum of 6 months between the samples, for agglomerations of 150 000 p.e. and above; (b) at least one sample every two years for agglomerations of between 10 000 p.e. and 150 000 p.e. Member States are obliged as of 2027 to report monitoring data on selected micropollutants. Emission limits are set for BOD, COD, total suspended solids (TSS), total organic carbon (TOC), total nitrogen (TN), total phosphorus (TP). At the moment, lack of data and information on the presence of micropollutants makes impossible the setting of specific emission standards that need to be met before discharging or reusing treated effluents.

The Directive promotes improved monitoring, energy efficiency and the application of the polluter-pays principle, ensuring that wastewater management contributes to the protection of surface waters, coastal areas and marine ecosystems and supports the EU's broader objectives for environmental sustainability and public health.

#### *2.4. Priority Substances and Environmental Quality Standards (EQS)*

Priority Substances are chemicals identified at EU level as posing a significant risk to the aquatic environment. Their monitoring is closely linked to the WFD and MSFD and is governed by Directive 2008/105/EC, as amended by 2013/39/EU (EQS Directive), which set legally binding Environmental Quality Standards (EQS) for 45 priority substances in surface waters. The list contains a wide range of contaminant classes covering both legacy and emerging pollutants: Heavy metals, Polycyclic Aromatic Hydrocarbons (PAHs), Pesticides & Biocides, Pharmaceuticals, Endocrine disruptors, Persistent chemicals (i.e., PFAS). For groundwaters Quality Standards (QS) are set by the Groundwater Directive 2006/118/EC which sets criteria for chemical status assessment and pollutant threshold values, at the moment focusing on conductivity, nitrates and total pesticides.

Member States are required to monitor Priority Substances in relevant water bodies to assess compliance with EQS for both annual average concentrations and, where applicable, maximum allowable concentrations. Monitoring must take into account appropriate matrices, including water, sediment and biota, depending on the properties of the substance and the applicable standard.

The monitoring of Priority Substances serves multiple purposes: assessing chemical/environmental status under the WFD/MSFD; identifying long-term trends in concentrations; and evaluating the effectiveness of measures aimed at reducing emissions, discharges and losses. Trend monitoring in sediment and biota is particularly important for substances that are persistent, bioaccumulative and toxic.

Data generated through EQS monitoring contribute to both river basin assessments, support compliance reporting and inform the review and update of the Priority Substances list. Together with biological and physico-chemical monitoring, EQS-based assessments provide a robust basis for integrated water management and the protection of aquatic ecosystems across the EU.

In addition to the Priority Substances List, the EU 'Watch List' includes substances suspected of posing a risk, but where data is insufficient to set EQS values. It is established through Commission Implementing Decisions, such as the 2025 update, and is not a legally binding instrument. Member States must monitor these substances for a limited period to generate comparable EU-wide data. Based on new evidence substances may be removed from the Watch List and added in the Priority substances List; removed totally if no risk is confirmed; or remain for further scientific evidence of risk related effects. In 2022 the fifth Watch List amendment (Commission Implementing Decision (EU) 2022/1307) took place and now includes 12 groups of substances including antibiotics, pharmaceuticals, industrial chemicals, sunscreens. Moreover, in 2022, 'Commission Decision, COM(2022) 540 final' for an amendment of the WFD and GWD proposes an updated priority substances list and EQS values and adds new pollutants, aligning water policy with current scientific evidence. The proposal has not yet been fully adopted, but it has reached a provisional political agreement in September 2025 on the revision of the Water Framework Directive and its related directives.

### 3.0 *In-situ* sensors and the Digital Twin

The use of real-time sensors for environmental observation marks a paradigm shift from traditional site-specific sampling, which often fails to capture the true maximum or mean concentrations of pollutants in water bodies with high temporal variability. *In situ* sensors enable continuous monitoring of physical parameters like pH, temperature, and dissolved oxygen, as well as complex chemical pollutants such as heavy metals, pesticides, and hydrocarbons. Depending on their target measurement several types of sensors have been developed such as wet chemical analysers, UV optical sensors, and electrochemical devices that can be deployed on fixed platforms, buoys, or mobile units like Unmanned Surface Vehicles (USVs) and gliders. The primary advantage of these systems is their ability to provide high temporal resolution data, allowing scientists to detect sporadic contamination outbreaks and transient events like algal blooms or floods in real time (Diaz-Gonzalez, et al., 2016).

A digital twin for environmental applications is basically a living digital copy of a real ecosystem—like a river, forest, coastline, or even an entire city’s air and water systems. It constantly updates itself using real-world data from sensors, satellites, drones, and weather stations, so the virtual model always reflects what’s happening outside. Because it behaves like the real environment, scientists and decision-makers can monitor conditions in real time, spot problems early—such as rising pollution or flood risks—and test “what if” scenarios safely in the digital space before taking action in the real world. This makes environmental management more accurate, proactive, and efficient, helping communities better protect natural resources and respond to climate challenges (Homaei et al., 2024).

As stated, continuous real time monitoring is essential for capturing sporadic peaks of concentrations which traditional manual sampling often occurring at fortnightly or monthly intervals, is unlikely to capture thus underestimating the true environmental response to pressures (O’Flynn et al., 2010). High-frequency data (e.g., sampling every 10 minutes) reveals much greater detail regarding the spatio-temporal dynamics of a water body or of discharges flows. This allows scientists to identify for example diurnal signals, observe the immediate impact of heavy rain on river flow, and when multi-sensors are applied understand the subtle interplay between different data streams. Moreover, real-time delivery of high-resolution data allows water management authorities and plant operators to move from a reactive to a proactive management approach. High-frequency data is pivotal for Digital Twins, as it allows for the assimilation of near-real-time observations into predictive models, enhancing their ability to forecast future states (Keller et al., 2024).

Connecting real-time observation streams to the concept of Digital Twins requires robust digital infrastructures capable of handling "big data". These infrastructures allow for the integration of heterogeneous datasets, including satellite imagery, UAV data, and *in situ* sensor streams, along a time dimension (Samarinas et al., 2023). This creates a multi-infrastructure monitoring environment where the digital model is constantly updated by the physical world. Artificial Intelligence (AI) and machine learning techniques, serve as the analytical engine for Digital Twins, by incorporating raw sensor signals into predictive models. For example, AI models can be used to estimate missing parameters or sharpen low-resolution data by coupling field data with satellite ones. Ultimately, the synergy of real-time sensing and AI-enhanced Earth Observation creates an operational monitoring framework that supports complex decision-making and the efficient implementation of environmental policies like the EU Water Framework Directive.

The deployment of real-time sensors for long-term environmental monitoring is essential for detecting short-term events and long-term trends, especially in a digitally transforming space. Yet it presents significant scientific, technical, and operational challenges—especially in harsh aquatic and urban environments (Liu et al., 2023; O’Flynn et al., 2010; Daniel et al., 2020). A major issue is biofouling—the accumulation of microorganisms, plants, and animals on sensor surfaces—which can impair performance and introduce significant measurement errors within days. Its severity varies depending on local conditions such as temperature, biological productivity, and water flow, meaning no universal mitigation strategy exists. In addition, sensors must withstand corrosion, extreme weather events like floods, and physical damage from debris. Technical and logistical limitations further complicate long-term monitoring. Power consumption restricts autonomous operation, especially in remote locations. Wet chemical analyzers are constrained by the limited stability and supply of reagents, which may degrade over time, and they generate hazardous waste that must be managed. Integrating sensors into mobile platforms like gliders and buoys demands ongoing miniaturization to reduce size, weight, and buoyancy effects. Analytical challenges include baseline and sensitivity drift caused by electronic changes, hydraulic issues, or surface coating, requiring careful calibration before and after deployment. Natural variability in salinity, temperature, and organic matter can interfere with measurements and reduce accuracy. In some environments, detection limits are insufficient to quantify low-concentration analytes reliably. Finally, real-time monitoring produces large, complex datasets that require robust digital infrastructure. The lack of standardized deployment protocols and quality control procedures limits comparability across systems and hampers integration into global databases.

## 4.0 The iMERMAID monitoring sensors

In the framework of the iMERMAID project the development and deployment of specialized sensor boxes designed to monitor chemical pollution in the Mediterranean Sea was made possible. Three types of sensors were developed targeting heavy metals (Cd, Cu, Pb, Zn), Nitrites, organic micropollutants (pharmaceuticals: p-aminophenol (PAP), diclofenac, ibuprofen, ketoprofen; industrial chemicals: BPA, PFAS; pesticides: bentazone, propamocarb) and oil compounds (crude oil hydrocarbons: benzene, toluene, xylene, 1,2-dichloroethane, tetrachloroethylene, naphthalene and benz[a]anthracene; chlorinated hydrocarbons: 1,3,5-trichlorobenzene, dichloromethane and trichloromethane; sunscreen agents: oxybenzone and avobenzone). They are electrochemical sensors, with a pretreatment step (acidification for heavy metals; screen printed electrode (SPE) for organic micropollutants), except the oil sensor which is based on membrane separation and mass spectrometry.

In Table 1 information on the specific techniques used and limits of detection for each targeted chemical substance are given.

Apart from the development of the sensors, the project has developed an electronic hub that collects raw data from electrochemical sensors operated in the 5 iMERMAID Use Cases, calculate pollutant concentrations, and transmit findings wirelessly to remote servers and ultimately to the iWire dashboard. To ensure high data quality, the hub utilizes Python-based algorithms and advanced noise filtering techniques for precise signal processing. Ultimately, this modular device provides a scalable framework for real-time environmental sensing and digital transformation in aquatic monitoring, in line with the concept of digital twins.

Table 1: The iMERMAID sensors targeted contaminants, measurement principles and corresponding limits of detection.

Contaminant group	Substance	UNITS	TECHNIQUE	Measurement Frequency	Duration	Limit of Detection -LOD
Heavy metals	Cd(II)	$\mu\text{g L}^{-1}$ (ppb)	Square Wave Anodic stripping voltametry (SWASV)	Continuous real time monitoring	Up to 100 measurement cycles	0.5 ± 0.1
	Cu(II)					1.2 ± 0.5
	Pb(II)					0.3 ± 0.1
Oil compounds	Benzene	$\mu\text{g L}^{-1}$ (ppb)	Membrane Inlet Mass Spectrometry (MIMS)	Continuous real time monitoring	24 h	4.88
	Toluene					7.43
	Xylene					7.46
	1,2-dichloroethane					3.45
	Tetrachloroethylene					4.3
Organic micropollutants	PAP	$\mu\text{g L}^{-1}$ (ppb)	SPE-A-M	Instantaneous	Up to 10 measurements	26
	BPA		(DPV)			1
	PFOA		SPE-A-M			0.2
	PFOS		(DPV)			TBD
	DCL		SPE-MIP			500
	KETO		(DPV)			500
	IBU		SPE-MIP (DPV)			500

	Nitrites		Unmodified SPE (LSV)			100
	Bentazone		Unmodified			60

*PAP= para-aminophenol; BPA= Bisphenol A; PFOA= Perfluoro-octanoic acid; PFOS = perfluoro-sulfonic acid; DCL= diclofenac; KETO = ketoprofen; IBU = ibuprofen; TBD =To be determined; A= activated; M= modified; MIP = Molecularly Imprinted Polymer; DPV = differential pulse voltammetry; LSV= linear sweep voltammetry; CV = cyclic voltammetry; SPE= screen printed electrode; ECS = electrochemical sensor*

## 5.0 Applicability of the iMERMAID sensors in European water bodies

Contaminants monitoring for the purposes of the EU Directives is important not only for assessing the status of water bodies against EQSs but also for understanding long term trends. Moreover, operational continuous monitoring helps in assessing the impact of pressures on the water bodies already identified being at risk. To that end, the adoption of real-time in situ sensors offers a transformative advantage over traditional sampling, which often fails to accurately estimate the true maximum or mean concentrations of pollutants in water bodies with significant temporal variability. By providing continuous measurements, the sensors can detect sporadic peaks of concentration and episodic events, such as algal blooms, or chemical contamination, that manual sampling typically misses. This high temporal resolution enables proactive environmental management and real-time decision support, allowing authorities to receive instant alerts via mobile or email when Environmental Quality Standards (EQS) are not met, thereby facilitating intervention in serious pollution incidents. Furthermore, real-time sensor networks provide the necessary spatial and temporal resolution to understand complex catchment responses and long-term trends while significantly reducing monitoring costs and the financial burden associated with traditional laboratory-based techniques (O’Flynn et al., 2010)). The integration of these sensors into monitoring frameworks directly supports WFD/MSFD/UWWTD implementation by increasing the number of observations and minimizing the percentage of water systems with unknown ecological status.

In this section, we assess the applicability of the iMERMAID sensors for monitoring under EU Directives, focusing primarily on the specific contaminants they target. We first examine their relevance in relation to priority substances and associated Environmental Quality Standards (EQS). We then examine each contaminant group separately (Sections 5.1–5.3), by reviewing available evidence on their occurrence and concentration levels in European and Mediterranean water bodies, in order to compare reported concentration ranges with the operational ranges of available sensors. For the purposes of this deliverable, selected review or country specific publications and data products from EMODNet Chemistry and reports from the European Environment Agency (EEA) were examined.

Out of the 17 substances targeted by the iMERMAID sensors, 6 are listed as Priority substances under the EQS Directive (2013/39/EU) and another 3 are included in the proposal for its amendment COM(2022) 540, as indicated in Table 2.

Moreover, 8 individual substances targeted by the iMERMAID sensors have established EQS values either for inland and coastal surface waters under the EQSD or for ground waters under the GWD and the proposal for their amendment COM(2022)540. PFAS and pesticides are dealt by these regulations as groups of contaminants, with EQS values referring to the sum of PFAS (in PFOA equivalents) or sum of pesticides monitored (Table 3).

Table 2: The iMERMAID target contaminants as listed under the relevant EU regulations.

Substance	EQSD (2013/39/EU)	COM(2022) 540 Proposal
Cd(II)	✓	✓
Cu(II)	-	-
Pb(II)	✓	✓
Benzene	-	-
Toluene	-	-
Xylene	-	-
1,2-dichloroethane	✓	✓
Tetrachloroethylene	✓	✓
p-aminophenol (PAP)	-	-
BPA	-	✓
PFAS	-	✓
Diclofenac	✓	✓
Ketoprofen	-	-
Ibuprofen	✓	✓
Nitrites	-	-
Bentazone	-	✓

Table 3: The iMERMAID target contaminants across established EQS values for various water bodies.

Group	Substance	AA-EQS inland surface waters $\mu\text{g L}^{-1}$	AA-EQS other surface waters $\mu\text{g L}^{-1}$	MAC-EQS inland surface waters $\mu\text{g L}^{-1}$	MAC-EQS other surface waters $\mu\text{g L}^{-1}$	QS-ground waters $\mu\text{g L}^{-1}$	Notes
Metals	Cd <sup>[1]</sup>	≤ 0.08 (Class 1) 0.08 (Class 2) 0.09 (Class 3) 0.15 (Class 4) 0.25 (Class 5)	0.2	≤ 0.45 (Class 1) 0.45 (Class 2) 0.6 (Class 3) 0.9 (Class 4) 1.5 (Class 5)	≤ 0.45 (Class 1) 0.45 (Class 2) 0.6 (Class 3) 0.9 (Class 4) 1.5 (Class 5)		priority hazardous tends to accumulate in sediment and/or biota
	Pb	1.2	1.3	14	14		priority hazardous tends to accumulate in sediment and/or biota
Oil	Benzene	10	8	50	50		priority hazardous
	Tetrachloroethylene	10	10			10 <sup>[2]</sup>	
	1,2-Dichloroethane	10	10				priority hazardous
Pharmaceuticals	Diclofenac	0.04	0.004	50	250		tends to accumulate in sediment and/or biota
	Ibuprofen	0.22	0.022				tends to accumulate in sediment and/or biota
	Total					0.25 <sup>[3]</sup>	
Industrial chemicals	BPA	3.4×10 <sup>-5</sup>		130	51		priority hazardous
	PFOS (sum of PFOA equivalents)	0.0044	0.0044			0.0044	priority hazardous Ubiquitous Persistent Bioaccumulative and Toxic tends to accumulate in sediment and/or biota
Pesticides <sup>[3]</sup>		0.5 (total)	0.5 (total)			0.1 (individual) 0.5 (total)	priority hazardous

<sup>[1]</sup> depending on the hardness of the water as specified in five class categories (Class 1: <40 mg CaCO<sub>3</sub>/l, Class 2: 40 to <50 mg CaCO<sub>3</sub>/l, Class 3: 50 to <100 mg CaCO<sub>3</sub>/l, Class 4: 100 to <200 mg CaCO<sub>3</sub>/l and Class 5: ≥200 mg CaCO<sub>3</sub>/l); <sup>[2]</sup> sum of trichloro- and tetrachloroethylene; <sup>[3]</sup> sum of all individual pharmaceuticals or pesticides detected and quantified in the monitoring procedure, including their relevant metabolites, degradation and reaction products.

## 5.1 Heavy Metals

Heavy metals such as Cd, Cu, and Pb are considered legacy pollutants and have been monitored in European water bodies for decades, resulting in extensive datasets across EU and Regional Seas databases, including EMODNet, WISE, OSPAR, and HELCOM, as well as a substantial body of scientific literature.

Available evidence shows that metal concentrations generally decrease from coastal to open marine waters, typically ranging from tenths of micrograms per liter down to picograms per liter, depending on the specific metal. In rivers and groundwaters, concentrations are influenced by the mineral composition of the catchment area and may reach somewhat higher levels. Elevated concentrations, often in the range of several micrograms per liter ( $\mu\text{g L}^{-1}$ ), are mainly observed in 'hot-spot' areas with intense anthropogenic pressures, such as mining or other metal-related industrial activities, and in enclosed or poorly flushed water bodies where contaminants can accumulate (Tzempelikou et al, 2021). Particularly, in groundwaters metals have a very wide range of concentrations and may reach several micrograms per liter, depending on the geological background, the solubility of metals and redox conditions as well as potential activities taking place nearby (Kubier & Pichler, 2019; Bird et al., 2009; Triassi et al., 2023).

Copper is not listed as a Priority Substance or on the Watch List under EU Directives, as it is an essential micronutrient at low concentrations, unlike cadmium and lead. However, at elevated levels, copper can be toxic to aquatic organisms. Beyond acute effects such as mortality, chronic exposure may impair survival, growth, and reproduction, and can also affect enzyme activity, and metabolism (ECI, 2008; Canning & Clode, 2011; Leal et al., 2016). The widespread use of copper-based antifouling agents on marine structures, boat hulls, and aquaculture nets further raises the risk of exposure to elevated copper concentrations in aquatic environments, which is why copper (Cu) is routinely included in environmental monitoring programmes (Chadwick & Burry, 2023; Kalantzi et al., 2016; Comber et al., 2025).

In Table 4 indicative concentration ranges for Cd, Cu and Pb are summarized for three types of water bodies along with the Limits of Detection (LOD) of the iMERMAID Heavy Metals sensor. Data comparisons reveal that the metals sensor can reliably detect Cd, Cu, Pb levels in groundwater, Cu and Pb in contaminated inland water bodies.

Table 4: Indicate concentration ranges of heavy metals (Cd, Cu, Pb) ( $\mu\text{g L}^{-1}$ ) in European/Mediterranean water bodies.

Water bodies	Cd	Cu	Pb	Source
	$\mu\text{g L}^{-1}$	$\mu\text{g L}^{-1}$	$\mu\text{g L}^{-1}$	
	LOD: 0.5		LOD: 0.3	
Coastal	0.003 – 0.04	0.01–2.0	0.02–1.9	EMODnet Caetano et al., 2022; Tzempelikou et al. 2021,
Freshwater/Transitional (lakes, rivers, estuaries, lagoons)	0.003 – 0.3	0.1 – 3.0	0.02 – 2	EMODnet, OSPAR Tzempelikou et al. 2021; Eklof, et al., 2024
Groundwaters	N.D. - >1.0	0.2 - >5.0	0.1 - >2.0	Bird et al., 2009; Triassi et al., 2023; Kubier et al, 2019; EEA

## 5.2 Organic micropollutants

Studies show that background micropollutant concentrations in natural waters are generally low, but they can vary widely depending on proximity to pollution sources and hydrological conditions. Typically, these compounds are present at nanogram per liter (ng L<sup>-1</sup>) levels, reflecting diffuse environmental inputs, but in areas influenced by point sources, such as wastewater treatment plant effluents, industrial discharges, or contaminated aquifers, concentrations can occasionally reach tens of micrograms per liter (µg L<sup>-1</sup>). Factors such as seasonal variations, rainfall, water temperature, and flow rates further influence the distribution and persistence of micropollutants in surface and groundwater systems, with higher loads often observed during periods of low dilution or increased anthropogenic input. From our synoptic review (Tables 5–7), it appeared that most studies in European and Mediterranean waters have focused on pharmaceuticals and industrial micropollutants. In contrast, few studies on pesticide contamination address bentazone, despite its widespread agricultural use, highlighting a notable gap in the monitoring and assessment of herbicide-related micropollutants in these regions.

In Tables 5 to 7 indicative concentration ranges for micropollutants are summarized for three types of water bodies along with the respective Limits of Detection (LOD) of the iMERMAID sensors. By comparing environmental data to sensors limits of detection it becomes clear that the iMERMAID sensors are most suitable for monitoring heavily contaminated waters. In particular, sensors designed for PFAS and BPA and bentazone appear to effectively capture their concentrations in groundwater or heavily polluted waters.

Table 5: Indicative concentration ranges of pharmaceuticals (ngL<sup>-1</sup>) in European/Mediterranean water bodies.

Water bodies	Diclofenac ng L <sup>-1</sup> LOD: 5 * 10 <sup>5</sup>	Ibuprofen ng L <sup>-1</sup> LOD: 5 * 10 <sup>5</sup>	Ketoprofen ng L <sup>-1</sup> LOD: 5 * 10 <sup>5</sup>	p- Aminophenol (PAP) ng L <sup>-1</sup> LOD: 26 * 10 <sup>3</sup>	Source
Coastal	N.D. - 16.0	N.D. - 1.08 Up to 5.00	0.014 - 0.18 Up to 5.00		Alygizakis et al., 2016 Lougkovois et al., 2026 Brumovsky et al., 2017 Patel et al., 2019
Freshwater/Transitional (lakes, rivers, estuaries, lagoons)	N.D. - 324	N.D. - 346 Up to 13317	N.D. - 75	42	Patel et al., 2019 Blasco et al., 2023 Martinez-Megias et al., 2024
Groundwaters	1 - 477	<1 - 150	1.5 - 200		Jurado et al., 2012

Table 6: Indicative concentration ranges of industrial micropollutants (ngL<sup>-1</sup>) in European/Mediterranean water bodies.

Water bodies	PFAS ng L <sup>-1</sup> LOD: 0.2 * 10 <sup>3</sup>	BPA ng L <sup>-1</sup> LOD: 1 * 10 <sup>3</sup>	Source
Coastal	0.3 - 0.5 Up to 2.0	N.D. - 3.6 Up to 298	Lougkovois, et al., 2025, 2026 Miserli et al., 2023 Brumovsky et al., 2016
Freshwater/Transitional (lakes, rivers, estuaries, lagoons)	1.5 - 1.8		Miserli et al., 2023
Groundwaters	1 - 42 10 <sup>3</sup>	N.D. - 10 <sup>3</sup>	Rasmusson & Fagerlund, 2024 Jurado et al., 2012

Table 7: Indicative concentration ranges of bentazone (ngL-1) and nitrites (µgL-1) in European/Mediterranean water bodies.

Water bodies	Bentazone ng L <sup>-1</sup> LOD: 6010 <sup>3</sup>	Nitrites µg L <sup>-1</sup> LOD: 100	Source
Coastal			
Freshwater/Transitional (lakes, rivers, estuaries, lagoons)	150 – 18010 <sup>3</sup>	0.46 - 23	Barbieri et al., 2021
Groundwaters		0.46 - 14	

### 5.3 Oil compounds

Oil compounds (benzene, toluene, xylene, 1,2-dichloroethane, tetrachloroethene) relevant to the iMERMAID sensor also known as BTEX volatile organic compounds (VOCs) commonly found in petroleum products and associated with fuel contamination but also with industrial manufacturing (pesticides, plastics, etc). Because of their volatile nature they are not commonly monitored in surface waters, and literature for European or Mediterranean aquatic environment is scarce (Table 8).

Individual BTEX concentration levels in various water matrices vary drastically depending on proximity to industrial activities, with levels ranging from nanograms in marine environments to hundreds of milligrams in contaminated industrial sites. Based on data from Asian countries, in heavily contaminated industrial groundwater, such as at pesticide manufacturing sites, benzene concentrations can reach extreme levels, averaging 173.3 µg L<sup>-1</sup> and peaking at 340,000 µg L<sup>-1</sup>. In these same environments, toluene and m- & p-xylenes have been detected at maximums of 4,070 µg L<sup>-1</sup> and 6,000 µg L<sup>-1</sup>, respectively (Huang et al., 2024). In contrast, in urban or energy-impacted aquifers, concentrations are significantly lower, with benzene averaging 0.71 µg L<sup>-1</sup> and both toluene and m,p-xylene averaging approximately 0.14 µg/L. In marine water, concentrations are typically measured at the nanogram per liter (ng L<sup>-1</sup>) scale. For instance, in surface seawater of the East China Sea ΣBTEX average at 235±168 ngL<sup>-1</sup> (Qiao et al., 2025), while in Iran surface seawater concentrations of benzene are 0.1 – 2.1 µg L<sup>-1</sup> toluene between <1 and 15 µg L<sup>-1</sup> and xylene up to 1.2 µg L<sup>-1</sup> (Yu et al., 2022).

Table 8: Indicative concentration ranges of BTEX (µgL-1) in European/Mediterranean water bodies.

Water bodies	Benzene µg L <sup>-1</sup> LOD: 4.88	Toluene µg L <sup>-1</sup> LOD: 7.43	Xylene µg L <sup>-1</sup> LOD: 7.46	1,2-dichloroethane µg L <sup>-1</sup> LOD: 3.45	Tetrachloroethylene µg L <sup>-1</sup> LOD: 4.3	Source
Coastal	N.D. -1.3	N.D. - 1.0	N.D. - 1.0			Moliner-Martinez et al., 2013
Freshwater/Transitional (lakes, rivers, estuaries, lagoons)						
Groundwaters	0.15 - 19	2.5 - 22	2.5 - 32	1 - 6.2	0.25 – 45 10 <sup>3</sup>	Di Lorenzo et al., 2015

In Table 8 indicative concentration ranges for BTEX compounds are summarized for three types of water bodies in European/Mediterranean sites along with the respective Limits of Detection (LOD) of the iMERMAID sensors. By comparing environmental data to sensors limits of detection it becomes clear that the iMERMAID sensors are most suitable for monitoring groundwaters.

## 6.0 Conclusion

The iMERMAID sensors are designed to monitor a variety of contaminants, but their alignment with Environmental Quality Standards (EQS) varies significantly depending on the specific substance and the type of water body being monitored. While some sensors meet the sensitivity required by EU regulations, others are better suited for detecting pollution ‘hot-spots’ or monitoring heavily contaminated environments like groundwaters.

**Heavy Metals (Cd, Pb, Cu):** The suitability of heavy metal sensors depends on the specific metal's EQS and the water matrix.

- Cadmium (Cd): The sensor's LOD is 0.5 µg/L, which is generally higher than the AA-EQS (ranging from 0.08 to 0.25 µg/L depending on water hardness). However, it remains a reliable tool for monitoring groundwater, where concentrations often exceed these levels.
- Copper (Cu): Although not currently listed as a Priority Substance under the WFD, it is monitored due to its extensive use in antifouling agents. The sensor is considered reliable for detecting copper levels specifically in contaminated surface waters groundwater environments.
- Lead (Pb): The iMERMAID sensor has a Limit of Detection (LOD) of 0.3 µg/L, which is well below the Annual Average EQS (AA-EQS) of 1.2–1.3 µg/L for surface waters. This makes it highly effective for compliance monitoring.

**Organic Micropollutants:** For many emerging contaminants, a significant gap exists between the sensor sensitivity and the strict legal standards.

- Pharmaceuticals (Diclofenac, Ibuprofen): The sensors have an LOD of 500 µg/L, which is drastically higher than the AA-EQS (0.004–0.04 µg/L for Diclofenac and 0.022–0.22 µg/L for Ibuprofen).
- Industrial Chemicals (BPA, PFAS): The BPA sensor (LOD 1 µg/L) and PFAS sensor (LOD 0.2 µg/L) also exceed their respective AA-EQS values, which are set at much lower parts per trillion levels.

Because of these higher detection limits, these sensors are most suitable for monitoring heavily contaminated waters, such as wastewater treatment effluents or industrial discharge points, rather than natural coastal or surface waters.

**Oil Compounds (BTEX):** iMERMAID sensors for volatile organic compounds (BTEX) are generally well-aligned with established EQS values.

- Benzene: The sensor LOD is 4.88 µg/L, which is comfortably below the AA-EQS of 8–10 µg/L.
- 1,2-dichloroethane & Tetrachloroethylene: These have sensor LODs of 3.45 µg/L and 4.3 µg/L respectively, both of which are below their AA-EQS of 10 µg/L.

These sensors are particularly effective for groundwater monitoring, where these industrial contaminants often appear in higher concentrations. In Table 9 these findings are summarized for those compounds with established EQS values.

*Table 9: Suitability of iMERMAID sensors for monitoring European water bodies in relation to established EQS according to 2013/39/EU.*

Contaminant	Sensor sensitivity Relative to EQS	Primary Recommended Use
-------------	------------------------------------	-------------------------

Cadmium (Cd)	Above AA-EQS	Groundwater & Pollution hotspots
Lead (Pb)	Below AA-EQS	Contaminated Surface water & Groundwater compliance
BTEX (Oil)	Below AA-EQS	Surface water, Groundwater & Industrial monitoring
Micropollutants	Significantly Above EQS	Heavily contaminated sites/wastewaters

Ultimately, the transformative advantage of these sensors is not just their detection limit, but their ability to provide real-time, high-frequency data. This allows authorities to detect sporadic pollution peaks that traditional monthly sampling might miss, even if the sensors are primarily used in more contaminated "at-risk" water bodies.

In this context, the revision of the Marine Strategy Framework Directive as well as the announcement of the revision of the Water Framework Directive should both be considered:

- Supporting the development of digital twins and deployment of sensors that provide real-time and high-frequency data. This approach can contribute to more agile monitoring of pollution, as well as reinforce synergies and coherence between the different requirements embedded in two of the directives of the European Water Acquis.
- Carefully including the conclusions of iMERMAID within the descriptors, particularly the descriptors 8 and 9. It also emphasises the benefits of including real-time sensor networks that provide long-term trends while significantly reducing monitoring costs and the financial burden associated with traditional laboratory-based techniques.
- Transboundary and regional cooperation is needed as type of pollution can change from one to another hotspot. Moreover, interoperability and standardisation in data collection will be welcome to facilitate integration in global platforms.

## REFERENCES

- Alygizakis, N. A., Gago-Ferrero, P., Borova, V. L., Pavlidou, A., Hatzianestis, I., Thomaidis N. S., 2016. Occurrence and spatial distribution of 158 pharmaceuticals, drugs of abuse and related metabolites in offshore seawater. *Science of the Total Environment* 541 1097–1105. <http://dx.doi.org/10.1016/j.scitotenv.2015.09.145>
- Barbieri M. V., A. Peris, C. Postigo, A. Moya-Garcés, L. S. Monllor-Alcaraz, M. Rambla-Alegre, E. Eljarrat, M. López de Alda, Evaluation of the occurrence and fate of pesticides in a typical Mediterranean delta ecosystem (Ebro River Delta) and risk assessment for aquatic organisms, *Environmental Pollution*, Volume 274, 2021, 115813, ISSN 0269-7491, <https://doi.org/10.1016/j.envpol.2020.115813>.
- Bird, G., Macklin, M.G., Brewer, P.A. et al. Heavy metals in potable groundwater of mining-affected river catchments, northwestern Romania. *Environ Geochem Health* 31, 741–758 (2009). <https://doi.org/10.1007/s10653-009-9259-0>.
- Brumovský M., J. Bečanová, J. Kohoutek, M. Borghini, L. Nizzetto, Contaminants of emerging concern in the open sea waters of the Western Mediterranean, *Environmental Pollution*, Volume 229, 2017, Pages 976-983, ISSN 0269-7491, <https://doi.org/10.1016/j.envpol.2017.07.082>.
- Brumovský M., P. Karásková, M. Borghini, L. Nizzetto, Per- and polyfluoroalkyl substances in the Western Mediterranean Sea waters, *Chemosphere*, Volume 159, 2016, Pages 308-316, ISSN 0045-6535, <https://doi.org/10.1016/j.chemosphere.2016.06.015>.
- Canning-Clode, J., Fofonoff, P., Riedel, G.F., Torchin, M., Ruiz, G.M., 2011. The effects of copper pollution on fouling assemblage diversity: a tropical-temperate comparison. *PLoS One* 6 (3), e18026. <https://doi.org/10.1371/journal.pone.0018026>.
- Chadwick M. & N. R. Bury (2023) Estuarine copper concentrations following boat-wash down and subsequent accumulation in blue mussels, *Toxicological & Environmental Chemistry*, 105:1-7, 111-127, DOI: 10.1080/02772248.2023.2203493
- Comber S. D. W., S. Baken, Future copper loads into the European aquatic environment, *Integrated Environmental Assessment and Management*, Volume 21, Issue 6, November 2025, Pages 1423–1438, <https://doi.org/10.1093/inteam/vjaf050>
- Daniel, A., Laës-Huon, A., Barus, C., Beaton, A. D., Blandfort, D., Guigues, N., Knockaert, M., Munaron, D., Salter, I., Woodward, E. M. S., Greenwood, N., & Achterberg, E. P. (2020). Toward a Harmonization for Using in situ Nutrient Sensors in the Marine Environment. *Frontiers in Marine Science* , 6, 773,.
- Di Lorenzo T., R. Borgoni, R. Ambrosini, M. Cifoni, D.M.P. Galassi, M. Petitta, Occurrence of volatile organic compounds in shallow alluvial aquifers of a Mediterranean region: Baseline scenario and ecological implications, *Science of The Total Environment*, Volume 538, 2015, Pages 712-723, ISSN 0048-9697, <https://doi.org/10.1016/j.scitotenv.2015.08.077>
- Díaz-González, M., Gutiérrez-Capitán, M., Niu, P., Baldi, A., Jiménez-Jorquera, C., & Fernández-Sánchez, C. (2016). Electrochemical devices for the detection of priority pollutants listed in the EU water framework directive. *Trends in Analytical Chemistry* , 77, 186–202.
- ECl, 2008. European Union Risk Assessment Report. Voluntary Risk Assessment of Copper, Copper II Sulphate Pentahydrate, Copper(I) oxide, Copper(II) oxide, Dicopper Chloride Trihydroxide. European Copper Institute (ECI). Final Version June 2008. Review Country: Italy.

- Eklöf K., C. von Brömssen, B. Huser, S. Åkerblom, A. Augustaitis, H. F. Veiteberg Braaten, H. A. de Wit, T. Dirnböck, Elustondo, U. f Grandin, A.a Holubová, . Kleemola, P. Krám, L. Lundin, Stefan Löfgren, Hampus Markensten, Filip Moldan, Gunilla Pihl Karlsson, Pernilla Rönnback, Salar Valinia, Jussi Vuorenmaa, Trends in mercury, lead and cadmium concentrations in 27 European streams and rivers: 2000–2020, *Environmental Pollution*, Volume 360, 2024, 124761, ISSN 0269-7491, <https://doi.org/10.1016/j.envpol.2024.124761>.
- Homaei, M., Di Bartolo, A. J., Ávila, M., Mogollón-Gutiérrez, O., & Caro, A. (2024). Digital transformation in the water distribution system based on the digital twins concept. *arXiv preprint*, arXiv:2412.06694.
- Huang, Y.; Chen, Y.; Wu, Q.; Shi, P.; Yang, B.; Xie, Y. Evaluation of BTEX Pollution and Health Risk for Sustainable Use of a Typical Chemical Pesticide Industrial Site. *Sustainability* 2024, 16, 6494. <https://doi.org/10.3390/su16156494>.
- Jurado A., E. Vázquez-Suñé, J. Carrera, M. López de Alda, E. Pujades, D. Barceló, Emerging organic contaminants in groundwater in Spain: A review of sources, recent occurrence and fate in a European context, *Science of The Total Environment*, Volume 440, 2012, Pages 82-94, ISSN 0048-9697, <https://doi.org/10.1016/j.scitotenv.2012.08.029>.
- Kalantzi I., Zeri C., Catsiki V.-A., Tsangaris C., Stroglyoudi E., Kaberi H., Vergopoulos N., Tsapakis M., 2016. 'Assessment of the use of copper alloy aquaculture nets: Potential impacts on the marine environment and on the farmed fish', *Aquaculture* 465, 209–222, <http://dx.doi.org/10.1016/j.aquaculture.2016.09.016>
- Keller, V., Dick, J., Dobel, A., Elliott, A., Fry, M., Harrison, S., Khamis, D., Kitson, E., Qu, Y., Blair, G., & Thackeray, S. (2024). WADITI - Developing a roadmap for a water quality digital twin. *UK Centre for Ecology & Hydrology*, NERC Open Research Archive.
- Khan, R. R., Dwivedi, S., Yadav, S., Sharf, R., Maurya, S., Pandey, U. P., & Kumari, S. (2025). Integrating AI With IoT Sensors For Real-Time Air Quality Monitoring And Prediction. *International Journal of Environmental Sciences*, 11(20s), 2275–2286,.
- Kubier A., T. Pichler, Cadmium in groundwater – A synopsis based on a large hydrogeochemical data set, *Science of The Total Environment*, Volume 689, 2019, Pages 831-842, ISSN 0048-9697, <https://doi.org/10.1016/j.scitotenv.2019.06.499>.
- Kühn, L., Bonari, J., von Danwitz, M., & Popp, A. (2025). Towards digital twins for real-time urban physics simulations via model order reduction. *3rd IACM Digital Twins in Engineering Conference (DTE 2025)*.
- Leal, P.P., Hurd, C.L., Sander, S.G., Kortner, B., Roleda, M.Y., 2016. Exposure to chronic and high dissolved copper concentrations impede meiosis development of the kelps *Macrocystis pyrifera* and *Undaria pinnatifida* (Ochrophyta). *Phycologia*. 55, 12–20. <https://doi.org/10.2216/15-87.1>.
- Liu, Y., Lu, H., & Cui, Y. (2023). A Review of Marine In Situ Sensors and Biosensors. *Journal of Marine Science and Engineering*, 11(7), 1469,.
- Loukovois R., G. Gkotsis, C. Parinos, I. Hatzianestis, M.-C.Nika, A. Pavlidou, and N.Thomaidis, Storm Daniel Extreme Flood Event in Thessaly, Greece: Assessing the Pollution Status of the Impacted Coastal Marine Areas through Extended Screening of Emerging Contaminants Using LC-TIMS-HRMS, *Environmental Science & Technology Letters* 2025 12 (4), 432-439, DOI: 10.1021/acs.estlett.5c00122
- Loukovois, R., Gkotsis, G., Parinos, C., Hatzianestis, I., Nika, M. C., Pavlidou, A., & Thomaidis, N. (2025). Storm Daniel Extreme Flood Event in Thessaly, Greece: Assessing the Pollution Status of the Impacted

- Coastal Marine Areas through Extended Screening of Emerging Contaminants Using LC-TIMS-HRMS. *Environmental Science and Technology Letters*. <https://doi.org/10.1021/acs.estlett.5c00122>
- Martínez-Megías, C., Arenas-Sánchez, A., Manjarrés-López, D. et al. Pharmaceutical and pesticide mixtures in a Mediterranean coastal wetland: comparison of sampling methods, ecological risks, and removal by a constructed wetland. *Environ Sci Pollut Res* 31, 14593–14609 (2024). <https://doi.org/10.1007/s11356-024-31968-0>
- Meng Y., P. Li, Effects of environmental factors on groundwater BTEX pollution: A quantitative analysis, *Journal of Environmental Chemical Engineering*, Volume 13, Issue 6, 2025, 119915, ISSN 2213-3437, <https://doi.org/10.1016/j.jece.2025.119915>.
- Miserli K., V. Athanasiou, V. Boti, D. Hela, I. Konstantinou, Determination of PFAS in wastewaters and natural waters by solid phase extraction and UHPLC LTQ/Orbitrap MS for assessing occurrence and removals, *Case Studies in Chemical and Environmental Engineering*, Volume 8, 2023, 100505, ISSN 2666-0164, <https://doi.org/10.1016/j.cscee.2023.100505>.
- Moliner-Martínez Y., R. Herraiz-Hernandez, J. Verdú-Andres, P. Campíns-Falcó, C. Garrido-Palanca, C. Molins-Legua, A. Seco, Study of the influence of temperature and precipitations on the levels of BTEX in natural waters, *Journal of Hazardous Materials*, Volume 263, Part 1, 2013, Pages 131-138, ISSN 0304-3894, <https://doi.org/10.1016/j.jhazmat.2013.07.037>.
- O'Flynn, B., Regan, F., Lawlor, A., Wallace, J., Torres, J., & O'Mathuna, C. (2010). Experiences and recommendations in deploying a real-time, water quality monitoring system. *Measurement Science and Technology*, 21(12), 124004 [stacks.iop.org/MST/21/124004](https://doi.org/10.1088/0957-0217/21/12/124004).
- Patel M., R. Kumar, K. Kishor, T. Mlsna, C. U. Pittman Jr., and D. Mohan, Pharmaceuticals of Emerging Concern in Aquatic Systems: Chemistry, Occurrence, Effects, and Removal Methods *Chemical Reviews* 2019 119 (6), 3510-3673 DOI: 10.1021/acs.chemrev.8b00299.
- Qiao H., J. Wang, W.-Z. Qiao, Z.-F. Liu, L.-M. Zhou, H.-H. Zhang, Occurrence, migration and environmental effects of neglected BTEX in the coastal multiple environments, *Journal of Hazardous Materials*, Volume 494, 2025, 138555, ISSN 0304-3894, <https://doi.org/10.1016/j.jhazmat.2025.138555>.
- Rasmusson K., F. Fagerlund, Per- and polyfluoroalkyl substances (PFAS) as contaminants in groundwater resources – A comprehensive review of subsurface transport processes, *Chemosphere*, Volume 362, 2024, 142663, ISSN 0045-6535, <https://doi.org/10.1016/j.chemosphere.2024.142663>.
- Sadutto D., Andreu V., Ilo T., Akkanen J., Picó Y., Pharmaceuticals and personal care products in a Mediterranean coastal wetland: Impact of anthropogenic and spatial factors and environmental risk assessment, *Environmental Pollution*, Volume 271, 2021, 116353, ISSN 0269-7491, <https://doi.org/10.1016/j.envpol.2020.116353>.
- Samarinas, N., Spiliotopoulos, M., Tziolas, N., & Loukas, A. (2023). Synergistic Use of Earth Observation Driven Techniques to Support the Implementation of Water Framework Directive in Europe: A Review. *Remote Sensing*, 15(8), 1983.
- Triassi M, Cerino P, Montuori P, Pizzolante A, Trama U, Nicodemo F, D'Auria JL, De Vita S, De Rosa E, Limone A. Heavy Metals in Groundwater of Southern Italy: Occurrence and Potential Adverse Effects on the Environment and Human Health. *Int J Environ Res Public Health*. 2023 Jan 17;20(3):1693. doi: 10.3390/ijerph20031693. PMID: 36767059; PMCID: PMC9914834.

Tzempelikou E., Zeri C., Iliakis S., Paraskevopoulou V., 2021. Cd, Co, Cu, Ni, Pb, Zn in coastal and transitional waters of Greece and assessment of background concentrations: Results from 6 years implementation of the Water Framework Directive. *Science of the Total Environment* doi:10.1016/j.scitotenv.2021.145177

Yu B., Z. Yuan, Z.Yu, F. Xue-song, BTEX in the environment: An update on sources, fate, distribution, pretreatment, analysis, and removal techniques, *Chemical Engineering Journal*, Volume 435, Part 1, 2022, 134825, ISSN 1385-8947, <https://doi.org/10.1016/j.cej.2022.134825>.

The Mediterranean Sea and its surrounding regions support a diverse variety of essential socioeconomic activities. It is one of the highly exploited water ways and the influence of anthropogenic activities on its marine habitats and ecosystems has grown significantly since the industrial revolution. Because of this, the Mediterranean Sea basin is very vulnerable to chemical contamination and build-up. To safeguard the Mediterranean Sea basin from contaminants for emerging concerns (CoEC), iMERMAID will integrate, coordinate, and synergize innovative preventive, monitoring, and remediation solutions. iMERMAID will build an evidence-based multidimensional framework that will guide policymaking and transform societal perceptions to reduce CoEC usage, emissions, and pollution. Furthermore, next generation sensor and remediation solutions will be developed within iMERMAID to monitor and remove prioritized chemicals from its source while reducing upstream pollution. iMERMAID builds an ideal interdisciplinary team by bringing together prominent SMEs, researchers, regulators, and innovation professionals who have been essential in improving the knowledge and awareness of CoEC. Beyond state-of-the-art techniques, iMERMAID will strive to strengthen regulations against CoEC, expand economic possibilities and competitiveness, improve the standard of living for EU residents, while preventing the accumulation of chemical pollution in the Mediterranean Sea basin. iMERMAID will empower the efforts to create a zero pollution, contaminant free waters by enabling the Chemical Strategy's goals to become a practical reality.



**Funded by  
the European Union**