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MArinE Litter SusTainable RemOval and Management

D5.4

Final Report on operation of the surface and water column removal technology in the Porto region

12/02/2025

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Executive Summary

The MAELSTROM project (2021 - 2024) aimed at testing and evaluating innovative technologies for the removal of aquatic litter in different coastal environments, to assess their impact on the ecosystems in chosen demo sites and to evaluate the economic and societal benefits of those solutions within local economies.

The purpose of this document (MAELSTROM's Deliverable 5.4) is to summarise the demonstration activities related with the installation and performance of the Bubble Barrier and the results of its overall effectiveness, the energy consumption and carbon footprint of the Bubble Barrier with and without the supply of solar energy, the riverine litter (RL) quantity and typology monitoring classification, and the ecological impacts of the technology.

The delays on the technology implementation due to unforeseen difficulties related with changes in the local government structure, permitting processes, local suppliers, poor weather conditions, delays in the delivery of material, and increase in raw materials prices, made that the Bubble Barrier in the Ave River estuary was implemented only in November 2023. Due to this delay, the calculation of the carbon footprint and the post-installation campaigns could only be performed along the last project year, until December 2024.

Several campaigns were performed to understand the impact of the technology on the local environment following the same protocols defined for the ecological assessment of the demo site, prior to the installation. The floating macrolitter (FML) campaigns were also maintained after the installation. Additional campaigns measured noise levels at several points, and the RL captured by the technology was classified following international classification lists. During the period after the installation, the technology was calibrated using pre-defined procedures to optimize it, and its effectiveness was assessed using the data collected during the ecological and the RL classification campaigns. At the same time, the energy consumption of the Bubble Barrier and the energy production by solar panels were monitored to understand the carbon footprint of the technology.

During this last year of the project, it was demonstrated the potential for significant reductions in the carbon footprint of the technology through the integration of renewable energy sources, using solar panels. Regarding the ecological assessment, no significant changes were observed during the limited period after implementation of the technology but changes in the ecological status of this estuary are expected

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to take much longer (possibly years) to be measurable. Underwater noise measured suggests that the noise levels produced by the Bubble Barrier compressor may pose a risk to noise-sensitive species, particularly when the technology is started, but that these levels are restricted to a small area close to the compressor shed.

During the operation period (one year), when the Bubble Barrier was performing near 80% of the time, it captured over 1450 kg of aquatic debris, with organic matter (mostly invasive species) accounting for more than 80% of this total. Excluding organic matter, it was estimated a collection of over 19 kg/month of riverine (macro)litter, with plastics accounting for most of that waste, around 17 kg/month. Due to the lightness of plastics, this waste corresponds to a significant number of items, with an estimated collection of 2750 items/month.

In terms of effectiveness in removing litter from the river, a reduction in the FML was observed downstream the technology after its implementation, clearly demonstrating that the litter quantities are reduced after passing the Bubble Barrier. Furthermore, an unexpected augment of the microplastics (MP) concentration over the bubble curtain indicates that the Bubble Barrier system may also contribute to removing these worrisome particles from the water column, before they reach the sea, where they will be almost impossible to retrieve.

The delays of almost two years until on the technology was finally deployed and operating demonstrate the complexity and the multi-fold challenges faced in implementing this pilot, namely of installing a permanent structure in a dynamic estuarine environment, with multiple authorities involved and without specific mandate (at EU, national or local level) to address riverine litter.

Nevertheless, the successful implementation of this innovative technology in an estuary demonstrates the potential for upscaling it to other locations and the meaningful collaboration across sectors. By bringing together partners from various European countries, this project has highlighted both the opportunities and challenges of the European Blue Innovation initiative.

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List of Acronyms

APA: Agência Portuguesa do Ambiente - Portuguese Environmental Agency

BB: Bubble Barrier

CCDR-N: Comissão de Coordenação e Desenvolvimento Regional do Norte - North Portugal Regional Coordination and Development Commission (CCDR-N).

CMIA: Centro de Monitorização e Interpretação Ambiental - Environmental Monitoring and Interpretation Centre

FML: Floating Macro Litter

GHG: Greenhouse Gas

IPMA: Instituto Portugues do Mar e da Atmosfera - Portuguese Institute for Sea and Atmosphere

LIPOR: Associação de Municípios para a Gestão Sustentável de Resíduos do Grande Porto - Municipalities Association for Sustainable Waste Management of Greater Porto

LOBE: Levels of Onset of Biological Adverse Effect

MP: Microplastics

RL: Riverine Litter

SUP: Single-use plastics

TG NOISE: Technical Group on Underwater Noise

TGBB: The Great Bubble Barrier

WFD: Water Framework Directive

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1. Introduction to the MAELSTROM project

MAELSTROM (2021 - 2024) was a project funded under the Topic CE-FNR-09-2020 Pilot action for the removal of marine plastics and litter. MAELSTROM strived to provide answers and diversified solutions to the complex question to the removal and sustainable treatment of marine litter legacy. MAELSTROM contemplates the integration of complementary technologies for marine litter removal in different European coastal ecosystems, compounded with full-fledged circular economy and societal oriented solutions. In particular, the project (i) set out a reliable multidisciplinary and scientifically sound approach for the assessment of marine debris distribution and impact on marine life in highly valuable ecosystems and protected areas; (ii) design and manufactures scalable, replicable and automated technologies, co-powered with renewable energy and second generation fuel, to identify, remove and sort marine litter; (iii) evaluates over time the performance of marine litter removal devices along with their impact on local ecosystems; (iv) integrates different technologies to track, sort and recycle all types of collected marine litter into valuable raw materials for future marketisation; (v) assesses the economic and societal impact of the MAELSTROM solutions providing also a comprehensive life-cycle assessment of the technologies and products; (vi) enhances social awareness about the marine litter issue and engages citizens and stakeholders in MAELSTROM activities; (vii) interplays with similar projects to maximize innovation uptake for marine litter removal within and outside the EU.

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2. Errore. Il segnalibro non è definito.MAELSTROM Consortium

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3. Errore. Il segnalibro non è definito.**Background**

3.1. About this document

The present document corresponds to MAELSTROM's Deliverable 5.4. This deliverable aims at summarising the implementation of the Bubble Barrier technology, including the supplying solar panels, in Ave River estuary, Portugal (MAELSTROM Task 5.4), the efforts performed to understand its impact on the environment (in terms of energy consumption, carbon footprint, noise and ecological impacts), and to present the technology effectiveness through the analysis of the riverine litter (RL) and microplastics (MP) retained by the technology during the pilot performing period.

The document is structured around the phases of installation, implementation, optimization, assessment and impacts of the Bubble Barrier technology.

3.2. MAELSTROM pilot site - the Ave River estuary

Located in the northwest of Portugal, the Ave River hydrological basin (Figure 3.1) has an approximate area of 1390 km^2. From its source in Serra da Cabreira to its mouth in Vila do Conde the river length is 101 km (Rocha et al., 2019). The Ave River estuarine area is located in the Vila do Conde municipality, in the district of Porto, with an area of 149.03 km^2 (data in 2013) and with 79739 inhabitants (data in 2019, mean annual population change = 0.050%), subdivided into 21 parishes (www.pordata.pt). It is a coastal municipality, limited to the west by the Atlantic Ocean (Figure 3.1). The municipality is limited to the north by the municipality of Póvoa de Varzim, to the east by Vila Nova de Famalicão and Trofa and to the south by Maia and Matosinhos.

The Ave River differs from other northern Portuguese rivers not only because of its high pollution levels, but also because of the large spatial and temporal variability of pollutant concentration (Gonçalves and Alpuim, 2011; Rocha et al., 2019). During the last years, several monitoring works have been developed in this river and its estuary to assess the anthropogenic pollution, including emerging contaminants (e.g., Ribeiro et al., 2016; Caetano et al., 2016; Couto et al., 2018, 2019; Rocha et al., 2019).

The Ave River basin exhibits a range of changes in land use and occupation, as well as distinct anthropogenic pressures (Figure 3.1; MAELSTROM Deliverable 2.3), which have contributed to the ecological degradation of its water bodies in recent years. More specifically, the Ave Estuary has not achieved good ecological status during the three Water Framework Directive's (WFD) monitoring cycles (Figure 3.2), failing to meet

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the directive's goal that states that all water bodies should attain good ecological status.

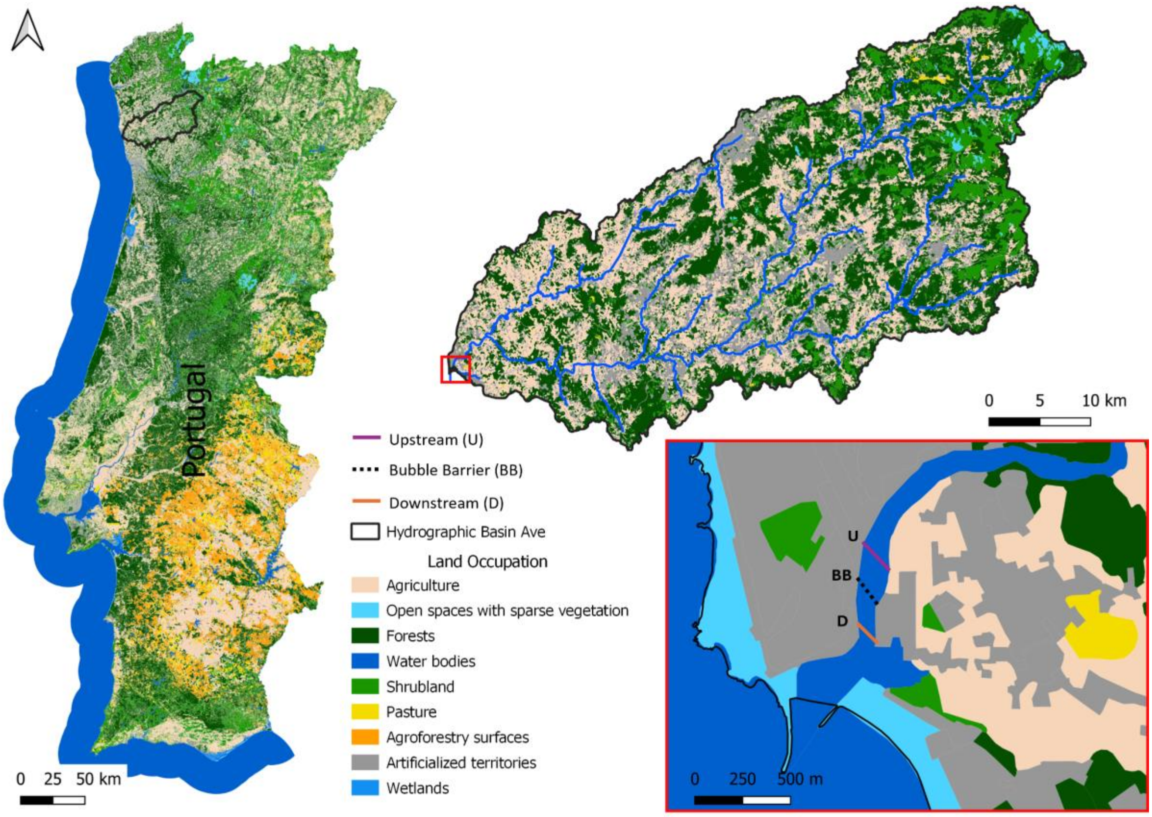

Figure 3.1 - Ave River hydrographic basin and estuary, and its land use and occupation.

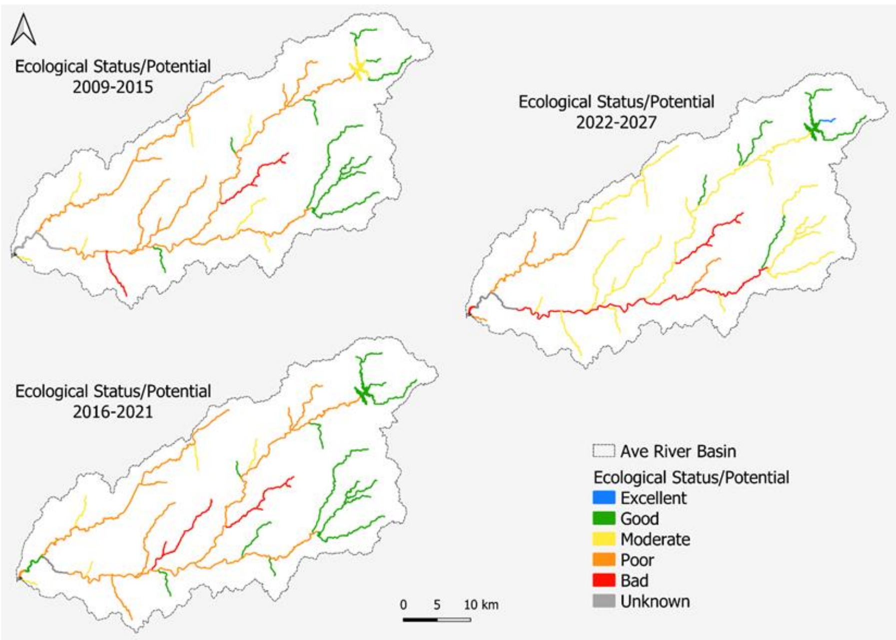

Figure 3.2 - Ecological status of the water bodies in the Ave River basin throughout the three monitoring cycles conducted under the WFD.

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Overall, the watercourses of the Ave River hydrographic basin (Figure 3.1) present serious disturbances, regarding physical, chemical and biological levels, with few exceptions recorded only in the upstream area close to the springs. These disturbances are translated into several effects in the ecosystem, namely the degradation of the riparian vegetation, the alteration of the channel, and the poor quality of the water. As expected, these disturbances have significant consequences for the aquatic communities. The surrounding area of the Ave Estuary is mainly urban, except on the left margin where a small wetland with a few species of ruderal plants and very low fauna densities can be found (Figure 3.1). The estuary is mainly used for fishing and nautical-related activities. A recreational marina, a fishing harbour and boat yards are present along the estuary.

Along the hydrographic basin of Ave River, several pressures were identified contributing to the occurrence of litter in the aquatic ecosystem (Figure 3.1). Regarding the land use and the potential contributions to the aquatic ecosystem degradation, the artificial territories and agriculture are the most significant sources of pollutants in the Ave River. This is because around 50% of the hydrographic basin is covered by these land cover uses. This area is one of the most industrialized areas of Portugal, hosting a huge number of industries, such as those of textiles, surface treatment, metal plating, leather tanning, rubber and plastic, cutlery and metalworking manufacturers (Rocha et al., 2019). These lead to high levels of pollution and to a decrease of water quality that have been registered in this region during the last decades (Couto et al., 2019). Other activities are also expected to contribute to litter in the aquatic ecosystem, such as landfills, aquaculture plants, port facilities, tourism and recreational activities. The latter two are more pronounced in the Ave River estuary due to the urban activities of the fishing town of Vila do Conde, located in the northern margin of the estuarine area.

However, and despite this strong impact, the information on the presence and categorization of aquatic litter is very limited in this estuary. According to González-Fernández et al. (2021) the Ave River basin annual floating litter loading is approximately 87306 items. Under the scope of MAELSTROM, Padilha (2022) and Pezzilli (2023) performed seasonal campaigns throughout a year and half. These works reported estimated FML means between 7.4 items/h and 24.33 ± 3.65 items/h with strong variability among seasons and spatial distribution Padilha (2022) also analysed the materials and sources of the debris. The most common material was plastic, and the most recorded item was styrofoam pieces, followed by plastic bottles, indicating that the sources of this litter are probably public litter, tourism and fishing

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activities. This also explains the abundance of cigarette butts and filters. All this litter is expected to have a substantial impact on the ocean and adjacent coastal regions, which also includes an important ornithological natural reserve (Ribeiro et al., 2016). These results were partially included in MAELSTROM Deliverable 2.3.

Regarding hydrodynamics, the Ave Estuary presents a weir roughly 2 km upstream from the river mouth that prevents salt water from travelling further inland. The Bubble Barrier system was installed downstream the weir, and so under the effect of the tide, following one of the objectives of this project that was to investigate the effects of changing tides on the technology. Due to the lack of data, specific campaigns were performed and a numerical model was implemented for the Ave Estuary to understand the flow dynamics associated with river discharge and tides, in order to estimate the transport and fate of litter and to help the detailed design of the Bubble Barrier system (MAELSTROM Deliverable 2.2). It was noticed that the flow in this estuary is mainly determined by the tides and the river discharge, and the effect of wind on the flow is limited. During low river discharge conditions, the estuary is likely to be highly stratified, meaning that a fresh-brackish water layer is on top of oceanic water, and the flow velocity magnitude does not exceed 0.5 m/s in the area selected to implement the Bubble Barrier system. RL transport to the ocean is accelerated by the estuarine circulation, since the flow velocity near the surface is directed towards the ocean for most of the tidal cycle and only changes direction in lower layers. At relatively high river discharge, salt water was flushed out of the estuary, and the entire water column was fresh. Considering an extreme river discharge of 300 m^3/s, the maximal flow velocity magnitude that can occur at a point in the cross section is 1.9 m/s. During high river discharge, the entire water column is more mixed, and the transport is mainly outwards, through which litter is likely transported efficiently to the ocean at all water depths.

4. Installation and optimization of the Bubble Barrier

4.1. Introduction

The implementation of the Bubble Barrier was initially foreseen for June 2022. Continuous functioning of the Bubble Barrier was intended from this time until the end of MAELSTROM to allow for the monitoring and evaluation tasks described in the project. Even though continuous operation was not included in the budget as such, it was agreed that The Great Bubble Barrier (TGBB), as the project partner responsible for this task, would take charge of the costs, to convince the local, regional and

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national stakeholders, in special the Vila do Conde Municipality, about the great benefit that this technology will bring to the region. A standout example of this collaboration was the placement of the Bubble Barrier catchment system, co-designed with the Municipality, which also provided financial support for some of the unforeseen implementation costs (e.g., the floating barge required to reach the catchment system).

CIIMAR, together with TGBB, have continuously engaged in conversations with the Vila do Conde Municipality and other local, regional and national stakeholders, especially the Vila do Conde Captaincy, DOCAPESCA - Portos e Lotas, S.A. (a Portuguese public company responsible for managing and operating fishing ports, fish auctions, and related infrastructure, as well as the landowner of the site where the land-based hardware would be installed), and the Portuguese Environment Agency (APA), to ensure their engagement and continued interest in a successful collaboration. However, the process took longer than initially foreseen, highlighting the challenges of the first international deployment of a Bubble Barrier outside the Netherlands.

As explained in MAELSTROM Deliverable 4.3, a change in the local government structure and a delay in the permitting process has resulted in moving implementation to the second half of 2023. It is important to note that being a technology with a fixed location and continuous operation, the permitting phase for a Bubble Barrier can be rather complex.

Implementation took place in November 2023, right on time for the launch event, held on 25/11/2023. The launch event is considered to have been very important for the project objectives, communication and retaining the relationships established with the stakeholders through continuous engagement and collaboration. The launch event was honoured by the presence of many high-level authorities including the representative of the Portuguese Government – the Secretary of State for Fisheries – as well as the Mayor of Vila do Conde, the Vice-President of the APA (now promoted to President), the Captain of Vila do Conde Captaincy, the Director of DOCAPESCA, the Director of the Municipalities Association for Sustainable Waste Management of Greater Porto (LIPOR), the CIIMAR Board of Directors, the Environmental Monitoring and Interpretation Centre (CMIA) Coordination, and representatives of the North Portugal Regional Coordination and Development Commission (CCDR-N).

The main challenges faced during implementation are presented in this chapter.

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4.2. Deployment

Following commencement of the MAELSTROM project, once the location for the Bubble Barrier in the Porto region was defined (MAELSTROM Deliverable 5.3), TGBB started working on planning the deployment operation in Portugal. It was June 2021, and this would be the first Bubble Barrier outside the Netherlands, where the company is based. Due to that, most tasks would have to be organized remotely.

For the previous installations in the Netherlands the company has been collaborating with a contractor that has co-developed their current deployment method and gained experience during other Bubble Barrier projects: Van den Herik, based in Schiedam (Netherlands). Assembling and positioning a bundle of hoses and anchoring them accurately in a straight line several meters deep in flowing water is an operation that requires specialized knowledge. The final position of the hose in the water is a crucial element to ensure the system will perform according to design.

Therefore, it was important for the project success to have the regular contractor working with TGBB. That meant some adjustments were needed to proceed with the operation abroad, in order to reduce the equipment that had to be brought to Portugal. Discussions with Van den Herik started early in the process, during which more lean methods of installation were drafted, using equipment that were presumed to be generally available, such as NATO-pontoons, general work vessels, and common cranes. The goal was to minimize the amount of mission equipment to be transported by truck from the Netherlands, and so the associated cost and the carbon footprint.

Initially TGBB was looking for rental equipment. As this attempt was not successful, the goal was redefined to find a local marine contractor with the right equipment that could pick up part of the operation. Contact with local suppliers was made, starting in the region, and later in other parts of Portugal and Spain.

Identifying a suitable partner with the required equipment, services, and experience needed to set up the operation was a challenge faced during the planning phase that impacted the deployment of the technology.

Just when timing started to become critical (August 2023) a local contractor was found that claimed to be able to deliver the equipment needed, was interested in the job and collaborated in setting up the operation together with the Dutch contractor. They are based in the region and were able to arrange a quay for mobilizing equipment which they would do according to technical drawings provided by TGBB.

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This would save a lot of time as the team and mission equipment would arrive when the temporary platform required for deployment would be ready. Also, as they are located next to Vila do Conde, they were familiar with the local authorities and applicable regulations. It was agreed that they were going to be the main contractor, while Van den Herik would provide technical assistance during the operation. The local contractor's equipment was meeting the local legislation, and they were in charge of permits and permissions for the part of their work.

The final agreement from the municipality of Vila do Conde and from DOCAPESCA was still pending at that time, and the authorization to proceed with deployment came in August 2023. The lead time between authorization and actual deployment was 3 months, during which it was possible to discuss the final details for implementation, check specifications on the equipment and negotiate quotes. The operation was scheduled to start on October 30, 2023. This was already late in the season with bad weather conditions approaching. Nevertheless, it was in the best interest of the consortium, in order to fulfil other project commitments, such as the post-implementation monitoring, to ensure that there would be one year of data about the system's operation.

An agreement was reached with Van den Herik for those days, also taking tidal conditions into account. However, days before the operation, the local contractor notified that, due to bad weather conditions, the operation had to be postponed. Indeed, as can be seen in Annex A, the conditions were very stormy and navigation from the estuary into the sea, and the other way around, was forbidden.

The operation was rescheduled, including flight tickets, hotels, transport, etc. One truck with mission equipment was packed in the Netherlands and ready to take the road, but had to stay at Van den Herik's premises and be rented for an additional week (see Figure 4.1 below). The supervisor from Van den Herik was not available a week later, so they had to bring in a replacement.

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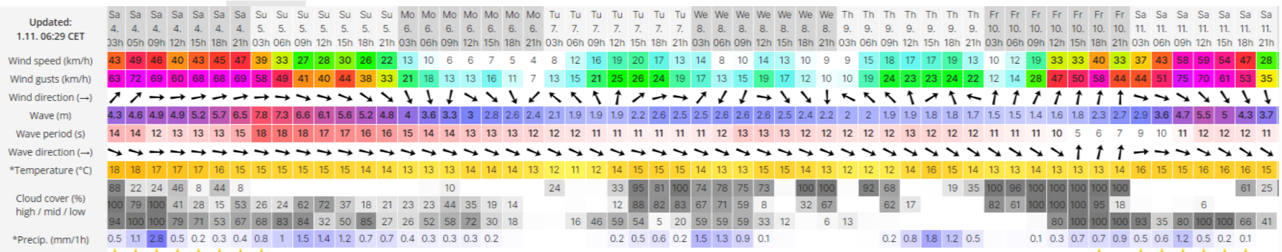
Figure 4.1 - Truck with mission equipment at Van den Herik's property to be taken to Vila do Conde for deploying the Bubble Barrier. Source: TGBB.

It was about that time that the local contractor explained that the equipment they were planning to use was not theirs, and they were still involved in another job for a big client that was extended. They could not commit to a specific timeline and could also not give solid guarantees about their supply of equipment and services. They refused to accept in writing the previous conditions that were discussed in the negotiation with TGBB and notified that they were not going to do the job.

At this point the project was faced with a very difficult situation. For the week after, relatively good weather was foreseen (see Figure 4.2 below). After that, as it is common in November, more storms were expected.



Updated: 1.11. 06:29 CET	Sa 4. 03h	Sa 4. 05h	Sa 4. 09h	Sa 4. 12h	Sa 4. 15h	Sa 4. 18h	Sa 4. 21h	Su 5. 03h	Su 5. 06h	Su 5. 09h	Su 5. 12h	Su 5. 15h	Su 5. 18h	Su 5. 21h	Mo 6. 03h	Mo 6. 06h	Mo 6. 09h	Mo 6. 12h	Mo 6. 15h	Mo 6. 18h	Mo 6. 21h	Tu 7. 03h	Tu 7. 06h	Tu 7. 09h	Tu 7. 12h	Tu 7. 15h	Tu 7. 18h	Tu 7. 21h
Wind speed (km/h)	43	49	46	40	43	45	47	39	33	27	28	30	26	22	13	10	6	6	7	5	4	8	12	16	19	20	17	13
Wind gusts (km/h)	63	72	69	60	68	68	69	58	49	41	40	44	38	33	21	18	13	13	16	11	7	13	15	21	25	26	24	19
Wind direction (→)	↗	↗	→	→	→	→	→	→	→	↘	↘	↘	↘	↘	↓	↓	↓	↘	↘	↓	↙	↖	↖	↖	↑	↗	→	→
Wave (m)	4.3	4.6	4.9	4.9	5.2	5.7	6.5	7.8	7.3	6.6	6.1	5.6	5.2	4.8	4	3.6	3.3	3	2.8	2.6	2.4	2.1	1.9	1.9	1.9	2.2	2.6	2.5
Wave period (s)	14	14	12	13	13	13	15	18	18	18	17	17	16	16	15	14	14	13	13	13	12	12	12	11	11	11	11	11
Wave direction (→)	↘	→	→	→	→	→	→	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	→	↘	↘
*Temperature (°C)	18	18	17	17	17	16	15	15	15	15	15	15	14	14	13	13	13	14	14	14	13	12	11	12	14	15	15	15
Cloud cover (%) high	88	22	24	46	8	44	8										10					24			33	95	81	100
Cloud cover (%) mid	100	79	100	41	28	15	53	26	24	62	72	37	18	21	23	23	44	35	19	14					12	88	82	83
Cloud cover (%) low	94	100	100	79	71	53	67	68	83	84	32	50	85	27	26	52	58	72	30	18			16	46	59	54	5	20
*Precip. (mm/1h)	0.5	1.1	2.8	0.5	0.2	0.3	0.4	0.8	1	1.5	1.4	1.2	0.7	0.7	0.4	0.3	0.3	0.3	0.2						0.2	0.5	0.6	0.2

Updated: 1.11. 06:29 CET	We 8. 03h	We 8. 06h	We 8. 09h	We 8. 12h	We 8. 15h	We 8. 18h	We 8. 21h	Th 9. 03h	Th 9. 06h	Th 9. 09h	Th 9. 12h	Th 9. 15h	Th 9. 18h	Th 9. 21h	Fr 10. 03h	Fr 10. 06h	Fr 10. 09h	Fr 10. 12h	Fr 10. 15h	Fr 10. 18h	Fr 10. 21h	Sa 11. 03h	Sa 11. 06h	Sa 11. 09h	Sa 11. 12h	Sa 11. 15h	Sa 11. 18h	Sa 11. 21h
Wind speed (km/h)	14	8	10	14	13	10	9	9	15	18	17	17	19	13	10	12	19	33	33	40	33	37	43	58	59	54	47	28
Wind gusts (km/h)	17	13	15	19	17	12	10	10	19	24	23	23	24	22	12	14	28	47	50	58	44	44	51	75	70	61	53	35
Wind direction (→)	↗	↙	↓	→	↘	↘	↓	↖	↖	↖	↑	↗	↑	←	↑	↑	↗	↑	↑	↑	↑	→	→	↘	↘	↘	↓	↓
Wave (m)	2.5	2.6	2.6	2.6	2.5	2.4	2.2	2	2	1.9	1.9	1.8	1.8	1.7	1.5	1.5	1.4	1.6	1.8	2.3	2.7	2.9	3.6	4.7	5.5	5	4.3	3.7
Wave period (s)	11	12	13	13	13	12	12	12	12	12	13	12	12	12	11	11	11	10	5	6	7	9	10	11	12	12	12	11
Wave direction (→)	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↑	↑	↑	→	→	↘	↘	↘	↘	↘
*Temperature (°C)	14	13	13	15	15	14	13	12	12	12	14	16	15	14	13	13	14	13	13	13	14	16	15	15	16	16	16	15
Cloud cover (%) high	74	78	75	73		100	100		92	68			19	35	100	96	100	100	100	100	100						61	25
Cloud cover (%) mid	67	71	59	8		32	67			62	17				82	61	100	100	100	95	18				6			
Cloud cover (%) low	59	59	59	33	12		6	13										80	100	100	100	93	35	80	100	100	66	41
*Precip. (mm/1h)	1.5	1.3	0.9	0.1						0.2	0.8	1.8	1.2	0.5			0.1	0.3	0.7	0.7	0.9	0.5	0.6	1.2	0.5	0.2	0.1	

Figure 4.2 - Weather forecast from 04/11/24 until 11/11/24 indicating wind speed and precipitation estimates. Source: https://windguru.cz.

Postponing deployment to spring, in order to have more time to find an alternative contractor locally and match with better weather conditions was not a feasible option. This delay would have jeopardized the post-implementation monitoring and evaluation activities to be undertaken by other project partners, due to a reduced time lead for them. To avoid another delay, the alternative option was to bring most of the equipment from the Dutch contractors in the Netherlands, and find additional

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parts locally. However, this option would mean facing unforeseen risks, due to lack of time for proper planning.

In an emergency meeting with WP5 project partners and with the Project Coordinator, it was decided to take those risks and move forward with the implementation in November 2023, since another delay was highly undesirable for MAELSTROM The Dutch contractor arranged in the last-minute three additional trucks for transport with NATO-pontoons, winches, anchoring poles and all other required equipment.

The operation proceeded according to a less detailed plan, in which only the overall activities were included. Most of the equipment came in by truck from the Netherlands in different vehicles, adding uncertainty to the logistics. Some materials were replaced locally or were overlooked due to last minute changes. Additionally, two more issues surfaced:

1) The local contractor was originally tasked with arranging a place for mobilisation of the work platforms and mission equipment. Since they were no longer contracted, TGBB reached out to DOCAPESCA to request use of the enclosed harbour close to the location where the system would be deployed. However, the harbour was unavailable due to a reconstruction of the fishermen's harbour, close to Vila do Conde's city centre.

An alternative location was found at the river mouth (see Figure 4.3 below). The combination from tides and stormy weather conditions was tricky to manage. Several damages had to be repaired, and equipment mobilization under these conditions took much more time than expected.

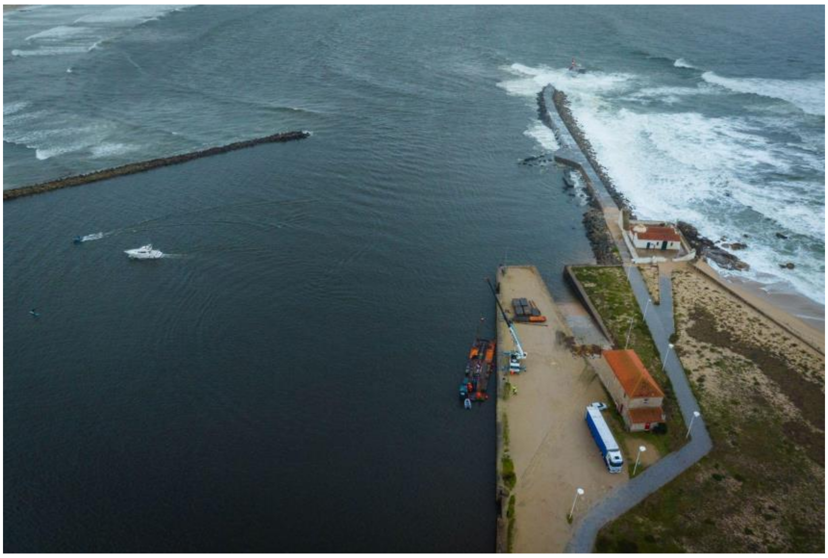

Figure 4.3 - Deployment platform being mobilized at the river mouth. Source: TGBB.

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2) Since the local contractor was in charge of contacting the authorities for the licences around deployment, there was a gap in the information available to TGBB. As a result, new information came to light on the day of the deployment and additional last-minute technical and safety checks had to be scheduled. This situation, aggravated by the stormy weather, led to several moments when the operation came close to being shut down. The flexibility of the whole team and trusted contracting partner, Van den Herik, made it possible to present alternatives to meet the conditions and fulfil the requirements from the authorities on a short notice.

The 230 m long Bubble Barrier hose-assembly was deployed according to the plan at the intended location in the Ave River Estuary (Figure 4.4 below), but not without significant effort. The weather was continuously challenging with constant rain and strong winds. Also, due to the time delays, the optimal tidal timeframe couldn't be met anymore and the tidal changes were bigger than initially planned for. This meant that some of the spud poles that were brought from the Netherlands ended up being too short for certain tidal conditions. The changes in planning, equipment, contractor, and the bad weather conditions led to a significant overspending of time and budget.

Figure 4.4 - Bubble Barrier Vila do Conde after deployment of bubble hose. Source: TGBB.

4.3. Compressor housing

The compressor and filters that provide air to a Bubble Barrier are usually placed in a housing. Typically, this is a refitted steel sea freight container, which was the option budgeted for MAELSTROM before the project started in 2021.

Because of geopolitical developments, especially the war in Ukraine starting in 2022, there was a dramatic increase in raw material prices. As the price for a container is

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linked to the steel price, there was a significant increase of the price for the foreseen container housing as well.

In a combined effort of the compressor supplier Kaeser, the suppliers in charge of building the compressor housing and TGBB, the technical specifications and design have been created. This process required a high level of coordination among the parties and became an unexpected innovation by-product from project MAELSTROM.

The final agreement on technical design and quotation was met in July 2023. In September, there was a technical visit from TGBB to the production site in Italy that showed that the technical challenges of production following the needed specifications were higher than expected, and led to a delay in final delivery time. The delay in manufacturing the container caused a delay on the installation of the compressor, which again impacted the installation of the other equipment, resulting in a delay in the whole production chain.

Despite the delays, the final result of this process was successful, resulting in a functional compressor housing with a working compressor and filter system. However, due to the complexity, new approach, new suppliers and waiting time, the equipment arrived several weeks later than expected. On December 15th 2023, the Bubble Barrier was connected to the compressor, the technical parts were integrated and the system started working in its planned configuration (see Figure 4.5 below). In total, the full container set up and connection to the system required more work and had higher costs than foreseen.

Figure 4.5 - Images from 15/12/2023, when the containerized compressor was placed at the right location and integrated into the Bubble Barrier. Source: TGBB.

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4.4. Catchment System

The decision to work with a local supplier instead of the regular contractor in the Netherlands was made because of several reasons:

1) Even though production costs were higher in Portugal, no transport would be required, making the total cost of production lower (as well as avoiding CO_2 emissions and supporting local craftsmanship);

2) The shipyard was located next to the foreseen Bubble Barrier location and it made itself available to quickly solve potential problems;

3) It was useful to have a local partner to assist in the deployment operation; and

4) In terms of stakeholder engagement, it seemed to be valuable to have a local company being hired for the project.

TGBB was aware that attention was required to supply the right information for a good result. Nevertheless, the amount of hours required to guide the production process to the desired final product was underestimated. With contact over email, video calls and messages, and a budget restriction for in person discussions on technical topics where the language barrier can play a big role, the process got distorted and many choices were made in production that did not benefit the end result. Nevertheless, it was possible to place the Catchment System in the water just before the launch event of the Bubble Barrier (Figure 4.6 below).

Figure 4.6 - Catchment System view from floating platform. Bubble curtain can be seen along the river in the top left corner of the picture. Source: TGBB.

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However, the hydraulic opening mechanism for the basket and the closing mechanism of the inflow guard, in combination with the locking pins, presented some issues due to some manufacturing faults. After having to turn the system down in mid-February 2024, to avoid any safety risk to its operation, a technical visit has been made in the following month, with limited impact. The Catchment System could only be made operational again by the end of April 2024. Since then, the Bubble Barrier has been working continuously (see Figure 4.7 below).

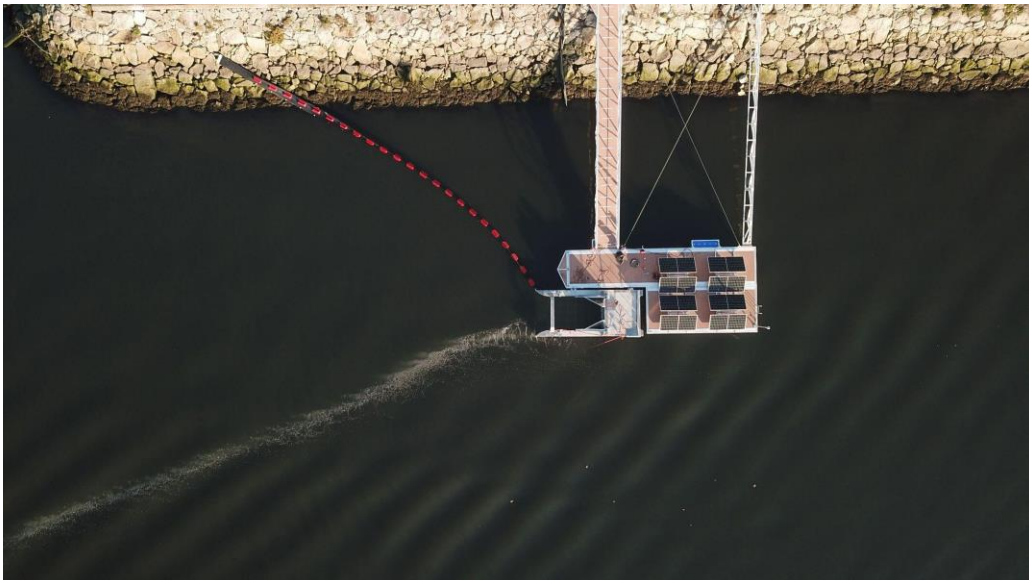

Figure 4.7 - Bubble Barrier Vila do Conde seem from above. Floating Platform anchoring the Catchment System and supporting the solar panels. Bubble curtain is in the lower left part. Source: TGBB.

4.5. Calibration and operation of the Bubble Barrier

After deployment of all system elements, the Bubble Barrier was commissioned and TGBB went through a series of visual and technical checks and optimisations that is referred to as the calibration of the system.

The interaction of the bubble curtain with the complex hydrodynamic patterns and the strong stratification of the estuary, described in MAELSTROM D2.2, were worth exploring. However, it was known that through project developments, the compressor would tightly match the design conditions, and not have a lot of extra air volume to overcome unforeseen effects.

The difficulty of an effective calibration is its dependence on specific meteo-oceanic conditions that allow the system to be optimised for these states. Due to lack of continuous data on the conditions in the estuary, it has been a challenge to schedule around the conditions and draw solid conclusions on the effectiveness.

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Initial calibration activities were executed in march 2024, during a week where flow velocity close to design values was foreseen.

A technical visit was conducted in July 2024 where several issues were solved, and an additional technical assessment was made (Figure 4.8).

Figure 4.8 - Technical assessment of the Bubble Barrier in Vila do Conde after the optimization. Indicated are points of interest: (A) section at the Catchment System (B) weaker part of the Bubble Barrier (C1,2) curves (D) exposed extremity. Important note: As photos are only a snapshot, one should be cautious to draw conclusions based on a single photo.

Figure 4.9 - At the northwest extremity of the Bubble Barrier, the bubble hoses would occasionally be exposed during low tide. The situation has been mitigated by shortening and repositioning.

Several observations were made during the technical assessment. The extremity of the bubble hoses would occasionally be exposed during the low tides. (Figures 4.8 and 4.9). This resulted in both a waste of air volume, causing a gap in another part of the same section, and the hose material potentially wearing out due to UV radiation. The section was adjusted, which seems to have solved the issue, and the gap was closed.

In two cases, clear deviations from the Bubble Barrier's linear design have been observed. The most important reason for the linear shape of the Bubble Barrier are its minimum angle requirements, which might differ over its length. A linear shape

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therefore, is a practical approach to maintain this minimal angle. While the existing curves in the Bubble Barrier might cause aesthetic worries, the Bubble Barrier effectively meets its minimum angle requirements over the entire length, as the deviations increase the angle in a beneficial way.

For unclear reasons, the part of the Bubble Barrier adjacent to the catchment system seems to have moved compared to the design and earlier air footage of the system. Instead of being aligned with the catchment system portside, the hose is compressed and ends in the centre of the catchment system inflow. In order to investigate this issue, divers' intervention is required. The operation has been elaborated but not scheduled.

Last observation were weaker parts in section 2 of the Bubble Barrier (Figure 4.8). Mitigation would in this case mean a diver intervention and should be performed jointly with the actions for restoring the section adjacent to the catchment system.

5. Installation, optimization and effectiveness of the solar panels

5.1. Installation of the solar panels

The installation of the solar panels in Vila do Conde involved several stages. Similarly to the Bubble Barrier, the installation of the solar panels was planned for 2021. However, due to delays in receiving the permits, the installation of the solar panels was also delayed to the end of 2023. The installation of the solar panels on the Environmental Monitoring and Interpretation Centre (CMIA) building rooftop took place in November 2023. In total, 66 solar panels were installed (36.3 kWp), connected to the CMIA building and the electricity grid with a 30 KW inverter. Electricity generation started being recorded in December 2023 and was accessible via an online platform to visualise real-time and past electricity generation of the system. Figure 5.1 shows an image of the solar panels installed on the rooftop of the CMIA building. The panels were installed with an East-West orientation and an inclination angle of 8.6°, maximising the rooftop's potential to generate the most electricity possible. A weather station was also installed on the rooftop of the CMIA building as part of the project. A Bettair weather monitoring system was installed in March 2024 to monitor temperature, humidity, and wind conditions. This allowed the comparison of calculated solar electricity generation data from the solar panels with real time weather patterns.

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Figure 5.1 - Solar panels installed on the rooftop of the CMIA building.

The floating solar panels could only be installed once the foundation for the floating dock and the floating dock itself were installed. Due to unforeseen circumstances during the installation of the Bubble Barrier in Vila do Conde, part of the material that was supposed to be procured locally in Vila do Conde had to be rented and transported from the Netherlands. The items included floating pontoons that were needed for the installation of the floating solar panels in Vila do Conde. The installation of the floating solar panels suffered the same delays described in Section 4.2 above. This meant a significant increase in cost associated with the required floating pontoons incurred together with TGBB.

In the case of the floating solar panels, 8 panels (4.4 kWp) were installed on the floating dock close to the catchment system, also with an East-West orientation. The inclination angle was higher in this case to ensure the panels fit on the dock with a safe distance for people to walk on the dock and conduct maintenance. Due to delays in the installation of the dock and the Bubble Barrier, the final installation could only be completed in January 2024. The floating solar panels started generating electricity in February 2024. Figure 5.2 shows an image of the solar panels installed in Vila do Conde.

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Figure 5.2 - Floating solar panels installed on the floating dock on the Ave River estuary.

5.2. Electricity generation of the solar panels

The electricity generation of the solar panels is reported for both the on-land and floating solar panels separately and monthly. Data are accessible via an online software for the on-land solar panels. However, since there is no internet connection at the floating dock, the monthly electricity generation is estimated based on electricity generation from the nearby on-land installation and the size of the installation. The total electricity generation was checked on the inverter of the floating solar panels in April and September to confirm the estimations. Table 5.1 shows the monthly electricity generation of the floating and on-land solar panels.

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<table>
<tr><th>Month</th><th>36.3 kWp CMIA Installation (kWh)</th><th>4.4 kWp Floating Installation (kWh)</th></tr>
<tr><td>December 2023</td><td>1496</td><td rowspan="6">1439</td></tr>
<tr><td>January 2024</td><td>1824</td></tr>
<tr><td>February 2024</td><td>2617</td></tr>
<tr><td>March 2024</td><td>3491</td></tr>
<tr><td>April 2024</td><td>5667</td></tr>
<tr><td>May 2024</td><td>6254</td></tr>
<tr><td>June 2024</td><td>6379</td><td>760</td></tr>
<tr><td>July 2024</td><td>6625</td><td>803</td></tr>
<tr><td>August 2024</td><td>5772</td><td>699</td></tr>
<tr><td>September 2024</td><td>4032</td><td>405</td></tr>
<tr><td>October 2024</td><td>3035</td><td>301</td></tr>
<tr><td>November 2024</td><td>2004</td><td>240</td></tr>
<tr><td>Total</td><td>49916</td><td>4647</td></tr>
</table>

Table 5.1 - Monthly electricity generation of the solar panels installed in Vila do Conde.

5.3. Carbon Footprint of the Bubble Barrier

This section of the report evaluates the carbon footprint of energy consumption associated with the installation of the Bubble Barrier on the estuary of the Ave River, in Vila do Conde, Portugal. The analysis aligns with the Greenhouse Gas (GHG) Protocol standards, utilising both **location-based** and **market-based** approaches for calculating Scope 2 emissions. Two operational scenarios are considered:

1. **Grid-Only Consumption**: The Bubble Barrier consumes 100% of its electricity from the local electricity grid.
2. **Hybrid Consumption**: The Bubble Barrier partially consumes electricity from the floating and on-land solar panels installed in Vila do Conde (assumed to

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have zero carbon footprint) and draws the remaining electricity from the local grid.

This report aims to provide a comprehensive understanding of the environmental impact of these scenarios and highlight opportunities for emission reductions through renewable energy integration. The methodology ensures transparency and consistency, enabling accurate emissions accounting in accordance with international standards.

For the location-based method, the most recent available data for emission factors of electricity consumption in Portugal are obtained from electricitymaps.com, which was 0.1073 $kgCO_2e$ per kWh of electricity consumed. For the market-based method, the electricity generation of the solar panels installed to provide electricity to the Bubble Barrier and the CMIA building was considered to have an emission factor of 0 $kgCO_2e$ per kWh, conforming to the GHG Protocol methodology. Since no market-based and residual-mix emission factors were available, the remaining electricity consumed from the grid in Portugal used the same emission factor of the location-based method to calculate the carbon footprint of electricity taken from the grid that wasn't considered to be renewable.

The Bubble Barrier started operating on the 15th of December 2023. For the purpose of this exercise, the final date of operation considered is the 5th of November 2024. Considering some adjustments and maintenance of the system between February and March, the Bubble Barrier operated for 79% of the time. During this time, 95779 kWh of electricity was consumed. Data for the electricity generation of the solar panels were obtained till 31 October 2024. In total, the solar panels generated 51714 kWh of electricity accounting for 53.4% of the electricity consumed by the Bubble Barrier. This is significantly higher than the estimated percentage of electricity generation from the solar panels, which was 25% of the electricity consumed by the Bubble Barrier. The reason behind this is due to the solar panels continuing to operate when the Bubble Barrier was not functioning. Table 5.2 shows the results of the calculation of the carbon footprint of the Bubble Barrier.

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	Scenario 1	Scenario 2
Electricity Consumption (kWh)	95779	95779
Renewable Generation (kWh)	0	51174
Net Electricity Consumption (kWh)	95779	44605
Emission Factor ($kgCO_2$/kWh)	0.1073	0.1073
Emissions ($kgCO_2$)	**10277.1**	**4786.1**

Table 5.2 - Carbon Footprint of the Bubble Barrier. Scenario 1 (Non-Renewable Energy), & Scenario 2 (With Renewable Energy).

This analysis highlights the potential for significant emissions reductions through the integration of renewable energy sources. The hybrid model demonstrates the role of solar energy in reducing the dependency on grid electricity of the Bubble Barrier, which carries an associated carbon footprint significantly higher than renewable energy.

6. Impact of the technology on the ecosystem

6.1. Introduction

An ecological assessment was carried out prior to the implementation of the Bubble Barrier system, in 2021 and again in 2023 to evaluate the original state of the ecosystem. This assessment showed that, according to WFD criteria, the status of the Ave River estuary can be classified as “moderate” to “poor” in what concerns nutrients and the biological element, here being benthic macroinvertebrates (more details in MAELSTROM, Deliverable 2.3). As described in Deliverable 2.3, during the ecological assessment campaigns, physical parameters of the water column and MP were also collected. Additionally, observational campaigns of FML were performed to establish a baseline of RL, against which new observations of FML after the implementation of the Bubble Barrier system could be compared

After the installation of the Bubble Barrier removal technology, the designed campaigns were maintained, and additional analysis were performed, to understand the impact of the technology on the Ave Estuary system.

The next sections provide details on the different assessment components and their main results.

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6.2. Ecological assessment

The ecological assessment of the Ave Estuary has been conducted since the beginning of the MAELSTROM project, covering the Spring and Autumn periods of each year (seasons with the highest biological activity for this type of water body) (Table 6.1). After the installation of the Bubble Barrier, ecological assessments were carried out seasonally to monitor the ecosystem's progression with the technology in place.

The general supporting physicochemical elements, specific pollutants, and priority substances analysed indicate that the Ave River estuary has historically been subjected to high nutrient input and diffuse pollution discharges into the ecosystem. These results may be linked to agricultural and industrial activities that exist throughout the Ave River Basin (Figure 3.1).

The biological elements evaluated in the Ave River estuary showed some variation in classification during the study period, particularly within the benthic macroinvertebrate community. However, a "good" ecological status was never achieved during the study period. Following the installation of the Bubble Barrier system, the ecological assessment results remained unchanged up to approximately 12 months post-installation, with no significant changes observed in any of the evaluated indicators. However, any significant potential changes in the ecological status of the Ave River estuary will probably take more time (years) to be measurable.

SAMPLING PERIODS	ECOLOGICAL STATUS (1)				ECOLOGICAL STATUS	CHEMICAL STATUS (2)	OVERALL STATUS (1) + (2)
	Physical and Chemical Elements	Specific Pollutants (Cu)	Biological elements			Priority Substances (Cd, Pb, Ni, Hg)	
			Chlorophyll *a* P90	BAT			
Spring21	Moderate	*	Excellent	Poor	Poor	Good	Poor
Autumn21	Moderate	*	Excellent	Moderate	Moderate	Good	Moderate
Spring22	Moderate	*	Excellent	Moderate	Moderate	Failing to achieve good	Moderate
Summer22	Moderate	*	Excellent	Poor	Poor		Poor
Autumn22	Moderate	*	Excellent	Poor	Poor	Good	Poor
Spring23	Moderate	*	Excellent	Poor	Poor	Failing to achieve good	Poor
Autumn23	Moderate	*	Excellent	Good	Moderate	Failing to achieve good	Moderate
UBB_Winter24(1)	Moderate	*	Excellent	Moderate	Moderate	Failing to achieve good	Moderate
DBB_Winter24(1)	Moderate	*	Excellent	Good	Moderate	Failing to achieve good	Moderate
UBB_Winter24(2)	Moderate	*	Excellent	Bad	Bad	Failing to achieve good	Bad
DBB_Winter24(2)	Moderate	*	Excellent	Good	Moderate	Failing to achieve good	Moderate
UBB_Spring24	Moderate	*	Excellent	Bad	Bad	Failing to achieve good	Bad
DBB_Spring24	Moderate	*	Excellent	Poor	Poor	Failing to achieve good	Poor
UBB_Summer24	Moderate	*	Excellent	Ongoing	Ongoing	Failing to achieve good	Ongoing
DBB_Summer24	Moderate	*	Excellent	Ongoing	Ongoing	Failing to achieve good	Ongoing
UBB_Autumn24	Moderate	*	Excellent	Ongoing	Ongoing	Failing to achieve good	Ongoing
DBB_Autumn24	Moderate	*	Excellent	Ongoing	Ongoing	Failing to achieve good	Ongoing

* Without reference values

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Table 6.1 - Summary of the results of evaluated elements used to assess water quality based on WFD metrics throughout MAELSTROM, including pre- and post-technology installation phases. Upstream Bubble Barrier (UBB) and Downstream Bubble Barrier (DBB) transects can be found at Figure 3.1.

6.3. Floating Macro Litter and Microplastics

FML and MP were assessed before and after the implementation of the Bubble Barrier system in the Ave River estuary. The selection of the observations and data collection sites encompassed different sections of the estuary, considering the location of the technology installation.

6.3.1. Floating Macro Litter (FML)

The evaluation of FML was conducted following European guidelines (Hanke et al., 2013, 2023) through visual observations, which examined the diversity and relative abundance of litter in the area. Monitoring campaigns were carried out monthly from June 2021 to December 2024. FML was observed using binoculars (Olympus 8-16x40 Zoom DPS I), during the ebb tide, at three different locations in the estuary: downstream, midstream, and upstream (S1: 41.340117°N, 8.748913°W; S2: 41.345022°N, 8.745227°W; S3: 41.351156°N, 8.741285°W) (Figure 6.1). The three observation points were located at the same plane, all of them at the margin of the estuary and with an averaged vertical distance to the water surface around 2 m (mean sea level), such that the viewing angle was similar and the results for the three locations can be compared. Although some FML objects could be masked by ripples produced by wind, or small waves produced by boats passing by, it is deemed unlikely to impact results as observational campaigns were performed during calm days with high visibility.

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Figure 6.1 - Map of the three observation points (S1 – S3) for FML record in the Ave River estuary. Reference system WGS84.

Significant differences ($\rho < 0.05$; ANOVA) were observed between seasons, sites, and their interaction (seasons*sites). The data indicated higher values of FML were recorded during Winter, Spring and Autumn, while lower values were observed in Summer (Figure 6.2). These patterns underscore the influence of both temporal (seasonal) and spatial (site-specific) factors on the measured variables. River discharge also related with the weather conditions can also explain part of the variation observed since the highest FML rates occurred during the highest river discharges (Figure 6.3). Most of the FML campaigns were carried out during low or average Ave River discharges, except for winter 2022 and autumn and winter 2023. Particularly the campaign of winter 2022 was performed after a long period with low river discharge and at the onset of a (very) high river discharge. Usually, after a long period of low river discharge, litter tends to accumulate on its river banks, and when the river discharge and water level start to rise, part of this litter is transported to the sea. This can explain the high FML items per hour observed in this season. This hypothesis can also explain the behaviour during autumn 2023, but in this season the FML presents less quantity because the river flow was also lower than during winter 2022. In winter 2024 high river discharges were also observed. However the values did not reach the winter 2022 measurements because the river discharge had been elevated already for months, washing away all the litter on the margins.

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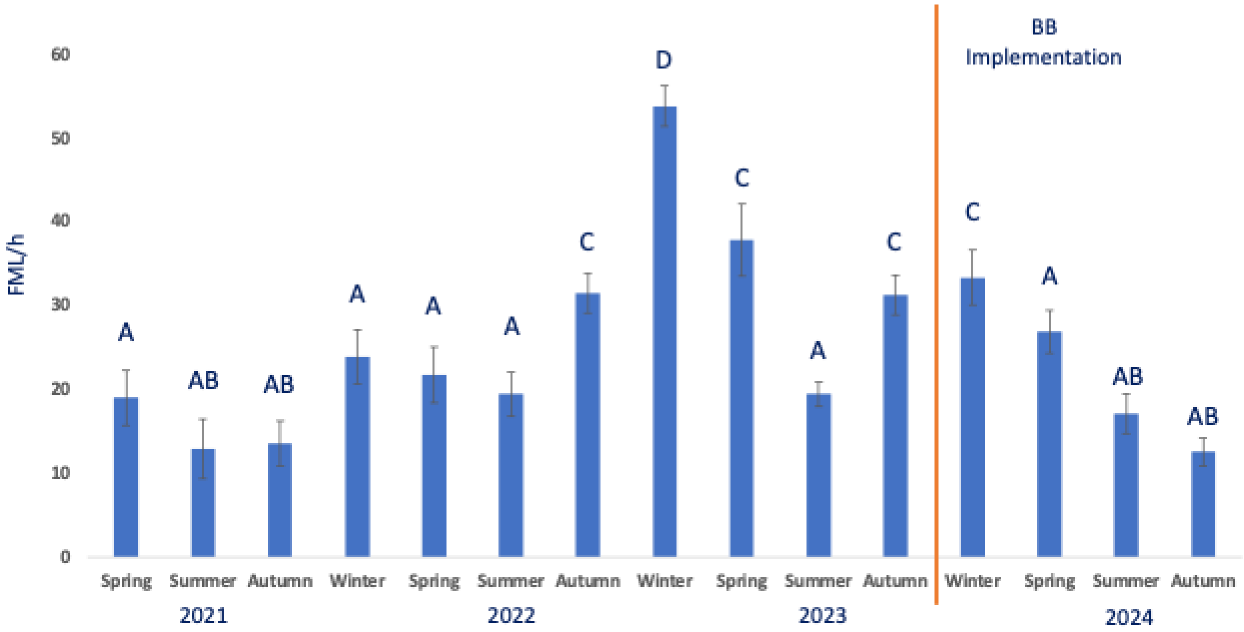

Figure 6.2 - Seasonal mean of the three FML observation sites (S1-S3) (± standard errors) in items per hour recorded monthly between 2021 and 2024, before and after the Bubble Barrier (BB) installation. Bars with different letters are significantly different between them (ρ < 0.05).

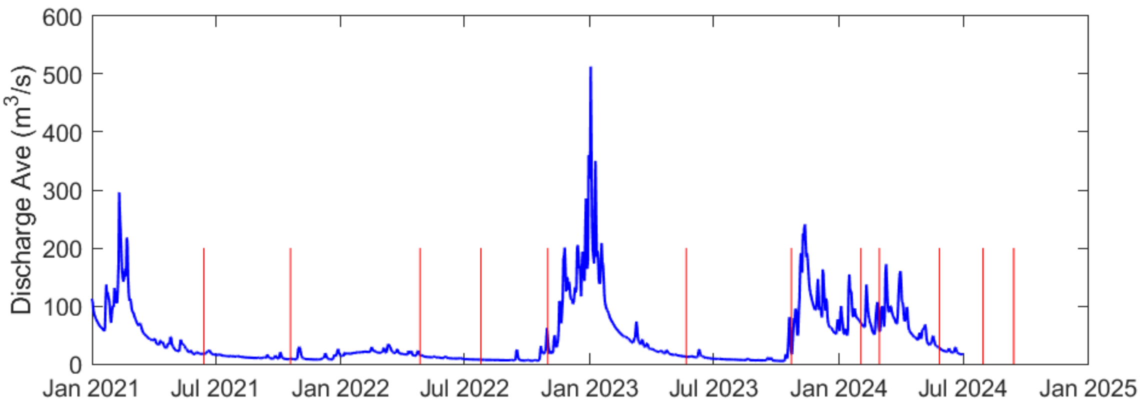

Figure 6.3 - The river discharge at the river mouth of the Ave River obtained from the hydrological model developed in the scope of the MAELSTROM project (blue, MAELSTROM D2.2) with the moments of the ecological assessments indicated (red).

Before the implementation of the Bubble Barrier, significantly higher values ($\rho < 0.05$) of floating macro-litter (FML) were observed near the mouth of the estuary (S1 - 42.5 ± 6.3 items/h) compared to other sites (S2 - 22.4 ± 2.1 items/h; S3 - 11.7 ± 2.3 items/h; see Figure 6.4). These results highlight the impact of the urban centre on the FML found in the estuary, with an increasing FML gradient from S3 to S1.

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After the Bubble Barrier was installed and began operation, a significant reduction in FML ($p < 0.05$) was observed downstream of the technology installation area (S1 - 25.5 ± 5.9 items/h; see Figure 6.4). No significant differences in FML were noted in S2 (27.6 ± 5.3 items/h) and S3 (12.1 ± 4.7 items/h) after the Bubble Barrier's operation. Consequently, an approximate reduction of 40% was recorded in FML near the mouth of the Ave estuary following the implementation of the technology.

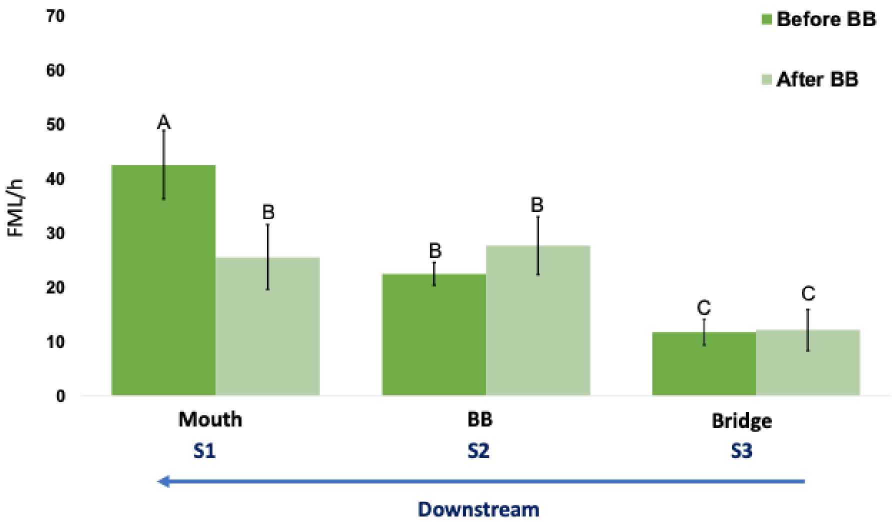

Figure 6.4 - Comparison of the FML items (mean ± standard errors) per hour recorded monthly, before and after) the Bubble Barrier (BB) implementation, in the three observation sites (S1-S3). Bars with different letters are significantly different between them (before and after BB) ($p < 0.05$).

Regarding the types of FML observed, although there was a high variability across different months and seasons, artificial polymer materials (plastics) were the most prevalent types of litter, representing more than 85.5% of the total items recorded. They were followed distantly by smoking-related litter (cigarette butts and packages; 7.3%), paper and cardboard items (6.4%), and metal objects, which accounted for less than 1% of the total floating litter observed.

When focusing on the visual campaigns in the mouth of the estuary (S1), located downstream of the BB, the top 5 FML items identified before the technology implementation were "non-foamed plastic fragments", "foamed plastic fragments", "plastic Bags", "cigarette butts" and "paper fragments" "representing respectively 39.3%, 30.1%, 12.4%, 9.2%, and 9%. After the installation of the ML removal technology, the 5 most commonly identified FML represented, by the same order, 54.7%, 13.1%, 4.1%, 19.8% and 8.3%, respectively.

It's important to note that seasonality and local anthropogenic activities such as tourism and other leisure pursuits in this area may also represent important sources of the litter observed.

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The overall results showed that the Bubble Barrier is already contributing to a significant reduction of FML, collecting most of these materials before they reach the Atlantic Ocean, contributing to both aquatic ecosystems and human health.

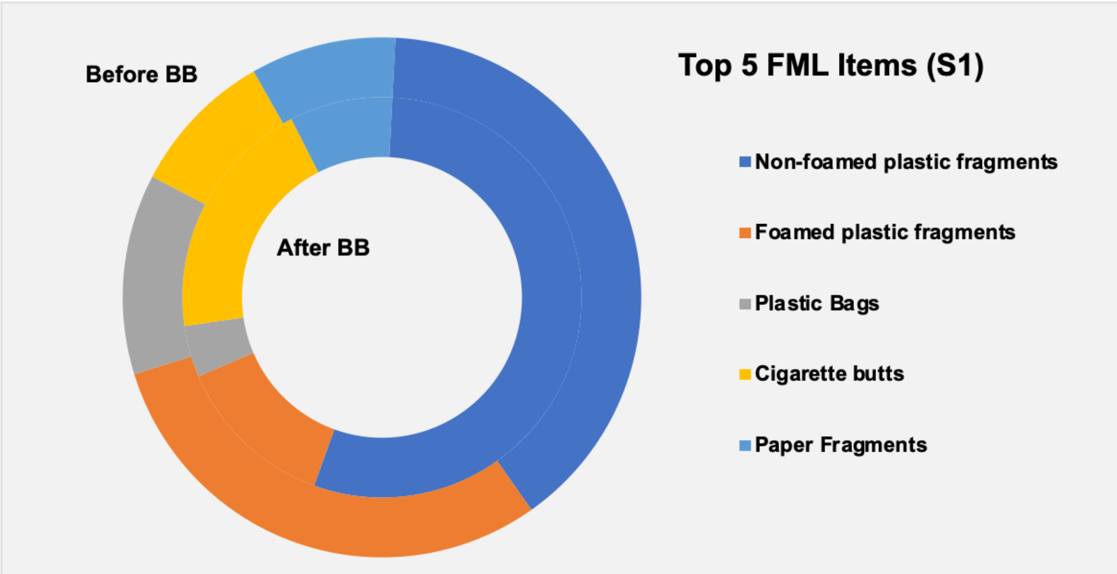

Figure 6.5 - Classification of the Top 5 materials found in the FML assessment in the estuarine mouth (S1) before and after the BB implementation.

6.3.2. Microplastics (MP)

Although the Bubble Barrier is not specifically designed to collect MP, an assessment of these worrisome emerging pollutants was also conducted in the estuary. Given that most MP originates from the fragmentation of larger plastics (secondary MP), this study served as a complement to the FML assessment.

MP particles in the water column were evaluated following standardized protocols (Gago et al., 2018). Samples for MP were collected under low tide conditions using a manta net with 200 μm mesh size. To quantify the filtered water volume, a flowmeter (Hydro-Bios 438115) was attached to the manta net. The planktonic trawls were performed seasonally (2021-2024) along five different transects, three downstream (T1 - T3) and two upstream (T4 and T5) the technology (Figure 6.6).

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Figure 6.6 - Map of the five selected transects (T1 – T5) for MP in the Ave River estuary. Reference system WGS84.

Significant differences ($p < 0.05$; ANOVA) were observed in identified MP between seasons, sites, and their interaction (seasons*sites). More than 25 MP/m^3 were recorded in the Ave River estuary, with higher values at upstream transects (Figure 6.7). Fibres and fragments represented more than 87% of the identified MP (Figure 6.8).

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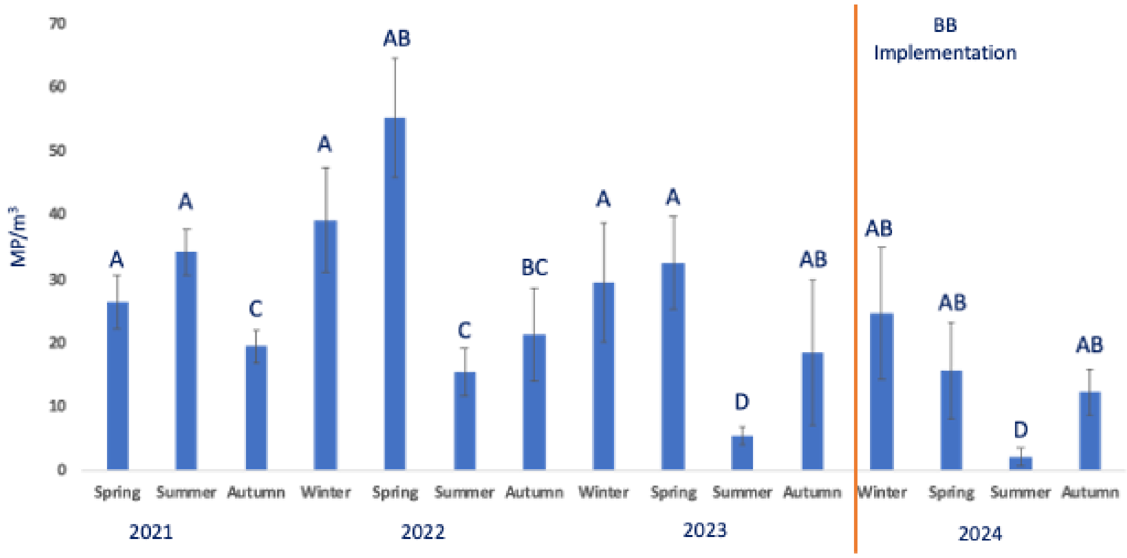

Figure 6.7 - Mean number of MP/m3 seasonal collected between 2021 and 2024 (mean ± standard errors) from the 5 sampled transects), before and after the Bubble Barrier (BB) installation. Bars with different letters are significantly different between them ($p < 0.05$).

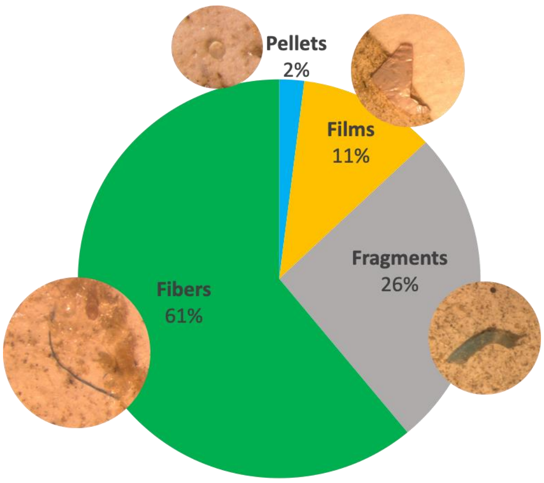

Figure 6.8 - Percentages of the most common MP collected in the Ave Estuary during the campaigns performed under the scope of MAELSTROM (aggregated observations, seasonal collected between 2021 and 2024).

After the installation of the Bubble Barrier, an additional MP collection transect was conducted seasonally over the bubble curtain, following the same methodology and with the same manta net described above. The average concentration of MP in the bubble curtain area was estimated to be 81 MP/m^3, which is substantially higher than in other transects, demonstrating that this technology effectively concentrates MP at the surface of the air bubble curtain (Figures 6.9 and 6.10).

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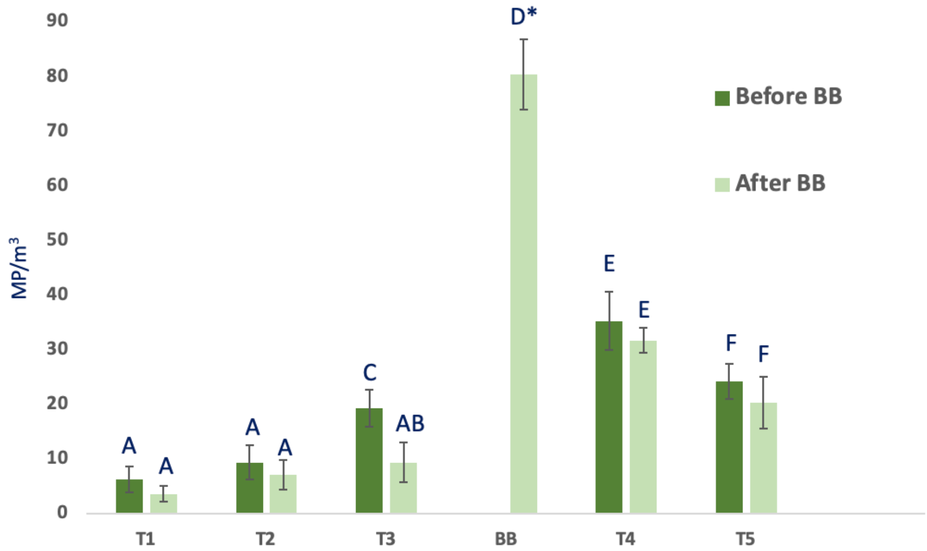

Figure 6.9 - Comparison of the MP (mean ± standard errors) collected between before and after the Bubble Barrier (BB) implementation. Bars with different letters are significantly different between them ($p < 0.05$) in MP collected before and after the technology operation. BB represents the transect on the bubble curtain.

Figure 6.10 - MP sample collected in the bubble curtain with the manta net.

6.4. Noise pollution

With increasing human activities in the ocean and coastal areas, anthropogenic noise has become ubiquitous and reached levels that are considered as pollution, harming aquatic ecosystems. Underwater noise pollution caused by human activities

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in estuaries can have devastating impacts on marine life, as it has the potential to mask some marine species' ability to communicate and navigate (Valenzisi et al., 2024). Next to communication and navigation, underwater noise has also been found to affect animal feeding, mating and defence, either directly or indirectly. For instance, Simpson et al. (2014) found that juvenile European eels (*Anguilla anguilla*), a species present in the Ave River estuary, exposed to increased underwater noise levels, became more prone to be caught by predators, had diminished spatial performance and elevated ventilation and metabolic rates, which are indicators of stress.

Most underwater soundscape studies focus on the ocean, with less than 5% of the literature related to estuarine habitats (Havlik et al., 2022). And little is known about specific impacts on estuarine organisms. Effects will depend on the hearing sensitivity of fishes, the frequency, and noise levels, and also on the difference between a sound and the local background noisescape. There are also suggestions that very loud noises from sonar, piling and explosions, which typically attract most attention, may have less impact on fish than less intense sounds that are of longer duration and that can potentially affect whole ecosystems (Slabbekoorn et al., 2010).

With this in mind, an acoustic survey was carried out on 11 November 2024 in the Ave Estuary, with a recently calibrated ICListen high-frequency hydrophone (https://oceansonics.com/iclisten-hf-hydrophone/), with an end-to-end sensitivity of =-171.19 dB re V/µPa, which allowed obtaining calibrated sound levels in decibels (dB) of the background noise. Calibrated data provide absolute measures of biotic, abiotic and anthropogenic sound levels, which are necessary to draw meaningful comparisons of habitats through time and at different locations.

The hydrophone was deployed from three piers (Figure 6.11): at the centre river-side of the Bubble Barrier pier (Pier 1); on the corner of a small pier near the end of the Bubble Barrier, 285 m from the centre of the Bubble Barrier pier (Pier 2); and at the end of the yacht pier, 628 m from the centre of the Bubble Barrier pier (Pier 3). The hydrophone was lowered into the water tied to a line, without extra weight (given that the current was very weak), and placed about 50 cm above the estuary bottom for recording. Recordings of at least 5 minutes were taken with the Bubble Barrier switched off and on – at Piers 1, 2, 3 – and during the start of the Bubble Barrier – at Pier 1.

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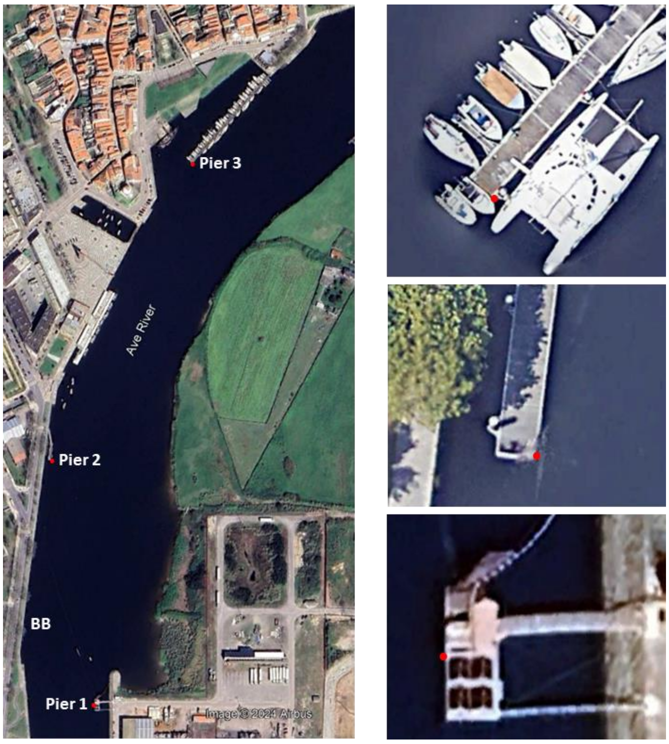

Figure 6.11 - Acoustic survey sites.

Broadband SPL (20-2000 Hz) values of the recordings are presented for the period during the start-up of the Bubble Barrier, and for recordings with the Bubble Barrier switched on and off (Table 6.2, Figure 6.12). For the comparison of conditions with the Bubble Barrier switched on and off, recorded minutes without exceptional noise events were selected to represent base noisescapes.

Graphs of the broadband SPL along time are also presented for the selected minutes (Figure 6.13).

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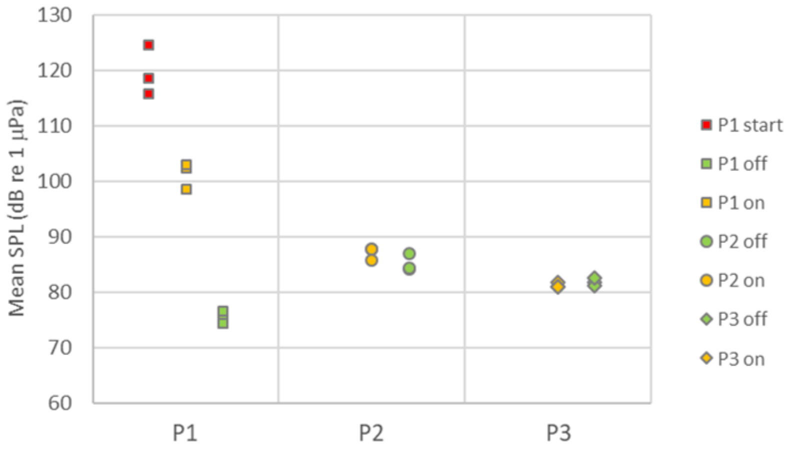

Figure 6.12 - Mean broadband SPL (20-2000 Hz) of the 3 minutes recorded during the start of the Bubble Barrier, at Pier 1, and of 3 minutes recorded at each site with the Bubble Barrier switched on and off (minutes without exceptional noise events were selected to represent base noisescapes).

Site	BB	RMS (mean)	Median	Mode
Pier 1	START	118.6	106.8	100.4
Pier 1	START	124.5	116.3	114.1
Pier 1	START	115.8	110.3	105.4
Pier 1	OFF	75.1	74.6	74.6
Pier 1	OFF	76.5	74.4	74.8
Pier 1	OFF	74.4	74.1	74.3
Pier 1	ON	102.3	97.6	94.0
Pier 1	ON	102.9	95.5	90.1
Pier 1	ON	98.5	90.9	92.5
Pier 2	OFF	86.9	82.7	84.4
Pier 2	OFF	84.1	81.8	81.7
Pier 2	OFF	84.4	82.9	82.4
Pier 2	ON	87.7	85.1	84.9
Pier 2	ON	87.8	85.3	85.3
Pier 2	ON	85.7	83.9	83.4
Pier 3	OFF	81.8	79.7	79.1

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Pier 3	OFF	81.1	79.7	78.1
Pier 3	OFF	82.6	80.7	79.3
Pier 3	ON	81.8	81.4	81.5
Pier 3	ON	80.9	80.3	79.8
Pier 3	ON	81.0	80.2	79.1

Table 6.2 - Broadband SPL (20-2000 Hz) values (dB) of the recordings for the different sites and conditions. BB: Bubble Barrier.

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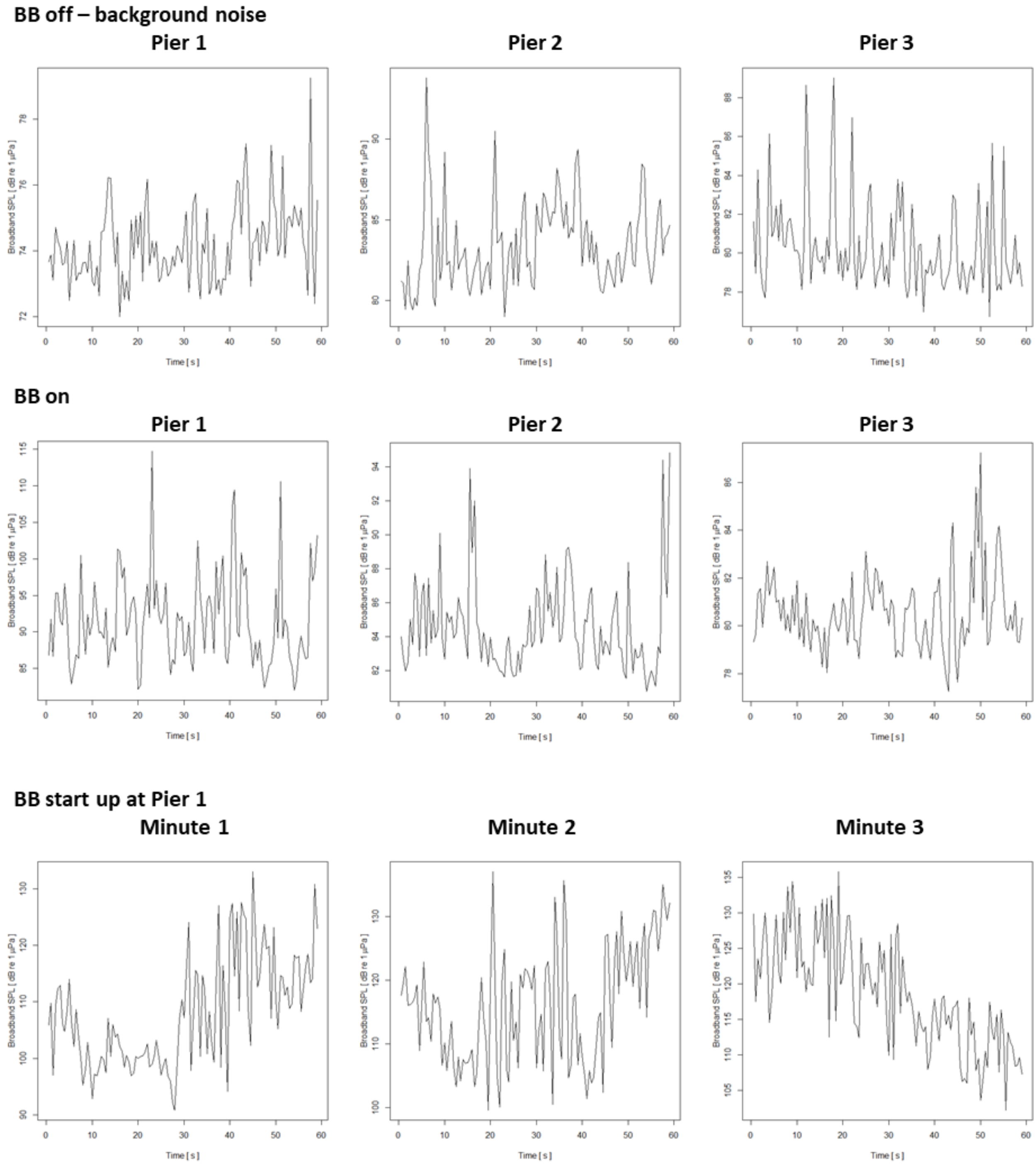

Figure 6.13 - Broadband SPL (20-2000 Hz) along time for minutes recorded when the Bubble Barrier was turned off (upper row) and on (center row), and for the first three minutes during start up, at Pier 1.

Overall, the background noise, with the technology switched off, was lowest at Pier 1, next to the compressor shed. With the Bubble Barrier on, noise levels were at their highest values at that site, decreasing with increasing distance from the compressor shed. The effect of the Bubble Barrier technology is clearly visible at Pier 1, but non-existing at Pier 3. At Pier 1, when the Bubble Barrier is switched on, the noise level

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increases rapidly to values around 120 dB, and decreases, probably when a working air pressure is achieved, to around 100 dB, which are maintained while the Bubble Barrier is working.

For comparison, noise levels (broadband SPL at 20-2000 Hz) measured in the Tagus River estuary (Vieira et al., 2021), which is affected by heavy navigation, particularly ferries, ranged between 81.8 and 138.7 dB re 1 μPa, averaging 99.4 ±10.3 dB re 1 μPa, which is close to the values measured with the running Bubble Barrier at Pier 1.

In 2022 the EU decided on the first ever EU-wide limits for underwater noise, in the context of the Marine Strategy Framework Directive. A Technical Group on Underwater Noise (TG NOISE) established recommendations on criteria and procedures to determine Levels of Onset of Biological Adverse Effect (LOBE) for continuous and impulsive underwater noise (reports can be found at: https://environment.ec.europa.eu/news/zero-pollution-and-biodiversity-first-ever-eu-wide-limits-underwater-noise-2022-11-29_en). Examples cited indicate that LOBE are reached at 90-100 dB and 110-120 dB, or when noise levels exceed normal sound levels by 6-20 dB, for continuous noise. TG NOISE also suggests that noise impact should be assessed regarding the impacted area, which should not exceed 20% of the target species habitat. For impulsive sound sources, many aspects have to be considered, like duration and frequency, with an example 130 dB for non-pulse sounds.

Bearing in mind that noise effects are species and habitat specific (in noisy habitats species adapt to a certain extent) the measured values suggest that the noise levels produced by the Bubble Barrier technology, particularly when the technology is started, may pose a risk to noise-sensitive species. However, these levels are limited to a small area close to the compressor shed.

6.5. Analysis of the litter collected by the Bubble Barrier

After the installation and launch of the Bubble Barrier system at the end of 2023, the litter collected in the catchment system was evaluated monthly from January to December 2024.

The catchment system was emptied by the Municipality's Environmental Services (SUMA) twice a month, with each collection occurring 7 to 15 days apart. The detailed characterization of the litter collected by the Bubble Barrier was conducted over one of the bi-monthly SUMA collections. SUMA would lift the catchment system and let the

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excess water out, but did not dry the litter. After that, it would weigh the debris removed from the catchment system and transport it to its final destination. So, the total amounts of the debris collected by the technology refer to wet weight.

The detailed assessment of the litter collected by the Bubble Barrier focused on the macrolitter fraction, i.e. all litter > 2.5 cm, following European guidelines for marine litter monitoring (Hanke et al., 2013, 2023). This process involved emptying the catchment system (Figure 6.14), and then separating the organic fraction from the litter and weighing, and categorizing each litter item. This work contributed to and it was developed in the scope of an ERASMUS+ Thesis (Alcalde, 2024).

Figure 6.14 - Emptying the catchment system and collected litter for classification.

Each item was classified by material type, including artificial polymers, rubber, glass/ceramics, metals, clothing/textiles, paper/cardboard, processed wood, chemicals, and food waste. Additionally, items were weighed and further classified into more detailed categories, following a European harmonised list used for monitoring marine litter (Fleet et al., 2021), which comprises more than 170 different item categories. To complement this analysis, the CIIMAR team also measured the estuary's current (Valeport 801 Electromagnetic Current Meter) at the surface and at 1 m depth, and the obtained results were included in the overall assessment.

By the end of 2024, the Bubble Barrier had collected over 1450 kg of aquatic debris (wet weight), with organic matter accounting for more than 80% of this total. The

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organic component was primarily composed of water hyacinths (*Eichhornia crassipes*), an invasive species in the Ave River that has significantly impacted the ecosystem.

The Bubble Barrier was originally designed and implemented to collect litter above 2.5 cm, so the waste characterization focused on the same class of sizes used for marine litter (i.e. macrolitter, >2.5 cm) to enable comparison. However, the Bubble Barrier system also collected smaller pieces (mesolitter: 5 mm - 25 mm) and even microplastics (< 5 mm). This was enhanced by the presence of organic matter (vegetation and algae) that retained these smaller particles, at least, in the catchment system. Thus, by indirectly collecting smaller plastics, the Bubble Barrier is not only removing plastic items (that would otherwise fragment into micro and nanoplastics over time) but also directly contributing to removing microplastics that are transported by the river into the sea.

While the Bubble Barrier's ability to capture a significant fraction of organic debris might initially seem like a disadvantage, it is important to note the impact of this organic fraction in the water quality of the estuary. As mentioned above, interceded vegetation often entangles microplastics, enabling the Bubble Barrier to capture them. This would otherwise be impossible due to the system's technical specifications, which do not encompass capturing MP. Previous studies show that certain invasive species, like *E. crassipes*, can retain up to 77% of surface plastics (Schreyers et al., 2024). This phenomenon was observed in the Bubble Barrier, since micro- and meso plastics were collected in the catchment system (Figure 6.15).

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Figure 6.15 - Micro- and mesoplastics collected in the catchment system.

Furthermore, capturing some of an invasive aquatic plant that creates massive issues in many rivers and estuaries in Portugal, could be beneficial, as their removal may support an improvement of the water quality and the overall local biodiversity.

Excluding organic debris, the results indicate an estimated collection of over 0.6 kg/day of aquatic litter, equivalent to approximately 20 kg/month, with plastics accounting for around 0.4 kg/day. Plastics represented 98% of the collected litter items (in number) and to approximately 60% of the total litter weight (wet). The volume of plastic collected may not sound significant but one must remember that plastics are, by nature, very light materials. However, when looking at the total number of macroplastic items collected by the Bubble Barrier, it was estimated an average monthly collection of more than 2750 plastic items. To put this into perspective, note that the agreed European threshold for “good environmental status” of the marine waters in relation to marine litter is only 20 litter items per 100m of beach (including plastic and non-plastic litter).

The classification of the litter items found in the catchment system showed that artificial polymer materials (more commonly referred to as “plastics”) dominated, accounting for 98% of the total pieces and 63% by weight. The next most common materials were “Processed Wood” (15.3%), “Rubber” (10.2%), “Glass/Ceramics” (6.3%), “Metal” (2.4%), “Paper/Cardboard” (1.5%), and “Clothing/Textile” (1.3%), as illustrated in Figure 6.16.

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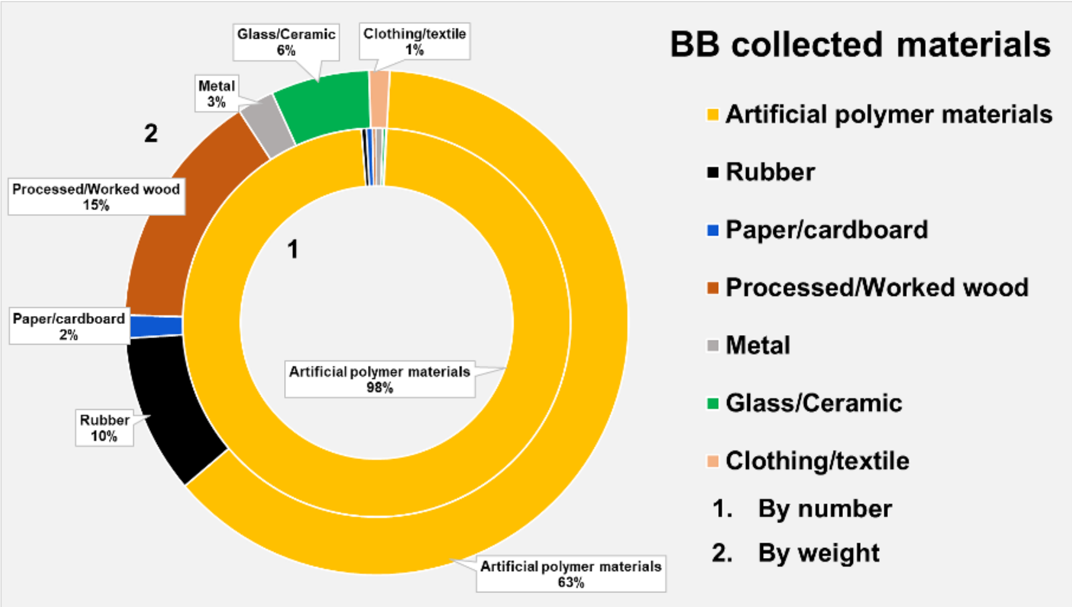

Figure 6.16 - Litter collected by the Bubble Barrier classified by materials, in terms of number (inner ring) and (wet) weight (outer ring).

Plastics were the most prevalent material in both number of items and weight, with most items consisting of small fragments (considering only those > 2.5 cm) from larger objects. This is in line with the observed FML, which revealed a dominant presence of plastic items, of more than 75% of the total items recorded. Among these, plastic fragments and single-use plastics (SUP), such as bottles and packaging materials, are particularly prevalent.

The litter data also showed significant seasonal variation considering precipitation, currents and river flow, with the highest amounts of litter collected in winter, coinciding with increased precipitation, stronger estuarine currents and higher river flows. The marine litter-to-organic matter ratio decreased from 35% in winter to <10% in summer (Figures 6.17 and 6.18).

The prevalence of local products in the RL composition, including SUP and plastic fragments found in both analyses, aligns with recent literature (Le et al., 2024). This highlights the potential of localized solutions like the Bubble Barrier to prevent the marine litter problem, as rivers play a critical role in transporting litter from land into the sea.

During some of the campaigns, a few small organisms, including crustaceans, amphipods and fish were observed in the catchment system, carefully collected, and returned to the estuary. Although these occurrences were not frequent, additional

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assessment and further ecological analysis are recommended to evaluate potential bycatch and minimize disturbance to these species.

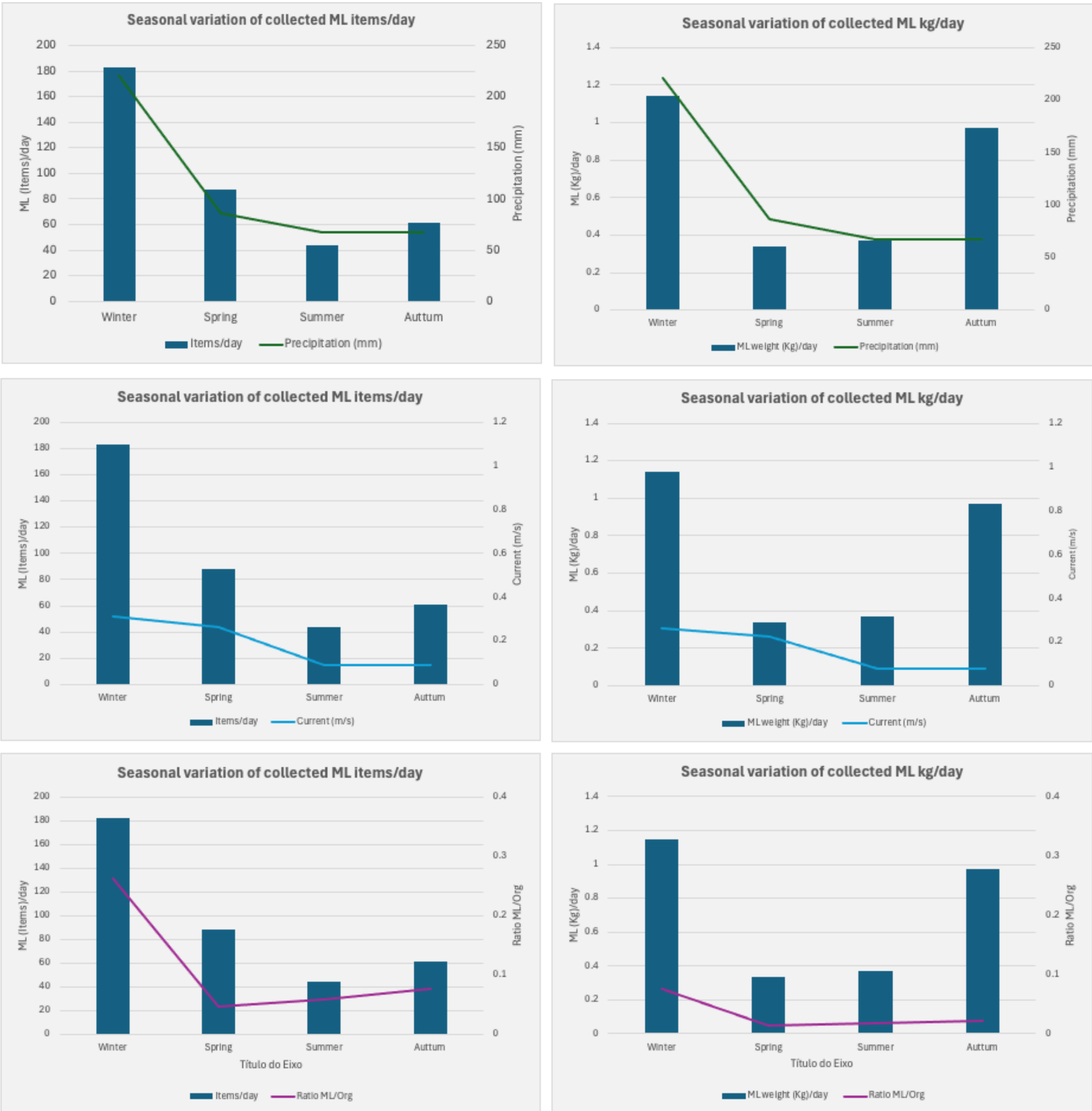

Figure 6.17 - Seasonal variation of the aquatic litter collected (both items/day and kg/day, wet weight) by the Bubble Barrier in Vila do Conde. Each bar corresponds to the seasonal average. Its relation with precipitation (source: Portuguese Institute for Sea and Atmosphere (IPMA)) and water current (measured by the CIIMAR team). The relation with the assessed ratios RL/organic debris is also indicated.

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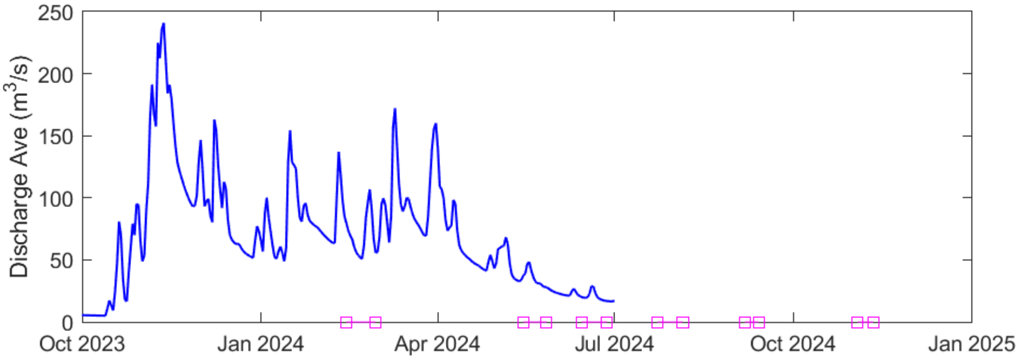

Figure 6.18 - River discharge at the mouth of the Ave River obtained from the hydrological model developed in the scope of the MAELSTROM project (blue, MAELSTROM D2.2. Rainfall data are only available up to 1 July 2024) with the periods indicated when RL was collected by the Bubble Barrier (purple).

6.6. Effectiveness of the Bubble Barrier

Previous tests carried out in a similar Bubble Barrier implemented in one of the canals in Amsterdam, where floating objects (tangerine) were purposefully released in several points upstream the Bubble Barrier, indicate that it can retain more than 90% of the objects in optimal conditions of water flow and wind (MAELSTROM Deliverable 4.1). Unfortunately, it was not possible to carry a similar test in the Bubble Barrier pilot in Ave River estuary. The fact that substantial amounts of debris were collected by the Bubble Barrier in the last months of MAESLTROM demonstrates that this technology is having a positive impact in reducing inputs of litter into the sea. However, since there is not a robust baseline in terms of the litter that is transported in the estuary in a cross section upstream of the Bubble Barrier and also suspended in the water column, the assessment of its effectiveness remains limited. Furthermore, the effectiveness of the Bubble Barrier will likely vary with different environmental conditions and for different litter items, depending on their size, shape and density, which also affects their behaviour in the water column.

Nevertheless, the FML observations performed before and after the technology installation and upstream and downstream the technology (section 6.3.1) clearly demonstrated that the RL quantities are reduced after passing the Bubble Barrier.

While the results regarding the efficiency of the Bubble Barrier system are promising, they come from an initial assessment conducted over 2024, and they represent the first installation of a system like the Bubble Barrier in an estuary. Temporal and spatial variability, such as in leakages of litter from different diffuse sources, variations in precipitation, and scenarios with strong river currents, can all have had an impact on the observed riverine litter abundances in the area and those captured

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by the system, affecting the inferred effectiveness of the Bubble Barrier in this location.

During monitoring in the BB area, some instances of aquatic litter leakage were observed. One example is the dispersal of litter from the catchment system, particularly during spring tides when the currents reverse upstream. To address this, the system's operation during tidal cycles should be tested in the next BB system optimization. Additionally, it is important to note that large items, such as processed wood, large bottles, and water hyacinths, are typically collected passively along the margin where the catchment system is installed, without direct intervention from the bubble curtain. These factors should be carefully considered in future interventions for the Bubble Barrier system.

Although not designed for MP, the Bubble Barrier also presented an effect over them. The performed campaigns, and the additional transect over the bubble curtain (section 6.3.2) indicated that the number of MP was substantially higher for the transects right through the bubble curtain. The elevated concentration shows that the MP were guided by the Bubble Barrier in the direction of the catchment system and, attached to the organic matter, were retained in the catchment system. However, which share of these MP were kept in the catchment system and to which extent they were washed out through the holes in the catchment system could not be established. At least, this observation shows that MP (probably the MP that are lighter than water) are guided by the Bubble Barrier.

Since the Bubble Barrier in the Ave River estuary is the first one installed in the middle of an estuary, an aim was to evaluate its effectiveness under estuarine conditions and compare it with the technology performance in a river location. In MAELSTROM Deliverable 2.2 we have presented that the Ave River estuary was (very) highly stratified during low river flow conditions, and most likely mixed during high river discharge. For the vertical distribution of salt, this means that the estuary changes from stratified (low river discharge), via partially mixed (medium range of river discharge) to fully mixed (high river discharge), as schematically shown in Figure 6.19. Usually, the estuary is stratified or partially mixed, meaning that an estuarine circulation occurs: averaged over a tidal cycle flow is directed seaward near the surface and landward in the lower layer near the bed.

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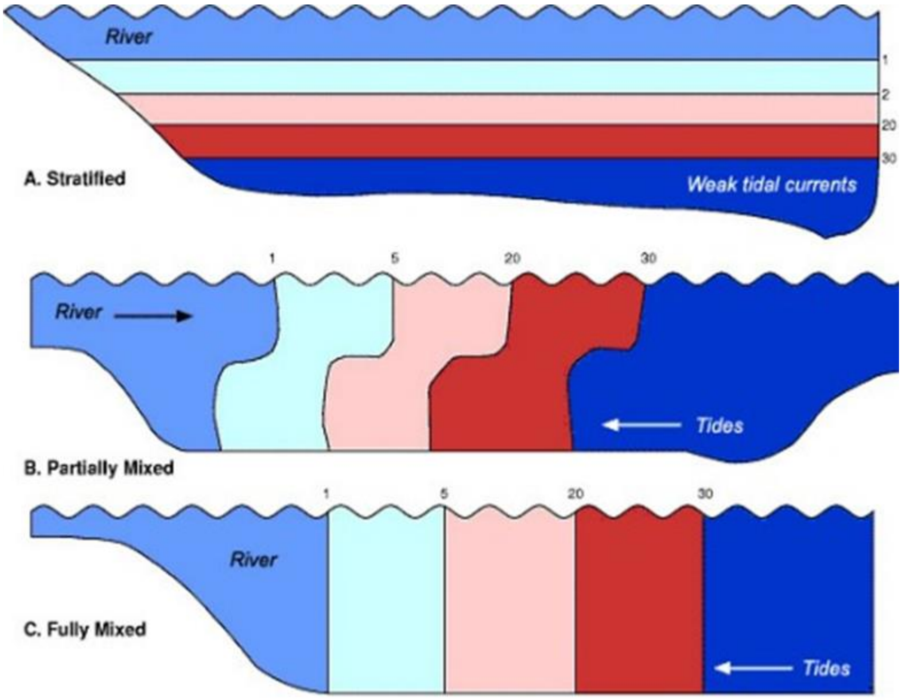

Figure 6.19 - Schematic showing three types of stratification, which may occur in the Ave Estuary.

Figure 6.20 shows an example of a velocity profile in an estuary, which could occur during ebb tide. As a comparison, also the flow velocity profile is included for a river. For both profiles the water depth is 4 m. The flow velocity magnitude is maximal about 0.4 m/s in this example, although this can be much higher in reality in both a river and an estuary. For this example, we have estimated the shape of the bubble curtain (right in Figure 6.20), assuming that soon after release, the bubbles rise with 0.3 m/s. Hence, the bubbles surface after about 13 s. In the case of a river, the bubbles have travelled a distance of about 5 m horizontally seawards. In the case of the estuary, the bubbles first move landwards in the lower part of the water column, and then seawards in the upper part. As a result of the stratification, the bubble curtain has a different orientation in each of the two layers of the water column. An inflection point occurs at the height where the flow changes direction (in the example at about 2 m depth). Hypothesizing what the result of such an inflection point could be on the effectivity, RL in the upper part of the water column is likely to be transported upwards and guided along the Bubble Barrier as in a river. However, litter in the lower layer may be transported from a location seaward of the Bubble Barrier up with the bubbles up to the inflection point and then in the upper layer it is transported again seawards with the flow. Hence, a Bubble Barrier in an estuary may be equally effective as in river for guiding and collecting suspended and floating litter, but possibly less effective for suspended litter transported in the layer with landwards flow.

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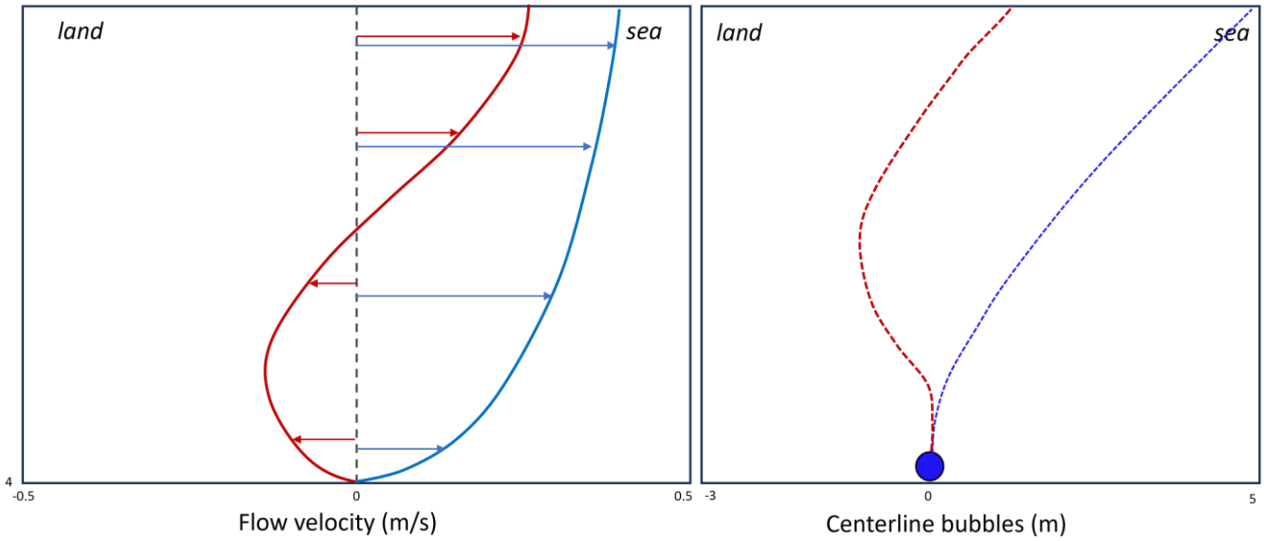

Figure 6.20 - a) Velocity profiles in an estuary during ebb tide (red) and in a river (blue). b) Shape of the bubble curtain in an estuary during ebb tide (red) and in a river (blue).

Generally, flow in an estuary cannot only change direction within the vertical, it also varies substantially with the tides. During peak ebb and peak flood, the flow velocities may be too high for optimal performance of the Bubble Barrier. Still, its performance may be optimal during most of a tidal period. The effect of so-called weak spots (lower bubble intensity) may be more important for the effectiveness. For the Ave River estuary this effect was not quantified. However, for the Bubble Barrier in Amsterdam, floating object tests were carried out (MAELSTROM deliverable 4.1). It was found on a day with low flow conditions that tangerines (the objects) that were released closer to the catchment system were collected for >91 %, whereas 2-41% of the tangerines released further away were collected. The difference was due to a weak spot in the bubble curtain. We hypothesize that a continuous bubble curtain may be more important for the effectiveness than the shape of the bubble curtain, if flow velocity magnitude is not too high.

7. Citizen awareness and local community perception

During the Sunset Beach Cleanup activities performed in Vila do Conde in september 2023 and september 2024, a survey was performed among the participants to gain insight into the perceptions of the local community on the general condition of their environment (rivers, coast, beaches, sea, Figure 7.1), and their opinions on the implementation of technology to remove RL, in this case the Bubble Barrier (Figure 7.2). Surveys were conducted before (23/09/2023; n = 40) and after (21/09/2024; n = 35) the technology implementation, during the annual Sunset Beach Cleanups promoted under the scope of MAELSTROM.

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The obtained results revealed valuable insights into public perceptions on the implemented technology and the impact of the Bubble Barrier installation on the Vila do Conde population. It is clear that the vast majority of the populace support the implementation of the technology and also call for more governmental support for these types of initiatives. When asked about which stakeholders the participants felt were most responsible for taking action on plastic pollution, in 2023 participants listed international governments such as the EU and intergovernmental bodies as most responsible (85%). While in 2024, when asked the same question, respondents indicated the highest share of responsibility laid with businesses (66%) and local governments (63%). Interestingly, the participants' perception of the cleanliness of the river improved after the implementation and in testimonials they reported seeing less visual litter in the river and on beaches). According to the respondent's perception, the installation of the Bubble Barrier had a positive impact on the estuary (91.9%) with an improvement of the water quality (79.7%) and a reduced number of visible items (95.2%) (Figure 7.2). Respondents to the survey demonstrated a strong awareness of the impacts of plastic pollution citing concerns such as "negative health impacts" and "food web/human ingestion" topics. 85% of the survey respondents reported that they would like to see more of these types of initiatives being carried out between science, industry, and local governments. Participants also expressed that seeing large-scale initiatives being enacted in their area inspired them to take more individual action to reduce waste and heightened awareness of waste and the impacts of pollution increased overall.

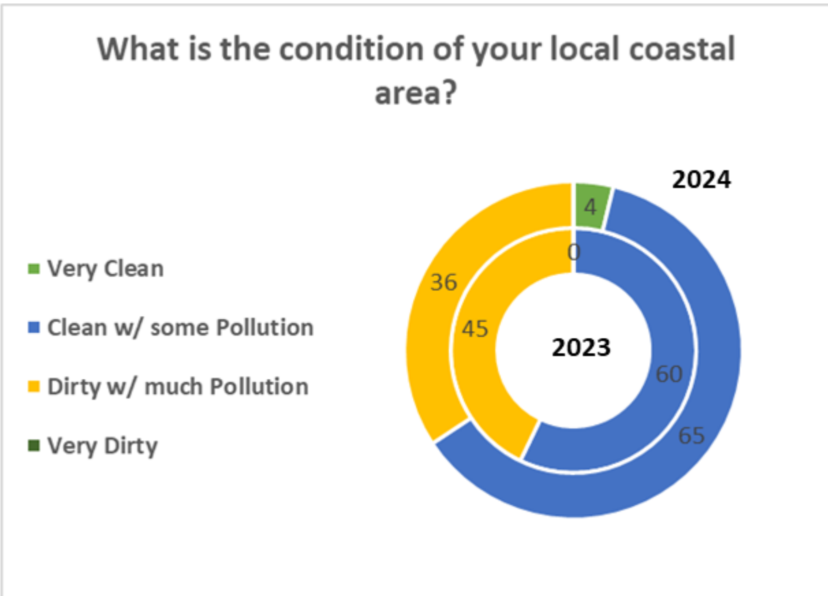

Figure 7.1 - Survey respondents' feedback on their perspective view of the condition of their local coastal area. Feedback was collected in 2023 (inner circle) and in 2024 (outer circle).

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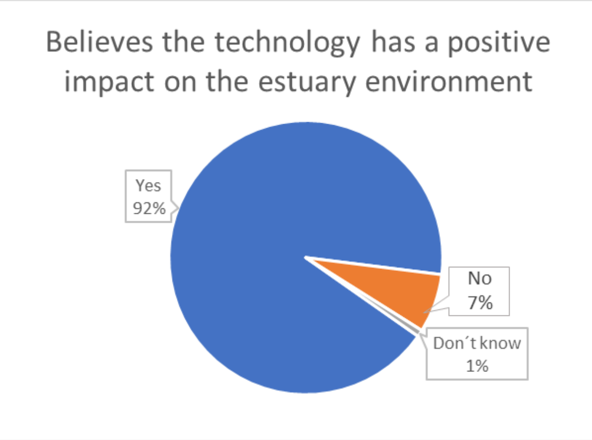

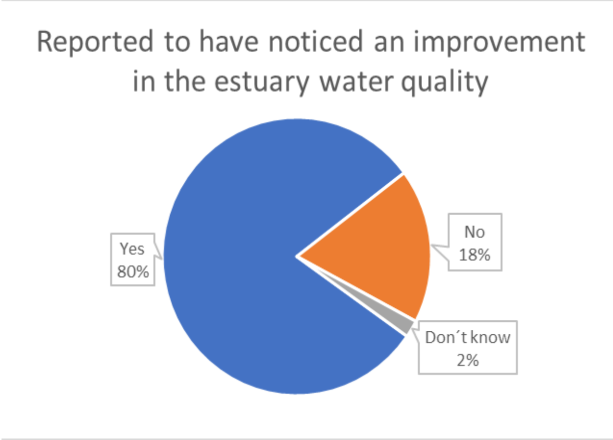

Figure 7.2 - Survey respondents shared personal opinions on a) the impact of the technology (Bubble Barrier) on the Ave Estuary environment, and b) whether or not they had noticed a change in the water quality of the Ave Estuary since its implementation.

8. Conclusions

This deliverable summarized the performed activities related with the implementation, operation and optimization of the Bubble Barrier and the results of its overall effectiveness, in terms of collecting and removing riverine litter. It described in detail the outcomes from the ecological assessment, possible impacts of the Bubble Barrier on the estuarine environment, and carbon footprint and how it could be reduced with the demonstrated supply from solar energy.

The delays of almost two years until the technology was finally deployed and operating demonstrate the complexity and the multi-fold challenges faced in implementing this pilot, namely of installing a permanent structure in a dynamic estuarine environment, with multiple authorities involved and without specific mandate (at EU, national or local level) to address riverine litter. Many of the lessons learned in this pilot are discussed and presented in the Legacy Document of MAELSTROM (Gomes et al., 2024).

Due to this delay, the post-installation campaigns to assess the impact and effectiveness of the Bubble Barrier system could only be performed along the last year of the project, until December 2024. Nevertheless, several important conclusions can be distilled from this assessment, which are described below.

- **Amounts and types of litter retained by the Bubble Barrier system:** During the period of one year (operating 80% of the time) the Bubble Barrier system captured over 1450 kg (wet weight) of aquatic debris, with vegetation (mostly invasive species) accounting for most of this volume. In terms of (macro)litter, it was

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estimated that 20 kg/month are removed from the water. As in the marine environment, plastics are the most abundant type of litter collected, representing 98% of the total litter items (in number) and to approximately 60% of the total litter weight (wet) collected. Plastics are, by nature, very light materials, so a limited mass will nevertheless be reflected in a high number of items. During its full performance more than 2750 plastic items (> 2.5 cm) were recorded from the debris removed by the system, dominated by plastic fragments and single-use items, such as plastic packaging. In addition to the litter collected, significant amounts of invasive vegetation were retained in the catchment system. Moreover, an unexpected increase in the MP concentration over the bubble curtain and at the catchment system was observed. Therefore, it can be concluded that not only RL but also MP and invasive species are retained by the Bubble Barrier system, showcasing the system's potential to tackle multiple environmental challenges simultaneously.

- **Effectiveness of the Bubble Barrier in removing RL and other debris**: The observations of FML carried throughout MAELSTROM demonstrated that litter quantities are reduced after passing the Bubble Barrier. Previous tests in Amsterdam revealed that the Bubble Barrier can retain as much as 90% of floating objects released upstream. More studies are needed to assess its operation in a estuarine environment, to better quantify how much litter is being transported under the surface, and how much of it is retained by the Bubble Barrier.
- **Energy consumption and carbon footprint**: Despite being energy-intensive, MAELSTROM demonstrated the potential for significant reductions in the carbon footprint of the Bubble Barrier technology through the integration of renewable energy sources, namely solar panels. Instead of operating continuously, the system could potentially be switched off in certain periods (for example, in less favourable conditions of tides, wind and river discharge). Operating in selective mode, the energy output of the solar panels could potentially cover almost all or fully the energy use of the Bubble Barrier.
- **Ecological Assessment:** no significant changes in water quality nor biological parameters were observed during the limited period of testing. Any potential significant ecological changes due to the operation of the Bubble Barrier in the estuary are expected to take much longer than what was available during the project. Measurements of the underwater noise suggested that the levels produced by the compressor may pose a risk to noise-sensitive species but that these levels are restricted to a small area close to the source.
- **Public perceptions regarding the technology and its impact in the surrounding environment**: Overall, the results from the public surveys demonstrate that there

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is consistent and growing support within communities for multidisciplinary practical solutions including innovative technologies when backed by science and facilitated by local, national, and international governments. However, these surveys were limited in scope and reach, and some bias likely occurs favouring positive environmental attitudes from those members of the community who choose to join the sunset beach cleanup efforts and to participate in the survey. These limitations were countered by engaging wider and more diverse members of the community, which is shown by the number of "new participants" who had never engaged with MAELSTROM or with a beach cleanup before, making up over half of the respondents in each year (2023: 50%, 2024: 65%). The results are deemed interesting given the high degree of support for such initiatives and the personal testimonials wherein participants shared knowledgeable and emotional causes for concern regarding environmental pollution.

Although the Bubble Barrier is already collecting litter before it reaches the sea and is expected to increase its efficiency when fully optimized, it holds promise as a long-term solution to the problem. Furthermore, this innovative technology has the potential to be replicated and adapted for use in other riverine and estuarine environments. Nevertheless, it is imperative that decision-makers and society at large, focus their efforts on preventing litter generation and leakages to address the issue at its source. Preventive measures will always be more cost-effective than remediation ones.

This technology, designed to minimize the impact of human activities on the estuary environment, was aligned with existing activities in the area and co-designed in collaboration with local stakeholders. The successful implementation of this innovative technology in an estuary demonstrates the potential for meaningful collaboration across sectors. By bringing together partners from various European countries, this project has highlighted both the opportunities and challenges of the European Blue Innovation initiative. Through effective teamwork, the technology was co-powered with renewable energy, ensuring its sustainability and minimizing environmental impact.

Furthermore, the project engaged local authorities, communities, schools, and the public, generating significant interest and support for the initiative. A standout example of this success, and an international model of good practices, is the collaboration with the Municipality of Vila do Conde, which partnered with the MAELSTROM team to co-design and support the implementation of the Bubble

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Barrier in the Ave River estuary. The success of the initiative was further strengthened by the coordinated involvement of key stakeholders, including DOCAPESCA - Portos e Lotas, S.A., APA, Vila do Conde Captaincy, the CMIA and the LIPOR, setting an example for similar initiatives worldwide.

This involvement fostered a sense of shared responsibility and demonstrated the importance of public participation in environmental conservation efforts. The project has received national and international recognition for its innovative approach and successful outcomes.

The implementation of this technology has sparked interest and attention from various sectors of society, including several international entities and forums. One example of this international recognition was the invitation from the Atlantic Arc Commission's Ocean Pollution Working Group to present the MAELSTROM project and The Bubble Barrier – Vila do Conde, in Brussels on 31 January 2025, as both a national and international model of innovative implementation, showcasing stakeholder collaboration to tackle marine litter (more information here: https://cpmr-atlantic.org/event/atlantic-arc-commission-hub-meetings-2).

The success of the Bubble Barrier implementation in Vila do Conde was also recognized during the 'Blue Connection - Portugal & The Netherlands' event in Amsterdam on 10 December 2024, attended by the President of Portugal, Marcelo Rebelo de Sousa, and King Willem-Alexander of the Netherlands, further strengthening international relations between the two countries.

In addition, MAELSTROM received the prestigious Atlantic Project Award in the category "Healthy Oceans and Resilient Coasts." The award recognized MAELSTROM's dedication to sustainable blue growth, fostering territorial cooperation, and promoting synergies across European ML projects. (https://atlantic-maritime-strategy.ec.europa.eu/en/news-and-events/events/atlantic-stakeholder-platform-conference-2023)

The project's legacy and its successful application of good practices will inspire other ongoing and future European projects and initiatives, contributing to a collective effort to protect our rivers, estuaries, and seas.

The social and environmental benefits of this initiative align with the One Health approach, emphasizing the interconnectedness of human, animal, and environmental health. By addressing pollution and promoting sustainability, the project contributes to the broader goal of fostering a healthier planet for all.

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ANNEX A

Vila do Conde Captaincy's communication

31/10/2023

Co-funded by the Horizon 2020 programme of the European Union

Comunicado Operacional n.º 08/2023
(31 de outubro de 2023)

- AGRAVAMENTO DA AGITAÇÃO MARÍTIMA -

1. FASES IMPLEMENTADAS

a) ALFA **–** Das 21:00 do dia 01 de novembro, às 19:00 do dia 02 de novembro.

b) BRAVO **–** Das 09:00 do dia 02 de novembro, às 07:00 do dia 03 de novembro.

NÍVEL	MEDIDAS	ESTADO DO MAR
FASE ALFA	1 - Emitir comunicado para entidades da Proteção civil. 2 - Interditar acessos aos molhes dos Portos da Póvoa de Varzim e Vila do Conde. 3 **–** Avaliar a necessidade de alterar o estado das Barras.	4 a 5 metros
FASE BRAVO	1 - Barras dos Portos da Póvoa de Varzim e de Vila do Conde - FECHADAS. 2 **–** Trocar informação entre Agentes da Proteção Civil (APC). 3 **–** Alargar o perímetro de segurança. 4 **–** Interditar os acessos pedonais (a definir entre os APC).	5 a 6 metros
FASE CHARLIE	1 **–** Interditar estradas. 2 - Garantir extração de pessoas das infraestruturas de risco. 3 **–** Constituição de célula de risco na Capitania do Porto da PV/VC.	Superior a 6 metros

2. MEDIDAS EM VIGOR:

a) Informados os APC através de *"Comunicado Operacional"* conjunto emitido pelas Capitanias dos Portos da Póvoa de Varzim e de Vila do Conde.

b) Informados os OCS locais.

c) Recomendado à comunidade piscatória e da náutica de recreio que se encontra no mar, o regresso ao porto de abrigo mais próximo e a adoção de medidas de precaução, de acordo com as recomendações das capitanias dos portos, evitando sair para o mar até que as condições melhorem.

d) **Barra fechada** a todas as embarcações desde as 18:00 do dia 25 de outubro (em permanente avaliação).

e) **Encerrado** o acesso pedonal aos molhes das Barras.

Largo Dr. Vasques Calafate,1
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3. MEDIDAS A IMPLEMENTAR:

a) Medidas da Fase Alfa e, posteriormente, da Fase Bravo.

4. RECOMENDAÇÕES:

a) Evitar circular na orla costeira e zonas ribeirinhas, nomeadamente molhes, esporões, praias expostas ao mar e sujeito(a)s ao efeito da rebentação;

b) Promover a vigilância e proteção de infraestruturas junto à linha de costa;

c) Proteger da ação do mar as máquinas utilizadas em obras ao longo da costa;

d) Reforçar a vigilância das amarrações das embarcações atracadas nos cais e marinas ou fundeadas/amarradas;

e) Acautelar a remoção, para locais seguros, de embarcações varadas em locais que possam ser afetados pela ação do mar e do vento;

f) Primar por uma postura de segurança e de preocupação ativa, não assumindo comportamentos de risco.

5. PRÓXIMA AVALIAÇÃO/COMUNICADO:

Quando ocorram alterações significativas.

6. PREVISÃO METEOROLÓGICA:

A previsão meteorológica, com base nos dados disponíveis, aponta para um agravamento da agitação marítima, prevendo-se:

AVISO	PERÍODO	ESTADO DO MAR
AMARELO	01NOV (21:00) - 02NOV (09:00)	Ondas de noroeste com 4 a 5 metros
LARANJA	02NOV (09:00) - 03NOV (07:00)	Ondas de noroeste com 5 a 7 metros, podendo atingir a altura máxima de 14 metros

Fonte: Instituto Português do Mar e da Atmosfera (IPMA)

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7. PREVISÃO DE MARÉS – MARÉS DE RISCO:

MARÉ			PREVISÃO DA ONDULAÇÃO	OBSERVAÇÕES
DIA	HORA	ALTURA		
01NOV (quarta-feira)	17:03	3.1 m	3.5 m / W / 12 s	1. Confluência do período de preia-mar e o agravamento da agitação marítima potencia a possibilidade de **galgamentos na orla costeira**. 2. Confluência do período de baixa-mar e o agravamento da agitação marítima potencia a possibilidade de **acidente na passagem das Barras**.
	22:59	0.9 m	4.3 m / W / 11 s	
02NOV (quinta-feira)	05:18	3.2 m	5.3 m / W / 13 s	
	11:35	1.0 m	6.7 m / NW / 15 s	
	17:47	2.8 m	6.4 m / W / 15s	
	23:40	1.2 m	7 m / W / 15s	
03NOV (sexta-feira)	06:03	2.9 m	6,5 m / NW / 15s	

Fonte: Instituto Hidrográfico e IPMA.

Póvoa de Varzim e Vila do Conde, 31 de outubro de 2023

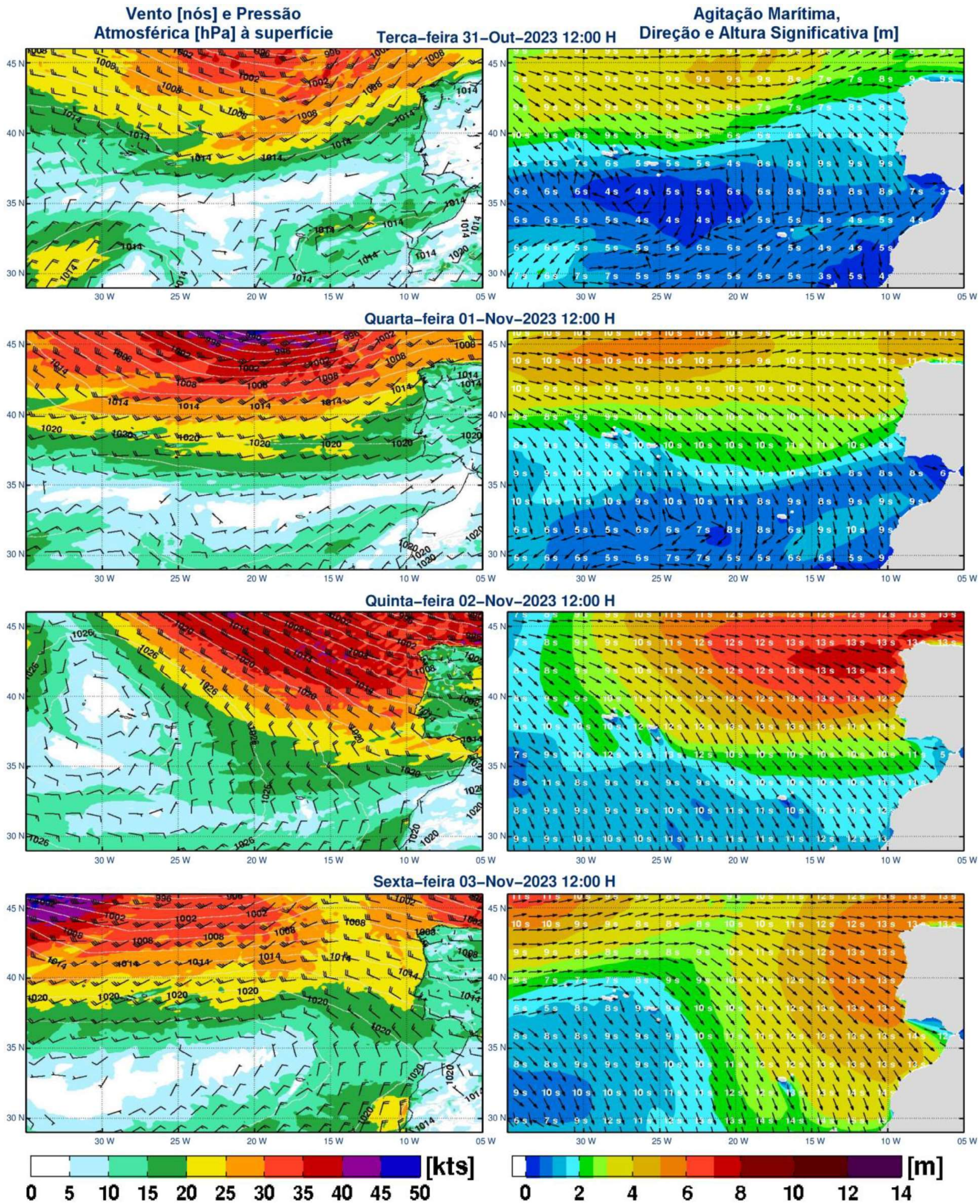
A Capitã do Porto da Póvoa de Varzim e de Vila do Conde,

Assinado por: **Mónica Alexandra Pereira Martins**
Num. de Identificação: 10783508
Data: 2023.10.31 12:17:49+00'00'

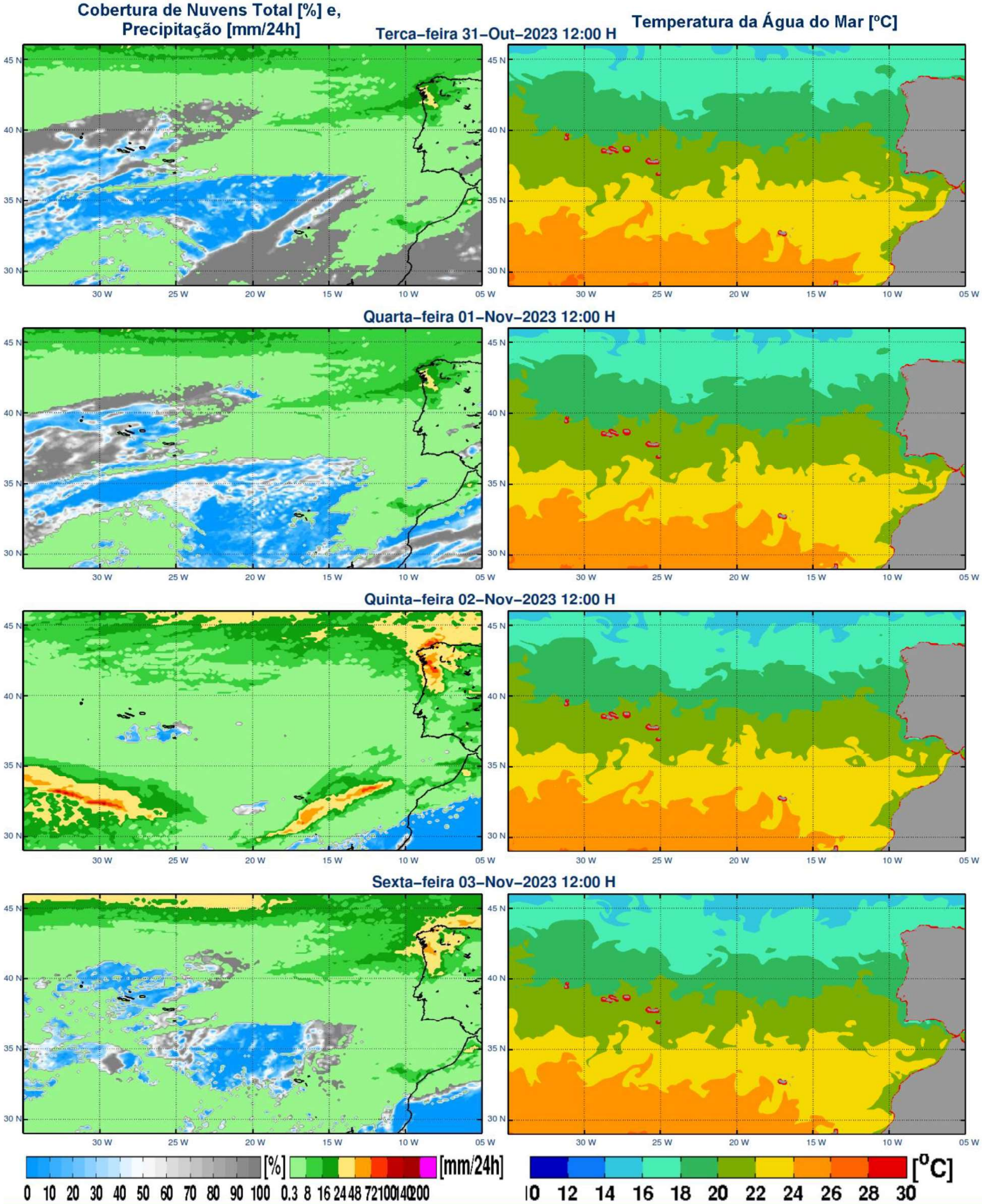
Mónica Alexandra Pereira Martins
Capitão-de-fragata

Anexo: Quadros de situação

ANEXO - QUADROS DE SITUAÇÃO:



Fonte: Instituto Hidrográfico



Fonte: Instituto Hidrográfico

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