Assessment of the contamination of the harbour bed at Port of Bar, Montenegro

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Contents

1. Introduction

This report presents the result of a comprehensive assessment of marine sediments from the Port of Bar, Montenegro, conducted within the framework of the UNEP/MAP Programme: "Small Scale Funding Agreement (SSFA) for development of an environmental sound management plan towards monitoring and remediation at Tivat Bay and assessment of contamination at Port of Bar in Montenegro". The study has been designed to provide an in-depth evaluation of sediment quality in a port area that represents both an economic hub and an environmental hotspot due to intensive maritime and industrial activities.

The purpose of the Small-Scale Funding Agreement (SSFA) is to support the implementation of the UNEP/MAP Programme of Work and the GEF MedProgramme Child Project 1.1 in Montenegro through activities focused on monitoring and remediation of pollution. Specifically, CETI is obliged to:

1. Develop an Environmental Sound Management (ESM) plan for monitoring and remediation of Tivat Bay (Porto Montenegro).
2. Prepare an assessment of contamination at the Port of Bar.
3. Carry out a risk assessment for the Port of Bar and relevant areas.
4. Develop an Environmental Sound Management plan for monitoring and potential remediation of the Port of Bar.

These activities aim to reduce pollution and improve environmental management in the targeted areas.

Sediments are widely recognized as both sinks and secondary sources of contaminants in aquatic systems. Their granulometric and geochemical characteristics govern the retention, mobility, and bioavailability of pollutants, making sediment monitoring an essential tool for evaluating long-term contamination trends and ecological risks. In port environments, where ore transshipment, industrial discharges, and shipping traffic converge, sediments often accumulate significant burdens of heavy metals and organic pollutants.

National marine ecosystem monitoring has indicated that sediments in this area contain concentrations of certain chemical elements and organic substances that exceed the threshold values, suggesting potential ecological risks. However, comprehensive characterization of sediment contamination patterns, source identification, and risk assessment have been lacking, necessitating detailed investigation to support evidence-based management decisions.

To ensure a robust assessment, the Port of Bar sediments have been analysed against internationally recognized sediment quality frameworks, with a particular focus on the French (N1/N2 levels and 2024 prohibition thresholds) and Dutch (Intervention Values under the Water Act) regulatory standards. These benchmarks provide complementary perspectives: while French criteria enable a tiered evaluation of ecological risk, Dutch values identify thresholds of serious contamination requiring mandatory management actions.

The primary objective of this study was to establish a comprehensive contamination profile of the Port of Bar sediments, identifying critical pollutants of concern, evaluating their spatial distribution, and determining the regulatory implications under European benchmark standards. The outcomes of this report are intended to support national and regional efforts in implementing environmentally sound management (ESM) of dredged material, reducing land-based pollution pressures in coastal and marine environments, and contributing to the broader goals of the MedProgramme in safeguarding the Mediterranean Sea.

1.1 Survey area

In the framework of the sediment quality assessment of the Port of Bar, the Center for Ecotoxicological Research carried out a systematic sampling campaign within the port aquatoria. Field activities were conducted in four successive campaigns, on June 18, June 20, June 25, and June 30, 2025**.**

A total of 19 zones within the port basin were selected for investigation (Map 1), along with one reference point located outside the influence of port activities. The reference station was chosen to represent natural background conditions, without direct anthropogenic impact, while maintaining comparable environmental settings (depth and sediment type) to the port zones.

Within each of the 19 defined zones, multiple sub-samples were collected in order to account for spatial heterogeneity of the sediments. These sub-samples were subsequently homogenized to create a representative composite sample for each zone. This approach ensured both statistical robustness and improved representativeness of the results across the complex port environment.

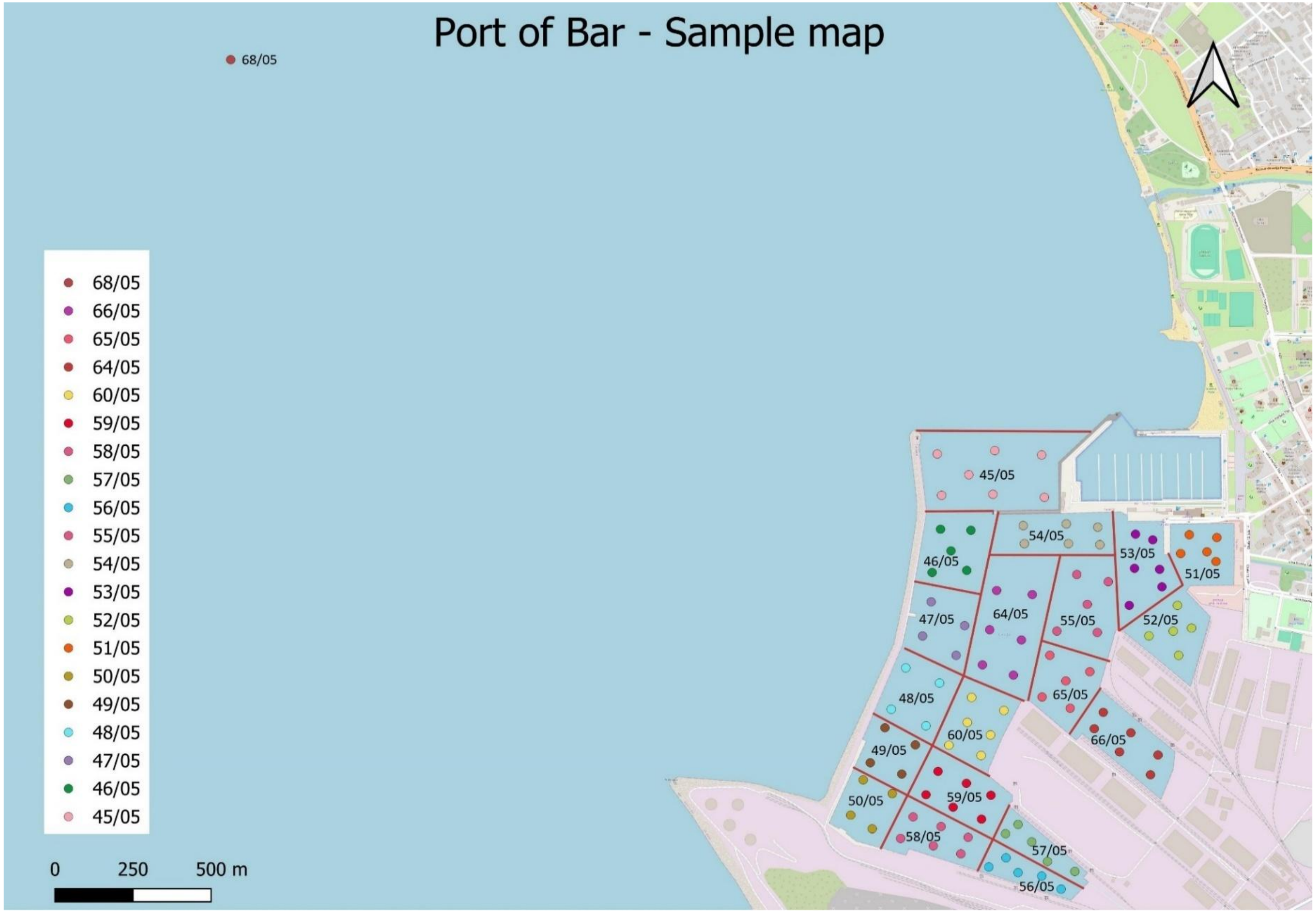
The selection of the sampling zones was based on known or potential sources of contamination (such as ore concentrate handling areas, bulk cargo terminals, ship berths, and maintenance facilities), as well as pathways of contaminant dispersion within the port basin. The applied scheme was designed to capture gradients of contamination from areas of intense port activity towards more peripheral and less impacted sites.

The adopted survey design allows for a comprehensive assessment of the spatial extent, distribution, and intensity of sediment contamination across the port aquatoria, while the inclusion of a reference point provides a baseline against which anthropogenic enrichment can be evaluated.

1.2 Scope of research

The present study was designed to provide a comprehensive assessment of sediment contamination in the Port of Bar, Montenegro, with particular focus on persistent organic pollutants (POPs) and mercury. The selection of contaminants for analysis was guided by the port's diversified operational profile and the potential environmental pressures associated with its activities. Specifically, the research focused on the following groups of contaminants: polychlorinated biphenyls (PCBs), organochlorine pesticides, and per- and polyfluoroalkyl substances (PFAS), organotin compounds, metals: mercury, cadmium, copper, nickel, iron, lead, zinc, chromium, and arsenic as well as other relevant contaminants such as polycyclic aromatic hydrocarbons (PAHs) and mineral oils.

While the primary goal of the study was to evaluate POPs and mercury contamination, the investigation also considered other metals and organic pollutants that could arise from port activities. The Port of Bar features a complex operational network, including bulk ore and concentrate handling, petroleum logistics, general cargo operations, and passenger transport, that creates multiple potential pathways for contaminant release into the marine environment.



Map 1. Sampling locations in Port of Bar

2.Description of the Port of Bar

Port of Bar is a joint-stock company majority-owned by the State of Montenegro, with its core activity being the handling and storage of goods (Activity Code 5224). Established on June 27, 1906, the port represents a complex organizational, material, and dynamic system that offers comprehensive logistics services, including transshipment, handling, loading and unloading, storage, sorting, container filling and emptying, maintenance, cargo inspection and documentation control, as well as customs, forwarding, IT management, and administrative operations related to all types of cargo in export, import, distribution, and transit.
Located in the southern part of the Adriatic Sea, Luka Bar is Montenegro's primary cargo port and a key entity within the country's transportation and logistics system. It is a complex economic structure featuring organized infrastructure, modern equipment, and a broad range of services. The port has a cargo handling capacity of up to five million tons per year. The infrastructurally developed area of the port covers 130 hectares, while the port's aquatic zone spans approximately 70 hectares.
According to the Detailed Urban Plan for the first phase of Bar's economic zone, an additional 350 hectares have been allocated for the future development of activities directly or indirectly linked to the port's primary function.
Two terminal operators operate within the port area: "Port of Bar" A.D., which manages terminals for liquid, dry bulk, and special cargoes, along with specialized storage facilities (cold storage, silos, etc.), Ro-Ro, and passenger terminals; and A.D. "Container Terminal and General Cargo", now Port of Adria, a separate entity in private ownership.

2.1 Historical Overview of the Port of Bar

Early Development (1905-1926) The Port of Bar's origins trace back to 1905 when Prince Nikola of Montenegro laid the foundation stone, following negotiations between Montenegrin authorities and Italian stakeholders through the "Bar Society." Construction officially began in 1908 under architect Cohen Kalja's plans. The port became operational in 1909 when the first ship, Galipoli, docked at the completed breakwater. The Bar-Virpazar railway connection was established simultaneously, enhancing inland transportation links.
Mid-20th Century Challenges and Growth (1914-1960) The port served military logistics during WWI and experienced stagnation in the 1920s due to inadequate infrastructure and high operational costs. During WWII, it was utilized by Italian and later German forces, who mined the facilities during their 1944 retreat. Post-war reconstruction began in the 1950s with the establishment of the state enterprise "Port of Bar" in 1954 and the completion of the Belgrade-Bar railway connection in 1959.
Major Expansion Era (1960-1989) The port officially opened to international traffic in 1960 and rapidly became Yugoslavia's leading Adriatic maritime center. The first phase concluded in 1965 with 1.2 million tons annual capacity, representing 53% of Yugoslav port transshipment. The second development phase (1971-1978) expanded capacity to five million tons, featuring the Volujica quay extension, container terminals, specialized warehouses, and comprehensive rail infrastructure totaling 8.5 kilometers of tracks.
Crisis and Recovery (1979-2000) A devastating earthquake in April 1979 severely damaged first-phase facilities, prompting reconstruction and the third development phase (1981-1983). The port achieved peak performance in 1989 with 2.74 million tons

handled. However, UN sanctions in the 1990s caused dramatic decline, with cargo handling dropping to historic lows of 22,904 tons in 1994. Operations gradually recovered following sanctions' suspension in 1995.
Modern Restructuring (2000-2021) The Free Zone was established in 2000, followed by privatization in 1998 and comprehensive restructuring in 2009. Recent modernization includes acquisition of Liebherr mobile cranes (LHM 550 in 2011, LHM 420 in 2020) and ongoing infrastructure rehabilitation, including the Volujica quay reconstruction initiated in 2021.

2.2 Economic Role and Infrastructure

The Port of Bar, located in the southern Adriatic Sea, serves as Montenegro's primary cargo port with an annual handling capacity of five million tons. As a key component of the national transport system, it operates across 130 hectares of developed infrastructure with a 70-hectare aquatorium, and has an additional 350 hectares designated for future expansion.

Two main terminal operators manage port activities:

- "Port of Bar" AD: handles liquid, dry bulk, and special cargo, plus specialized warehouses, Ro-Ro and passenger terminals
- AD "Container Terminal and General Cargo" (Port of Adria): operates independently under private ownership.

Most facilities operate within a free zone framework (excluding Pier V), offering users customs duty exemptions, VAT relief, unlimited storage, and simplified administrative procedures.
The port features 3,484 meters of operational quay with water depths of 5-14 meters, supported by 125,000 m^2 of covered storage and 22 km of internal railway network. Key facilities include 30,000-ton grain silos, petroleum/oil storage tanks, and specialized vehicle warehouses.
Transport connections include the electrified Belgrade-Bar railway line (25 kV, 50 Hz, 22-ton axle capacity) and the M-2.4 highway linking to Podgorica via the Sozina Tunnel, ensuring efficient cargo movement to regional and international markets.

The capacities of the Port of Bar are functionally divided into:

1) Dry Bulk Terminal – Strategic Hub for Grain and Bulk Cargo Logistics
The Dry Bulk Terminal (Figure 1) at the Port of Bar serves as a strategic hub for grain and bulk cargo logistics, equipped with a 30,000-ton grain silo, a 554-meter quay with 14-meter depth for large vessels, and advanced handling technology including three 12-ton ship loaders and two high-capacity mobile harbor cranes (Liebherr LHM 550 and LHM 420). With 5 hectares of open storage space, the terminal provides flexible and cost-effective solutions for bulk cargo management, while all operations adhere to international standards to ensure safety and environmental protection.

Photo 1. Dry Bulk Terminal

2) Liquid Bulk Terminal – A Strategic Hub for Safe and Efficient Cargo Handling in the Port of Bar

The Liquid Bulk Terminal (Photos 2 and 3) at the Port of Bar specializes in handling crude oil, petroleum products, and chemicals, with a 13.5-meter water depth that accommodates vessels of various sizes. It includes 23 storage tanks with a total capacity of 116,000 m^3 (owned by Jugopetrol – Kotor and Montenegrobonus – Cetinje), a 600 t/h acetic acid transfer station operated by MSK Kikinda, and 3,000 m^3 of lye storage managed by Uniprom LLC. All operations are conducted under strict international standards to ensure the safe handling of hazardous liquids, protect personnel, and minimize environmental risks.

Photos 2-3. Liquid Bulk Terminal

3) RO-RO, General Cargo, and Container Terminal: A Versatile Hub for Modern Freight Operations

The RO-RO, General Cargo, and Container Terminal (Photos 4 and 5) at the Port of Bar offers versatile transshipment and storage services, combining modern technology with efficient organization to handle RO-RO shipments, general cargo, and containers. Its facilities include a 7,800 m^2 refrigerated warehouse with a temperature range of -25°C to +13°C for perishable goods, along with universal warehouses (10 and 13) for varied cargo types. Equipped with advanced handling systems and operated under strict safety standards, the terminal ensures secure, efficient, and reliable logistics solutions for a wide range of freight operations.

Photos 4-5. RO-RO, General Cargo, and Container Terminal

4) Passenger Terminal of the Port of Bar

The Passenger Terminal at the Port of Bar serves passenger and Ro-Pax vessels with a 5.9-meter water depth that ensures safe embarkation and disembarkation. It offers comfortable waiting areas, information desks, and quick access to the city center, while its strategic location provides direct connections to railway and bus stations, enabling easy access to Montenegro's main tourist routes.

Photos 6-7. Passenger Terminal of the Port of Bar

5) Specialized Warehouses – Safety and Expertise Serving Modern Logistics

Luka Bar provides specialized warehouses designed to safely handle hazardous materials and temperature-sensitive food products. For IMO Class 1 cargo, purpose-built facilities ensure the secure storage of explosives and dangerous goods in line with the highest international safety standards. Additionally, a cold storage facility with a 4,500-ton capacity and a temperature range from -25°C to +13°C supports the storage of fruits, meat, and fish, conveniently located near the operational quay to enable fast and efficient distribution.

Photos 8-9. Specialized Warehouses

Port of Adria

Port of Adria is located on the western border of Bar in Montenegro. It is strategically located non-EU port in the Adriatic region. Global Ports Holding acquired the operating rights of Port of Adria through privatization in 2013. GPH owns 62.09% shares in Port of Adria. Port of Adria is a multipurpose port featuring quay length of 1,440 m with dedicated terminals for container ships, general cargo ships, RO RO and cruise ships. The port covers the total area of 518.790 m2 with nine berths and annual handling capacity of 750,000 TEU and 6.0 million tons of general cargoes.Whole area of Port of Adria is completely comprehended by the Free zone regime.

Photo 10. Port of Adria (View of organizational units)

The capacities of the Port of Adria are divided into:

1) **Timber terminal services**

The Timber Terminal at the Port of Bar is directly connected to both rail and road networks and equipped with modern facilities to ensure safe and efficient cargo management. A tracking system with integrated signage allows real-time monitoring of goods and direct communication with the Operations Department. The terminal includes four rail sidings totalling 480 meters, 45,000 m^2 of open storage, 21,213 m^2 of covered storage, and spans a total area of 5.8 hectares, with an annual throughput capacity of approximately 100,000 m^3.

2) Service to cruise ship

The Port of Bar began developing as a cruise destination with the arrival of its first cruise ship in 2014, and by 2016, it had welcomed seven vessels from Thomson Cruises, establishing its presence on the Mediterranean cruise map. The terminal can accommodate cruise ships over 300 meters, offers significant potential for further development, includes a 4,000 m^2 bus parking area for up to 80 buses, and plans for a 1,000-meter terminal facility to enhance passenger services.

3) Container Services

The Container Terminal at the Port of Bar is designed for unloading, handling, stuffing, and stripping containers in both warehouses and open storage areas, with a video surveillance system ensuring maximum security. Occupying two-thirds of Pier I, it is strategically positioned between the quay, railway tracks, and road access. The terminal features a 330-meter operational quay with two berths (12 m and 10 m draught), two 440-meter railway lines, storage capacity for 2,500 TEU, 270 reefer connections, and a terminal area of 80,000 m^2 with potential expansion of 50,000 m^2, supporting an estimated annual throughput of 50,000 TEU.

Photos 11-12. Container Services

4) General Cargo Services

The General Cargo Terminal at the Port of Bar, situated on Piers 1 and 2, is fully equipped to handle all types of general cargo, including palletized goods, food products, and metal items such as coils, slabs, strips, pipes, and bundles. It features both closed and open storage areas along with a modern handling zone. The terminal has a 1,010-meter operational quay with seven berths (11.5 m draught), railway lines totaling 8,110 meters (Pier 1 – 1,780 m; Pier 2 – 6,330 m), storage capacity of 51,250 m^2 open and 76,732 m^2 in warehouses, a total terminal area of 39.3 hectares (Pier 1 – 11.8 ha; Pier 2 – 27.5 ha), and an annual handling capacity of approximately 2,139,800 tons

Photos 13-14. General Cargo Services

Photo 15. Warehouses

5) Reefer station

Reefer Station, with the capacity of 270 reefer containers (with the possibility to increase to 360), is equipped with a new substation and diesel generator and provides maximum power supply reliability, quality service for storing reefer containers and conserving goods in them. It is constructed of nine steel scaffolds structures on three levels, each equipped with 30 sockets for powering reefer containers.

Photo 16. Reefer Station

3. Background information on the site and surrounding environmental media

The city and municipality of Bar lies on Montenegro's Adriatic coast, on the seaward foothills of mountain Rumija (1,594 m). Bar covers 598 km^2 of land within a total administrative area of 726 km^2. It`s shoreline includes 46 km on the Adriatic (≈9 km of beaches) and 65 km along Lake Skadar. The municipal seat is at 42°06′ N, 19°06′ E. According to the 2023 census, Bar has 45754 inhabitants.

3.1 Geomorphological and geological characteristics

Bar presents a sharp morphostructural contrast between the steep High-Karst carbonate chain Rumija–Sutorman–Sozina and a narrow coastal lowland. The Rumija front rises abruptly above the Adriatic and grades gently toward the Skadar Lake basin, producing high local relief and active slope processes. Along the shore, the Volujica ridge closes Bar Bay and forms a cliffed coast with small coves and sea caves; behind it, the Bar Field is a karst depression with limited surface drainage.

The bedrock framework is dominated by shallow-marine platform limestones and dolomites of Jurassic–Cretaceous age that build the mountain core (including Lower Jurassic units such as the Budoš Limestone). Toward the coast, these are overlain by a transgressive Paleogene succession—Liburnia limestones → Nummulitic limestones → pre-flysch marls → Adriatic Flysch—widely developed in the Budva/Bar sector. Flysch is cleanly exposed south of Bar (e.g., Crnjak Cove) in classic Bouma turbidite sequences. Structurally, Bar lies within the NW–SE Dinaridic fold-and-thrust belt, overprinted by incipient Quaternary normal faulting (5–7 km scarps) along the SW Rumija front. Hydrogeologically, springs concentrate at limestone–flysch and alluvial contacts, while steep carbonate slopes are prone to rockfalls and debris remobilization.

3.2 Climatic characteristics

Bar has a classic Mediterranean climate: mild, wet winters and warm to hot, sunny summers. Along the coast the mean annual air temperature is ≈16 °C, with summer months exceeding 20 °C and a July mean around 23.5 °C. The swimming season typically spans mid-May to mid-October, when sea temperatures reach ~26 °C. Annual precipitation is ~1,400–1,500 mm, with a maritime regime—maxima in November–January (and February) and a pronounced summer minimum; ZHMS long-term station statistics indicate an annual total near 1,392 mm for Bar. Sunshine is abundant: Bar records about 270 sunny days per year, placing it among the sunniest towns on the Adriatic. Prevailing winds follow the regional Adriatic pattern: bura (NE, cold/dry) in winter, jugo (SE, warm/moist) in autumn–winter bringing heavy rain and stormy seas, and the summer maestral (NW–W) as a regular sea-breeze regime. Relative humidity is high for a coastal setting (annual mean around ~69 %), consistent with the marine influence.

3.3 Hydrogeological characteristics of the terrain — Bar / Port of Bar

The hydrogeology of the Bar coast and the Port of Bar (Volujica–Bar Bay) is controlled by lithology and porosity type, with three functional groups of rocks/sediments:

(1) Karstified carbonates (Jurassic–Cretaceous limestones/dolomites) — dominantly fissure-/karst-permeable units in the Rumija–Sutorman foothills. They enable rapid infiltration and subsurface drainage toward the coastal plain; springs concentrate where carbonates abut flysch or alluvium.
(2) Flysch (Eocene marls, sandstones) — largely low-permeability to practically impermeable; they act as regional barriers that laterally guide groundwater and help confine shallower intergranular aquifers along the coast.
(3) Quaternary and anthropogenic deposits (Bar Field and port platform) — intergranularly porous gravels–sands with clayey interbeds, overlain locally by engineered fills at the port. In the Bar Field (Rikavac plain), alluvium is heterogeneous and thick (several to >100 m) with variable hydraulic conductivity; water table depths commonly reach up to ~10 m. Toward the coast/Port of Bar, artificial limestone rubble fills are ~2–12 m thick and highly permeable, while underlying clayey–silty horizons (often 30–45 m cumulative thickness) are of very low permeability, limiting vertical migration. Groundwater levels measured on the port plateau range from ~5 m below ground to approximately 0.0 m (at hydrological maxima), and are only weakly influenced by sea-level dynamics. Where sandy–muddy marine layers occur toward the shoreline, locally semi-confined behavior is possible.

3.4 Hydrological characteristics — Bar / Port of Bar

Bar coast exhibits high annual precipitation but marked seasonal contrasts. Because of the karstic substrate and steep relief, runoff is rapid and surface drainage is sparse, with much of the flow routed underground and (locally) discharging at the coast. As a result, summer low-flow conditions and localized water deficits can occur despite abundant rainfall in the cold season.
The municipality's coastal strip is cut by short, torrential streams that rise and fall abruptly and carry significant sediment during storm episodes. The Željeznica River (perennial) enters the Adriatic at Šušanj, while several torrents are identified as hydraulically critical in municipal plans—Rikavac (the most energetic torrent on the Bar littoral), Đurmanski potok, Suvi potok (Sutomore), and the Rena canal in the urban core. These watercourses have produced damaging flash-flood events (e.g., 2005–2010) along their channels and urban reaches.
At the Port of Bar (Volujica–Bar Bay), there are no natural perennial surface channels on the port platform, stormwater from the platform and adjacent urbanized areas is conveyed to Bar Bay via the urban/port drainage network. In heavy rain, short ephemeral flows descend from the surrounding slopes, while high groundwater in the coastal plain reduces infiltration capacity and can contribute to shallow inundation.
In the Skadar Lake sector of the municipality (Virpazar and lakeside settlements), hydrological conditions are governed by lake-level fluctuations: high stages expand inundation zones along the shoreline and back up local drains, producing periodic flooding independent of coastal storms.

3.5 Municipal and Port wastewater systems

Municipal collection and conveyance are operated by PUC "Vodovod i kanalizacija" Bar. The service area is organized into four largely independent subsystems: Bar, Sutomore, Čanj, and Virpazar. Overall sewer coverage is reported at ≈56–57 % of the municipal population, with a built network of ≈86.03 km (≈82.63 km gravity + ≈3.4 km pressure mains). Major wastewater pump stations include Volujica, Topolica, Botun, Čanj, with smaller stations at Šušanj and Čanj 2 (and several small stations in Virpazar). Three submarine outfalls serve the coast: Bar ~345 m, Sutomore ~1,040 m, and Čanj ~1,502 m.

3.5.1 Current disposal practice and treatment status

In urban Bar, municipal wastewater (without treatment) is conveyed by sewers to the Volujica pumping station (PS Volujica) and then discharged via a submarine outfall outside the harbour basin (beyond the Volujica tunnel). A technical report on the state of the marine environment specifies for the Bar outfall a length of approximately 348 m, a depth of approximately 34 m, and a capacity of about 500 L/s; in the event of a failure at PS Volujica, an emergency discharge occurs into the port.

3.5.2 Port of Bar - port/industrial and ship-generated wastewaters

The port platform has no natural perennial channels, sanitary and storm flows are handled by the port/urban drainage network and ultimately routed to the Bar submarine outfall beyond Volujica, with short-lived overland runoff during intense rainfall. For ship-generated oily waters and residues, the Port of Bar is covered by REMPEC/IMO Port Reception Facility requirements; a functional specification for oily-water treatment has been prepared, aligned with MARPOL provisions that apply to the Mediterranean special area.

4. Overview of the previous site investigations

4.1 Introduction

The aim of this section of the report is to provide a detailed and integrated overview of historical data obtained from previous environmental investigations in the Port of Bar. This includes:

- A review of the physical and chemical properties of marine sediments and the presence of key contaminants over the monitoring period 2017-2024;
- An assessment of contaminant bioaccumulation in selected marine organisms, bivalve mollusks;
- Wastewater Discharges: Previous Findings
- Assessment of Ambient air quality in the period 2021-2024 in the port
- Results of the sediment analysis conducted in the period 2020-2024 for “AD Port of Adria” Bar in the scope of monitoring programme in accordance with the Environmental Impact Assessment Study
- Results of the sediment analysis conducted in the period 2023-2025 for “AD Port of Bar”, in the scope of monitoring programme in accordance with the Environmental Impact Assessment Study

This comprehensive review of those data serves as the scientific foundation for the current investigation project, which aims to reassess and update the contamination status of the port basin. The ultimate objective is to strengthen the environmental stewardship of Montenegro’s coastal waters through informed decision-making and to ensure compliance with international marine protection commitments.

4.2 National monitoring programs of marine ecosystem

4.2.1 Study area

Over the past 15 years, a series of environmental monitoring activities have been conducted within the broader scope of national marine ecosystem monitoring programs. These programs, implemented in phases from 2009 to 2011 and from 2016 to 2024, have generated valuable datasets on sediment quality parameters in zone of the Port of Bar.
In addition to sediment analysis, an integral part of these monitoring programs has been the assessment of contaminant accumulation in marine biota, particularly in bivalve mollusks, which are recognized as effective bioindicators due to their filter-feeding nature and ability to bioaccumulate pollutants over time.

The results of analysis of sediment and biota samples analysed in the scope of the National monitoring programme are presented in tables 1 and 2.

Table 1. The results of analysis of contaminats in sediment samples for period 2017-2024

Location		Port of Bar								
Date of sampling		**18.05.2017.**	**19.10.2018.**	**10.09.2019.**	**12.11.2020.**	**01.06.2021**	**25.11.2022.**	**21.04.2023.**	**25.01.2024**	**30.05.2024**
Parameter	**Unit***	**Results of analysis**								
Cadmium	**µg/kg**	9000	4200	390	1610	1935	1083	779	762	525
Mercury	**µg/kg**	260	100	39	102	130.6	82	104	85	78
Copper	**µg/kg**	358000	86000	25000	60900	152837	133339	179935	126042	339759
Nickel	**µg/kg**	90000	103000	33000	100300	84646	76065	67461	73160	70024
Iron	**µg/kg**	28600000	38680000	11280000	36210000	24197657	29510000	33400000	33020100	29019000
Manganese	**µg/kg**	397000	600000	410000	565300	592970	560681	625364	545725	486717
Lead	**µg/kg**	356000	238000	86000	166500	440321	149947	79257	82460	118872
Zinc	**µg/kg**	2530000	740000	174000	356900	635323	250757	238220	171790	199900
Chromium	**µg/kg**	61000	77000	37000	169500	-	111403	147434	105960	126449
Tin	**µg/kg**	-	14000	1800	6800	-	3181	2356	2143	4206
Arsenic	**µg/kg**	20000	23000	11000	12300	17463	16424	12361	9821	28234
Polycyclic Aromatic Hydrocarbons Hydrocarbons										
Naphtalene	**µg/kg**	<5	27	50	15	22.5	27.4	14.2	9.5	17
2-methylnaphtalene	**µg/kg**	59	15	64	20	14.8	13.7	15.2	11.3	16
1-methylnaphtalene	**µg/kg**	36	15	32	18	12.2	11.0	12.9	10.3	11
Acenaphtylene	**µg/kg**	10	1	<5	<2	1.0	1.2	<1	1.2	<1
Acenaphtene	**µg/kg**	22	16	16	7	14.5	5.1	4.9	3.8	9.2
Fluorene	**µg/kg**	26	18	20	8	13.3	5.6	7.1	5.2	7.2
Phenanthrene	**µg/kg**	184	128	76	66	126	56.4	44.1	39.3	23
Anthracene	**µg/kg**	43	28	13	16	25.8	3.3	6.9	6.7	3.4
Fluoranthene	**µg/kg**	356	218	102	87	184	84.2	62.2	59.1	38
Pyrene	**µg/kg**	280	185	81	77	157	72.1	55.9	54.0	35
Benzo(a)anthracene	**µg/kg**	201	157	57	56	142	68.6	41.6	36.4	22
Chrysene	**µg/kg**	203	179	55	54	132	47.0	39.2	46.2	18
Benzo(b)fluoranthene	**µg/kg**	386	263	82	103	198	93.7	52.4	49.3	23
Benzo(k)fluoranthene	**µg/kg**	131	102	30	39	85.1	40.0	21.6	20.2	9.7
Benzo(a)pyrene	**µg/kg**	242	209	63	73	170	65.9	55.7	52.8	27
Indeno(1.2.3-cd)pyrene	**µg/kg**	196	157	33	51	135	54.8	43.8	31.2	13

Dibenzo(a.h)anthracene	**µg/kg**	58	32	8	13	31.8	3.9	9	9.1	4.4
Benzo(g.h.i)perylene	**µg/kg**	179	147	35	57	128	53.3	41.4	38.0	21
Σ16PAHs	**µg/kg**	2600	1900	818	760	1593	707	500.5	484	271
Mineral oils:	**mg/kg**	-	-	22699	81100	-	<10	31	23	64
PCB congeners:										
PCB 18	**µg/kg**	4	0.5	<0.1	0.3	0.17	1.2	<0.05	<0.05	<0.05
PCB 31	**µg/kg**	10	0.5	<0.1	0.7	0.56	1.4	0.26	0.16	0.42
PCB 28	**µg/kg**	9	0.7	<0.1	0.7	0.56	1.3	0.2	0.16	0.28
PCB 52	**µg/kg**	7	0.7	<0.1	0.8	1.6	1.5	0.8	<0.05	<0.05
PCB 44	**µg/kg**	7	0.3	<0.1	<0.1	0.45	1.2	0.33	<0.05	<0.05
PCB 101	**µg/kg**	5	1.4	0.15	0.2	2.4	2.3	0.52	0.30	0.59
PCB 149	**µg/kg**	5	2	0.15	0.4	2.4	2.9	0.72	0.45	0.44
PCB 118	**µg/kg**	8	3.2	0.56	0.6	2.7	2.2	0.39	0.50	0.96
PCB 153	**µg/kg**	7	5.8	0.8	1.1	5.2	6.5	1.4	0.90	0.76
PCB 138	**µg/kg**	7	5.4	0.7	0.9	3.8	4.8	1.4	0.90	0.78
PCB 180	**µg/kg**	<2	3.5	0.49	0.6	3.4	6.5	1.1	0.65	0.55
PCB 194	**µg/kg**	3.2	0.6	<0.1	<0.1	1.0	1.5	<0.05	0.16	<0.05
∑7PCBs ICES	**µg/kg**	44.0	20.7	2.80	4.90	19.7	25.1	5.81	3.44	3.93
Organotin compounds:										
Monobutiltin	**µg/kg**	25	<1	<1	5	6.2	<4	4.5	<4	<4
Dibutiltin	**µg/kg**	45	6.6	3.7	7	5.1	<4	4	<4	<4
Tributiltin	**µg/kg**	132	9.4	7.4	14	11	4.9	11.2	<4	11
Monooktiltin	**µg/kg**	<5	<1	<1	<1	1.2	<4	<4	<4	<4
Tetrabutiltin	**µg/kg**	<5	<1	<1	<1	<1	<4	<4	<4	<4
Dioktiltin	**µg/kg**	<5	<1	<1	<1	<1	<4	<4	<4	<4
Trifeniltin	**µg/kg**	<5	<1	<1	<1	<1	<4	<4	<4	<4
Tricyclohexyltin	**µg/kg**	<5	<1	<1	<1	<1	<4	<4	<4	<4
Organochlorine pesticides:										
HCB	**µg/kg**	<5	<5	<0.1	<0.1	<0.1	<0.05	<0.05	<0.05	<0.05
Aldrin	**µg/kg**	<5	<5	<0.1	<0.1		<0.05	<0.05	<0.05	<0.05
α-BHC	**µg/kg**	<5	<5	<0.1	<0.1	<0.1	<0.05	<0.05	<0.05	<0.05
β-BHC	**µg/kg**	<5	<5	<0.1	<0.1	<0.1	<0.05	<0.05	<0.05	<0.05
Lindane	**µg/kg**	<5	<5	<0.1	<0.1	<0.1	<0.05	<0.05	<0.05	<0.05

δ-BHC	**µg/kg**	<5	<5	<0.1	<0.1	<0.1	<0.05	<0.05	<0.05	<0.05
α-Chlordane	**µg/kg**	<5	<5	<0.1	<0.1	-	<0.05	<0.05	<0.05	<0.05
γ-Chlordane	**µg/kg**	<5	<5	<0.1	<0.1	-	<0.05	<0.05	<0.05	<0.05
4,4′-DDT	**µg/kg**	<5	<5	<0.1	<0.1	<0.1	0.76	1,4	0.34	<0.05
4,4′-DDD	**µg/kg**	<5	<5	<0.1	<0.1	<0.1	0.3	1,0	0.94	0.57
4,4′-DDE	**µg/kg**	<5	<5	<0.1	<0.05	0.8	0.19	<0.05	0.65	0.38
Dieldrin	**µg/kg**	<5	<5	<0.1	<0.1	-	<0.05	<0.05	<0.05	<0.05
α-Endosulfan	**µg/kg**	<5	<5	<0.1	<0.1	-	<0.05	<0.05	<0.05	<0.05
β-Endosulfan	**µg/kg**	<5	<5	<0.1	<0.1	-	<0.05	<0.05	<0.05	<0.05
Endosulfan sulfate	**µg/kg**	<5	<5	<0.1	<0.1	-	<0.05	<0.05	<0.05	<0.05
Endrin	**µg/kg**	<5	<5	<0.1	<0.1	-	<0.05	<0.05	<0.05	<0.05
Endrin aldehyde	**µg/kg**	<5	<5	<0.1	<0.1	-	<0.05	<0.05	<0.05	<0.05
Endrin ketone	**µg/kg**	<5	<5	<0.1	<0.1	-	<0.05	<0.05	<0.05	<0.05
Heptachlor	**µg/kg**	<5	<5	<0.1	<0.1	<0.1	<0.05	<0.05	<0.05	<0.05
Heptachlor epoxide	**µg/kg**	<5	<5	<0.1	<0.1	-	<0.05	<0.05	<0.05	<0.05
Mirex	**µg/kg**	<5	<5	<0.1	<0.1	-	<0.05	<0.05	<0.05	<0.05
Toxafen	**µg/kg**	<5	<5	<0.1	<0.1	-	<0.1	<0.05	<0.05	<0.05
Chlorphenols:	**µg/kg**									
2-Chlorophenol	**µg/kg**	-	-	-	-	-	<20	<20	<20	<20
2,4- Dichlorophenol	**µg/kg**	-	-	-	-	-	<20	<20	<20	<20
2,6- Dichlorophenol	**µg/kg**	-	-	-	-	-	<20	<20	<20	<20
2,4,5-Trichlorophenol	**µg/kg**	-	-	-	-	-	<20	<20	<20	<20
2,4,6-Trichlorophenol	**µg/kg**	-	-	-	-	-	<20	<20	<20	<20
2,3,4,6-Tetrachlorophenol	**µg/kg**	-	-	-	-	-	<20	<20	<20	<20
Pentachlorophenol	**µg/kg**	-	-	-	-	-	<20	<20	<20	<20
PFOS	**µg/kg**	-	-	-	-	-	-	<5	<0.02	<0.02

***d.w.**

Table 2. The results of analysis of contaminats in shellfish samples for period 2018-2024

Location		Port of Bar							
Date of sampling		**27.05.2018.**	**09.05.2019.**	**08.04.2020.**	**19.04.2021.**	**27.12.2022.**	**28.04.2023.**	**02.02.2024.**	**30.05.2024.**
Parameter	**Unit***	**Results of analysis**							
Cadmium	**µg/kg**	73	170	2188	1067	1470	1323	1889	603
Mercury	**µg/kg**	20	16	102	114	143	270	224	90
Lead	**µg/kg**	2300	5800	167857	110897	80000	47250	44085	33300
Copper	**µg/kg**	-	1200	9821	15437	55700	131625	1122000	49500
Zinc	**µg/kg**	-	14900	313482	166288	370000	214650	32725	198000
Nickel	**µg/kg**	-	410	3366	2043	6300	2700	3927	900
Iron	**µg/kg**	-	40000	81000	305335	1666000	533250	2298230	351000
Manganese	**µg/kg**	-	1400	1740	9421	40000	11880	21505	9900
Chromium	**µg/kg**	-	130	2125	1544	3400	1890	3272	927
Tin	**µg/kg**	-	<250	<250	<1250	<1250	<1250	<1250[2]	<1250[2]
Arsenic	**µg/kg**	-	5600	3220	27242	27500	24300	73397	21600
Polycyclic Aromatic Hydrocarbons Hydrocarbons									
Acenaphtylene	**µg/kg**	0.21	<0.5	<0.5	<0.5	1.5	<0.5[2]	<0.5[2]	0.78
Acenaphtene	**µg/kg**	0.15	<0.5	<0.5	<0.5	0.5	8.4	<0.5[2]	<0.5[2]
Fluorene	**µg/kg**	0.28	<0.5	<0.5	<0.5	3.3	7.8	<0.5[2]	<0.5[2]
Phenanthrene	**µg/kg**	0.42	1.5	<0.5	4.7	28.8	45.8	2.9	<0.5[2]
Anthracene	**µg/kg**	<0.04	<0.5	<0.5	<0.5	5.2	3.1	<0.5[2]	<0.5[2]
Fluoranthene	**µg/kg**	0.69	2.3	<0.5	8.7	112	13.3	7.2	3.7
Pyrene	**µg/kg**	0.19	1.1	<0.5	10.8	116.3	16.4	5.9	4.5
Benzo(a)anthracene	**µg/kg**	0.17	<0.5	0.60±0.07	2.1	28.1	9.9	1.8	0.78

Chrysene	**µg/kg**	0.52	2.0±0.2	<0.5	3.5	53.9	16.2	2.4	4.2
Benzo(b)fluoranthene	**µg/kg**	0.51	0.7±0.1	<0.5	4.1	14.5	8.9	2.9	<0.5[2]
Benzo(k)fluoranthene	**µg/kg**	0.38	0.5	<0.5	1.0	14.4	3.2	3.2	<0.5[2]
Benzo(a)pyrene	**µg/kg**	0.36	<0.5	<0.5	<0.5	31.5	3.1	1.8	<0.5[2]
Indeno(1.2.3-cd)pyrene	**µg/kg**	0.24	<0.5	<0.5	<0.5	9.8	2.0	1.1	<0.5[2]
Dibenzo(a.h)anthracene	**µg/kg**	<0.10	<0.5	<0.5	<0.5	3.8	<0.5[2]	<0.5[2]	<0.5[2]
Benzo(g.h.i)perylene	**µg/kg**	0.23	0.8	<0.5	<0.5	20.2	4.2	1.4	<0.5[2]
Σ 16 PAHs	**µg/kg**	6.5	9.5	0.60±0.07	34.7	454	157.3	38.6	14.0
PCBs congeners:									
PCB 18	**µg/kg**	-	0.27	0.89	0.4	<0.05	<0.05	<0.05	<0.05
PCB 31	**µg/kg**	-	<0.1	1.65	<0.2	<0.05	2.95	<0.05	<0.05
PCB 28	**µg/kg**	-	<0.1	1.55	<0.2	<0.05	2.70	<0.05	<0.05
PCB 52	**µg/kg**	-	<0.1	1.61	0.9	<0.05	1.58	0.2	<0.05
PCB 44	**µg/kg**	-	<0.1	1.16	<0.2	<0.05	4.56	<0.05	<0.05
PCB 101	**µg/kg**	-	<0.1	6.62	1.8	18.3	3.85	5.5	10.9
PCB 149	**µg/kg**	-	0.44	8.79	2.3	18.1	3.16	4.3	15.0
PCB 118	**µg/kg**	-	0.32	4.83	1.7	33.3	<0.05	<0.05	<0.05
PCB 153	**µg/kg**	-	0.84	15.43	5.2	48.4	7.03	9.0	32.3
PCB 138	**µg/kg**	-	0.79	11.39	3.9	56.5	3.92	7.6	21.9
PCB 180	**µg/kg**	-	<0.1	0.98	1.1	10.9	1.38	2.8	7.6
PCB 194	**µg/kg**	-	<0.1	<0.2	<0.2	<0.05	<0.05	<0.05	<0.05
Sum 7 PCBs	**µg/kg**					167.4	20.5	25.2	72.8
Organotin compounds:									
Monobutiltin	**µg/kg**	-	<1.0	<1.0	<1.0	<1[2]	1.1	1.2	<1[2]
Dibutiltin	**µg/kg**	-	<1.0	<1.0	3.3	<1[2]	1.2	2.4	8.7
Tributiltin	**µg/kg**	-	3.0	48	12.4	<1[2]	9.9	6.2	28.2

Monooktiltin	**µg/kg**	-	<1.0	<1.0	<1.0	<1[2]	<1[2]	1.0	<1[2]
Tetrabutiltin	**µg/kg**	-	<1.0	<1.0	<1.0	<1[2]	<1[2]	<1[2]	<1[2]
Dioktiltin	**µg/kg**	-	<1.0	<1.0	<1.0	<1[2]	<1[2]	<1[2]	<1[2]
Trifeniltin	**µg/kg**	-	<1.0	<1.0	<1.0	<1[2]	<1[2]	<1[2]	<1[2]
Tricyclohexyltin	**µg/kg**	-	<1.0	<1.0	<1.0	<1[2]	<1[2]	<1[2]	<1[2]
Organochlorin pesticides:									
HCB	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Aldrin	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
α-BHC	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
β-BHC	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Lindane	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
δ-BHC	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
α-Chlordane	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
γ-Chlordane	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
4,4′-DDT	**µg/kg**	<0.05	<0.05	<0.05	<0.05	5.5	<0.05	<0.05	<0.05
4,4′-DDD	**µg/kg**	<0.05	<0.05	<0.05	<0.05	1.1	1.7	2.8	<0.05
4,4′-DDE	**µg/kg**	<0.05	<0.05	<0.05	1.6	1.5	2.9	5.8	<0.05
Dieldrin	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
α-Endosulfan	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
β-Endosulfan	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Endosulfan sulfate	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Endrin	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Endrin aldehyde	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Endrin ketone	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Heptachlor	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Heptachlor epoxide	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05

Mirex	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Toxafen	**µg/kg**	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<5.0[2]	<5.0[2]
Chlorphenols:									
2-Chlorophenol	**µg/kg**	-	-	-	<20	<20	<20	<20	<20
2,4- Dichlorophenol	**µg/kg**	-	-	-	<20	<20	<20	<20	<20
2,6- Dichlorophenol	**µg/kg**	-	-	-	<20	<20	<20	<20	<20
2,4,5- Trichlorophenol	**µg/kg**	-	-	-	<20	<20	<20	<20	<20
2,4,6- Trichlorophenol	**µg/kg**	-	-	-	<20	<20	<20	<20	<20
2,3,4,6- Tetrachlorophenol	**µg/kg**	-	-	-	<20	<20	<20	<20	<20
Pentachlorophenol	**µg/kg**	-	-	-	<20	<20	<20	<20	<20
PFOS	**µg/kg**	-	-	-	-	-	<2.5	<0.025	<0.025
Hexabromobiphenyl	**µg/kg**	-	-	-	-	-	-	<0.05	<0.05

***d.w.**

4.2.2 Evaluation of monitoring results and environmental status at the Port of Bar

The evaluation of environmental quality at the Port of Bar (sampling station CCH-BA02) for the period 2017–2024, based on data obtained through sediment and biota (mussel) monitoring, is given in table 3. The assessment was conducted using the NEAT (Nested Environmental status Assessment Tool) methodology in accordance with the criteria defined under UNEP/MAP.

Table 3. Evaluation of results of individual contaminants in sediment and shellfish using the NEAT method for the Port of Bar

SAU	NEAT value	Status class	CI17_Cd sed	CI17_Hg sed	CI17_Pb sed	Σ16 PAHs sed	Σ7 PCBs sed	CI17_Cd mus	CI17_Hg mus	CI17_Pb mus	Σ7 PCBs mus	Σ16 PAHs mus
MNE-1-C-CCH-BA02	0.393	poor	0.283	0.682	0.184	0.196	0.196	0.690	0.713	0.136	0.516	0.336

The calculated NEAT value for this location is **0.393**, which falls within the **"poor" status class**, indicating **non-achievement of Good Environmental Status (non-GES)**. This classification reflects a cumulative impact from multiple contaminants, both in sediments and in biota, particularly with respect to:

- **Cadmium (Cd)** and **Lead (Pb)** in sediment, where concentrations consistently exceeded GES/nGES thresholds across multiple years.
- **Σ16 Polycyclic Aromatic Hydrocarbons (PAHs)** and **Σ7 Polychlorinated Biphenyls (PCBs)** in sediment, which also displayed elevated values, suggesting long-term contamination from petrochemical and industrial sources.
- **Lead (Pb)** and **Σ16 PAHs** in **mussels (Mytilus galloprovincialis)**, with values indicating significant bioaccumulation and potential ecological and human health risks through trophic transfer.

Moreover, although several individual parameters show variation over time, the overall contaminant load remains concerning. This includes episodic spikes in concentrations of certain compounds, suggesting potential ongoing or intermittent inputs from maritime, port maintenance, or urban runoff activities.

4.3 Wastewater discharges at the Port of Bar- previous findings

As part of the Montenegrin national marine ecosystem monitoring program, a wastewater monitoring program was implemented in coastal municipalities.
Systematic assessment of municipal wastewater discharges was carried out along the Montenegrin Adriatic coast between 2016 and 2021. The monitoring aimed to evaluate the potential impact of untreated and treated municipal effluents on coastal water quality and marine ecosystem.

4.3.1 Monitoring sites and sampling regime

The municipality of Bar has no municipal wastewater treatment plant. Instead, untreated municipal wastewater is discharged directly into the Adriatic Sea via a marine outfall. Sampling was conducted at this outfall over the period 2016–2021 at location with the following coordinates: latitude N: 42°05.330, longitude E: 019°05.374 (Photo 17).

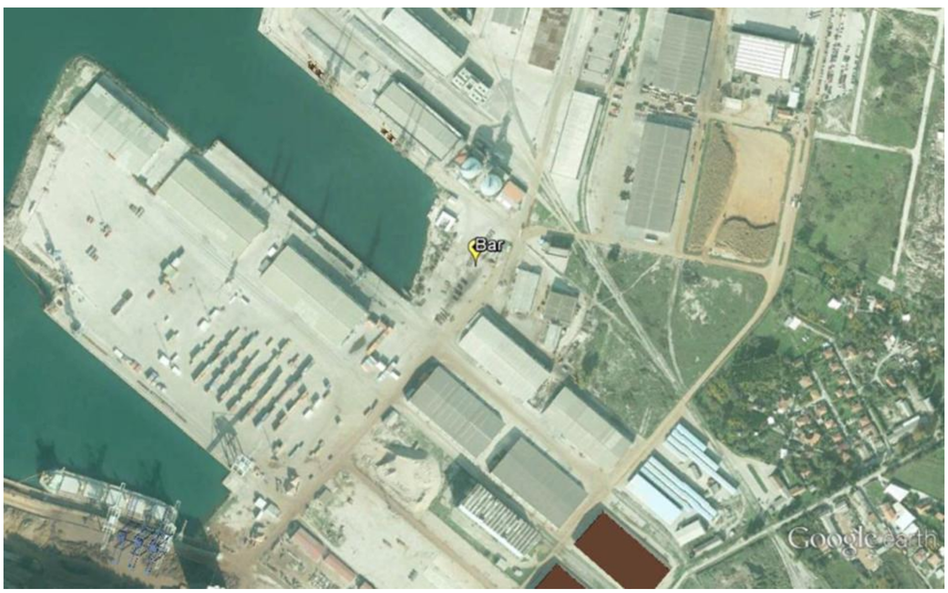


Photo 17. Sampling location for municipal wastewater in Bar

The parameters analyzed encompassed a broad spectrum of contaminants and water quality indicators:

- general physico-chemical parameters (temperature, pH, salinity, transparency, suspended solids, dissolved oxygen, BOD5, COD)
- nutrients (nitrates, nitrites, ammonia, total nitrogen, orthophosphates, total phosphorus, silicates, detergents, phenols, total organic carbon, molar ratios such as Si:N, N:P, Si:P, chlorophyll-a, TRIX index)
- microbiology,
- toxicants, including Persistent Organic Pollutants (POPs) such as organochlorine pesticides (e.g., DDT, aldrin, dieldrin), PCBs, perfluorooctane, hexabromobiphenyl, dioxins and furans,
- Heavy metals (e.g., Cd, Hg, Pb, Cu, Ni, Zn, Cr, As, Sb, Sn).

4.3.2 Summary of Results (2016–2021)

4.3.2.1 Persistent Organic Pollutants (POPs) and Organic Contaminants

Throughout the monitoring period (2016–2021), none of the targeted POPs were detected in wastewater effluent samples from Bar. This includes:

- organochlorine pesticides (e.g., DDT, aldrin, dieldrin, heptachlor, HCB, toxaphene, mirex),
- polychlorinated biphenyls (PCBs),
- dioxins and furans
- polycyclic aromatic hydrocarbons (PAHs),
- chlorobenzenes and chlorinated phenols.

Among the organic pollutants analyzed, only mineral oils were detected in the wastewater effluent, with concentrations generally ranging from below 0.2 mg/L up to around 2 mg/L over the monitoring period.

4.3.2.2 Heavy Metals

Heavy metals analyses were performed for samples collected in 2016 and 2017. Results showed:

- cadmium, mercury, arsenic, and antimony were consistently below detection limits or at low levels (<0.001 mg/L).
- lead ranged up to 0.03 mg/L (single value in 2016) but was typically ≤0.008 mg/L.
- copper concentrations ranged from 0,02 to 0,05 mg/L.
- zinc ranged between 0.03 and 0.08 mg/L.
- nickel and chromium generally remained low, up to about 0.035 mg/L.
- tin concentration was generally below the limit of quantification except 0.310 mg/L in October 2016.

Based on the available data, no evidence was found of significant pollution from Persistent Organic Pollutants or heavy metals in municipal wastewater discharged at the Port of Bar during the monitored period. The absence of these substances in measurable concentrations suggests that, despite the lack of wastewater treatment infrastructure, the discharge did not represent a source of hazardous contaminants to the marine environment — at least in terms of the POPs and heavy metals analysed.

4.4 Assessment of ambient air quality – Port of Bar (2021-2024)

To evaluate the potential impact of bulk cargo operations, specifically the transshipment of copper concentrate, on ambient air quality in the Port of Bar, the Center for Ecotoxicological Research (CETI) Podgorica conducted a series of monitoring campaigns focusing on PM_{10} particulate matter and associated heavy metal concentrations. The transshipment of copper concentrate is quantitatively dominant compared to that of other concentrates, such as lead and zinc, and was therefore prioritized in the monitoring scope.

These monitoring activities were performed in strict compliance with national legislative frameworks, including:

- The Law on Air Protection ("Official Gazette of Montenegro", No. 25/10, 40/11, 43/15),
- The Regulation on Types of Pollutants, Limit Values, and Other Air Quality Standards ("Official Gazette of Montenegro", No. 25/12),
- The Rulebook on the Manner and Conditions for Air Quality Monitoring ("Official Gazette of Montenegro", Nos. 21/11, 32/16), and
- The Regulation on the Establishment of the Air Quality Monitoring Network ("Official Gazette of Montenegro", Nos. 44/10, 13/11).

The initial measurement campaign was carried out in 2021, lasting 14 days and serving as a preliminary assessment of particulate pollution. Before this campaign, air quality monitoring and assessment of activity-related impacts were either sporadic or conducted only as part of environmental impact assessments or permit requirements, and as such cannot be considered adequate for reliable evaluation. Between 2022 and 2024, four separate 14-day monitoring cycles were conducted annually, establishing a more systematic approach to assessing potential environmental impacts.

4.4.1 Monitoring Sites

Three strategically selected locations were monitored to capture both the direct influence of port activities and the urban background air quality:

- **MM1**: Situated southeast at the periphery of the Port of Bar, near the "Old Station" (Coordinates: 42°05'02.79"N, 19°05'23.84"E), representing the zone closest to bulk cargo handling activities.
- **MM2**: Located north of the port area, adjacent to sports facilities and administrative buildings (Coordinates: 42°05'33.82"N, 19°05'38.35"E).
- **MM3**: A control site near the "Topolica" sports hall, in the urban center of Bar, outside the immediate influence of port emissions (Coordinates: 42°06'13.54"N, 19°05'39.95"E).

The map with sampling locations is presented in Photo 18.

Photo 18. Map of sampling locations

Site selection was based on proximity to known emission sources while ensuring representativeness, measurement safety, and minimal interference from localized non-port activities.

4.4.2 Summary of Monitoring Results

Table 4 presents an overview of the main findings regarding PM_{10} concentrations (90.4th percentile values) and the presence of selected heavy metals at the three monitoring stations during the 2021–2024 period.

Table 4. Summary of PM_{10} and heavy metal monitoring results (2021–2024)

Year	Number of 14-day Cycles	PM_{10} 90.4th Percentile (μg/m^3)	Exceedance of Limit Value (50 μg/m^3)	Arsenic (As) Status	Observations on Other Metals
2021	1*	Not determined (measurement lasted 2 weeks)	Informal regime; concluding remarks absent (insufficient coverage)	As exceeded limit value	Ni, Cd, Pb below limit; Cu, Zn, Fe, Al elevated at MM1 and MM2
2022	4	MM1 = 52.81 MM2 = 55.81 MM3 = 29.87	Yes (MM1, MM2)	Exceeded limit values (MM1, MM2)	Ni, Cd, Pb below limit but higher at MM1, MM2; Cu, Zn, Fe, Al elevated

Year	Number of 14-day Cycles	PM_{10} 90.4th Percentile (μg/m³)	Exceedance of Limit Value (50 μg/m³)	Arsenic (As) Status	Observations on Other Metals
2023	4	MM1 = 73.19 MM2 = 56.44 MM3 = 29.87	Yes (MM1, MM2)	Exceeded limit values (MM1, MM2)	Similar pattern to 2022; absolute metal concentrations somewhat increased
2024	4	MM1 = 51.71 MM2 = 72.40 MM3 = 23.13	Yes (MM1, MM2)	As above target values at MM1 and MM2	Ni, Cd, Pb below limit but elevated compared to control; Cu, Zn, Fe, Al elevated at MM1 and MM2

*Note: The 2021 campaign was preliminary and consisted of a single 14-day measurement cycle.

Table 5 presents the statistical summary of heavy metal concentrations in ambient air measured at three monitoring locations (MM1, MM2, and MM3) during the period 2020–2024.

Overall, concentrations varied across locations and years, with MM1 generally showing the highest average values for most elements, particularly in 2023. Notably elevated levels of arsenic and lead were recorded at MM1 in 2023, with maximum concentrations of 530 ng/m³ and 1.049 μg/m³, respectively. MM2 showed a sharp increase in arsenic and copper concentrations in 2024, with arsenic reaching a maximum of 281 ng/m³ and copper peaking at 5.121 μg/m³. On the other hand, MM3 consistently exhibited the lowest average concentrations for all measured elements throughout the observed period.

Temporal trends indicate that:

- **Ni and Pb** levels at MM1 peaked in 2023 and decreased in 2024.
- **Cd** concentrations were below 0.5 ng/m³ in most cases and generally lower in 2024 across all sites.
- **As** values fluctuated significantly, with a marked increase at MM2 in 2024, likely linked to specific atmospheric conditions or emission events.
- **Cu, Al, Fe, and Zn** showed moderate variability, with MM1 and MM2 recording higher levels than MM3, particularly during 2022–2023.

The data also highlight considerable variability within each year, as seen in the range between minimum and maximum values and the high 98th percentile concentrations, especially for As and Cu at MM1 and MM2.

Key Findings (2021–2024)

- **PM_{10} Concentrations**

At the measurement sites located at the port boundary (MM1 and MM2), the 90.4th percentile of PM_{10} concentrations consistently exceeded the prescribed limit value of 50 μg/m³ throughout all years. This indicates a persistent presence of elevated suspended particulate matter concentrations in the immediate vicinity of the port. Conversely, the control site (MM3), located outside the direct influence of port activities, systematically exhibited PM_{10} levels below the limit value, confirming that the source of pollution is localized within the port area and does not significantly affect the wider urban environment.

- **Arsenic (As)**

Arsenic concentrations at MM1 and MM2 consistently exceeded the target limit values each year. These persistent exceedances are associated with the transshipment operations of copper concentrate and other bulk materials, constituting a continuous challenge for air quality management in the port vicinity.

- **Nickel (Ni), Cadmium (Cd), and Lead (Pb)**

Annual average concentrations of these metals remained below regulatory limits. However, their concentrations were two to four times higher at MM1 and MM2 compared to the control location MM3, indicating a localized influence of industrial activities on air quality in the port area.

- **Copper (Cu), Zinc (Zn), Iron (Fe), and Aluminium (Al)**

Although no regulatory limits are prescribed for these metals, their concentrations were regularly elevated at the port boundary sites (MM1 and MM2). This suggests ongoing emissions linked to bulk cargo handling, with emission intensity correlating with the operational volume of port activities.

Table 5. Statistic of heavy metal monitoring results in air (2022–2024)

Sampling location	Year	Statistic	Ni (ng/m³)	Cd (ng/m³)	Pb (µg/m³)	As (ng/m³)	Cu (µg/m³)	Al (µg/m³)	Fe (µg/m³)	Zn (µg/m³)
MM1	2022	Average	1.457	0.371	0.051	16.9	0.529	0.289	1.137	0.050
		Min	<1	<0.5	<0.005	<0.5	<0.01	<0.01	0.029	<0.01
		Max	3.800	3.300	0.215	109.0	3.144	1.915	5.159	0.670
		Median	1.600	<0.5	0.036	9.6	0.280	0.111	0.702	0.025
		98th perc.	3.300	2.140	0.210	89.2	2.522	1.858	4.888	0.214
	2023	Average	2.416	0.670	0.122	44.4	0.919	0.342	1.500	0.058
		Min	<1	<0.5	<0.005	<0.5	0.022	0.015	0.027	<0.01
		Max	7.100	8.700	1.049	530.0	6.832	1.972	9.278	0.243
		Median	2.200	0.540	0.083	26.0	0.670	0.267	1.089	0.048
		98th perc.	6.490	3.190	0.384	196.9	5.039	1.432	6.502	0.191
	2024	Average	1.614	0.369	0.180	27.8	0.600	0.144	0.679	0.033
		Min	<1	<0.5	<0.005	0.5	0.003	0.027	0.099	<0.01
		Max	11.000	1.600	0.424	114.0	1.496	0.673	1.515	0.079
		Median	1.600	<0.5	0.179	20.5	0.574	0.088	0.646	0.031
		98th perc.	5.740	1.550	0.423	87.6	1.487	0.557	1.500	0.068
MM2	2022	Average	1.622	0.381	0.056	19.3	0.733	0.393	1.236	0.051
		Min	<1	<0.5	<0.005	<0.5	<0.01	0.011	0.036	0.002
		Max	6.500	1.600	0.218	149.0	4.469	2.626	6.319	0.296
		Median	1.600	0.525	0.040	12.0	0.367	0.130	0.528	0.037
		98th perc.	5.890	1.550	0.192	75.6	3.348	1.526	5.287	0.189
	2023	Average	0.682	0.337	0.042	30.7	0.652	0.213	0.927	0.031
		Min	<1	<0.5	<0.005	<0.5	0.004	<0.01	0.071	<0.01
		Max	3.300	1.600	0.567	126.0	3.478	1.488	4.055	0.145
		Median	<1	<0.5	0.026	13.0	0.351	0.150	0.604	0.024
		98th perc.	3.240	1.600	0.181	123.8	2.497	0.728	3.724	0.085
	2024	Average	1.445	0.138	0.105	96.2	1.643	0.197	1.719	0.032
		Min	<1	<0.5	<0.005	0.5	0.048	0.032	0.147	<0.01
		Max	4.400	1.200	0.469	281.0	5.121	1.841	4.888	0.180
		Median	1.200	<0.5	0.081	83.0	0.949	0.144	1.406	0.027
		98th perc.	4.350	1.044	0.450	280.6	5.120	0.739	4.874	0.079

Sampling location	Year	Statistic	Ni (ng/m³)	Cd (ng/m³)	Pb (µg/m³)	As (ng/m³)	Cu (µg/m³)	Al (µg/m³)	Fe (µg/m³)	Zn (µg/m³)
MM3	2022	Average	0.904	0.019	0.002	0.6	0.022	0.230	0.218	0.008
		Min	<1	<0.5	<0.005	<0.5	<0.01	<0.01	<0.01	<0.01
		Max	2.700	0.540	0.049	2.7	0.164	1.648	1.327	0.050
		Median	1.100	<0.5	<0.005	<0.5	0.012	0.029	0.054	0.005
		98th perc.	2.200	0.450	0.030	2.2	0.094	1.263	1.285	0.034
	2023	Average	0.264	<0.5	0.003	0.2	0.044	0.297	0.290	0.017
		Min	<1	<0.5	<0.005	<0.5	<0.01	0.003	0.010	<0.01
		Max	2.700	<0.5	0.126	6.5	0.131	1.438	1.309	0.107
		Median	<1	<0.5	<0.005	<0.5	0.049	0.095	0.137	0.011
		98th perc.	2.200	<0.5	0.022	2.0	0.095	1.291	1.255	0.061
	2024	Average	0.595	<0.5	<0.005	1.0	0.017	0.069	0.164	0.004
		Min	<1	<0.5	<0.005	<0.5	0.001	0.006	0.039	<0.01
		Max	4.700	<0.5	<0.005	5.1	0.092	0.458	0.450	0.016
		Median	<1	<0.5	<0.005	0.7	0.010	0.053	0.132	0.003
		98th perc.	4.550	<0.5	<0.005	5.0	0.087	0.311	0.353	0.016

4.5 Results of the sediment analysis in the scope of monitoring programme for “AD Port of Adria” and Port of Bar

In line with the Environmental Impact Assessment Study and the defined monitoring program, the Centre for Ecotoxicological Research carried out sediment sampling at the request of AD Port of Adria (2020–2024) and AD Port of Bar (2023–2025). The purpose of this monitoring was to evaluate and track sediment quality over the specified periods.

Criteria for the risk assessment

Regulations prescribing maximum permissible concentrations of pollutants in sediments in Montenegro do not exist. Therefore, the results of sediment sample analyses conducted in 2020-2024 were assessed against the Dutch standards for certain substances, which apply to dredged sediments.

The Dutch Sediment Quality Standard establishes threshold level (*Intervention value*) which define the situation where remediation is required. The intervention values for sediment remediation indicate when the functional properties of sediment for humans, plants, animals, or the aquatic ecosystem are seriously impaired or endangered. They point to the level of contamination above which a case is considered serious sediment pollution.

Table 6. Intervention values for sediment

No	Parametar	Intervention value (mg/kg d.w.)	Corrected Intervention value (mg/kg d.w.)
1	Cadmium (Cd)	14	11
2	Lead (Pb)	580	457
3	Mercury (Hg)	10	8
4	Arsenic (As)	85	64
5	Chrome (Cr)	380	274
6	Nickel (Ni)	210	126
7	Fluorine	/	/
8	Copper (Cu)	190	113
9	Zinc (Zn)	2000	1314
10	Borone	/	/
11	Cobalt (Co)	240	135
12	Molybdenum (Mo)	200	200
13	Σ10PAHs*	80	40
14	Σ7PCB**	2	0.6
15	Mineral oil	5000	3000

*-Σ10PAHs=Naphthalene, Anthracene, Phenantrene, Fluoranthene, Benzo(a)anthracene, Chrysene, Benzo(a)pyrene, Benzo(ghi)peryleen, Benzo(k)fluorantheen, Indeno(1,2,3-cd)pyrene

**-Σ7PCB= 28, 52, 101, 118, 138, 153 i 180

In sediment quality assessment according to these guidelines, the reference values provided for a standard sediment must be adjusted to reflect the specific characteristics of the sediment under investigation. This adjustment is carried out using the measured content of organic matter and clay in the sample. The resulting corrected values represent the appropriate threshold concentrations for the given sediment type and are then used as the basis for comparison with the measured contaminant concentrations.

4.5.1 Results of the sediment analysis “AD Port of Adria”

Sediment sampling was conducted at the following locations (Photo 18):

- Bar – “AD Port of Adria”, North Quay of Pier I
- Bar – “AD Port of Adria”, South Quay of Pier I

Photo 19. Overview of sediment sampling locations for the period 2020–2024

The results of analysis of sediment samples in the scope of monitoring programme based on the request of “AD Port of Adria” Bar are shown in table 7.

Table 7. Comparative presetation of the sediment analysis results for 2020-2024- Port of Adria

Comparative Presentation of Sediment Analysis Results – 2020, 2021, 2022, 2023, 2024											
		North Quay of Pier I	**South Quay of Pier I**	**North Quay of Pier I**	**South Quay of Pier I**	**North Quay of Pier I**	**South Quay of Pier I**	**North Quay of Pier I**	**South Quay of Pier I**	**North Quay of Pier I**	**South Quay of Pier I**
Laboratory ID		**312/11**	**336/11**	**270/05**	**276/05**	**608/05/22**	**607/05/22**	**256/05/23**	**255/05/23**	**180/05/24**	**179/05/24**
Date of sampling		**01.06.2020.**	**15.06.2020.**	**18.11.2021.**	**24.11.2021.**	**30.11.2022.**	**30.11.2022.**	**21.12.2023.**	**21.12.2023.**	**27.11.2024.**	**27.11.2024.**
Coordinate		**42°05.367'N 19°05.211'E**	**42°05.230'N 19°05.034'E**	**42°05.342'N 19°05.252'E**	**42°05.230'N 19°05.046'E**	**42°05.342'N 19°05.284'E**	**42°05.169'N 19°05.049'E**	**42° 05.342'N 19° 05.284'E**	**42° 05.169'N 19° 05.049'E**	**42° 05.399'N 19° 05.237'E**	**42° 05.217'N 19° 04.962'E**
Parameter	Unit *	Result and expanded measurement uncertainty[1]									
Cadmium	mg/kg	3.8±0.3	4.7±0.4	2.4±0.2	5.2±0.5	2.5±0.2	11±1	2.4±0.2	9.3±0.9	2.6±0.3	2.5±0.3
Lead	mg/kg	1021±74	404±32	593±58	340±34	795±99	581±73	566±71	490±61	634±79	214±27
Mercury	mg/kg	0.10±0.02	0.065±0.011	0.15±0.02	0.15±0.02	0.23±0.02	0.14±0.01	0.32±0.03	0.18±0.02	0.11±0.01	0.12±0.01
Arsenic	mg/kg	20±2	19±2	14±1	18±2	22±2	62±6	56±6	81±8	47±5	32±3
Chromium	mg/kg	59±6	70±7	54±5	51±5	105±9	94±8	95±8	92±8	81±8	90±9
Nickel	mg/kg	75±7	72±7	61±6	76±8	89±9	133±14	74±7	83±8	102±10	112±12
Fluorine	mg/kg	280	271	415	258	340	330	247	212	292	286
Copper	mg/kg	133±12	101±11	188±19	289±29	528±45	1764±152	862±74	1852±159	1630±140	909±78
Zinc	mg/kg	963±98	1050±107	632±64	1116±114	653±54	2004±128	619±40	1936±124	606±39	569±36
Boron	mg/kg	32±3	32±3	31±3	14±1	18±2	16±2	23±2	17±2	21±2	23±2
Cobalt	mg/kg	10±1	10±1	8.2±0.8	9.1±0.9	13±1	13±1	15±1	15±1	10±1	12±1
Molybdenum	mg/kg	3.6±0.5	<1	2.7±0.3	<1	7.6	3.6	8.3	4.5	6.8±0.7	2.1±0.2
PAHs:											
Naphtalene	mg/kg	0.04±0.01	0.03±0.01	0.04±0.01	0.011±0.003	0.10±0.03	0.030±0.008	0.038±0.010	0.029±0.008	<0.005[2]	0.028±0.008
2-Methylnaphtalene	mg/kg	0.02±0.01	0.05±0.01	/	/	0.04±0.01	0.04±0.01	0.028±0.008	0.04±0.01	0.022±0.006	0.05±0.01
1-Methylnaphtalene	mg/kg	0.009±0.002	0.016±0.004	/	/	0.018±0.005	0.017±0.005	0.019±0.005	0.025±0.007	0.016±0.005	0.033±0.009
Acenaphtylene	mg/kg	<0.005	<0.005	<0.005	<0.005	<0.005[2]	<0.005[2]	<0.005[2]	<0.005[2]	<0.005[2]	<0.005[2]
Acenaphtene	mg/kg	0.05±0.01	0.020±0.004	0.036±0.006	0.009±0.002	0.019±0.003	0.007±0.001	0.030±0.005	0.019±0.003	0.015±0.003	0.016±0.003
Fluorene	mg/kg	0.045±0.007	0.023±0.004	0.030±0.005	0.012±0.002	0.019±0.003	0.011±0.002	0.029±0.005	0.025±0.004	0.018±0.003	0.023±0.004
Phenanthrene	mg/kg	0.4±0.1	0.18±0.03	0.28±0.04	0.13±0.02	0.19±0.03	0.10±0.01	0.23±0.03	0.18±0.03	0.12±0.02	0.15±0.02
Anthracene	mg/kg	0.10±0.01	0.036±0.004	0.063±0.008	0.017±0.002	0.031±0.004	0.010±0.001	0.038±0.005	0.033±0.004	0.021±0.003	0.026±0.003
Fluoranthene	mg/kg	0.7±0.1	0.25±0.04	0.46±0.07	0.17±0.03	0.33±0.05	0.15±0.02	0.41±0.06	0.25±0.04	0.20±0.03	0.25±0.04
Pyrene	mg/kg	0.6±0.1	0.20±0.03	0.38±0.06	0.14±0.02	0.30±0.05	0.15±0.02	0.35±0.05	0.21±0.03	0.17±0.03	0.23±0.04
Benzo(a)anthracen	mg/kg	0.46±0.06	0.33±0.04	0.29±0.04	0.10±0.01	0.29±0.04	0.13±0.02	0.29±0.04	0.18±0.02	0.12±0.02	0.16±0.02
Chrysene	mg/kg	0.4±0.1	0.14±0.02	0.32±0.05	0.14±0.02	0.27±0.04	0.11±0.02	0.28±0.04	0.18±0.03	0.13±0.02	0.15±0.02
Benzo(b)fluoranthene	mg/kg	0.7±0.1	0.35±0.05	0.34±0.05	0.17±0.03	0.31±0.05	0.12±0.02	0.29±0.04	0.19±0.03	0.13±0.02	0.23±0.03
Benzo(k)fluoranthene	mg/kg	0.2±0.1	0.06±0.01	0.17±0.04	0.07±0.02	0.14±0.04	0.06±0.01	0.12±0.03	0.07±0.02	0.06±0.01	0.09±0.02
Benzo(a)pyrene	mg/kg	0.5±0.1	0.20±0.03	0.35±0.05	0.11±0.01	0.26±0.03	0.13±0.02	0.36±0.05	0.21±0.03	0.17±0.02	0.23±0.03
Indeno(1,2,3-cd)pyrene	mg/kg	0.4±0.1	0.24±0.04	0.27±0.04	0.10±0.02	0.16±0.03	0.08±0.01	0.16±0.03	0.10±0.02	0.08±0.01	0.14±0.02
Dibenzo(a,h)anthracene	mg/kg	0.09±0.02	0.07±0.02	0.06±0.01	0.018±0.004	0.036±0.008	0.018±0.004	0.054±0.013	0.038±0.009	0.029±0.007	0.05±0.01
Benzo(g,h,i)perylene	mg/kg	0.4±0.1	0.15±0.03	0.25±0.05	0.09±0.02	0.16±0.03	0.09±0.02	0.23±0.04	0.15±0.03	0.11±0.02	0.19±0.04
Σ10PAHs**	mg/kg	3.6±0.7	1.6±0.3	2.5±0.4	0.94±0.21	1.9±0.3	0.89±0.15	2.2±0.4	1.4±0.2	1.0±0.2	1.4±0.2
Σ18PAHs	mg/kg	5.1±0.9	2.3±0.4	3.4±0.6	1.3±0.2	2.7±0.5	1.2±0.2	3.0±0.5	1.9±0.3	1.4±0.2	2.1±0.4
Mineral Oils	mg/kg	56	<10	266	236	209	183	357	139	253	78

PCB Congeners:											
PCB 18	mg/kg	<0.002	<0.002	<0.002	<0.002	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 31	mg/kg	<0.002	<0.002	<0.002	0.0025±0.0003	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 28	mg/kg	<0.002	<0.002	<0.002	0.0025±0.0003	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 52	mg/kg	0.0020±0.0003	<0.002	0.0036±0.0004	0.0028±0.0003	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 44	mg/kg	<0.002	<0.002	0.0010±0.0001	<0.002	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 101	mg/kg	0.005±0.001	<0.002	0.0051±0.0006	0.0034±0.0004	0.0025±0.0003	0.0031±0.0003	<0.002[2]	0.0024±0.0003	<0.002[2]	<0.002[2]
PCB 149	mg/kg	0.018±0.002	<0.002	0.012±0.001	0.0033±0.0003	0.012±0.001	0.0035±0.0003	<0.002[2]	<0.002[2]	0.0023±0.0002	<0.002[2]
PCB 118	mg/kg	0.005±0.001	0.0032±0.0003	0.0033±0.0003	0.0034±0.0003	0.0032±0.0003	0.005±0.001	<0.002[2]	0.0027±0.0003	<0.002[2]	0.0028±0.0003
PCB 153	mg/kg	0.038±0.004	0.0060±0.0006	0.018±0.002	0.0046±0.0005	0.028±0.003	0.008±0.001	0.0033±0.0003	0.0030±0.0003	0.0037±0.0004	0.0027±0.0003
PCB 138	mg/kg	0.029±0.003	0.0030±0.0003	0.013±0.001	0.0040±0.0004	0.011±0.001	0.008±0.001	0.0027±0.0002	0.0033±0.0003	0.0031±0.0003	0.0027±0.0002
PCB 180	mg/kg	0.054±0.008	<0.002	0.022±0.003	0.0027±0.0004	0.039±0.006	0.004±0.001	0.0045±0.0007	0.0022±0.0003	0.005±0.001	<0.002[2]
PCB 194	mg/kg	0.013±0.002	<0.002	0.0052±0.0006	<0.002	0.009±0.001	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
Σ7PCB***	mg/kg	0.13±0.02	0.012±0.001	0.056±0.006	0.020±0.004	0.08±0.01	0.029±0.004	0.010±0.001	0.011±0.002	0.012±0.002	0.008±0.001
Organotin Compounds	mg/kg	/	/	/	/	/	/	/	/	0.041±0.004	0.024±0.003
Monobutyltin	mg/kg	/	/	/	/	/	/	/	/	0.0041±0.0005	0.0053±0.0006
Dibutyltin	mg/kg	/	/	/	/	/	/	/	/	0.0067±0.0008	0.0057±0.0006
Tributyltin	mg/kg	/	/	/	/	/	/	/	/	0.030±0.004	0.013±0.002
Monooctyltin	mg/kg	/	/	/	/	/	/	/	/	<0.001[2]	<0.001[2]
Tetrabutyltin	mg/kg	/	/	/	/	/	/	/	/	<0.001[2]	<0.001[2]
Dioctyltin	mg/kg	/	/	/	/	/	/	/	/	<0.001[2]	<0.001[2]
Triphenyltin	mg/kg	/	/	/	/	/	/	/	/	<0.001[2]	<0.001[2]
Tricyclohexyltin	mg/kg	/	/	/	/	/	/	/	/	<0.001[2]	<0.001[2]

*-d.w.

[1]Expanded measurement uncertainty is expressed as the combined standard measurement uncertainty multiplied by a coverage factor k = 2, corresponding to a confidence level of 95%.

[2]Limit of quantification (LOQ)

**- Naphthalene, Anthracene, Phenantrene, Fluoranthene, Benzo(a)anthracene, Chrysene, Benzo(a)pyrene, Benzo(ghi)peryleen, Benzo(k)fluorantheen, Indeno(1,2,3-cd)pyrene

***-Σ7PCB= 28, 52, 101, 118, 138, 153 i 180

Based on the results of sediment analyses for chemical elements, mineral oils, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) at the locations "South Quay of Pier I" and "North Quay of Pier I" during the investigation period 2020–2024, the following conclusions can be drawn:

South Quay of Pier I

Lead (Pb)
- Average concentration was below the intervention value.
- In 2022 (581 mg/kg), lead exceeded the intervention value, representing a critical exceedance.
- Lead levels showed decreasing values in 2023–2024 compared to 2022.

Arsenic (As)
- Concentrations in 2022 and 2023 were above the intervention value.
- In 2024, arsenic content showed decreasing value compared to 2022-2023.

Nickel (Ni)
- Concentration in 2022 exceeded the intervention value.
- Other years remained below the threshold.

Copper (Cu)
- Average concentration was significantly above the intervention value.
- In 2022 (1764 mg/kg), 2023 (1852 mg/kg), and 2024 (909 mg/kg), copper was far above the corrected intervention value showing extremely high exceedances.
- A pronounced increasing trend was observed compared to 2020–2021.

Zinc (Zn)
- In 2022 and 2023, concentrations exceeded the intervention value.
- In 2020 (1050 mg/kg), 2021 (1116 mg/kg) and 2024 (569 mg/kg), results were below the intervention value (1314 mg/kg).
- In 2022 (2004 mg/kg) and 2023 (1936 mg/kg), zinc exceeded the intervention value.

Cadmium (Cd), Mercury (Hg), Chromium (Cr), Molybdenum (Mo), Cobalt (Co), Σ10PAHs, Mineral Oils, Σ7PCBs
- All results were below the intervention value.

North Quay of Pier I

Lead (Pb)
- The concentration in 2020 significantly exceeded the intervention value.
- In the following years (2021–2024), lead levels decreased, remaining close to but above the threshold.

Copper (Cu)
- Average concentration was above the intervention value.
- High values were recorded in 2022–2024, significantly exceeding the threshold.
- Results clearly indicate a rising trend compared to 2020–2021.

Arsenic (As), Zinc (Zn), Chromium (Cr), Cadmium (Cd), Mercury (Hg), Nickel (Ni), Cobalt (Co), Molybdenum (Mo), Σ10PAHs, Mineral Oils, Σ7PCBs concentrations in all years remained below the intervention value.

The monitoring of sediment quality at the locations South Quay of Pier I and North Quay of Pier I in the period 2020–2024 indicates that the overall sediment condition is characterized by stable concentrations for most parameters, remaining well below the intervention values. However, several heavy metals demonstrated exceedances of the intervention values, with particular concern at specific years and locations. At the South Quay of Pier I, exceedances were recorded for lead (Pb) in 2022, arsenic (As) in 2022 and 2023, nickel (Ni) in 2022, copper (Cu) in 2021–2024, and zinc (Zn) in 2022–2023, with copper showing extremely high concentrations in 2022–2023 far above the intervention value. At the North Quay of Pier I, exceedances were most evident for lead (Pb) in 2020 and subsequent years, and copper (Cu) in 2020–2024, while zinc values remained below the intervention value but showed higher levels in 2020 compared to later years.
These findings confirm that the most critical contaminants of concern are heavy metals, particularly copper, lead, arsenic, zinc, and nickel, which in several instances exceeded the intervention values, pointing to a potential ecological risk for sediment quality and associated ecosystems.
In conclusion, although a number of parameters remain consistently below the threshold levels, the observed exceedances of certain heavy metals highlight the necessity for continuous and systematic monitoring of sediment quality.

4.5.2 Results of the sediment analysis Port of Bar

For the monitoring programme in Port of Bar, sediment sampling was conducted at the following locations:

- Bar – “AD Port of Bar”, M1
- Bar – “AD Port of Bar”, M2
- Bar – “AD Port of Bar”, M3

Photo 20. Overview of sediment sampling locations for the period 2023–2025

Table 8. Comparative presentation of sediment analysis results- Port of Bar

Comparative Presentation of Sediment Analysis Results – 2023, 2024, 2025										
Locations		**Port of Bar, M3**	**Port of Bar, M1**	**Port of Bar, M2**	**Port of Bar, M3**	**Port of Bar, M1**	**Port of Bar, M2**	**Port of Bar, M3**	**Port of Bar, M1**	**Port of Bar, M2**
Laboratory ID		**93/05/22**	**94/05/22**	**95/05/22**	**134/05/24**	**132/05/24**	**133/05/24**	**38/05/25**	**36/05/25**	**37/05/25**
Date of sampling		**23.06.2023.**	**23.06.2023.**	**23.06.2023.**	**19.08.2024.**	**19.08.2024.**	**19.08.2024.**	**23.04.2025.**	**23.04.2025.**	**23.04.2025.**
Coordinate		**42° 05.859'N 19° 04.844'E**	**42° 05.208'N 19° 04.993'E**	**42° 05.316'N 19° 04.787'E**	**42° 05.859'N 19° 04.844'E**	**42° 05.208'N 19° 04.993'E**	**42° 05.316'N 19° 04.787'E**	**42° 05.859'N 19° 04.844'E**	**42° 05.208'N 19° 04.993'E**	**42° 05.316'N 19° 04.787'E**
Parameter	Unit *	Result and expanded measurement uncertainty[1]								
Cadmium	mg/kg	0.22±0.02	8.0±0.8	0.99±0.09	0.70±0.07	6.0±0.6	1.0±0.1	0.90±0.09	4.0±0.4	4.2±0.4
Lead	mg/kg	30±3	273±28	58±6	47±5	263±27	57±6	52±5	185±19	210±21
Mercury	mg/kg	0.060±0.006	0.22±0.02	0.090±0.009	0.046±0.005	0.10±0.01	0.039±0.004	0.075±0.008	0.13±0.01	0.13±0.01
Arsenic	mg/kg	10±1	42±4	18±2	11±1	70±7	19±2	23±2	56±6	52±5
Chromium	mg/kg	139±14	156±16	190±19	96±10	121±12	109±11	117±18	121±12	211±21
Nickel	mg/kg	71±7	110±11	95±9	72±7	102±10	88±9	92±9	101±10	112±11
Antimony	mg/kg	<2[2]	<2[2]	<2[2]	<2[2]	4.0	<2[2]	<2[2]	<2[2]	<2[2]
Copper	mg/kg	56±6	1551±133	144±14	92±9	1556±161	117±12	97±10	1481±154	1124±117
Zinc	mg/kg	84±8	1240±129	180±18	118±12	889±89	156±16	121±12	747±75	806±81
Cobalt	mg/kg	14±1	15±1	16±2	10±1	13±1	12±1	21±2	20±2	21±2
Molybdenum	mg/kg	1.1±0.1	2.1±0.2	7.3±0.7	<1[2]	3.4±0.3	7.7±0.8	1.1±0.1	4.0±0.4	2.3±0.2
PAHs:										
Naphtalene	mg/kg	0.015±0.004	0.019±0.005	0.009±0.002	0.016±0.004	0.027±0.007	0.013±0.004	0.014±0.004	0.020±0.005	0.030±0.008
2-Methylnaphtalen	mg/kg	0.014±0.004	0.029±0.008	0.012±0.003	0.017±0.005	0.04±0.01	0.017±0.005	0.013±0.004	0.021±0.006	0.025±0.007
1-Methylnaphtalen	mg/kg	0.014±0.004	0.018±0.005	0.009±0.002	0.012±0.003	0.023±0.006	0.012±0.003	0.013±0.004	0.016±0.004	0.019±0.005
Acenaphtylene	mg/kg	<0.005[2]	<0.005[2]	<0.005[2]	<0.005[2]	<0.005[2]	<0.005[2]	<0.005[2]	<0.005[2]	<0.005[2]
Acenaphtene	mg/kg	<0.005[2]	<0.005[2]	<0.005[2]	0.007±0.001	0.014±0.002	0.008±0.001	<0.005[2]	0.006±0.001	0.006±0.001
Fluorene	mg/kg	<0.005[2]	0.009±0.001	<0.005[2]	0.009±0.002	0.020±0.003	0.010±0.002	<0.005[2]	0.009±0.002	0.010±0.002
Phenanthrene	mg/kg	0.024±0.004	0.063±0.010	0.032±0.005	0.045±0.007	0.09±0.01	0.04±0.01	0.021±0.003	0.062±0.009	0.058±0.009
Anthracene	mg/kg	<0.005[2]	0.013±0.002	0.005±0.001	<0.005[2]	0.015±0.002	<0.005[2]	<0.005[2]	0.007±0.001	0.006±0.001
Fluoranthene	mg/kg	0.019±0.003	0.09±0.01	0.040±0.006	0.038±0.006	0.11±0.02	0.032±0.005	0.026±0.004	0.11±0.02	0.10±0.02
Pyrene	mg/kg	0.017±0.003	0.09±0.01	0.036±0.006	0.033±0.005	0.10±0.02	0.028±0.004	0.025±0.004	0.10±0.02	0.10±0.02
Benzo(a)anthracen	mg/kg	0.012±0.002	0.07±0.01	0.029±0.004	0.020±0.003	0.067±0.009	0.018±0.002	0.016±0.002	0.07±0.01	0.07±0.01
Chrysene	mg/kg	0.011±0.002	0.07±0.01	0.026±0.004	0.023±0.004	0.07±0.01	0.018±0.003	0.014±0.002	0.07±0.01	0.07±0.01
Benzo(b)fluoranthene	mg/kg	0.018±0.003	0.09±0.01	0.038±0.006	0.027±0.004	0.08±0.01	0.024±0.004	0.030±0.005	0.10±0.01	0.12±0.02
Benzo(k)fluoranthene	mg/kg	0.006±0.001	0.038±0.009	0.015±0.004	0.011±0.003	0.035±0.009	0.010±0.002	0.009±0.002	0.04±0.01	0.04±0.01
Benzo(a)pyrene	mg/kg	0.012±0.002	0.10±0.01	0.037±0.005	0.026±0.003	0.10±0.01	0.023±0.003	0.017±0.002	0.09±0.01	0.09±0.01
Indeno(1,2,3-cd)pyrene	mg/kg	0.010±0.002	0.06±0.01	0.027±0.004	0.016±0.002	0.050±0.008	0.014±0.002	0.015±0.002	0.07±0.01	0.07±0.01
Dibenzo(a,h)anthracene	mg/kg	<0.005[2]	0.018±0.004	0.007±0.002	<0.005[2]	0.019±0.005	0.005±0.001	<0.005[2]	0.018±0.004	0.017±0.004
Benzo(g,h,i)perylene	mg/kg	0.012±0.002	0.07±0.01	0.03±0.01	0.024±0.005	0.08±0.02	0.023±0.004	0.019±0.004	0.09±0.02	0.08±0.02
Σ10PAHs**	mg/kg	0.12±0.02	0.6±0.1	0.25±0.04	0.20±0.04	0.6±0.1	0.18±0.03	0.15±0.03	0.6±0.1	0.6±0.1
Σ18PAHs	mg/kg	0.18±0.03	0.8±0.1	0.35±0.06	0.32±0.06	0.9±0.2	0.30±0.05	0.23±0.04	0.9±0.2	0.9±0.2
Mineral Oils	mg/kg	<10[2]	69	<10[2]	<10[2]	115	<10[2]	37	114	112

PCB Congeners:										
PCB 18	mg/kg	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 31	mg/kg	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 28	mg/kg	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 52	mg/kg	<0.002[2]	0.0026±0.0003	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 44	mg/kg	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 101	mg/kg	<0.002[2]	0.0023±0.0002	<0.002[2]	<0.002[2]	0.0046±0.0005	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 149	mg/kg	<0.002[2]	0.0021±0.0002	<0.002[2]	<0.002[2]	0.0031±0.0003	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 118	mg/kg	<0.002[2]	0.0033±0.0003	<0.002[2]	<0.002[2]	0.0068±0.0007	<0.002[2]	<0.002[2]	<0.002[2]	0.0021±0.0002
PCB 153	mg/kg	<0.002[2]	0.0044±0.0004	<0.002[2]	<0.002[2]	0.0049±0.0005	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 138	mg/kg	<0.002[2]	0.0051±0.0005	<0.002[2]	<0.002[2]	0.0059±0.0005	<0.002[2]	<0.002[2]	<0.002[2]	0.0021±0.0002
PCB 180	mg/kg	<0.002[2]	0.0025±0.0004	<0.002[2]	<0.002[2]	0.0028±0.0004	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
PCB 194	mg/kg	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]	<0.002[2]
Σ7PCB***	mg/kg	<0.01[2]	0.020±0.003	<0.01[2]	<0.01[2]	0.025±0.004	<0.01[2]	<0.01[2]	<0.01[2]	<0.01[2]
Organotin Compounds:										
Monobutyltin	mg/kg	<0.004[2]	<0.004[2]	<0.004[2]	<0.004	0.0040±0.0005	<0.004	<0.004[2]	0.007	<0.004[2]
Dibutyltin	mg/kg	<0.004[2]	<0.004[2]	<0.004[2]	<0.004	<0.004	<0.004	<0.004[2]	<0.004[2]	0.0044±0.0005
Tributyltin	mg/kg	<0.004[2]	0.031±0.004	0.010±0.001	0.0053±0.0006	0.012±0.002	<0.004	0.0044±0.0005	0.018±0.002	0.083±0.010
Monooctyltin	mg/kg	<0.004[2]	<0.004[2]	<0.004[2]	<0.004	<0.004	<0.004	<0.004[2]	<0.004[2]	<0.004[2]
Tetrabutyltin	mg/kg	<0.004[2]	<0.004[2]	<0.004[2]	<0.004	<0.004	<0.004	<0.004[2]	<0.004[2]	<0.004[2]
Dioctyltin	mg/kg	<0.004[2]	<0.004[2]	<0.004[2]	<0.004	<0.004	<0.004	<0.004[2]	<0.004[2]	<0.004[2]
Triphenyltin	mg/kg	<0.004[2]	<0.004[2]	<0.004[2]	<0.004	<0.004	<0.004	<0.004[2]	<0.004[2]	<0.004[2]
Tricyclohexyltin	mg/kg	<0.004[2]	0.005	<0.004[2]	<0.004	<0.004	<0.004	<0.004[2]	0.01	<0.004[2]

*-d.w.

[1]Expanded measurement uncertainty is expressed as the combined standard measurement uncertainty multiplied by a coverage factor k = 2, corresponding to a confidence level of 95%.

[2]Limit of quantification (LOQ)

**- Naphthalene, Anthracene, Phenantrene, Fluoranthene, Benzo(a)anthracene, Chrysene, Benzo(a)pyrene, Benzo(ghi)peryleen, Benzo(k)fluorantheen, Indeno(1,2,3-cd)pyrene

***-Σ7PCB= 28, 52, 101, 118, 138, 153 i 180

Summary of Sediment Quality Monitoring in the Port of Bar (2023–2025)

Based on sediment analyses (Table 8) at locations M1, M2, and M3, compared with Dutch Intervention Values, the following conclusions were made:

M1

Copper (Cu): Extremely high concentrations in all years (2023–2025), well above the intervention value (113 mg/kg).

Arsenic (As): Slight exceedance in 2024 (70 mg/kg vs. threshold 64 mg/kg).

Lead (Pb), Nickel (Ni), Zinc (Zn): Elevated, but consistently below intervention values.

Other parameters: Remained below intervention values.

M2

Copper (Cu): Consistently above intervention values in all years (2023–2025).

Other parameters: Well below intervention values.

M3

No exceedances: All measured parameters stayed below intervention values.

Trend: Stable concentrations of heavy metals and organic pollutants throughout the period.

Key Findings

Monitoring results clearly identify copper (Cu) as the most critical contaminant, with persistent exceedances at M1 and M2. Arsenic (As) represents a localized risk at M1 in 2024. Other parameters, including metals, PAHs, PCBs, and mineral oils, remained below intervention values with stable trends.

Recommendation

Continuous sediment quality monitoring is essential, with special focus on copper and arsenic, the dominant pollutants of concern.

5. Conceptual site model

The Conceptual Site Model (CSM) provides a structured overview of contamination processes in the Port of Bar, Montenegro. It identifies potential pollution sources, chemicals of potential concern, transport and exposure pathways, and sensitive receptors, thereby supporting risk evaluation, regulatory compliance, and management strategies.

As Montenegro's largest maritime hub, the Port of Bar hosts diverse activities: ore transshipment, petroleum handling, shipping operations, stormwater inflows, and wastewater discharges, which collectively contribute to a complex contamination profile. Long-term operations have resulted in enrichment of fine-grained sediments with heavy metals and organic pollutants.

The CSM emphasizes how these contaminants are mobilized and redistributed through runoff, atmospheric deposition, spills, sediment accumulation, and resuspension, creating exposure routes to benthic organisms, fish and shellfish, port workers, and local communities. By integrating sources, pathways, and receptors into a single framework, the CSM explains current contamination patterns and provides a practical tool to guide monitoring, dredging decisions, and long-term environmental management of the port basin.

5.1 Site setting and environmental context

The Port of Bar is located on the Montenegrin Adriatic coast, at the foot of the Rumija–Sutorman mountain range, serving as the country's largest maritime and industrial hub. Its strategic position makes it a key gateway for regional trade, encompassing bulk cargo, petroleum products, general goods, and passenger transport. The port's intensive activities, combined with its geomorphological and oceanographic setting, create conditions highly relevant for the accumulation and persistence of environmental contaminants in sediments.

The harbour basin is characterized by fine-grained marine sediments rich in silts and clays, which provide high surface area and cation exchange capacity. These characteristics favour the adsorption and long-term retention of trace metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and organotin such as tributyltin (TBT). Climatic conditions, wet winters, dry summers, and strong seasonal winds, exacerbate the mobilization and dispersion of contaminants via runoff, atmospheric deposition, and sediment resuspension.

5.2 Port Operations and Potential Sources of Contamination

The Port of Bar, as the largest maritime and industrial facility in Montenegro, plays a central role in the country's economy and regional trade. Its diversified operational profile, ranging from bulk ore and concentrate handling to petroleum logistics, general cargo, and passenger transport, creates a complex network of potential contamination sources. The interaction of these activities with the marine environment has resulted in a contamination signature dominated by metals, hydrocarbons, and persistent organic pollutants. The principal sources of contamination are summarized below:

Dry bulk terminal operations (S1)

The transshipment and storage of mineral concentrates, including copper, lead, and zinc ores, represent the most significant source of trace metal enrichment in sediments. Particulate matter generated during unloading, stockpiling, and wind dispersion settle onto water and land surfaces, while accidental spillage during handling directly enters the marine basin. These materials are highly mobile under stormwater runoff, contributing to widespread deposition of metals in fine-grained harbour sediments. The pronounced elevation of copper and zinc in recent monitoring data is strongly consistent with this source.

Liquid bulk terminal (S2)

The Port of Bar hosts extensive infrastructure for the transfer and storage of petroleum products. Despite operational safeguards, the inherent risk of spills, leaks, and line flushing activities creates pathways for hydrocarbons and polycyclic aromatic hydrocarbons (PAHs) to enter the aquatic environment. Once released, lighter hydrocarbons form surface sheens that impair water quality and oxygen exchange, while heavier fractions bind to sediments, where they persist over long timescales.

Ship-related activities (S3)

Shipping operations and additional inputs stem from bilge and ballast water discharges, which may carry oil residues, metals, and chemical additives, as well as emissions from fuel combustion that deposit particulate-bound contaminants into the harbor. Routine maintenance and vessel traffic therefore constitute chronic sources of organic and inorganic pollutants.

Industrial and urban runoff (S4)

Precipitation across the port platform mobilizes particulates, petroleum residues and other chemicals from paved surfaces, storage yards, and cargo handling areas. This runoff is directed into the harbor basin via a network of stormwater channels, effectively transferring land-based contaminants into the aquatic system. Suspended particles carried by runoff subsequently settle, further enriching sediments with fine-grained contaminants.

Wastewater discharges (S5)

The Volujica pumping station collects and directs combined sanitary sewage and stormwater to a submarine outfall beyond the port basin. However, system bypasses, failures, or emergency releases can lead to untreated discharges directly within the harbor. Such episodes introduce a mixture of nutrients, organic matter, pathogens, and trace contaminants, with the potential to degrade sediment quality and influence benthic ecology.

Legacy contamination (S6)

The Port of Bar has been in operation for decades, during which time continuous ore handling, fuel storage, and vessel activity have left a long-lasting chemical imprint on sediments. Metals such as copper, zinc, lead, cadmium, mercury, chromium, and nickel, together with persistent organic pollutants including PAHs, polychlorinated biphenyls (PCBs), and organotin compounds, are routinely detected at concentrations reflecting both historical and ongoing contamination. These legacy pollutants are of particular concern because of their persistence, ability to bioaccumulate, and cumulative ecological impact.

5.3 Contaminants of potential concern

Based on historical records and recent investigations, the principal contaminants of potential concern in the Port of Bar include:

- Metals: As, Cd, Cu, Ni, Pb, Zn, Hg, Cr.
- Organic pollutants: PAHs, PCBs, tributyltin.
- Hydrocarbons: Petroleum products, lubricants, fuel residues.
- Airborne particulates: Dust rich in metal sulfides from ore handling and storage.

5.4 Transport and exposure pathways

The release, redistribution, and eventual ecological and human exposure to contaminants within the Port of Bar are governed by a range of physical, chemical, and biological processes. These pathways determine not only the immediate dispersion of pollutants but also their long-term persistence and potential risks for marine and coastal environments. The main pathways identified in this assessment are described below:

Atmospheric dispersion

Ore handling and bulk cargo operations at the port generate fine particulate matter rich in metals such as copper, lead, and zinc. These particles are readily entrained into the air by wind, especially under dry conditions, and subsequently deposited onto water surfaces, soil, and built infrastructure. Atmospheric fallout represents an important route of secondary contamination, contributing to sediment enrichment over time. Port workers and nearby residents may also be exposed directly through inhalation of dust or indirect contact via contaminated surfaces, making airborne dispersion a relevant occupational and public health concern.

Surface water runoff

Rainfall mobilizes particulates, spilled cargo, oil residues, and other contaminants from paved surfaces, storage areas, and stockpiles. This runoff is transported through stormwater channels and ultimately discharged into the port basin, often without sufficient pre-treatment. Runoff events can deliver short but intense contaminant pulses to marine waters, elevating concentrations of metals, hydrocarbons, and suspended solids in both the water column and deposited sediments. Given the high intensity of rainfall events typical of the Adriatic climate, stormwater runoff represents one of the dominant mechanisms of contaminant transfer from land-based activities to the marine environment.

Sediment accumulation

Once contaminants reach the harbor basin, fine-grained sediments (silts and clays) act as the primary sink due to their high surface area and strong adsorption capacity for hydrophobic organic compounds and metal cations. This process leads to the progressive build-up of contaminants in the benthic environment, creating long-term reservoirs of pollution. Sediment-bound contaminants may remain buried and relatively immobile for years, yet they still pose an ecological risk due to potential remobilization and bioavailability under changing environmental conditions.

Resuspension and bioavailability

Harbor sediments are frequently disturbed by vessel traffic, propeller wash, dredging operations, and storm events. These disturbances resuspend contaminated particles into the water column, where they can be redistributed throughout the basin or transported beyond the immediate harbor area. Resuspension increases the bioavailability of pollutants by enhancing their contact with benthic organisms and by facilitating their incorporation into the aquatic food web. This pathway is especially critical for hydrophobic organic pollutants and fine particulate-bound metals, which may be ingested by filter-feeding species and subsequently bioaccumulated.

Spills and leaks

Accidental releases of petroleum products or chemicals during loading, unloading, or storage operations create acute pollution events. Hydrocarbons form surface films on the water, impeding oxygen transfer, reducing light penetration, and directly affecting planktonic communities. With time, lighter fractions evaporate, while heavier components adsorb to sediments or accumulate in benthic habitats. Such events can cause immediate ecological damage and may also contribute to chronic sediment contamination if not adequately remediated.

5.5 Potential Receptors

The distribution of contaminants within the Port of Bar environment implies that multiple environmental and human receptors are at risk of exposure. These receptors interact with contaminants through direct contact, ingestion, or indirect ecological pathways, each with distinct implications for ecological and human health:

Sediment compartment

Marine sediments act as the ultimate sink for both trace metals and hydrophobic organic pollutants. Due to their fine-grained nature and high adsorption capacity, sediments accumulate contaminants over extended timeframes. This compartment therefore serves not only as a long-term repository of historical pollution but also as a continuing source of secondary contamination through resuspension and desorption processes.

Benthic organisms

Organisms inhabiting the seabed are in direct and continuous contact with contaminated sediments. They are exposed through physical contact, ingestion of sediment particles, and uptake of porewater contaminants. This leads to adverse effects on survival, reproduction, and community structure, with sensitive taxa often being replaced by more tolerant species. Benthic invertebrates also play a key role in sediment bioturbation, meaning that their exposure can further influence the mobilization and redistribution of pollutants.

Fish and shellfish

Fish and commercially important shellfish species accumulate contaminants through trophic transfer, as well as direct uptake from water and sediments. Hydrophobic organic compounds such as PAHs and PCBs, together with trace metals, have strong potential for bioaccumulation and, in some cases, biomagnification along the food chain. This poses risks not only to ecosystem integrity but also to human consumers of seafood harvested from or near the port area.

Aquatic ecosystem

At the ecosystem level, contamination can alter biodiversity, modify benthic community composition, and disrupt trophic interactions. Persistent pollutants contribute to long-term ecological stress, reducing resilience to other pressures such as eutrophication, climate variability, and invasive species. Impacts may extend beyond the immediate port basin, as contaminants are dispersed to adjacent coastal and nearshore ecosystems.

Humans

Human exposure occurs through several pathways. Seafood consumption represents the most critical route, particularly in coastal communities where fish and shellfish form an important part of the diet. Occupational exposure is also relevant for port workers, who may inhale contaminated dust generated during ore handling or come into dermal contact with polluted sediments and waters. Additionally, nearby residents may be indirectly exposed through airborne particulates and volatilization of hydrocarbons from port operations.

5.6 Data gaps and uncertainties

- Lack of long-term seasonal monitoring to capture variability in contaminant dynamics.
- Limited data on metal speciation and bioavailability, which are key for ecological risk assessment.
- Absence of ecotoxicological testing on local biota, which would clarify biological effects.

- Insufficient assessment of cumulative and synergistic effects from combined contamination sources.
- Limited quantitative data on atmospheric dust emissions from ore handling.

Table 9. presents the main sources of contamination in the Port of Bar, the mechanisms by which pollutants are released, their environmental pathways, and the potential receptors affected, while the figure 21 illustrates the schematic view of CSM for Port of Bar with relationships between chemical sources, exposure pathways and potential receptors.

Table 9. Relationship between chemical source, exposure pathway and receptors

Source	Release Mechanism	Pathway	Receptor
S1: Ore handling & storage	Dust, spillage, stormwater runoff	Direct deposition, runoff, and airborne dust dispersion	Sediments, benthos, fish, shellfish, humans (via air and seafood)
S2: Petroleum & chemicals	Leakage, spills	Water column → sediment	Sediments, aquatic biota, humans (seafood)
S3: Ship operations	Antifouling paints, bilge water, fuel residues	Leaching, deposition	Sediments, benthos, aquatic ecosystem
S4: Industrial runoff	Drainage of oils, particulates	Runoff → harbor waters	Sediments, benthic fauna, fish
S5: Wastewater discharges	Outfall failures, bypasses	Direct input to basin	Water column, sediments, ecosystem
S6: Legacy contamination	Historic accumulation	Sediment mixing, resuspension	Sediments, benthos, food web

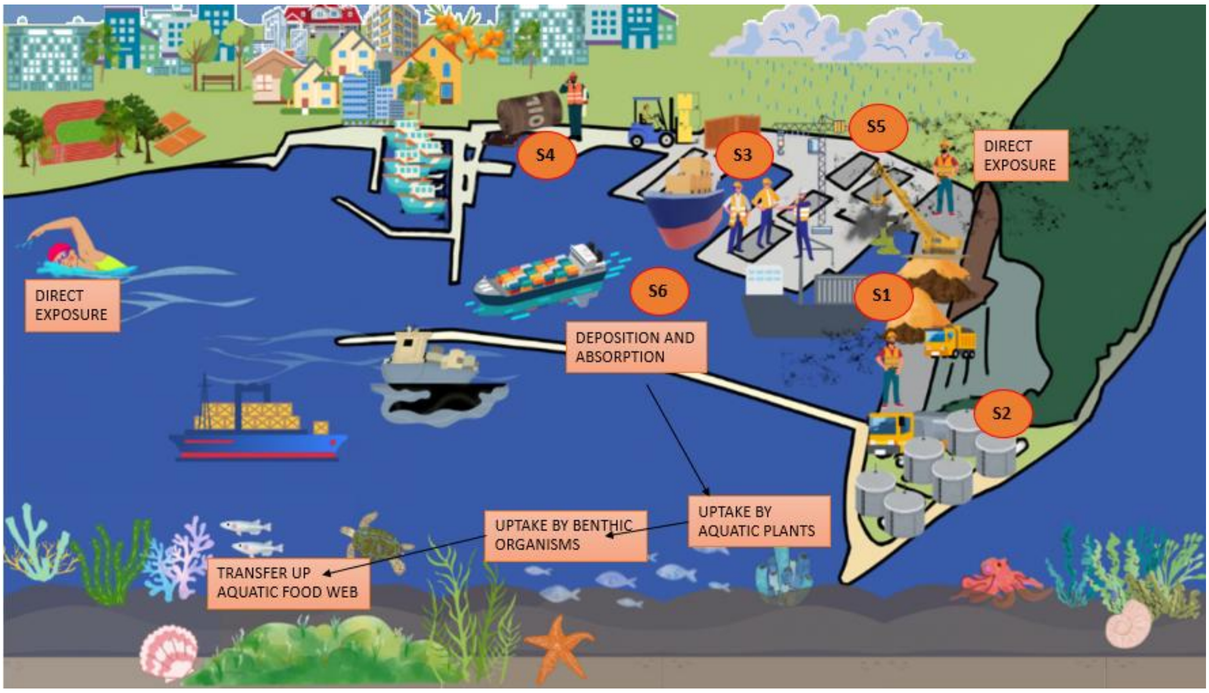


Figure 21. Schematic view of CSM for Port of Bar with relationship between a chemical source, exposure pathway and potential receptor

The Conceptual Site Model (CSM) for the Port of Bar demonstrates a complex contamination scenario driven by multiple sources and interconnected pathways. Among the pollutants of concern, heavy metals, most notably copper, zinc, lead, and arsenic, are the dominant contributors, with clear associations to intensive ore-handling and transshipment activities. Other contaminants, including hydrocarbons, PCBs, PAHs, and TBT, are present at comparatively lower levels, yet their detection reflects both ongoing operational inputs and the legacy of historical activities within the harbour basin.

The fine-grained sediments of the port act as the primary environmental sink, concentrating particle-bound and hydrophobic pollutants. This creates direct exposure risks for benthic communities, with potential for bioaccumulation and biomagnification along the aquatic food web. Fish and shellfish, as key trophic intermediaries, represent critical pathways through which contaminants may ultimately impact human health, particularly via seafood consumption.

In addition to deposition into sediments and aquatic ecosystems, airborne particulate matter (PM) emissions represent a significant pathway for pollutant dispersion during ore handling and transshipment. The emissions were estimated using activity-specific emission factors, which account for all handling and transfer processes. For bauxite, the emission factor is 0.6 kg per tonne of ore, while for all other minerals, including copper concentrates, it is 0.06 kg per tonne of ore.

Based on the quantities of ore handled at the Port of Bar, PM emissions from bauxite have been substantially higher than those from copper concentrates, reflecting both the volume of material transshipped and the higher emission factor. For example, in 2020, bauxite handling produced 431,524 kg of PM, while copper concentrate emissions reached 3,021 kg, increasing to 45,358 kg by 2023 due to rising throughput. These results highlight the importance of dust mitigation measures, including improved storage, enclosed conveyors, and continuous air quality monitoring, to reduce environmental and human health impacts.

6. Criteria for risk assessment

The assessment of environmental contamination stands as a basis in understanding the interplay between natural ecosystems and anthropogenic activities. In aquatic systems, sediments function not only as physical substrates but also as long-term repositories of various pollutants. These sediments accumulate contaminants from multiple origins like industry, maritime traffic, port activities including industrial effluents, agricultural runoff, urban discharges, and atmospheric deposition. Over time, this accumulation results in a complex mixture of substances that mirror both the historical and current state of environmental quality. Consequently, the study of sediments has become a vital approach in environmental monitoring, as they provide critical insights into the persistence, mobility, and potential ecological impacts of hazardous substances.

Pollutants embedded in sediments, such as heavy metals, persistent organic pollutants (POPs), and hydrocarbons, can pose serious risks to aquatic organisms and, by extension, to human health through bioaccumulation and trophic transfer. The intricate dynamics between sediments and the overlying water column highlight the dual role sediments play: while they act as sinks for contaminants, under changing physicochemical conditions they may also act as secondary sources, releasing pollutants back into the aquatic environment. This duality demonstrates the importance of continuous and methodical assessment of sediment contamination to better predict ecological consequences and support sustainable environmental management.

To adequately evaluate these risks, structured methodologies such as ecological risk assessment (ERA) are applied. ERA provides a scientific framework for identifying, characterizing, and prioritizing ecological hazards, thereby guiding regulatory decision-making and remediation planning. Within this framework, sediment quality guidelines (SQGs) represent reference tools for screening-level evaluations. By comparing measured concentrations of contaminants in sediments against established threshold values, SQGs enable a transparent and consistent appraisal of potential toxic effects. The application of these guidelines within a tiered assessment strategy ensures that the evaluation is both comprehensive and efficient, allowing for the identification of contamination hotspots, the estimation of potential risks to benthic and aquatic organisms, and the establishment of clear decision criteria for further investigative or corrective actions.

Tier 1 sediment risk assessment represents the preliminary step in evaluating potential contamination risks in sediments. This initial screening provides a rapid and systematic evaluation using predefined decision criteria to identify whether any contaminants may pose a risk. Typically, this assessment involves comparing sediment chemical data against established sediment quality guidelines (SQGs). The goal is to highlight areas of concern and prioritize them according to how frequently and to what extent the SQGs are exceeded, enabling targeted follow-up assessments where potential risks are identified.

In the present study, the French and Dutch regulatory framework were selected for evaluating sediment quality in the Port of Bar.

6.1 French regulatory framework

The choice of the French regulatory framework is justified by the ecological, geographical, and socio-economic similarities between Montenegro and France. Both countries are Mediterranean, with coastlines that are heavily utilized for tourism, maritime trade, fisheries, and aquaculture. These shared pressures create comparable risks of sediment contamination, making the French model a suitable and robust framework for application in the Montenegrin context. In addition, France has a long tradition of regulating and managing contaminated sediments, and its criteria are widely recognized as among the most comprehensive in Europe. By adopting this framework, the current study aligns Montenegro with best practices in sediment assessment and provides results that are directly comparable to international standards.

The Port of Bar, as the country's main commercial seaport, experiences continuous maritime traffic, ship maintenance, and cargo handling. These activities create pathways for contaminants to accumulate in sediments over time. Although Montenegro does not yet have its own national legislation for dredged sediment management, the application of the French standard provides a scientifically robust and internationally recognized method for assessing sediment quality. Moreover, it creates a benchmark against which future national guidelines may be developed, ensuring harmonization with broader European environmental policy.

The adoption of French sediment quality guidelines in this study also reflects the practical need for regional comparability. Ports across the Mediterranean face similar challenges, and the use of a shared framework enhances the ability to compare datasets and develop cooperative management strategies. By situating Montenegrin sediment assessments within this context, the study contributes to a larger body of knowledge on Mediterranean sediment contamination and supports efforts toward coordinated regional environmental governance.

The application of French SQGs to the Port of Bar sediments ensures that the evaluation is both scientifically rigorous and policy-relevant. The results provide not only an assessment of current contamination levels but also information for decision-makers tasked with balancing economic activity, environmental protection, and public health.

The evaluation of sediment quality in France is governed by a comprehensive regulatory framework that combines ecological guideline levels with legally binding thresholds. The foundation of this framework was established by the "Arrêté du 30/06/20 modifiant l'arrêté du 9 août 2006 relatif aux niveaux à prendre en compte lors d'une analyse de rejets dans les eaux de surface ou de sédiments marins, estuariens ou extraits de cours d'eau ou canaux relevant respectivement des rubriques 2.2.3.0, 3.2.1.0 et 4.1.3.0 de la nomenclature annexée à l'article R. 214-1 du code de l'environnement" (JO n° 162 du 2 juillet 2020). This decree sets the reference levels known as N1 and N2, which serve as benchmarks in ecological risk assessment.

These thresholds N1 and N2 are defined for a set of priority contaminants including trace metals, polychlorinated biphenyls (PCBs), tributyltin (TBT), and polycyclic aromatic hydrocarbons (PAHs). For metals, the regulated elements are arsenic (As), cadmium (Cd), copper (Cu), nickel (Ni), lead (Pb), zinc (Zn), mercury (Hg), and chromium (Cr). For PAHs, the guidelines consider a 16 specific compounds: naphthalene, acenaphthylene, acenaphthene, fluorene, phenanthrene, anthracene, fluoranthene, pyrene, benzo (a) anthracene, chrysene, benzo (b) fluoranthene, benzo (k) fluoranthene, benzo (a) pyrene, indeno (123-cd) pyrene, dibenzo (a,h) anthracene and benzo (g,h,i) perylene, while PCBs are assessed for seven indicator congeners (PCB-28, PCB-52, PCB-101, PCB-118, PCB-138, PCB-153, and PCB-180). TBT is considered separately given its strong toxicological relevance and historical importance as an antifouling agent.

Under this system, sediments with contaminant concentrations below the N1 level are considered to pose negligible risk and may be disposed of at sea without restrictions. Concentrations between N1 and N2 indicate potential concern, requiring additional ecotoxicological testing before immersion or reuse is permitted. Sediments exceeding the N2 level are classified as contaminated and are generally excluded from offshore disposal, requiring land-based or otherwise restricted management solutions.

A significant update was introduced by the "Arrêté du 27/03/24 fixant les prescriptions générales applicables aux dragages ou aux rejets y afférent relevant de la rubrique 4.1.3.0 de la nomenclature annexée à l'article R. 214-1 du code de l'environnement en application des articles L. 214-1 à L. 214-3" (JO n°83 du 9 avril 2024). This decree defines general requirements for dredging operations and related discharges and, for the first time, establishes immersion prohibition thresholds. These thresholds apply to a wide range of contaminants (metals, PAHs, PCBs, TBT), and their exceedance results in an automatic legal ban on offshore disposal.

Together, these two regulatory instruments provide a dual framework: N1 and N2 levels remain the reference for ecological evaluation, while the 2024 prohibition thresholds act as absolute legal limits. This approach ensures that sediments are evaluated not only for their ecological impact but also against internationally recognized guideline values, providing a structured and science-based framework for informed sediment management decisions.

The three threshold levels for the above-listed contaminants are presented in Table 10.

Table 10. List of contaminants and selected French SQGs

Parameters	**N1**	**N2**	**Immersion prohibition threshold**
Metals (mg/kg dry wt.)			
Hg	0.4	0.8	1.2
As	25	50	100
Cd	1.2	2.4	10
Cr	90	180	370
Cu	45	90	368
Pb	100	200	500
Ni	37	74	140
Zn	276	552	600
Polychlorinated biphenyls (µg/kg dry wt.)			
PCB 28	5	10	13
PCB 52	5	10	13
PCB 101	10	20	26
PCB 118	10	20	26
PCB 138	20	40	53
PCB 153	20	40	53
PCB 180	10	20	26

Polycyclic aromatic hydrocarbons (µg/kg dry wt.)			
Naphthalene	160	1130	1590
Acenaphthene	15	260	370
Acenaphthylene	40	340	480
Fluorene	20	280	390
Anthracene	85	590	830
Phenanthrene	240	870	1230
Fluoranthene	600	2850	4020
Pyrene	500	1500	2120
Benzo [a] anthracene	260	930	1310
Chrysene	380	1590	2240
Benzo [b] fluoranthene	400	900	1270
Benzo [k] fluoranthene	200	400	560
Benzo [a] pyrene	430	1015	1430
Di benzo [a, h] anthracene	60	160	230
Benzo [g, h, i] perylene	1700	5650	7970
Indeno [1,2,3-cd] pyrene	1700	5650	7970
Organotin compounds (µg/kg dry wt.)			
TBT	100	400	400

Sediments typically contain complex mixtures of contaminants, which can interact and produce combined effects on aquatic organisms even when individual compounds are present at concentrations below their respective thresholds. To account for these cumulative or additive effects and to provide a more realistic assessment of ecological pressure, two indicators based on French methodology, ΣQN1 and QPECm, were applied to quantify potential sediment toxicity. The ΣQN1 index sums the ratios of individual contaminant concentrations to their corresponding French N1 thresholds, offering an overall measure of pollutant pressure. QPECm is derived by averaging these ratios across all measured contaminants, reflecting the general sediment risk. Values of QPECm below 1 indicate contaminant levels within regulatory limits and suggest non-toxic conditions, whereas values above 1 highlight potential ecological risks. This approach enables identification of areas where the combined effects of multiple contaminants may pose a risk, thereby guiding further site-specific investigations and management actions.

6.2 Dutch regulatory framework

In addition to the French Sediment Quality Guidelines, the Dutch Guidance Document for Sediment Assessment was applied to support the decision-making process in evaluating sediment quality in the Port of Bar. The rationale for using the Dutch system lies in its well-established, internationally recognized framework for soil and sediment quality management, which provides explicit threshold values for a wide range of contaminants, including heavy metals, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and tributyltin (TBT). The Dutch standard for soil and sediment quality establishes an upper threshold, referred to as the Intervention Value, which designates the point at which remediation measures are required. Exceedance of the intervention values indicates that the integrity of the aquatic ecosystem is seriously impaired or at risk. Contaminant levels above this threshold are considered to constitute a serious case of sediment pollution. The advantage of adopting the Dutch standard in this assessment is its comprehensive and risk-based approach, which not only distinguishes between background and polluted conditions but also establishes a clear threshold for defining serious contamination cases. This is particularly relevant in harbour environments, where sediments act as long-term sinks for both metal and organic contaminants. The concentration heavy metals, PAHs, PCBs and TBT is compared to the intervention levels, which are published in the Dutch 'Staatscourant' of 8 April 2009, as part of the Dutch 'Amendment of the Circular concerning the remediation of sediments 2008' (table 11).

Table 11. Intervention values for sediment

Substance (group)	Intervention value sediment (mg/kg d.w.)
Metals	
antimony (Sb)	**15**
arsenic (As)	**85**
cadmium (Cd)	**14**
chrome (Cr)	**380**
cobalt (Co)	**240**
copper (Cu)	**190**
mercury (Hg)	**10**
lead (Pb)	**580**
molybdenum (Mo)	**200**
nickel (Ni)	**210**
zinc (Zn)	**2000**
Polycyclic aromatic hydrocarbons (PAHs)	
PAHs total (sum of 10)	**40**
Polychlorinated biphenyls	
PCBs (sum 7)	**1**
Organochlorine pesticides	
chlordane (sum)	**4**
DDT/DDE/DDD (sum)	**4**
drins (sum)	**4**
α-endosulfan	**4**
HCH-compounds (sum)	**2**
heptachlor	**4**
heptachlor epoxide (sum)	**4**
Organotin compounds (sum)	**2.5**
Mineral oil	**5000**

In sediment quality assessment according to these guidelines, the reference values provided for a standard soil/sediment must be adjusted to reflect the specific characteristics of the sediment under investigation. This adjustment is carried out using the measured content of organic matter and clay in the sample. The resulting corrected values represent the appropriate threshold concentrations for the given sediment type and are then used as the basis for comparison with the measured contaminant concentrations.

7. Results of analysis and data interpretation

The results of analysis of sediment samples in Port of Bar are presented in table in Annex 1. Data interpretation was done against the French sediment quality guidelines and Dutch Guidance document for sediment assessment.

7.1 Results interpretation according to French sediment quality guidelines

7.1.1 Metals

Cadmium

Figure 22 shows cadmium concentrations in the analysed sediment samples, compared with the French sediment quality guidelines.

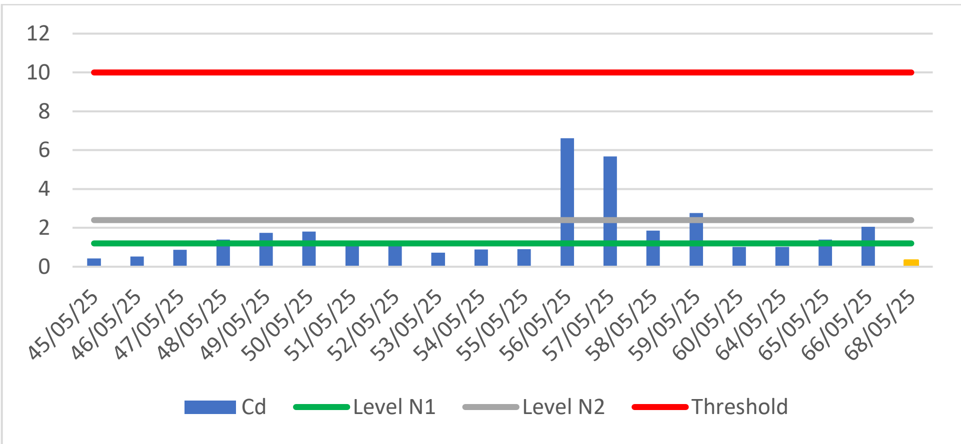


Figure 22. Cadmium concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Cadmium concentrations ranged from 0.24 mg/kg to 6.6 mg/kg. The N1 threshold (1.2 mg/kg) was exceeded in more than half of the samples, while three samples showed concentrations above the N2 threshold (2.4 mg/kg).
The highest value was recorded in sample 56/05 (6.6 mg/kg), which is significantly elevated and is linked to anthropogenic inputs such as the handling and storage of ore concentrates, intensive port operations, all of which are known to contribute to localized heavy metal accumulation in sediments. The widespread exceedance of N1 suggests a broad distribution of Cd pollution, while localized peaks point to potential point-source discharges.

In addition to the N1 and N2 framework, the recently adopted French Order of 27 March 2024 establishes absolute prohibition thresholds for sediment immersion. For cadmium, this value is set at 10 mg/kg. All measured cadmium concentrations in the Port of Bar sediments remain below this French regulatory value.

Lead

Lead concentrations in the sediment samples exhibited significant spatial variability (Figure 23). At the reference location, the concentration was 25 mg/kg, representing baseline conditions with minimal anthropogenic influence. In contrast, within the port area, lead concentrations ranged from 55 mg/kg to as high as 580 mg/kg.

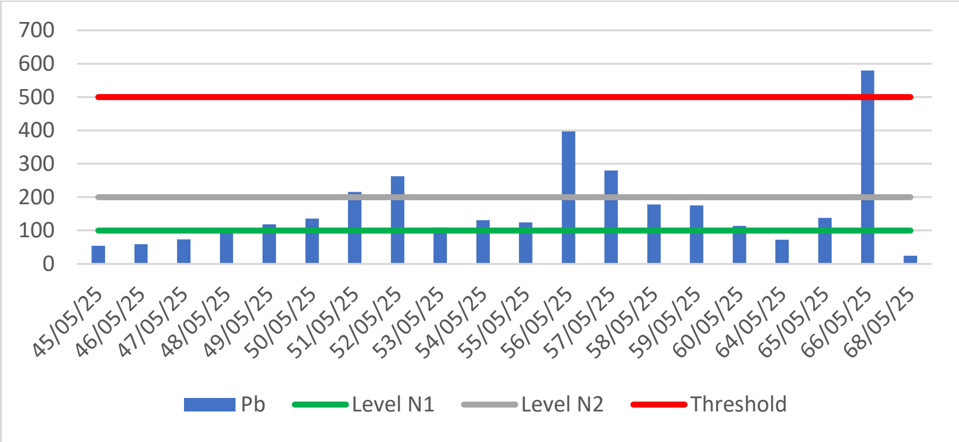


Figure 23. Lead concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Exceedance of the N2 threshold (200 mg/kg) was observed in five samples, pointing to potential point-source pollution within the port area. The highest values are recorded in samples 66/05 and 56/05, suggesting localized hotspots, linked to port-related activities such as the handling and storage of ore concentrates. Lead's strong affinity for fine particles and organic matter suggests potential for long-term accumulation in sediment, raising concerns about its remobilization under changing environmental conditions. Regarding the updated French legal framework, the Order of 27 March 2024 specifies an immersion prohibition threshold of 500 mg/kg for lead. While most samples remain below this regulatory limit, one station (66/05) exceeded the 500 mg/kg limit, meaning that offshore disposal of sediments from this location would be legally prohibited under the decree.

Arsenic

Figure 24 shows the arsenic concentrations in the analysed samples, compared with the French sediment quality guidelines.

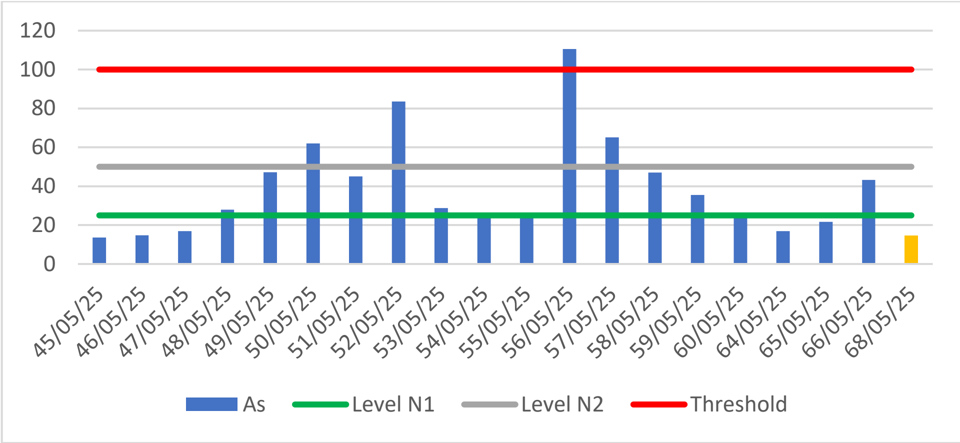


Figure 24. Arsenic concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Arsenic concentrations in the analysed samples (excluding reference location) ranged from 13.6 mg/kg to 216 mg/kg. Half of analysed samples exceeded the N1 threshold of 25 mg/kg, and four also surpassed the N2 threshold of 50 mg/kg. The highest values are recorded in samples 56/05 and 52/05, indicating potential hotspots of arsenic contamination. Arsenic is commonly associated with mining activities. Its occurrence in toxic inorganic forms such as arsenite (As^{3+}) or arsenate (As^{5+}) may pose significant risks to benthic organisms and contribute to bioaccumulation within the aquatic food web.

Under the provisions of the Order of 27 March 2024, an immersion prohibition threshold of 100 mg/kg is established for arsenic. Although most samples fall below this limit, station 56/05 exceeded the threshold, which would render offshore disposal from this location legally prohibited as of 1 January 2025.

Copper

Figure 25 graphically shows copper concentrations by sampling location, compared with the Level N1, N2 and thresholds immersion values, highlighting the significant contamination within the port area.

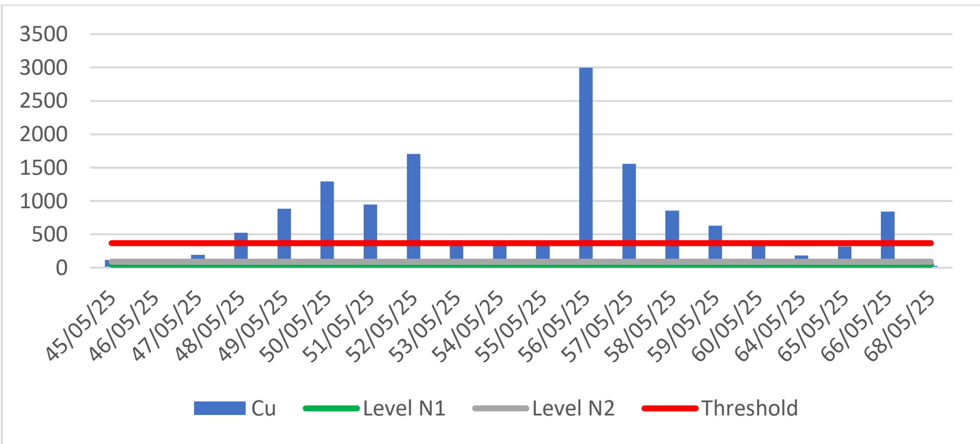


Figure 25. Copper concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Copper concentrations are exceptionally high across all samples collected within the port area. The maximum value reaches 2997 mg/kg (sample 56/05), which is over 60 times higher than the N2 threshold (90 mg/kg). All samples from the port exceed both Level N1 (45 mg/kg) and Level N2 thresholds, indicating extreme copper enrichment of the sediments. This is strongly associated with the transshipment of copper ore concentrates within the port, which resulted in significant deposition of copper-rich particulates in the sediment. In contrast, reference sample collected outside the port boundaries shows substantially lower copper concentrations, below to the N1 threshold. This sharp difference highlights the port activities as a primary source of copper contamination in the area.

The French Order of 27 March 2024 further reinforces these findings by establishing an immersion prohibition threshold of 368 mg/kg for copper. Most of analysed sample from the port substantially exceeded this regulatory limit, with maximum concentrations nearly eight times higher than the legal cut-off. Consequently, offshore disposal of copper-contaminated sediments from the port would be strictly prohibited under the new French regulatory framework from 1 January 2025, regardless of any supplementary testing. This places copper among the most critical contaminants for the Port of Bar.

Nickel

Nickel levels ranged from 72 mg/kg to 121 mg/kg, consistently exceeding the Level N2 threshold (74 mg/kg) in all samples, including the samples from reference location (Figure 26).

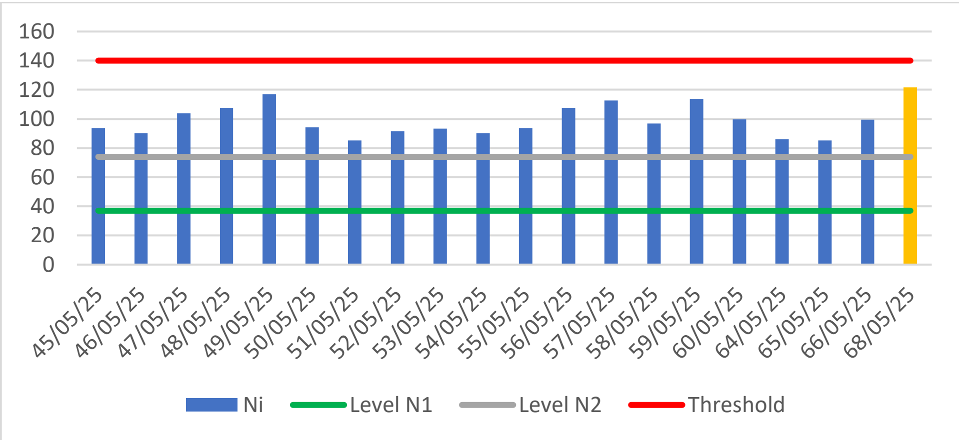


Figure 26. Nickel concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

The highest concentration was recorded at sample 68/05. Given the relatively uniform distribution of nickel across the study area, including outside the port zone, it is therefore assumed that the sediments are naturally enriched in this element which is later proved through additional comparisons with other methodology, like sequential analysis and enrichment factor calculations.

According to the Order of 27 March 2024, the immersion prohibition threshold for nickel is 140 mg/kg. All recorded concentrations from the Port of Bar fall below this regulatory cut-off. Nevertheless, the systematic exceedance of both N1 and N2 values highlights potential ecological risks, underlining the need for careful monitoring.

Chromium

Figure 27 graphically shows chromium concentrations by sampling location, compared with the Level N1, N2 and thresholds immersion values.

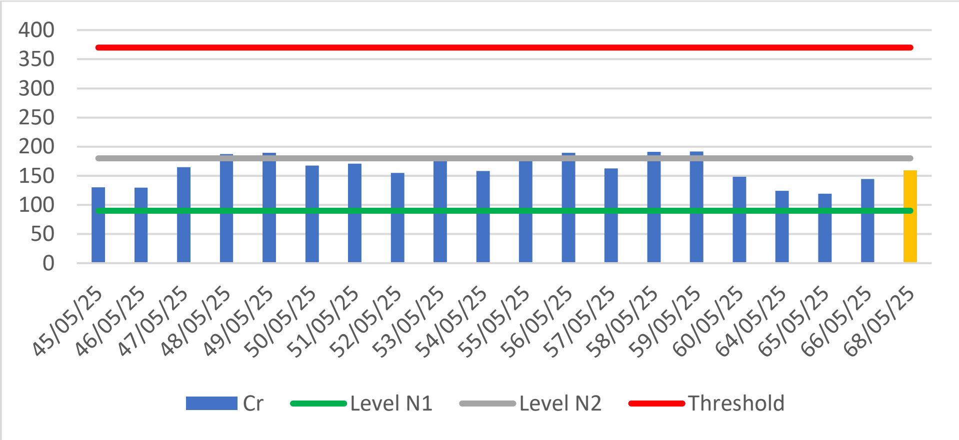


Figure 27. Chromium concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

All samples showed chromium concentrations above the N1 threshold (90 mg/kg), including those from reference (non-port) location, suggesting that the background level of Cr in sediments from this area may be naturally elevated. However, five samples exceeded the N2 threshold (180 mg/kg), with the maximum value reaching 192 mg/kg (sample 59/05). These pronounced peaks, observed exclusively within the port area, indicate anthropogenic influence and altered sediment conditions, linked to maritime activities.

According to the Order of 27 March 2024, the immersion prohibition threshold for chromium is set at 370 mg/kg**.** All measured concentrations in the Port of Bar sediments are well below this limit. However, the consistent exceedance of the N1 guideline and the occurrence of several values above the N2 threshold demonstrate that chromium represents a contaminant of concern. These findings suggest a dual origin: a natural geochemical background that appears elevated in this region, combined with additional inputs associated with port-related activities. Differentiating between these geogenic contributions and anthropogenic sources is therefore essential for accurate risk assessment and management planning.

Zinc

Zinc concentrations in the analysed samples ranged from 84 mg/kg (reference site) to a maximum of 1371 mg/kg (sample 56/05). A graphical presentation of zinc concentrations in relation to Level N1, N2 and thresholds immersion values is shown in Figure 28. The N1 threshold (276 mg/kg) was exceeded in 11 out of 19 port samples, while 5 samples also surpassed the more stringent N2 threshold (552 mg/kg), indicating zones of severe contamination.

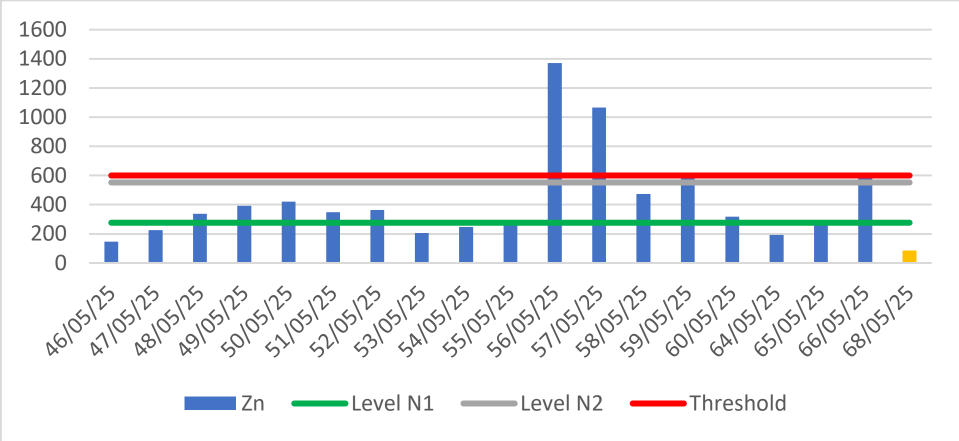


Figure 28. Zinc concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

These elevated concentrations are linked to ore concentrate handling, industrial runoff, ship maintenance, or storage activities within the harbour. The significant gap between reference and port samples strongly suggests that sediments in the port area are altered and impacted by human activity, particularly related to bulk cargo operations.

The Order of 27 March 2024 establishes an immersion prohibition threshold of 600 mg/kg for zinc. Several samples exceeded this limit, with the most extreme case (56/05) reaching more than twice the French legal cut-off. This means that, the offshore disposal of sediments from these stations would be strictly prohibited. The coexistence of widespread N1/N2 exceedances and multiple values above the 2024 threshold confirms zinc as one of the key pollutants of concern in the Port of Bar.

Mercury

Figure 29 provides a graphical representation of mercury levels across all sampling sites, compared with the regulatory thresholds (N1, N2, and immersion threshold values).

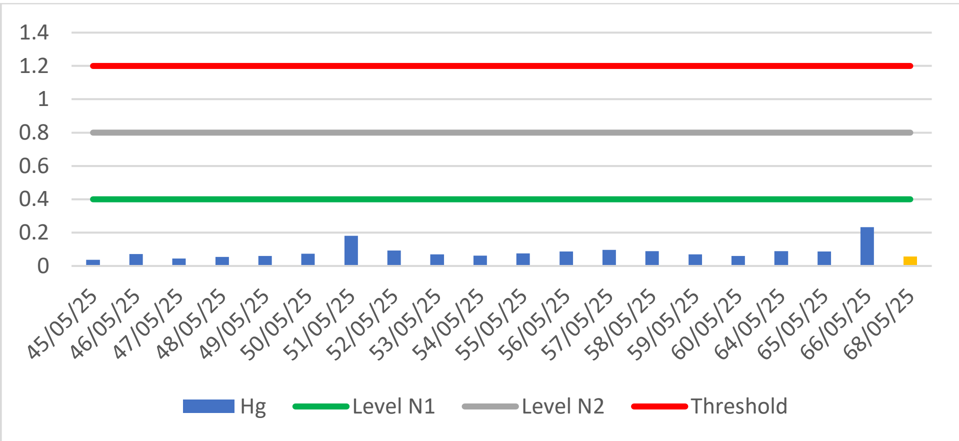


Figure 29. Mercury concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Mercury concentrations are consistently low across all samples, ranging from 0.037 mg/kg to a maximum of 0.23 mg/kg (sample 66/05), well below both the N1 (0.4 mg/kg) and N2 (0.8 mg/kg) thresholds. These values indicate an absence of significant Hg contamination in the study area. Similar levels are observed at both port and reference sites, suggesting no substantial local input of mercury from port-related operations.

In line with the Order of 27 March 2024, the immersion prohibition threshold for mercury is set at 1.2 mg/kg. All measured concentrations in the Port of Bar sediments are considerably below this legal cut-off. Taken together, the consistently low levels across all sites further support the conclusion that mercury is not a contaminant of concern in this area.

7.1.2 Polychlorinated biphenyls

PCB-28

Figure 30 show a graphic review of the concentrations of PCB 28 in the sediment samples sampled at the Port of Bar site in relation to the French values of sediment quality guidelines.

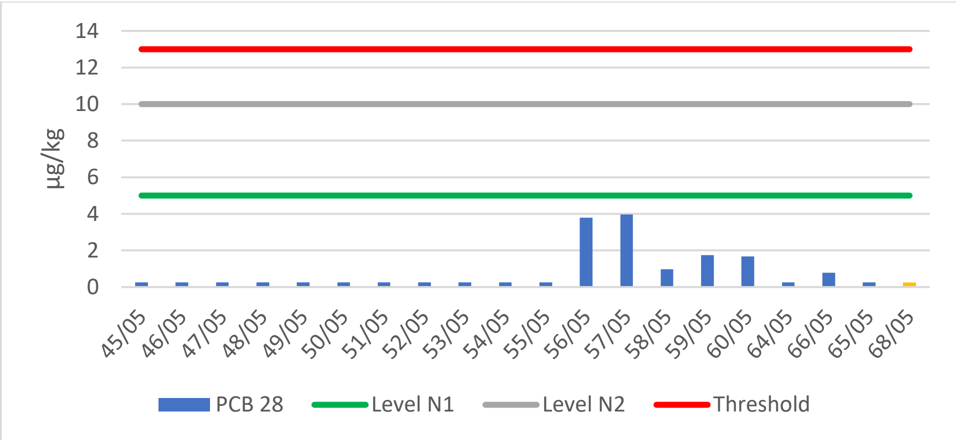


Figure 30. PCB 28 concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Concentration of PCB 28 across all zones of the Port of Bar remain consistently low and do not exceed the French N1 threshold of 5 µg/kg. The dataset shows stable values without notable variation between zones, and no exceedances of regulatory criteria are recorded. PCB 28 therefore does not contribute to sediment management restrictions and is not a parameter of concern in the context of this assessment.

PCB-52

Figure 31 show a graphic review of the concentrations of PCB 52 in the sediment samples sampled at the Port of Bar site in relation to the French values of sediment quality guidelines.

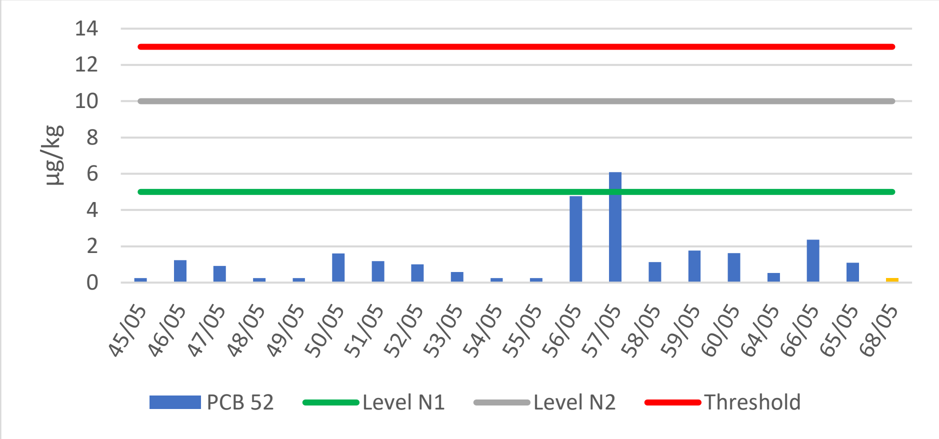


Figure 31. PCB 52 concentration by sampling location
in relation to Level N1, N2 and thresholds immersion values

The results of the analysis indicate that PCB 52 was measured at generally low levels throughout the port, with most zones in the range of concentrations below the N1 limit of 5 µg/kg. One zone recorded value slightly above N1 but below the N2 threshold of 10 µg/kg. These findings indicate that while minor exceedances occur, they are not widespread or severe. In accordance with French regulations, zones where concentrations exceed N1 require additional attention, but PCB 52 does not emerge as a dominant contaminant in the port.

PCB-101

Figure 32 shows a graphical representation of PCB 101 concentrations in the sediment samples collected at the Port of Bar, compared with the French sediment quality guideline values.

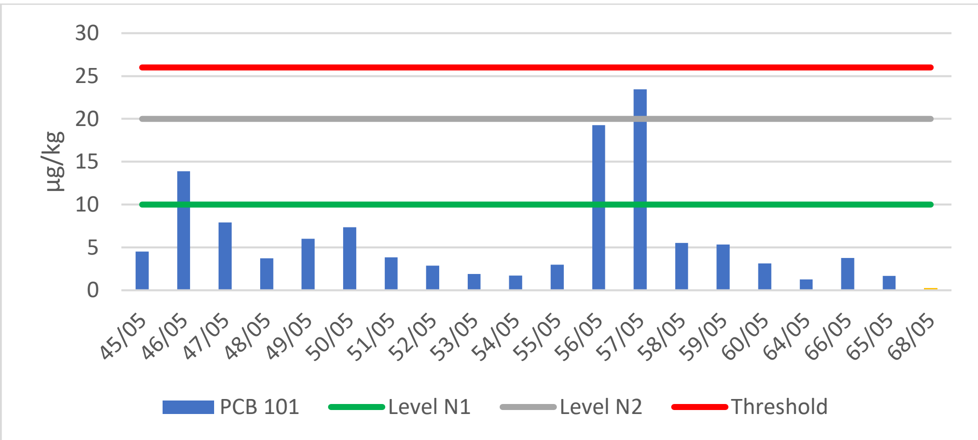


Figure 32. PCB 101 concentration by sampling location
in relation to Level N1, N2 and thresholds immersion values

PCB 101 shows higher variability compared to PCB 28 and PCB 52, with several zones presenting concentrations above the French N1 level of 10 µg/kg. Concentration in one

zone, 57/05 exceeds the N2 threshold of 20 µg/kg. The exceedances demonstrate that PCB 101 is one of the more critical PCB congeners in the dataset, and sediments from zones with elevated concentrations must be managed under stricter conditions.
Under the provisions of the Order of 27 March 2024, the immersion prohibition threshold for PCB-101 is 26 µg/kg. The highest concentration observed in the dataset, recorded at station 57/05, was elevated but still below this French regulatory value.

PCB-118

Figure 33 shows a graphical representation of PCB 118 concentrations in the sediment samples collected at the Port of Bar, compared with the French sediment quality guideline values.

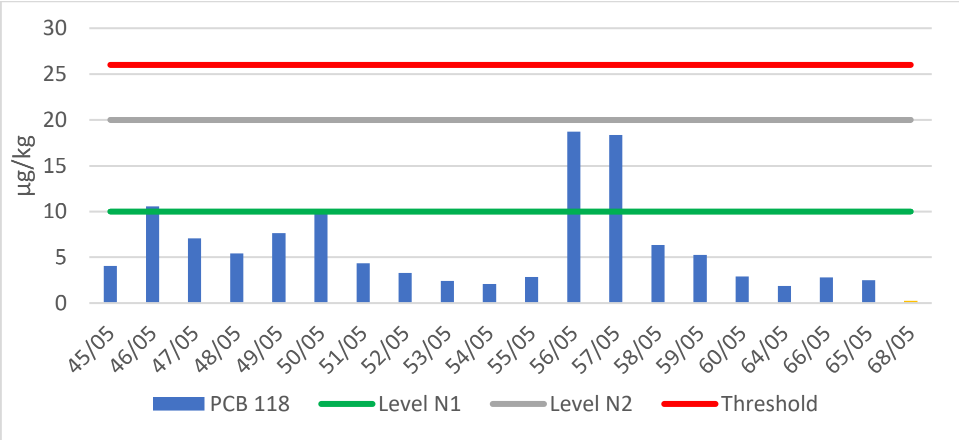


Figure 33. PCB 118 concentration by sampling location
in relation to Level N1, N2 and thresholds immersion values

Concentrations of PCB 118 shows exceedances of N1 10 µg/kg, at several zones. None of the values surpass the N2 criterion of 20 µg/kg, which indicates moderate but not extreme contamination. These results identify PCB 118 as a contaminant of interest requiring closer examination, particularly in zones where levels exceed N1. While it does not dominate the contamination profile, its presence above threshold values has implications for sediment management.

PCB-138

Figure 34 shows a graphical representation of PCB 138 concentrations in the sediment samples collected at the Port of Bar, compared with the French sediment quality guideline values.

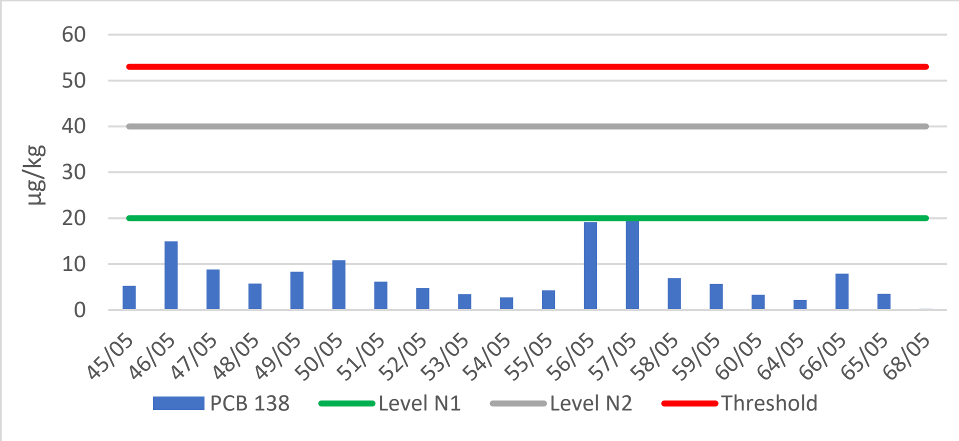


Figure 34. PCB 138 concentration by sampling location
in relation to Level N1, N2 and thresholds immersion values

The measured values of PCB 138 are consistently low across all zones, remaining below the N1 limit of 20 µg/kg. No exceedances are observed, and the results confirm that this congener is not present at concentrations that would influence sediment classification or management strategies.

PCB-153

Figure 35 shows a graphical representation of PCB 153 concentrations in the sediment samples collected at the Port of Bar, compared with the French sediment quality guideline values.

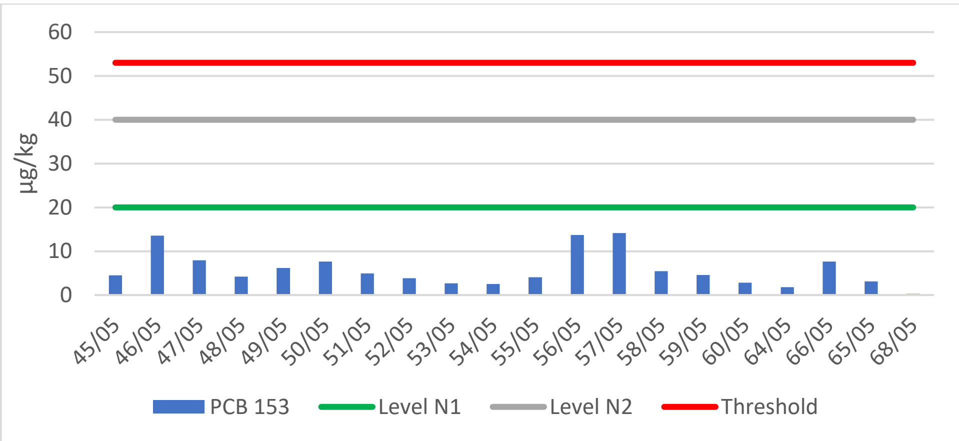


Figure 35. PCB 153 concentration by sampling location
in relation to Level N1, N2 and thresholds immersion values

PCB 153 follows the same pattern as PCB 138, with concentrations in all stations remaining below the French N1 limit. The absence of elevated values demonstrates that PCB 153 is not a parameter of concern in the studied area.

PCB-180

Figure 36 shows a graphical representation of PCB 180 concentrations in the sediment samples collected at the Port of Bar, compared with the French sediment quality guideline values.

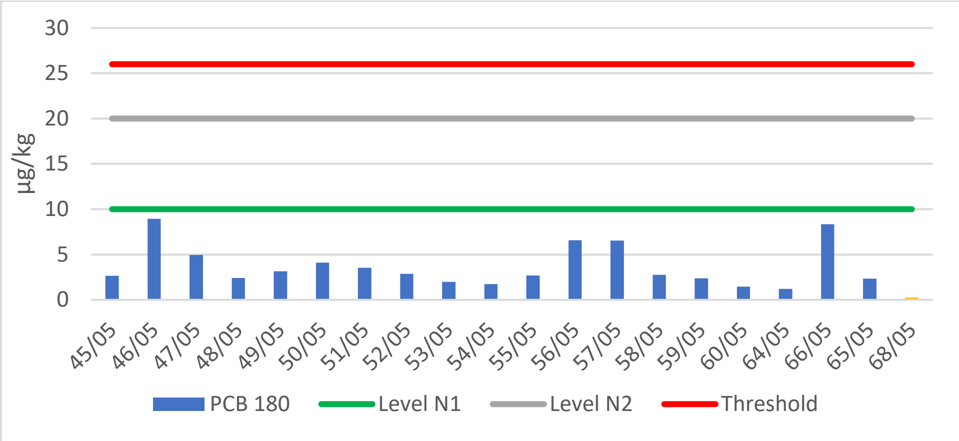


Figure 36. PCB 180 concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Concentrations of PCB-180 are uniformly low and consistently below the N1 threshold of 10 µg/kg across all zones. This congener does not show signs of accumulation in the sediments and does not represent a limitation under French sediment management guidelines.

Regarding the updated legal framework, the Order of 27 March 2024 specifies an immersion prohibition threshold of 26 µg/kg for PCB-180. The maximum concentrations detected in the Port of Bar are several-fold lower than this cut-off, confirming that PCB-180 does not represent a regulatory obstacle for offshore disposal. Overall, PCB-180 can be considered negligible in the contamination profile of the port, both from an ecological and French legal perspective.

7.1.3 Polycyclic Aromatic Hydrocarbons

Naphthalene

Figure 37 shows a graphical representation of naphthalene concentrations in the sediment samples collected at the Port of Bar, compared with the French sediment quality guideline values.

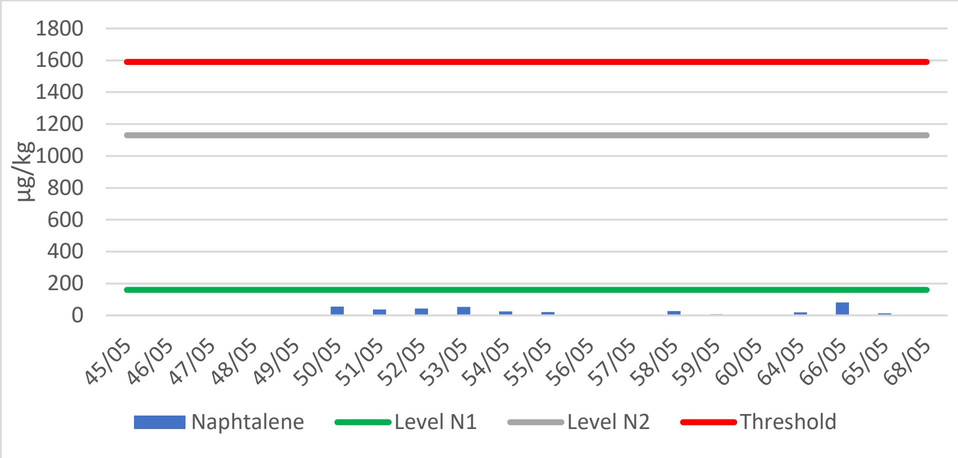


Figure 37. Naphthalene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Acenaphthylene

Figure 38 shows a graphic representation of the concentrations of acenaphthylene in the sediment samples sampled at the Port of Bar compared with the French sediment quality guideline values.

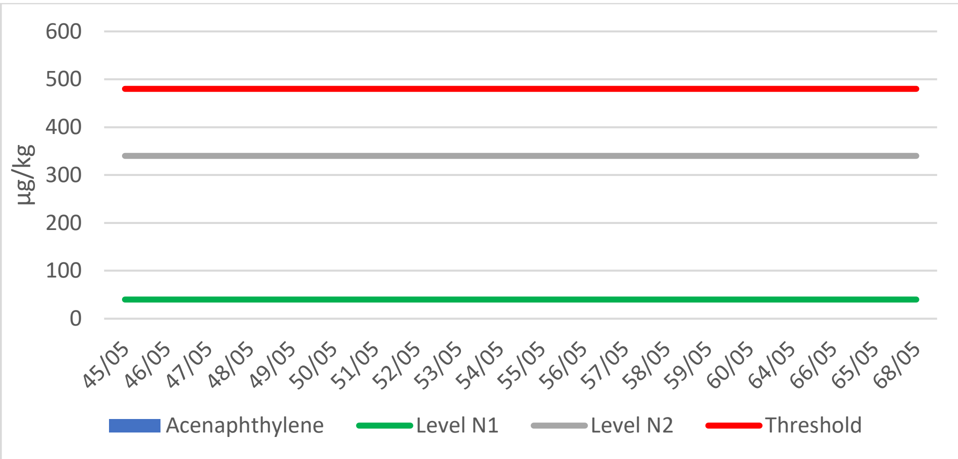


Figure 38. Acenaphthylene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

The measured concentrations of acenaphthylene are below of the limit of quantification in almost all sampling zones, and consequently below the N1 criterion of 40 µg/kg.

Acenaphthene

Figure 39 shows a graphic representation of the concentrations of acenaphthene in the sediment samples sampled at the Port of Bar compared with the French sediment quality guideline values.

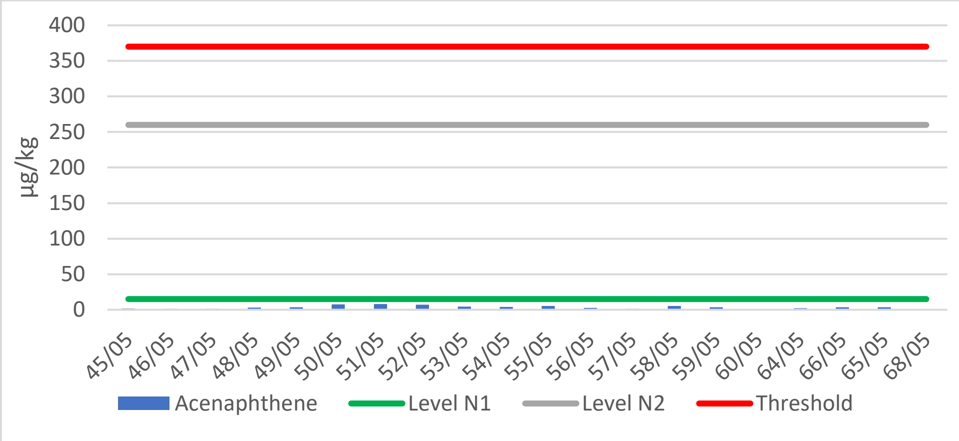


Figure 39. Acenaphthene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

The measured concentrations of acenaphthene are below of the N1 level of 15 µg/kg in all zones.

Fluorene

Figure 40 shows a graphic review of the concentrations of fluorene in the sediment samples at the Port of Bar compared with the French sediment quality guideline values.

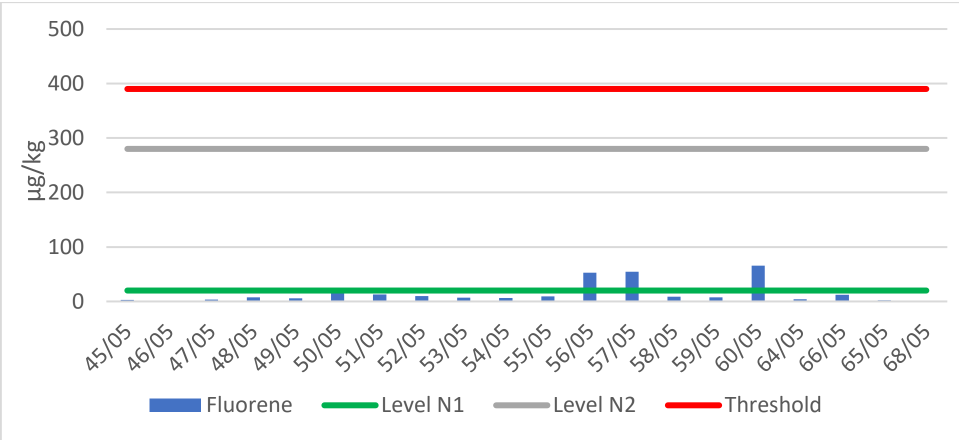


Figure 40. Fluorene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Fluorene is the only PAH in this dataset showing exceedances of the French N1 threshold. Most zones present values below 20 µg/kg, however, three zones—56/05, 57/05, and 60/05 has concentrations in the range of 53–66 µg/kg. These values fall between N1 (20 µg/kg) and N2 (280 µg/kg). This means that while the majority of the port area does not present any concern for this parameter, these three zones can be under additional attention. Thus, fluorene defines localized areas of moderate contamination, while the wider port environment remains unaffected.

The Order of 27 March 2024 defines an immersion prohibition threshold of 390 µg/kg for fluorene. All measured concentrations in the Port of Bar sediments are substantially below this cut-off, meaning offshore disposal would not be restricted under the updated framework.

Phenanthrene

Figure 41 shows a graphic review of the concentrations of phenanthrene in the sediment samples sampled at the Port of Bar compared with the French sediment quality guideline values.

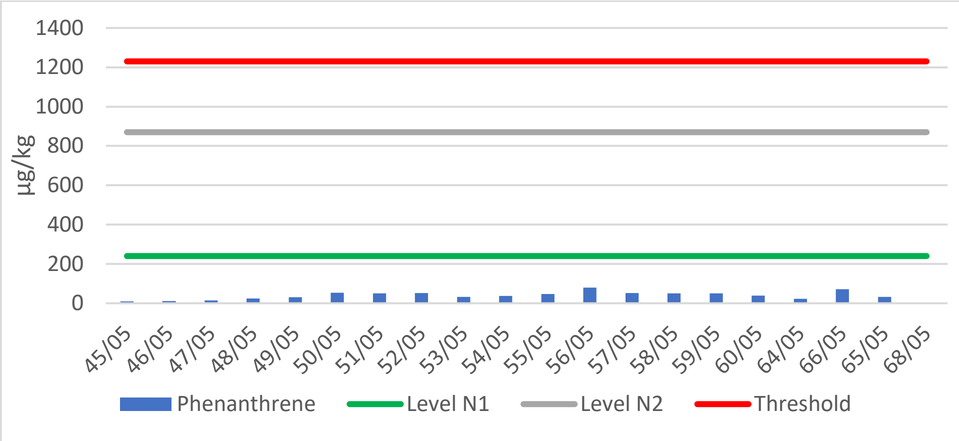


Figure 41. Phenanthrene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Phenanthrene concentrations are consistently low across all investigated zones and remain well below the French N1 threshold of 240 µg/kg. No exceedances are recorded in any station. The results indicate stable background levels without any zones showing signs of elevated accumulation. The absence of elevated levels suggests that phenanthrene is present only at background concentrations, without indications of localized accumulation or anthropogenic hotspots.

Anthracene

Figure 42 shows a graphic review of the concentrations of anthracene in the sediment samples sampled at the Port of Bar site in relation to the French values of sediment quality guidelines.

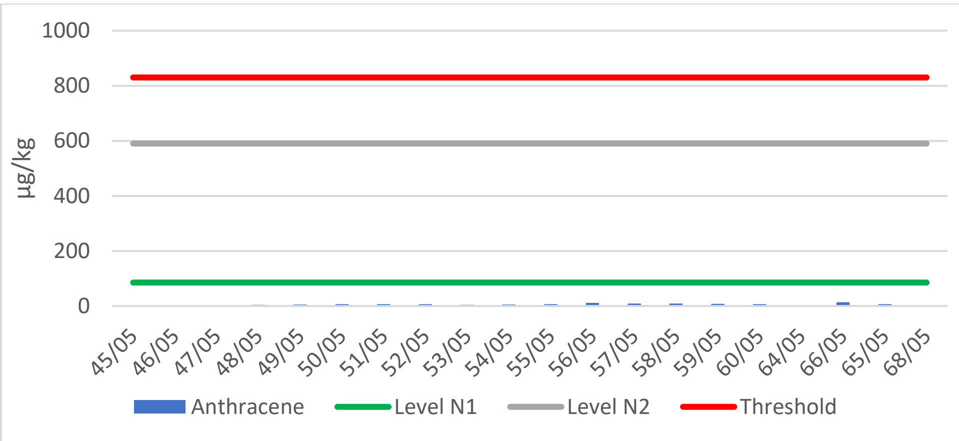


Figure 42. Anthracene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Anthracene concentrations are uniformly low across all investigated zones, with values consistently below the N1 guideline of 85 µg/kg. No exceedances of either N1 or N2 (590 µg/kg) are recorded, and the results show no spatial variability that would suggest localized enrichment or anthropogenic hotspots. These findings confirm that anthracene is not a relevant contaminant in the current sediment quality profile of the Port of Bar.

Fluoranthene

Figure 43 shows a graphic review of the concentrations of fluoranthene in the sediment samples sampled at the Port of Bar compared with the French sediment quality guideline values.

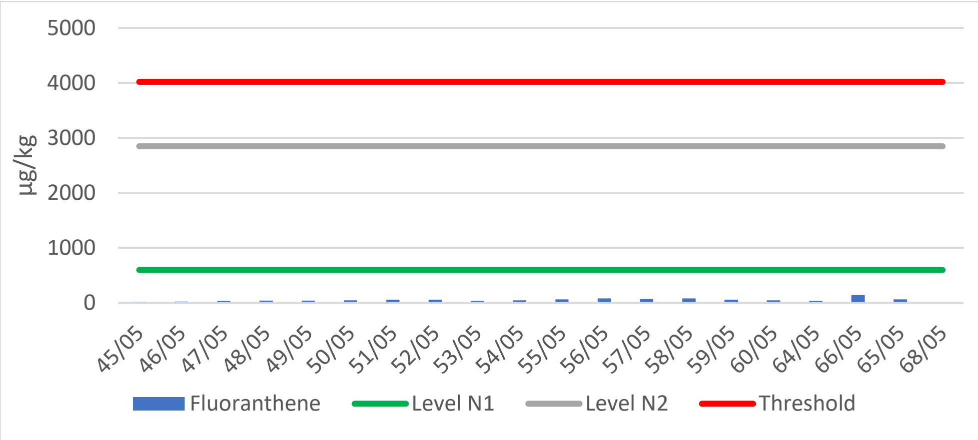


Figure 43. Fluoranthene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

The analysis shows that fluoranthene concentrations across all sampling zones are consistently low, with no zone exceeding the N1 threshold of 600 µg/kg.

Pyrene

Figure 44 shows a graphic review of the concentrations of pyrene in the sediment samples sampled at the Port of Bar compared with the French sediment quality guideline values.

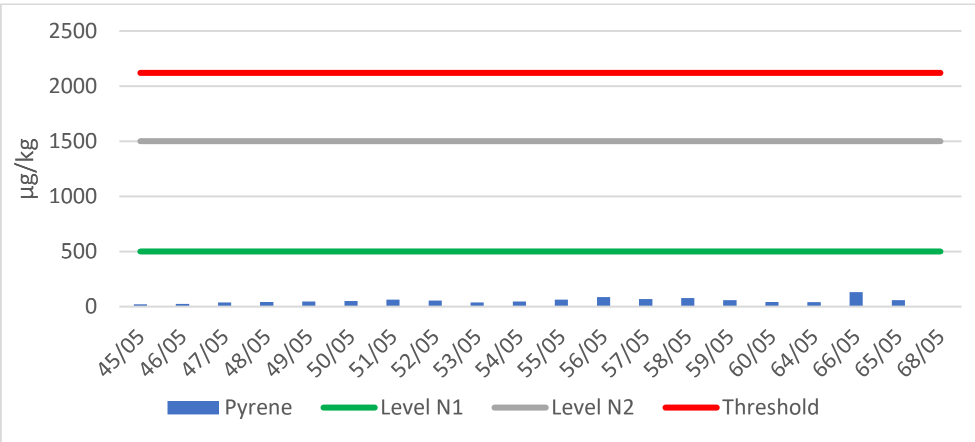


Figure 44. Pyrene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Pyrene is detected at low concentrations across all sampling zones, with every measured value falling below the N1 limit of 500 µg/kg. Dataset shows a uniform distribution across the port basin, without evidence of localized accumulation. These findings indicate that pyrene is not a parameter of ecological concern within the Port of Bar sediments.

Benzo[a]anthracene

Figure 45 shows a graphic review of the concentrations of benzo[a]anthracene in the sediment samples sampled at the Port of Bar site in relation to the French values of sediment quality guidelines.

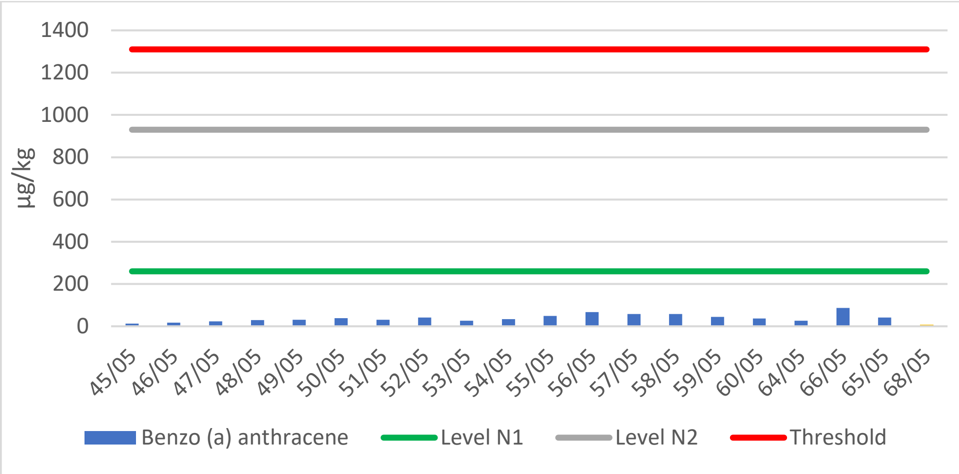


Figure 45. Benzo[a]anthracene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

The results of analysis show that benzo[a]anthracene concentrations remain consistently below the N1 threshold of 260 µg/kg, with no exceedances across any sampling zones. The relatively uniform distribution indicates that this PAH is not accumulating at elevated levels in either harbour zones or reference sites, and thus does not play a role in shaping the contamination profile of the port sediments.

With regard to legal thresholds, the Order of 27 March 2024 specifies an immersion prohibition limit of 1310 µg/kg. The concentrations recorded in all samples are far lower than this value.

Chrysene

Figure 46 shows a graphic review of the concentrations of chrysene in the sediment samples sampled at the Port of Bar site in relation to the French values of sediment quality guidelines.

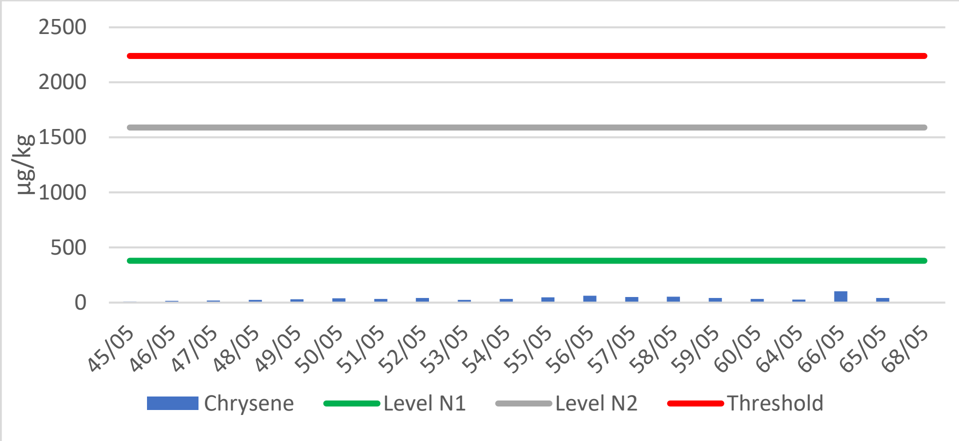


Figure 46. Chrysene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Chrysene values are measured at low concentrations in all zones and are below the French N1 limit of 380 µg/kg. The absence of elevated values indicates that chrysene is not present at levels that would require management consideration. This parameter is of no concern for sediment quality in Port of Bar. This outcome suggests that chrysene is not influenced by port-related activities and occurs only at background levels within the study area.

Benzo[b]fluoranthene

Figure 47 shows a graphic review of the concentrations of benzo[b]fluoranthene in the sediment samples sampled at the Port of Bar site in relation to the French sediment quality guidelines.

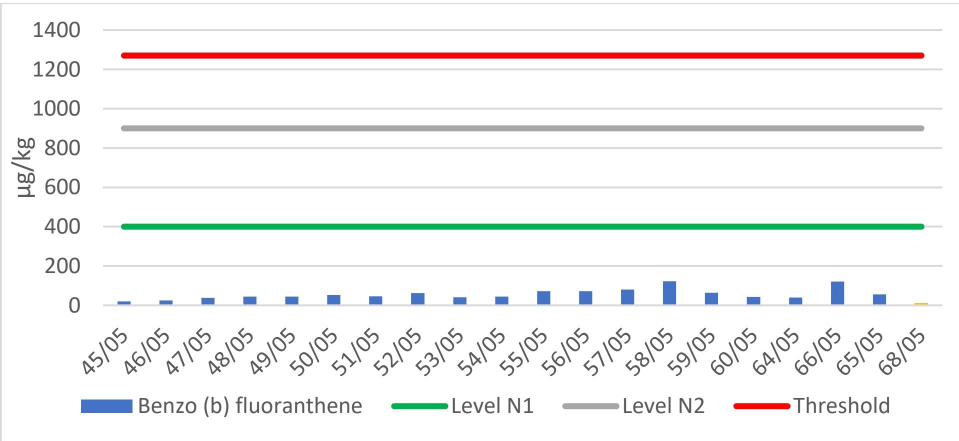


Figure 47. Benzo[b]fluoranthene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

The results show that benzo[b]fluoranthene concentrations are consistently low, with all measured values falling below the N1 threshold of 400 µg/kg. Dataset reflects a relatively uniform distribution across the port basin. This suggests that the compound is not influenced by harbour-related activities and does not contribute to localized contamination hotspots.

Benzo[k]fluoranthene

Figure 48 shows a graphic review of the concentrations of benzo[k]fluoranthene in the sediment samples sampled at the Port of Bar compared with the French sediment quality guideline values.

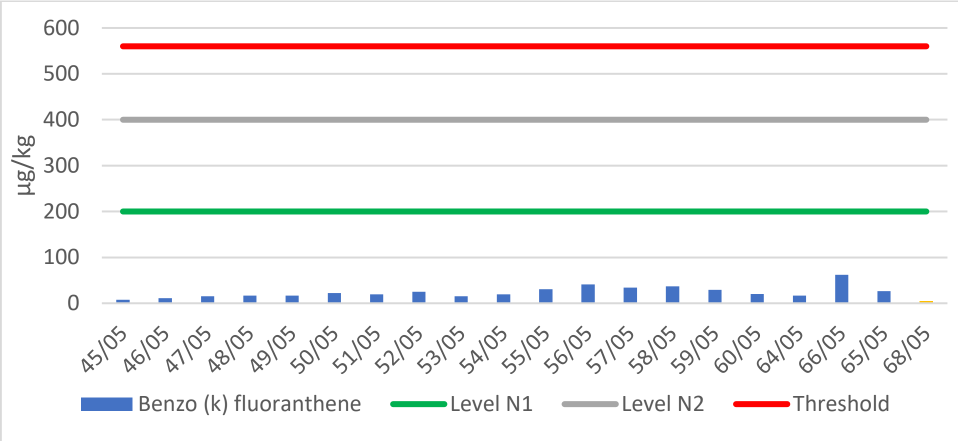


Figure 48. Benzo[k]fluoranthene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

All measured concentrations of benzo[k]fluoranthene are found to be below the N1 threshold of 200 µg/kg. The distribution is uniform, and no particular zone shows signs of localized accumulation, indicating that this PAH is not significantly influenced by anthropogenic inputs in the port.

Benzo[a]pyrene

Figure 49 shows a graphic review of the concentrations of benzo[a]pyrene in the sediment samples sampled at the Port of Bar compared with the French sediment quality guideline values.

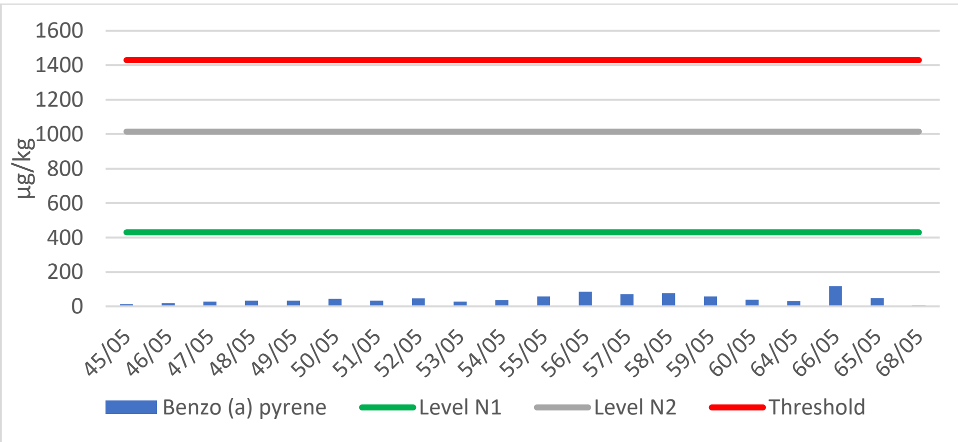


Figure 49. Benzo[a]pyrene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Benzo[a]pyrene, one of the most toxicologically significant PAHs due to its mutagenic and carcinogenic properties, was detected at uniformly low concentrations across all sampling zones. All values remain well below the N1 threshold of 200 µg/kg. This finding indicates that benzo[a]pyrene is not enriched in the sediments of the Port of Bar.

Indeno[1,2,3-cd]pyrene

Figure 50 shows a graphic review of the concentrations of indeno[1,2,3-cd]pyrene in the sediment samples sampled at the Port of Bar site in relation to the French values of sediment quality guidelines.

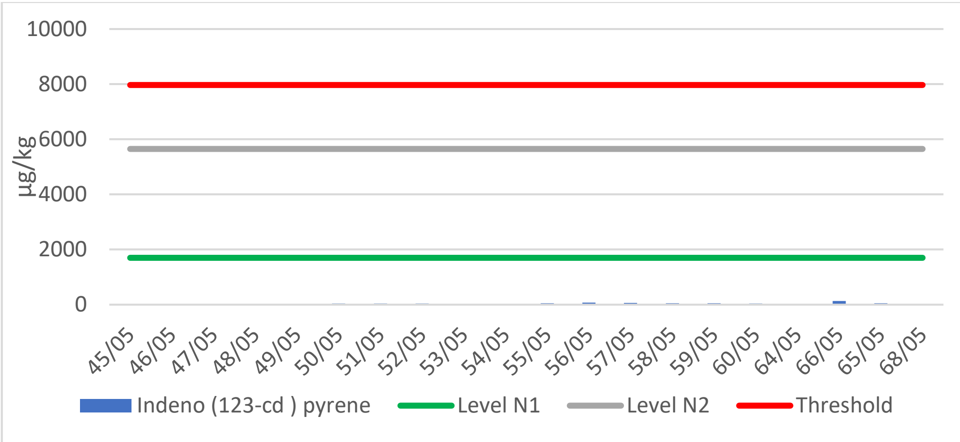


Figure 50. Indeno[1,2,3-cd]pyrene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

The results of analysis show that indeno[1,2,3-cd]pyrene is present at very low levels, with all values well below the N1 threshold of 1700 µg/kg and the data reveal a uniform distribution across the study area.

Dibenzo[a,h]anthracene

Figure 51 shows a graphic review of the concentrations of dibenzo[a,h]anthracene in the sediment samples sampled at the Port of Bar site in relation to the French sediment quality guidelines.

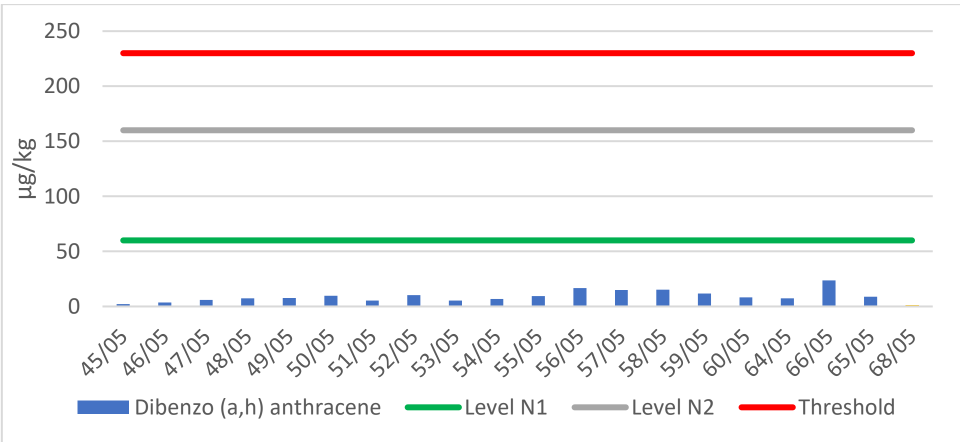


Figure 51. Dibenzo[a,h]anthracene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

Dibenzo[a,h]anthracene, with all concentrations remaining well below the N1 threshold of 60 µg/kg, results reveal a uniform distribution without evidence of localized enrichment. This indicates the absence of notable anthropogenic inputs of this high-molecular-weight PAH.

Benzo[ghi]perylene

Figure 52 shows a graphic review of the concentrations of benzo[ghi]perylene in the sediment samples sampled at the Port of Bar site in relation to the French sediment quality guidelines.

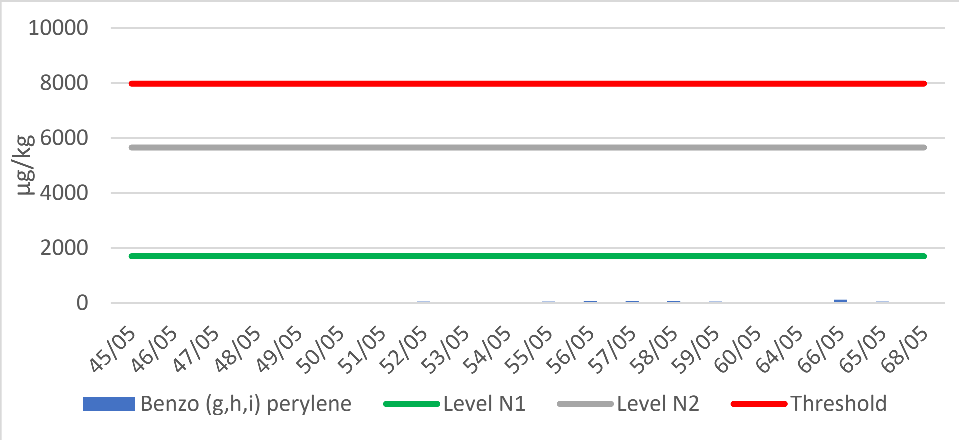


Figure 52. Benzo[ghi]perylene concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

The concentrations of benzo[ghi]perylene are uniformly low across all sampling sites, remaining well below the N1 limit value of 1700 µg/kg and the dataset provides no indication of localized accumulation or anthropogenic enrichment. This indicates that benzo[ghi]perylene is not significantly impact on the sediments in the port area.

7.4 Organotin compounds

Tributyltin

Figure 53 shows a graphic review of the concentrations of tributyltin in the sediment samples sampled at the Port of Bar compared with the French sediment quality guideline values.

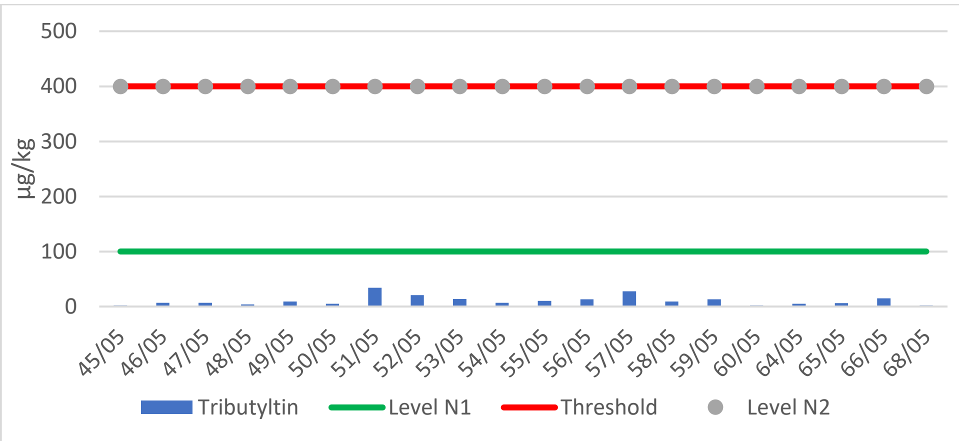


Figure 53. Tributyltin concentration by sampling location in relation to Level N1, N2 and thresholds immersion values

The concentration of tributyltin (TBT) in the sediments of the Port of Bar range from 4 μg/kg to 34 μg/kg, which is below the French N1 threshold of 100 μg/kg. No zone recorded concentrations near the threshold, and the results are relatively uniform across the port basin, including central areas and outer reference stations. These findings indicate that TBT does not present a significant contamination problem in the port sediments.

From a regulatory perspective, the Order of 27 March 2024 sets the immersion prohibition threshold for tributyltin at 400 μg/kg**.** All concentrations in the Port of Bar sediments fall well below this limit.

7.1.6 Summary

The comprehensive evaluation of sediments from the Port of Bar, conducted in accordance with French sediment quality guidelines (Levels N1/N2) and the updated regulatory framework from 2024, highlights a heterogeneous contamination profile strongly influenced by port-related activities.
This assessment was carried out in line with the "Arrêté of 30 June 2020", amending the "Arrêté of 9 August 2006" on the levels to be considered during the analysis of discharges into surface waters or marine, estuarine, or dredged river/canal sediments (JO n°162 of 2 July 2020), as well as the **"**Arrêté of 27 March 2024", establishing the general requirements applicable to dredging operations and related discharges under section 4.1.3.0 of the nomenclature annexed to Article R.214-1 of the Environmental Code (JO n°83 of 9 April 2024).

Metals

The sediment quality assessment across the studied area reveals notable spatial variations in heavy metal concentrations, closely linked to anthropogenic activities within the port zone. Elevated levels of cadmium, lead, arsenic, copper, zinc, and chromium in sediments from the port area frequently exceed established French sediment quality guideline thresholds (N1 and N2), indicating localized contamination hotspots likely associated with ore concentrate transshipment, industrial runoff, and maritime operations.

Copper and zinc exhibit particularly high enrichment within the port, with concentrations far exceeding guideline values and substantially higher than those recorded at reference locations outside the port boundaries. This strongly implicates port-related handling and storage activities as significant sources of sediment contamination. Similarly, localized peaks in cadmium, lead, and arsenic further highlight potential point-source pollution within the harbour.

In contrast, nickel and chromium show elevated concentrations even at reference sites, suggesting that natural geochemical background levels contribute substantially to their presence in sediments. In order to better differentiate between natural and anthropogenic contamination, the results will be further evaluated by calculations of enrichment factors and the Metal Pollution Load Index (MPLI).

Mercury concentrations remain low and consistent across all sampled locations, including both port and reference sites, indicating no significant mercury pollution within the study area.

Against the 2024 immersion-prohibition thresholds, the sediment data reveal isolated exceedances for lead (500 mg/kg), arsenic (100 mg/kg), and zinc (600 mg/kg), while copper shows a far more critical situation, with ten or more stations surpassing the threshold value of 368 mg/kg. These exceedances mean that offshore immersion of sediments from the affected locations would be categorically prohibited under the French 2024 decree, irrespective of any supplementary ecotoxicological testing. Consequently, while Cd, Ni, Cr and Hg remains below the legal cut-off values at all zones, copper stands out as the dominant regulatory constraint, complemented by localized but significant restrictions for Pb, As, and Zn.

PCB congeners exhibit a generally low contamination pattern, with most values below N1. However, exceedances of N1 were noted for PCB-101 and PCB-118, and one location surpassed the N2 threshold for PCB-101, identifying this congener as a parameter of concern. Nevertheless, all PCB concentrations remain well below the 2024 prohibition thresholds, meaning they do not represent a legal barrier to disposal, though they may warrant closer ecological consideration in zones with recurrent N1 exceedances.

PAHs present a contrasting picture. Most analysed PAHs, including naphthalene, phenanthrene, anthracene, chrysene, pyrene, and high-molecular-weight PAHs such as benzo[a]pyrene and indeno[1,2,3-cd]pyrene, remain far below N1 thresholds across all zones, demonstrating negligible contribution to sediment contamination. Fluorene is the only PAH displaying N1 exceedances, confined to three stations within the port basin, though still well below N2 values. These exceedances suggest localized enrichment, but the overall PAH contamination level is very low compared with metals.

Organotin compounds, represented by tributyltin (TBT), were found at concentrations far below the N1 threshold. The absence of elevated values across both port and reference sites indicates no current ecological or regulatory concern from organotin contamination.

The findings demonstrate that the contamination of Port of Bar sediments is driven primarily by heavy metals, particularly copper, lead, arsenic, cadmium, zinc, and nickel. In several zones, these metals reach or exceed levels that not only trigger N2 classification but also cross the 2024 prohibition thresholds, which came into force on 1 January 2025, mandating alternative land-based management. By contrast, organic pollutants (PCBs, PAHs, TBT) remain at relatively low levels, with only isolated N1/N2 exceedances, and do not contribute substantially to overall regulatory restrictions.

In conclusion, the Port of Bar sediments exhibit a contamination pattern characteristic of industrial and ore-transshipment harbours. The consistent exceedances of guideline values, particularly for copper and other trace metals, provides evidence of the strong anthropogenic imprint associated with port operations.

7.2 Results interpretation according to Dutch Sediment quality guidelines

7.2.2 Metals

Mercury

Figure 54 shows a graphical representation of mercury concentrations in the sediments of the Port of Bar, compared with the corrected Dutch intervention values for sediments.

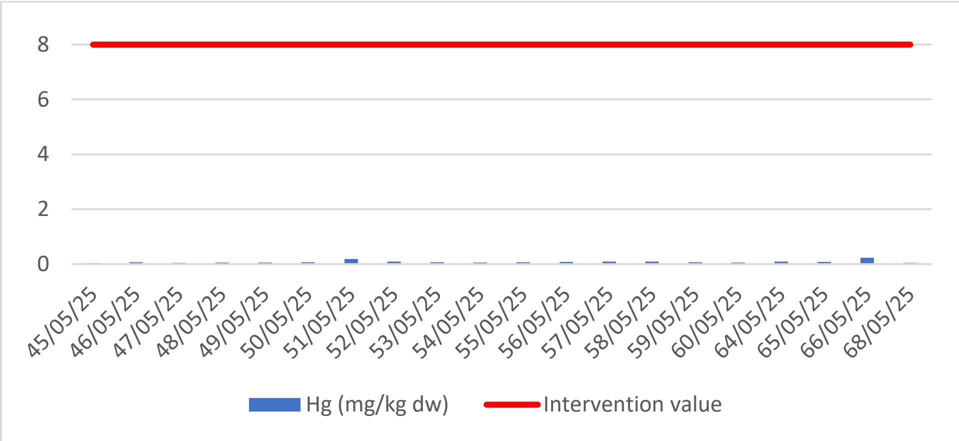


Figure 54. Mercury in relation to the intervention value

Mercury concentrations in the sediment across the sampled zones are well below the Dutch intervention value of 8 mg/kg, indicating that none of the sites exhibit levels of serious contamination. Across the port and surrounding zones, Hg concentrations range from 0.05 mg/kg at the reference zone 68/05, to the highest concentration observed at zone 66/05 (0.23 mg/kg). Despite some variability, there is no clear evidence of systematic contamination linked to port activities.

Cadmium

Figure 55 shows a graphic representation of the concentration of Cadmium in the sediment of Port of Bar in relation to the corrected Dutch intervention values for sediment.

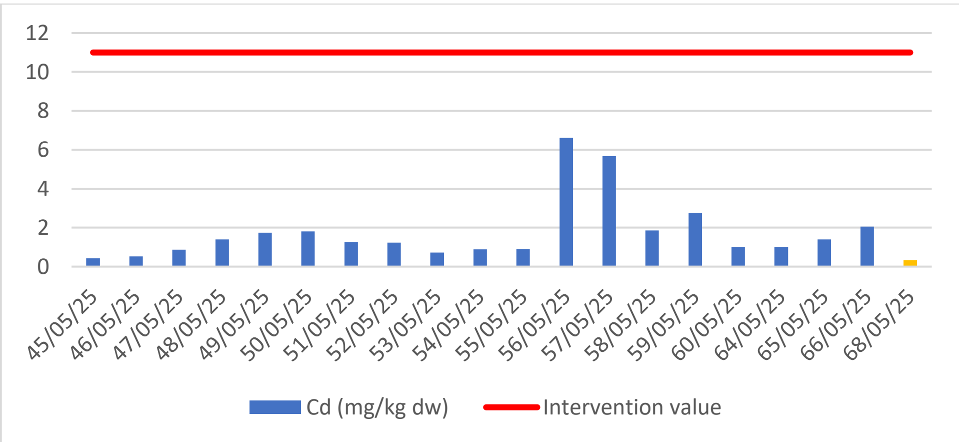


Figure 55. Cadmium in relation to the intervention value

All measured concentrations of Cd are below the Dutch Intervention Value. Most samples are well below 2 mg/kg, i.e., less than 20% of the intervention threshold. The highest recorded value (6.61 mg/kg at station 56/05/25) approaches 60% of the intervention level, making it the location of greatest concern for cadmium accumulation. The majority of stations remain low, indicating generally moderate cadmium levels across the harbour.

Lead

Figure 56 shows a graphic representation of the concentration of Lead in the sediment of Port of Bar in relation to the corrected Dutch intervention values for sediment.

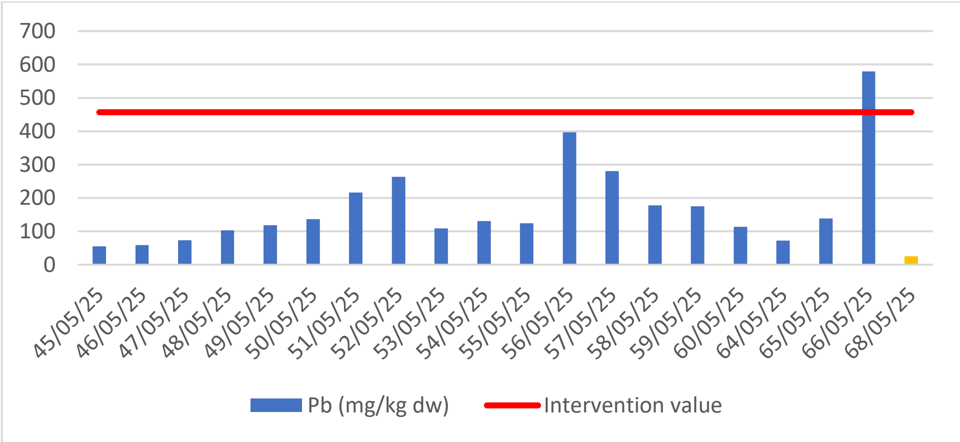


Figure 56. Lead in relation to the intervention value

Lead concentrations across the investigated sites range between72.6 and 579.7 mg/kg. The vast majority of samples remain below the corrected Dutch Intervention Value of 457 mg/kg, with only one zone (66/05) exceeding the threshold, indicating that, lead contamination in the sediment of Port of Bar does not generally constitute a case of serious pollution under the Dutch framework.

Arsenic

Figure 57 shows a graphic representation of the concentration of Arsenic in the sediment of Port of Bar in relation to the corrected Dutch intervention values for sediment.

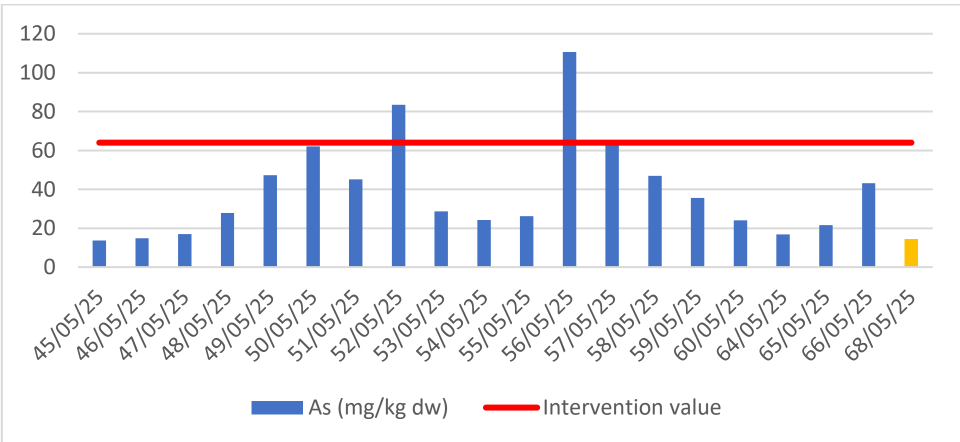


Figure 57. Arsenic in relation to the intervention value

Arsenic concentrations across the zones range from 13.6 to 110.6 mg/kg. Most zones fall below the Dutch Intervention Value of 64 mg/kg, but several exceedances are observed, indicating localized contamination hotspots. Concentration of arsenic in the sediment excees the Dutch Intervention Value in two zones 52/05 and 56/05, as well as is near or slightly above the intervention value as in zones 50/05 and 57/05.

Copper

Figure 58 presents the concentrations of copper in the sediments of the Port of Bar, compared with the corrected Dutch intervention values for sediment.

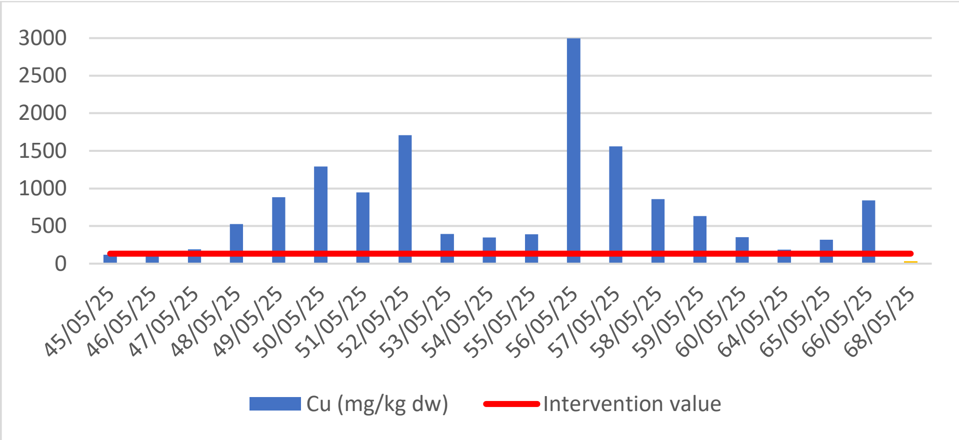


Figure 58. Copper in relation to the intervention value

The assessment of copper concentrations across the sampling zones shows a wide range of values, with several locations substantially exceeding the corrected Dutch intervention value of 133 mg/kg, which represents the threshold for serious contamination. At the lower end, zones such as 45/05 (118.5 mg/kg) and 46/05 (120.1 mg/kg) are close to but still below the intervention limit, indicating concentrations that are elevated compared to natural background levels (zone 68/05 -concentration of copper 28 mg/kg) but do not yet constitute a case of serious contamination. However, starting from zone 47/05 (191.5 mg/kg), exceedances become evident, and from that point onward, many zones present copper levels several times higher than the intervention threshold. The most pronounced contamination is observed at zones 50/05 (1293 mg/kg), 52/05 (1708 mg/kg), 56/05 (2997 mg/kg), and 57/05 (1559 mg/kg). These values are 10–20 times higher than the intervention value, clearly pointing to severe copper pollution.

Nickel

Figure 59 presents the concentrations of nickel in the sediments of the Port of Bar, compared with the corrected Dutch intervention values for sediment

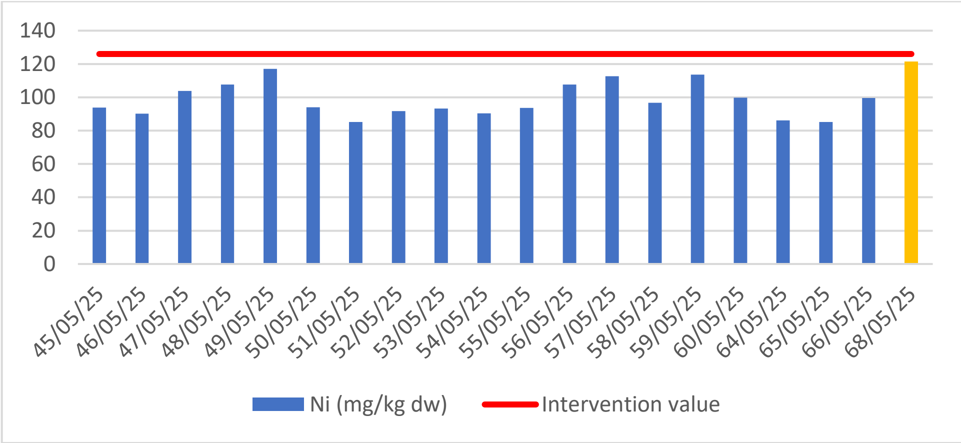


Figure 59. Nickel in relation to the intervention value

Nickel concentrations across the sampled zones are below the Dutch intervention value of 126 mg/kg, indicating that most zones do not reach the intervention value. The assessment of nickel concentrations across the sampling zones indicates that the port area is largely unaffected by anthropogenic contamination. Zone 68/05, which is a reference point has nickel concentration of 121.4 mg/kg. This value suggests that naturally occurring nickel in the sediments is relatively elevated compared to global averages but represents the baseline for this area. The data do not indicate any systematic increase in nickel concentrations that could be attributed to port activities, as all there is relatively uniform distribution of nickel across the study area, inside and outside the port.

Chromium

Figure 60 presents the concentrations of chromium in the sediments of the Port of Bar, compared with the corrected Dutch intervention values for sediment

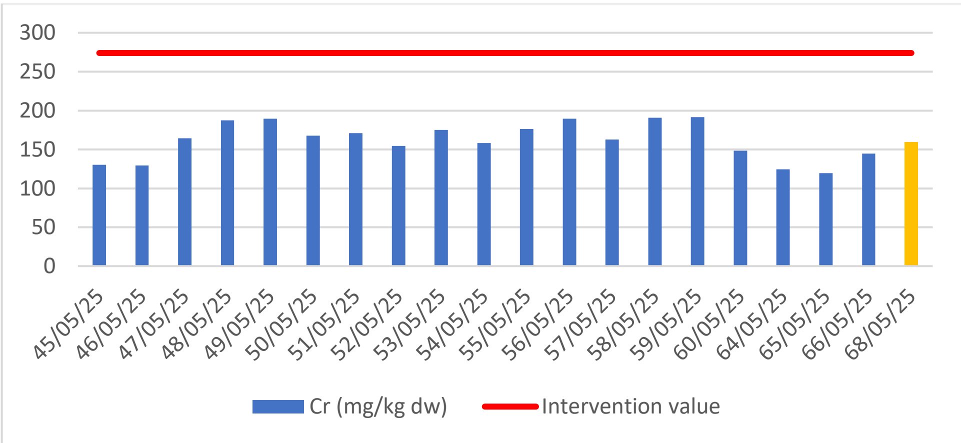


Figure 60. Chromium in relation to the intervention value

Chromium concentrations across the sampled zones are well below the Dutch intervention value of 274 mg/kg, indicating that none of the zones present levels of serious contamination. Concentrations within the port and surrounding zones range from 119.4 mg/kg to 191.5 mg/kg, showing a relatively uniform distribution without any clear evidence of enrichment due to port activities. The data suggest that chromium in the sediments primarily reflects natural geochemical conditions rather than anthropogenic contamination. Zone 68/05, serving as a reference point, exhibits a Cr concentration of 159.2 mg/kg.

Zinc

Figure 61 presents the concentrations of zinc in the sediments of the Port of Bar, compared with the corrected Dutch intervention values for sediment

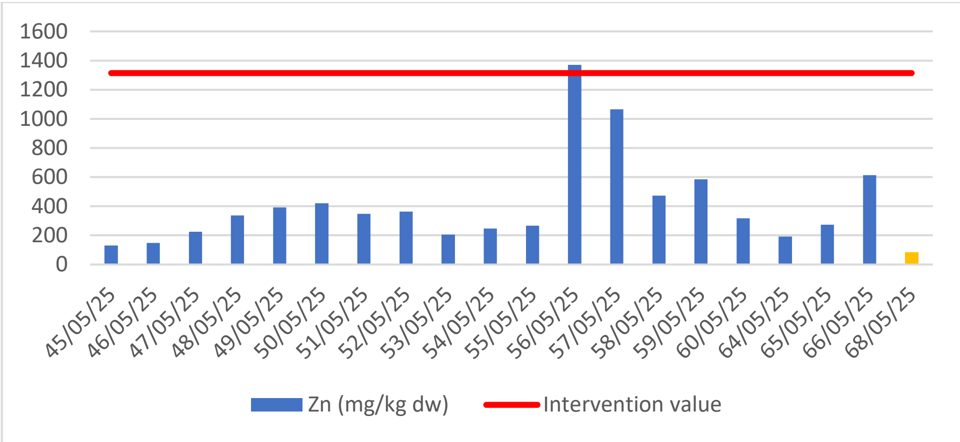


Figure 61. Zinc in relation to the intervention value

Zinc concentrations across the sampled zones exhibit a wide range, with most values below the Dutch intervention value of 1314 mg/kg. Within the port Zn concentrations in sediment vary from 131.2 mg/kg to 1371 mg/kg, with the only exceedance observed at zone 56/05 (1371 mg/kg).

7.2.3 Polychlorinated biphenyls

Figure 62 presents the concentrations of the sum of seven PCBs (PCB 28, 52, 101, 118, 153, 138, 180) in sediment samples from the Port of Bar, compared with the Dutch intervention values for sediment corrected for organic matter.

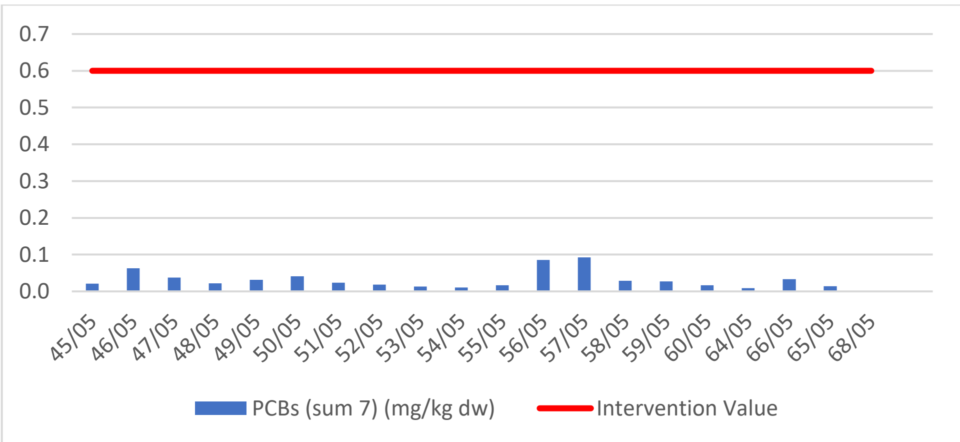


Figure 62. Sum of 7 PCBs in relation to the intervention value

The measured concentrations of PCBs (sum of 7 congeners) across all sampling zones (45/05–68/05) range between limit of quantification and 0.092 mg/kg, with the highest values observed in zones 56/05 (0.086 mg/kg) and 57/05 (0.092 mg/kg). When compared to the corrected Dutch Intervention Value of 0.6 mg/kg, all measured concentrations remain well below the threshold.

7.2.4 Polycyclic aromatic hydrocarbons

Figure 63 presents the concentrations of the sum of ten PAHs (Naphthalene, Phenanthrene, Anthracene, Fluoranthene, Chrysene, Benzo(a)anthracene, Benzo(a)pyrene, Benzo(k)fluoranthene, Indeno(1,2,3-cd)pyrene, Benzo(ghi)perylene) in sediment samples from the Port of Bar, compared with the Dutch intervention values for sediment.

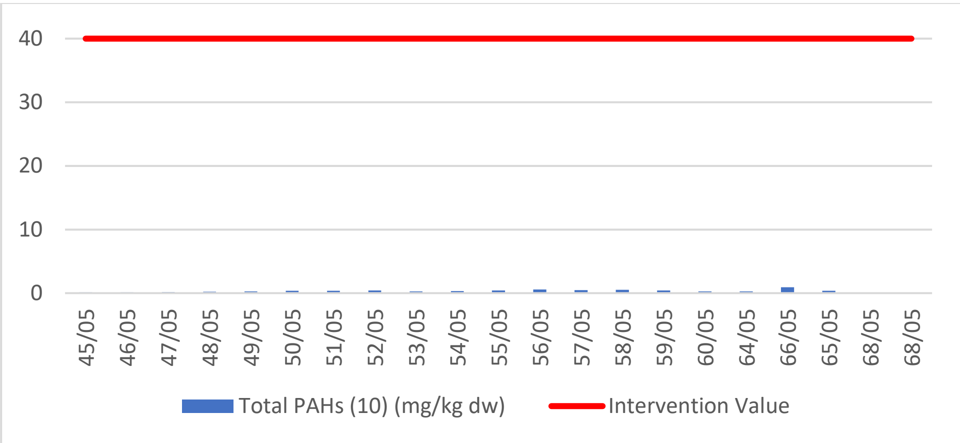


Figure 63. Sum of 10 PAHs in relation to the intervention value

All measured concentrations are well below the intervention value (0.05–0.93 mg/kg). Even the highest observed concentration (0.93 mg/kg at 66/05) is less than 3% of the intervention threshold. This indicates that, with respect to PAHs, the sediments do not pose a serious contamination problem.

7.2.5 Mineral oils

Figure 64 presents the concentrations of mineral oils in sediments from the Port of Bar, compared with the Dutch intervention values for sediment, corrected for organic matter content.

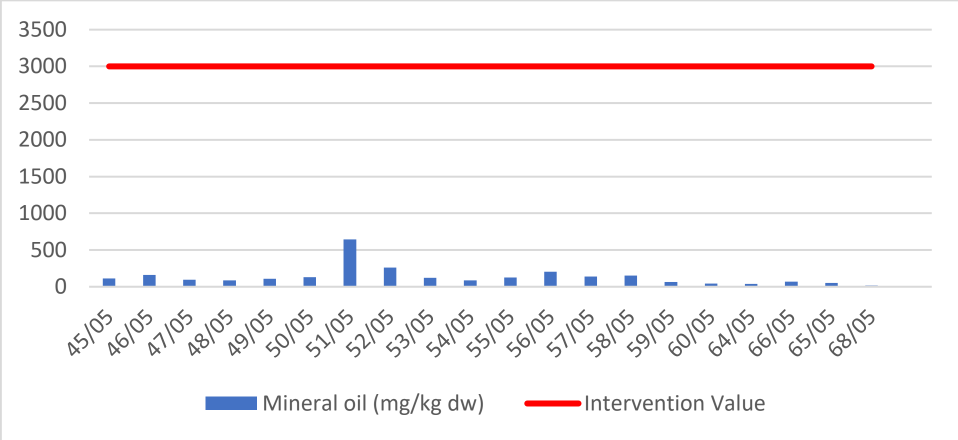


Figure 64. Mineral oils content in relation to the intervention value

Measured concentrations range between 39–643 mg/kg and are well below the intervention value (3000 mg/kg). Even the highest concentration (643 mg/kg at 51/05 zone) represents only about 21% of the intervention threshold. The levels, however, do indicate the presence of anthropogenic influence, since at the background reference point (68/05) concentration of mineral oils is much lower.

7.2.6 Organotin compounds

Figure 65 shows a graphic representation of the concentration of sum of the analysed organotin compounds in the sediment of Port of Bar in relation to the corrected Dutch intervention value for sediment.

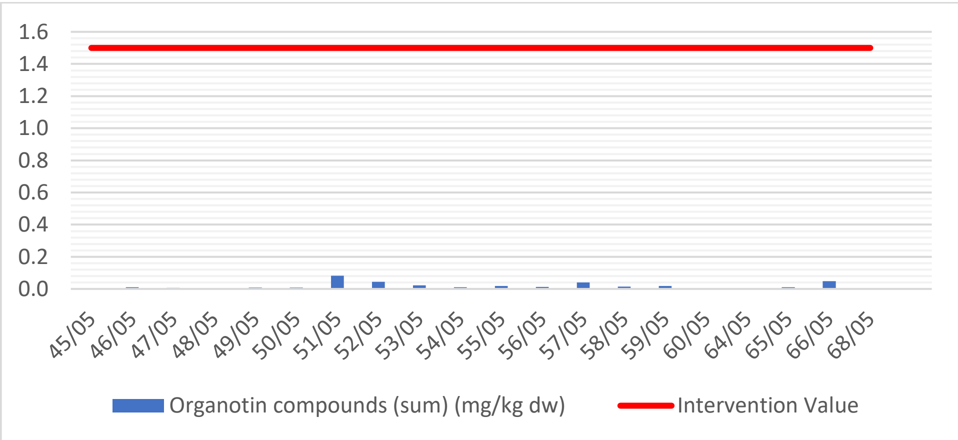


Figure 65. Organotin compounds content in relation to the intervention value

Concentration of organotin compounds range from 0.004 mg/kg (lowest, at 48/05) to 0.082 mg/kg (highest, at 51/05). All measured concentrations are much below 1.5 mg/kg. The presence of measurable levels in several samples suggests historic contamination sources (linked to antifouling paints which were used in the past).

7.2.7 Summary

The assessment of sediment quality in the Port of Bar was conducted in accordance with the Dutch Soil and Sediment Quality Standards, using the Intervention Values as the primary regulatory benchmark. Since 22 December 2009, sediment quality and management in the Netherlands have been regulated under the Water Act, which serves as the overarching legal framework for sediment assessment. Within this framework, exceeding an Intervention Value classifies the sediment as seriously contaminated, triggering mandatory management actions and prohibiting its unrestricted disposal.

Metals

The evaluation of heavy metals in Port of Bar sediments identifies clear contamination hotspots, strongly reflecting port-related activities. **Copper** emerges as the most critical contaminant, with concentrations at multiple stations exceeding the Dutch Intervention Value of 133 mg/kg. This positions copper as the dominant regulatory and ecological constraint, directly linked to the handling and storage of ore concentrates within the port. **Zinc** also exhibits elevated levels, with exceedances of its Intervention Value (1314 mg/kg) observed in one zone, further evidencing the influence of port operations.

Lead and **arsenic** show localized exceedances of their respective Intervention Values (457 mg/kg and 64 mg/kg), indicating specific hotspots of concern likely associated with bulk cargo and industrial runoff. In contrast, **cadmium, nickel**, and **chromium** remain below Intervention Values across all investigated sites. **Mercury** is consistently low, presenting no regulatory or ecological concern under the Dutch criteria.

PCBs

Sediment quality for PCBs is evaluated using the sum of seven indicator congeners (Σ7 PCBs: 28, 52, 101, 118, 138, 153, 180). Measured concentrations across all sampling sites remain well below the Dutch Intervention Value of 0.6 mg/kg, indicating that PCBs do not pose regulatory limitations or ecological risks in this context.

PAHs

Similarly, the sum of ten priority PAHs (Σ10 PAHs: naphthalene, phenanthrene, anthracene, fluoranthene, chrysene, benzo[a]anthracene, benzo[a]pyrene, benzo[k]fluoranthene, indeno[1,2,3-cd]pyrene, benzo[ghi]perylene) is used for assessment. In Port of Bar sediments, Σ10 PAHs concentrations remain well below the Dutch Intervention Value of 40 mg/kg at all stations, confirming that PAHs are not significant contributors to sediment contamination.

Organotin Compounds

Organotin concentrations are substantially below the Dutch Intervention Value (1.5 mg/kg). This confirms that organotin compounds do not pose either ecological risk or regulatory constraints in the current assessment.

Mineral Oil (TPH)

The Dutch framework sets an Intervention Value of 3000 mg/kg for mineral oils in sediments. In the Port of Bar, all measured concentrations remain well below this threshold, indicating that petroleum hydrocarbons are not a concern in the study area.

Overall Assessment

Overall, the contamination profile of Port of Bar sediments is primarily driven by heavy metals, particularly copper, with additional localized contributions from zinc, lead, and arsenic. Exceedances of Dutch Intervention Values for these metals indicate **serious contamination**, necessitating management interventions under the Water Act. By contrast, organic contaminants—including PCBs, PAHs, and organotin compounds—remain at relatively low levels and do not impose significant regulatory restrictions.

Conclusion

The sediment contamination pattern in the Port of Bar reflects typical characteristics of industrial and ore-transshipment harbours, where trace metals—especially copper—dominate both the ecological risk profile and regulatory implications under Dutch law. The results provide clear evidence of strong anthropogenic influence from port activities, highlighting the need for **continuous monitoring**, strict compliance with regulatory standards, and the implementation of **targeted sediment management strategies** to prevent further environmental degradation and to protect benthic ecosystems and the wider marine environment.

7.3 Organochlorine Pesticides and PFAS

In addition to heavy metals, PCBs, PAHs, and organotin compounds, the present study also included an analytical screening of organochlorine pesticides (OCPs) and per- and polyfluoroalkyl substances (PFAS) in sediments from the Port of Bar. These groups of pollutants are recognized globally for their environmental persistence, bioaccumulation potential, and adverse effects on human health and aquatic ecosystems. Their inclusion in the present assessment reflects their relevance as priority hazardous substances under various international conventions, including the Stockholm Convention on Persistent Organic Pollutants.

Unlike metals, PCBs, and PAHs, however, neither the French sediment quality guidelines (N1/N2 levels, 2024 prohibition thresholds) nor the Dutch Soil and Sediment Quality Standards (Intervention Values under the Water Act) establish regulatory thresholds for all analysed OCPs or PFAS in sediments. As a result, there are no officially defined benchmark values against which the measured concentrations can be directly evaluated under these frameworks.

Therefore, the results for OCPs and PFAS presented in this report are interpreted primarily in descriptive and comparative terms, focusing on the occurrence, distribution, and potential implications of their presence in the port environment. While they do not contribute to regulatory classification under French or Dutch standards, their persistence and toxicological significance warrant careful attention in the context of long-term environmental monitoring and integrated pollution management strategies for the Port of Bar.

7.3.1 Organochlorine pesticides

A total of 21 organochlorine pesticides were analyzed in sediment samples. All analyzed pesticides except for transformation products of DDT, were found to be below method detection limits in all samples. Metabolites of DDT, including 4,4′-DDD, 2,4′-DDD, and 4,4′-DDE, were consistently detected across all sampling locations.

The concentration of 4,4′-DDD ranged from 0,21 µg/kg dry weight at the reference location (68/05) to 1,03 µg/kg at zone 53/05. 2,4′-DDD was not detected at the reference site but was present in other locations at low concentrations, just above the detection limit, ranging from 0,06 µg/kg to 0,27 µg/kg dry weight, with the highest value also observed at site 53/05. A similar pattern was observed for 4,4′-DDE, with concentrations varying from 0,20 µg/kg in the reference sample to 2,20 µg/kg at zone 58/05. The detection of these metabolites at the reference location suggests that the presence of DDT degradation products is not related to any recent or current port activities.

The parent compound DDT (both 4,4′-DDT and 2,4′-DDT) was not detected in any of the examined sediment samples, indicating the absence of recent inputs. The presence of only degradation products suggests historical application of DDT in the area. Compared with The Dutch regulatory framework, where for the sum of DDE, DDD and DDT intervention value is 4mg/kg, found concentrations are approximately 2,000 times lower and therefore do not indicate a level of contamination that would warrant any action and it is unlikely to have significant adverse environmental or human health impacts under current conditions.

7.3.2 Perfluorinated Compounds

A total of 19 per- and polyfluoroalkyl substances (PFAS) were analyzed in sediment samples. With the exception of PFDoDA and PFTeDA, all compounds were below the limit of quantification (LOQ) of 0.04 µg/kg in all sampling locations.

Concentration of PFDoDA was 0,078µg/kg in zone 51/05 and 0,095µg/kg in zone 66/05. PFTeDA was also quantified in zone 51/05 at a concentration of 0,078 µg/kg. These values, although above the LOQ, remain low and within the range commonly reported for background environmental levels.

7.4 Grain size analysis

Sediments represent complex, multi-phase systems composed primarily of silicates, carbonates, hydroxides/oxides, sulfates, and organic matter. Among the various physical and chemical properties that determine their role as pollutant sinks, grain size is a fundamental controlling factor. The granulometric composition of sediments not only governs their geotechnical behavior but also strongly influences their capacity to adsorb, accumulate, and release contaminants.

The size of sediment particles directly determines their specific surface area, porosity, and cation exchange capacity. Fine-grained fractions (silt and clay) possess significantly larger surface areas compared to coarser materials such as sand or gravel, providing more active binding sites for metals, organic pollutants, and nutrients. As a result, fine sediments generally exhibit higher contaminant concentrations. In addition, cohesive forces within fine-grained deposits promote long-term accumulation and hinder contaminant release, thus amplifying their ecological relevance.

Grain size distribution also affects biogeochemical conditions within sediments. Fine-grained deposits typically retain more organic matter and restrict oxygen penetration, fostering reducing or even anaerobic environments. Such conditions influence microbial processes, redox reactions, and the speciation of heavy metals, as well as the degradation or persistence of organic pollutants. Conversely, sandy deposits tend to be more oxygenated, less cohesive, and less efficient in retaining contaminants, reflecting their lower environmental significance for long-term pollutant accumulation.

Hydrodynamic behavior further emphasizes the role of grain size. Fine sediments are prone to resuspension and secondary transport under physical disturbances such as ship traffic, dredging, or storms. During resuspension, contaminants bound to fine particles can be released into the water column, enhancing their mobility, bioavailability, and ecological risk potential**.** Thus, granulometric composition is not only a static property but also a dynamic factor governing contaminant cycling in marine ecosystems.

Results of Grain Size Analysis – Port of Bar

The granulometric composition of sediments from the Port of Bar indicates a predominantly fine-grained character, with the following proportions:

- Gravel (2.0–60 mm): 4%
- Sand (0.06–2.0 mm): 32%
- Silt (0.002–0.06 mm): 52%
- Clay (<0.002 mm): 12%

The dataset clearly shows that sediments in the port basin are dominated by silt (52%), followed by sand (32%), with smaller contributions from clay (12%) and gravel (4%). Such a distribution is typical of semi-enclosed port environments characterized by reduced hydrodynamic energy, where fine particles settle and accumulate.

The predominance of silt and clay fractions is of particular importance for sediment quality assessment. With over two-thirds of the sediment composed of fine-grained material (silt + clay = 64%), the sediments provide highly favourable conditions for the retention of heavy metals and organic pollutants. Moreover, the cohesive and poorly oxygenated nature of these fine-grained deposits supports pollutant persistence and limits natural recovery processes.

In contrast, the modest sand fraction (32%) contributes to local textural variability but does not substantially alter the overall fine-grained character of the port sediments. The low gravel content (4%) further emphasizes the depositional nature of the environment, where coarse materials are scarce and fine sediments predominate. The granulometric profile of the Port of Bar sediments indicates a system with high contaminant retention potential, typical of industrial harbours. The dominance of silt and clay fractions underscores the need for continuous monitoring, as these sediments act as both a sink and a potential secondary source of pollutants under changing hydrodynamic or redox conditions.

8. Risk assessment of sediment contamination

Chemical analysis of sediment samples revealed elevated concentrations of several heavy metals that exceed international sediment quality guidelines. However, the presence of elevated metal concentrations does not necessarily indicate anthropogenic contamination, as some metals may occur naturally in elevated levels due to regional geological characteristics. To distinguish between natural geochemical background and human-induced pollution, a comprehensive evaluation using established contamination indices is essential.

In order to better distinguish between natural geochemical backgrounds and anthropogenic contributions to metal contamination in the Port of Bar sediments, the data has been further evaluated using a suite of diagnostic indices and fractionation analyses. The Contamination Factor (CF) provides a measure of the degree of enrichment of individual metals relative to background levels, highlighting the magnitude of local pollution inputs. The Metals Pollution Load Index (MPLI) integrates multiple CF values into a single index, offering a comprehensive overview of the overall sediment quality and allowing for the identification of zones of cumulative contamination. The Enrichment Factor (EF) further refines this assessment by normalizing metal concentrations against conservative reference elements, thereby facilitating the discrimination between natural geogenic sources and anthropogenic enrichment.

Complementing these indices, the sequential extraction procedure was applied to characterize the partitioning of metals into different geochemical fractions (exchangeable, reducible, oxidizable, and residual). This method provides essential information on the mobility, bioavailability, and potential ecological risk of each metal, distinguishing between stable background-associated fractions and those more likely to enter the aquatic food web. Together, these analytical approaches provide a comprehensive framework for characterizing the extent, origin, and environmental significance of metal contamination in the studied sediments, enabling informed risk assessment and management decisions.

An additional challenge in sediment assessment is the co-occurrence of multiple contaminants. As it can be seen from results of analysis sediment in Port of Bar contain except metals PAHs, PCBs, organotin compounds. These substances may interact in synergistic ways. Synergistic effects can amplify ecological risks, as combined exposure to several contaminants may cause more severe impacts than would be expected from each compound individually. Recognizing these interactions is therefore essential, since relying only on single-chemical assessments could underestimate the true ecological hazard posed by contaminated sediments in the Port of Bar. To evaluate sediment toxicity in the study area, indicators of potential ecological effects on the aquatic environment ΣQN1 and QPECm were used.

8.1 Contamination factor (CF), Metals pollution load index (MPLI) and Enrichment factor

Chemical analysis of sediment samples from the Port of Bar revealed that a significant number of samples exceed international sediment quality guidelines, particularly the French and Dutch threshold values for several heavy metals. To determine whether these elevated concentrations represent actual contamination rather than natural background variability, pollution indices were applied.

Three widely recognized indicators were used:

- **Contamination factor (CF):** Quantifies the level of contamination by individual metals.
- **Metals pollution load index (MPLI):** Assesses overall contamination from all studied metals.
- **Enrichment factor (EF):** Differentiates between natural (geogenic) and anthropogenic sources of metals.

These indices offer an integrated and comparative approach to evaluating contamination levels across the study area. The following sections present the results and interpretations in the context of port activities and potential anthropogenic inputs.

Contamination Factor (CF) and Metals Pollution Load Index (MPLI)

The **Contamination Factor (CF)** was calculated for nine metals (Hg, As, Cd, Cr, Cu, Pb, Ni, Zn, Fe), using the ratio between the concentration in each sample and the corresponding background value (reference location 68/05). According to standard classification, CF values are interpreted as follows:

- CF < 1: Low contamination
- 1 ≤ CF < 3: Moderate contamination
- 3 ≤ CF < 6: Considerable contamination
- CF ≥ 6: Very high contamination

The results (Table 12) indicate that copper, lead, cadmium, and zinc exhibit the most pronounced contamination, with CF values for copper reaching extreme levels—over 100 in some samples. These elevated values are most prominent at sampling points located adjacent to the berth area, where copper and lead concentrates are routinely handled. The spatial distribution of CF values strongly suggests that port operations are a major contributor to sediment contamination, particularly in zones of active loading and unloading.

Table 12. Heavy metals contamination factor (CF) and metal pollution load index (MPLI)

Zones	CF								MPLI
	Hg	As	Cd	Cr	Cu	Pb	Ni	Zn	
45/05/2	0.7	0.9	1.3	0.8	4.2	2.3	0.8	1.6	**1.3**
46/05/2	1.3	1.0	1.6	0.8	4.2	2.4	0.7	1.8	**1.5**
47/05/2	0.8	1.2	2.7	1.0	6.7	3.0	0.9	2.7	**1.8**
48/05/2	1.0	1.9	4.2	1.2	18.5	4.3	0.9	4.0	**2.7**

Zones	CF								MPLI
	Hg	As	Cd	Cr	Cu	Pb	Ni	Zn	
49/05/2	1.1	3.3	5.3	1.2	31.1	4.9	1.0	4.7	**3.3**
50/05/2	1.3	4.3	5.5	1.1	45.4	5.6	0.8	5.0	**3.7**
51/05/2	3.3	3.1	3.8	1.1	33.4	8.9	0.7	4.1	**3.7**
52/05/2	1.7	5.8	3.8	1.0	60.0	10.8	0.8	4.3	**4.1**
53/05/2	1.2	2.0	2.2	1.1	13.9	4.5	0.8	2.5	**2.3**
54/05/2	1.1	1.7	2.7	1.0	12.2	5.4	0.7	2.9	**2.3**
55/05/2	1.4	1.8	2.7	1.1	13.8	5.1	0.8	3.2	**2.4**
56/05/2	1.6	7.6	20.1	1.2	105.	16.4	0.9	16.3	**7.2**
57/05/2	1.7	4.5	17.3	1.0	54.8	11.6	0.9	12.7	**5.6**
58/05/2	1.6	3.2	5.7	1.2	30.1	7.4	0.8	5.6	**3.7**
59/05/2	1.3	2.5	8.4	1.2	22.2	7.2	0.9	7.0	**3.7**
60/05/2	1.1	1.7	3.1	0.9	12.4	4.7	0.8	3.8	**2.3**
64/05/2	1.6	1.2	3.1	0.8	6.5	3.0	0.7	2.3	**1.9**
65/05/2	1.6	1.5	4.2	0.7	11.2	5.7	0.7	3.3	**2.4**
66/05/2	4.2	3.0	6.3	0.9	29.5	23.9	0.8	7.3	**4.8**

Green	Low contamination	Light green	Perfection
Orange	Moderate contamination	Light yellow	Baseline level of
Red	Considerable	Light red	Deterioration of site quality
Dark red	Very high contamination		

To assess cumulative contamination at each location, the Metals Pollution Load Index (MPLI) was calculated using the geometric mean of CF values for all analyzed metals. According to the classification:

- MPLI < 1: Perfection (unpolluted)
- MPLI = 1: Baseline level of contamination
- MPLI > 1: Deterioration of site quality

All sampling sites within the port exhibit MPLI values greater than 1, indicating a general deterioration of sediment quality throughout the basin. The highest MPLI values, reaching up to 5.9, were recorded at stations closest to the loading berth, reinforcing the conclusion that these areas are under intense anthropogenic pressure. The consistency of elevated MPLI values across the port further supports the notion of widespread contamination, rather than isolated anomalies.

Enrichment Factor (EF)

To better understand the origin of the observed metal concentrations, the Enrichment Factor (EF) was calculated using iron (Fe) as a reference element, under the assumption that Fe is of predominantly natural origin. The EF values reveal a clear distinction between metals of geogenic origin and those influenced by human activity. The interpretation of EF is as follows:

- EF < 1: Natural origin
- 1 ≤ EF < 3: Minor to moderate enrichment
- 3 ≤ EF < 5: Moderate to significant enrichment

- 5 ≤ EF < 10: Significant enrichment
- EF ≥ 10: Very high enrichment (strong anthropogenic input)

The obtained EF values for heavy metals are shown in Table 13.

Table 13. Heavy metals Enrichment Factor for analyzed samples (EF)

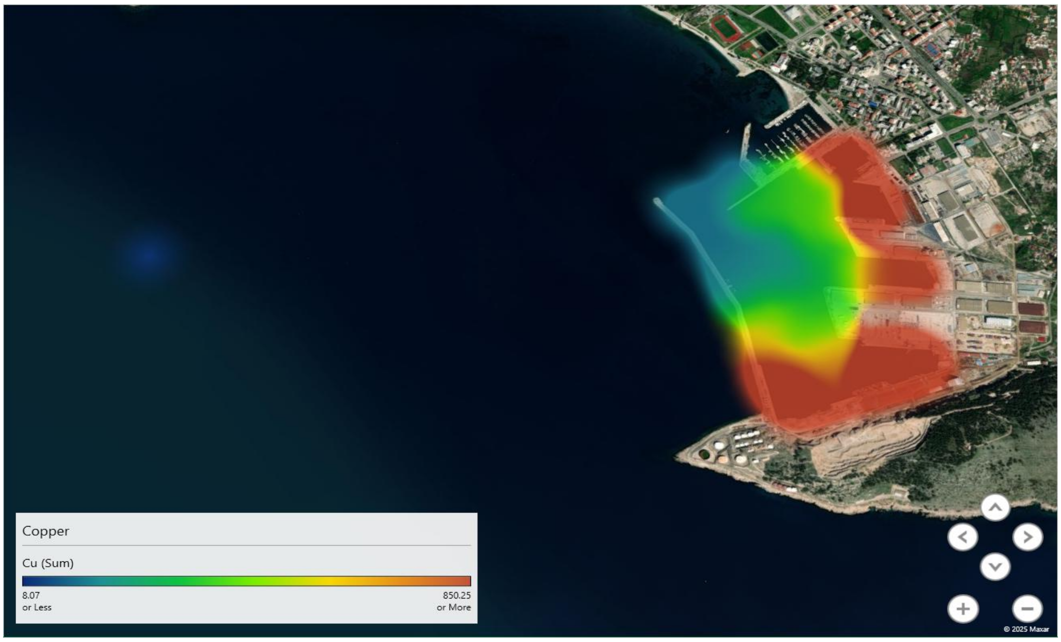
Zones	Hg	As	Cd	Cr	Cu	Pb	Ni	Zn
45/05/25	0.6	0.9	1.2	0.8	4.1	2.2	0.8	1.5
46/05/25	1.3	1.0	1.6	0.8	4.2	2.4	0.7	1.7
47/05/25	0.8	1.1	2.5	1.0	6.3	2.8	0.8	2.5
48/05/25	0.9	1.7	3.8	1.1	16.7	3.9	0.8	3.6
49/05/25	1.0	2.9	4.7	1.1	27.6	4.3	0.9	4.1
50/05/25	1.2	3.7	4.8	0.9	39.8	4.9	0.7	4.4
51/05/25	3.1	2.9	3.6	1.0	31.4	8.4	0.7	3.9
52/05/25	1.5	5.3	3.5	0.9	55.4	10.0	0.7	4.0
53/05/25	1.1	1.8	2.0	1.0	12.4	4.0	0.7	2.2
54/05/25	1.1	1.7	2.7	1.0	12.4	5.5	0.8	3.0
55/05/25	1.2	1.6	2.5	1.0	12.5	4.7	0.7	2.9
56/05/25	1.3	6.3	16.5	1.0	86.3	13.4	0.7	13.4
57/05/25	1.5	3.8	14.6	0.9	46.3	9.8	0.8	10.7
58/05/25	1.6	3.2	5.6	1.2	30.0	7.3	0.8	5.6
59/05/25	1.1	2.1	7.4	1.1	19.4	6.3	0.8	6.1
60/05/25	1.1	1.7	3.3	1.0	13.0	4.9	0.9	4.0
64/05/25	1.6	1.2	3.2	0.8	6.7	3.1	0.7	2.3
65/05/25	1.6	1.5	4.2	0.8	11.2	5.7	0.7	3.3
66/05/25	4.2	3.0	6.3	0.9	29.7	24.1	0.8	7.3

(green)	Deficiency to minimal enrichment
(blue)	Moderate enrichment
(orange)	Significant enrichment
(red)	Very high enrichment
(dark red)	Extremely high enrichment

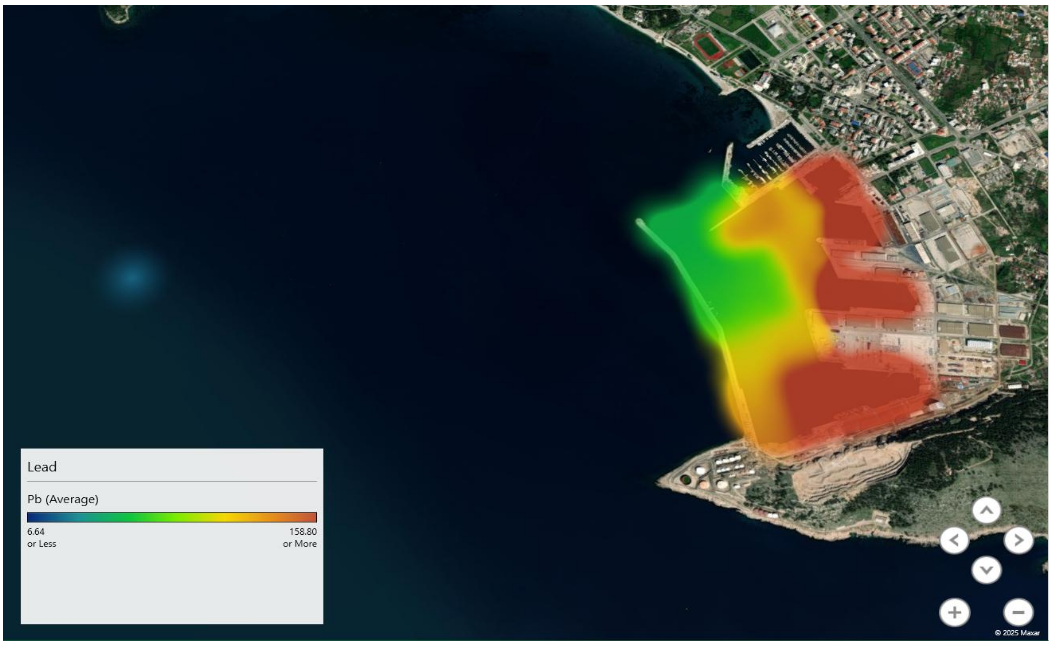
Copper and lead, in particular, show extremely high enrichment, EF values for copper exceed 80 at some sites, while lead surpasses 24, indicating strong anthropogenic input. These findings are consistent with the operational profile of the port, where bulk handling of metal concentrates is a routine activity. Cadmium also demonstrates significant enrichment, with EF values reaching up to 16.5, further pointing to industrial sources. In contrast, elements such as nickel and chromium maintain EF values close to or below 1, suggesting their presence in sediments is primarily due to natural geological processes.

Taken together, the CF, MPLI, and EF indices paint a coherent picture of sediment contamination in the Port of Bar. The data not only confirm the presence of elevated concentrations of heavy metals but also attribute their origin to specific anthropogenic activities within the port. The spatial correlation between contamination hotspots and operational zones underscores the need for targeted mitigation strategies and ongoing environmental monitoring to manage and reduce the impact of port-related pollution.

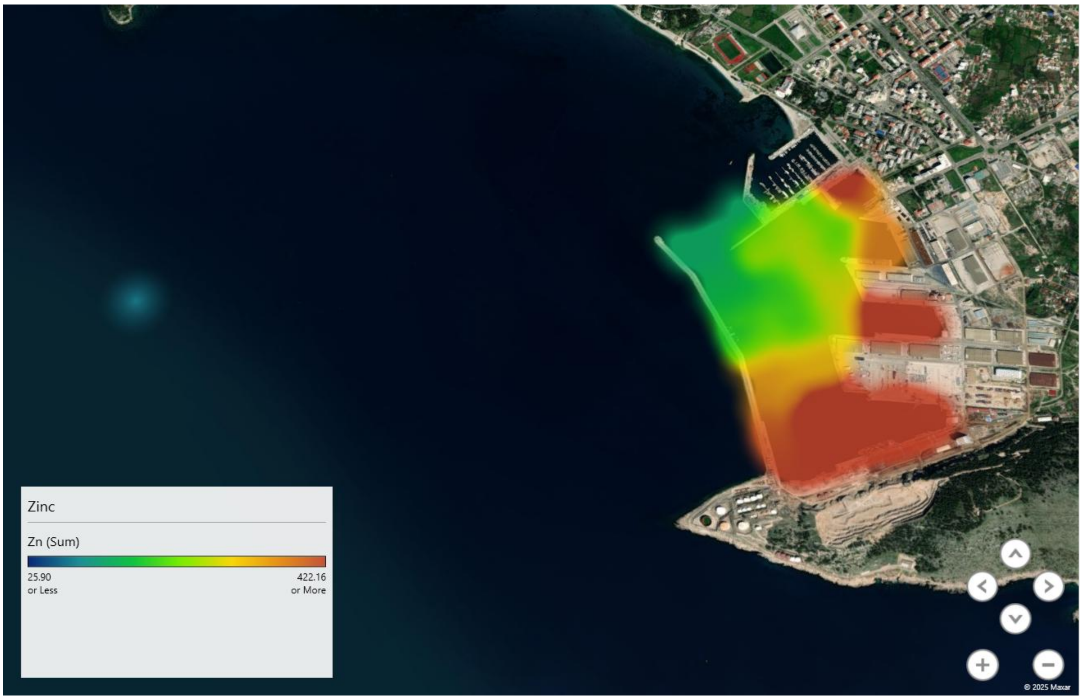
To provide a clearer representation of the contamination status across the study area, spatial distribution maps of metal concentrations are presented in the following sections. These maps illustrate the geographic variability of contamination and help identify localized hotspots influenced by port activities. Given the elevated values observed in the analytical results, maps have been generated for **copper** (map 2), **lead** (map 3), **cadmium** (map 5) and **zinc** (map 4) —the elements that exhibited the highest contamination factors and enrichment levels. Their spatial patterns offer valuable insight into the extent and origin of pollution, particularly in areas adjacent to the cargo-handling zone for metal concentrates.



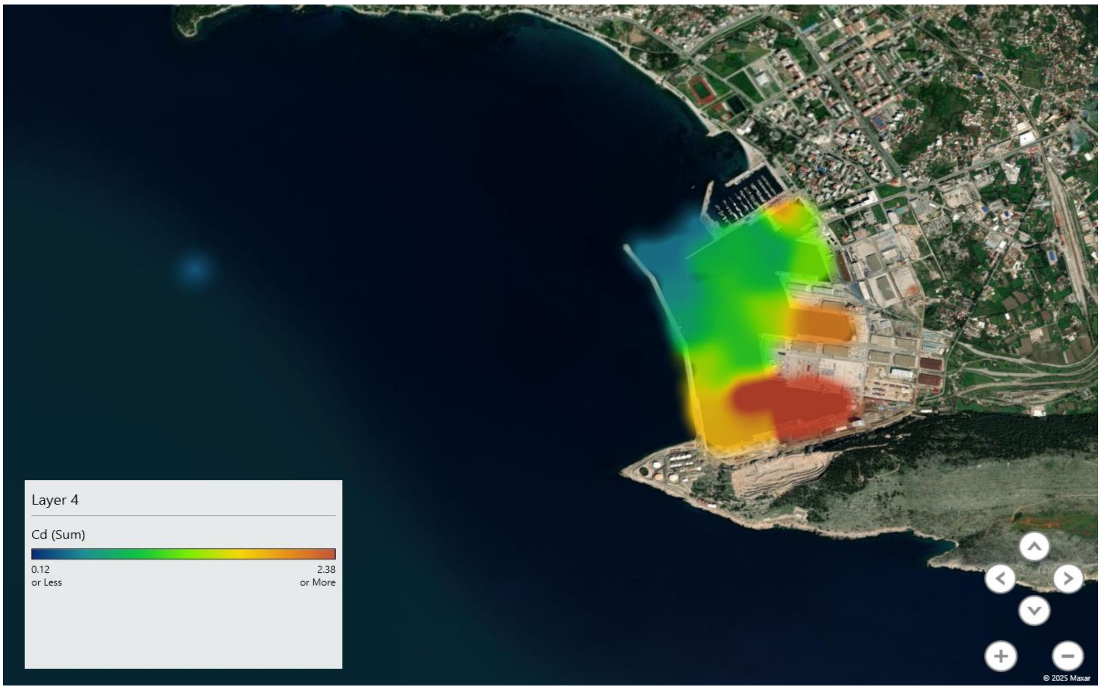
Map 2- Spatial distribution of coper concentration in sediment



Map 3. Spatial Distribution of Lead Concentration in Sediment



Map 4. Spatial distribution of Zinc concentration in sediment



Map 5. Spatial distribution of cadmium concentration in sediment

8.2 Sequential extraction procedure

Based on the results of the sequential extraction procedure, a risk assessment can be done by calculating the so-called risk assessment code (RAC), i.e. the percentage of elements found in the exchangeable, i.e. carbonate fraction (Jain, 2004; Dalmacija, 2010; Krčmar, 2010). It is considered that sediment containing less than 1% of total metals in the exchangeable and carbonate fraction is safe for the environment, that is, there is no risk for the environment (table 14). Sediment that releases, for example, 50% of total metals from the same fraction is considered highly dangerous for the environment and metals can easily be included in the food chain (Perin et al., 1985; Jain, 2004). Unlike the content of total or pseudo-total content of elements that do not provide a clear picture of the possible origin, nor of the way of their attachment to the sediment, based on the results of the sequential extraction procedure, such an assessment can be made. Also, based on the results of the sequential extraction procedure, the origin of the metal in the sediment can be estimated. It is considered that metals in the adsorptive, exchangeable and carbonate phase, are weaklier bound, more easily and quickly bioavailable, and are therefore of anthropogenic origin. Metals in the inert, residual fraction indicate a natural origin (Förstner, 1983; Blasco et al., 2000; Jain, 2004).

Table 14. Risk assessment based on the percentage of metals in the exchangeable and carbonate fraction of sediments in relation to the total concentration of metals in the sediment (Jain, 2004)

Risk assessment	**Criteria %**
None	< 1
Low	1-10
Medium	11-30
High	31-50
Very High	>50

The most popular sequential procedure used in research is the Tessier scheme. Tessier's procedure foresees the division of elements into five defined fractions:
exchangeable, bound to carbonates and specifically sorbed; bound to iron and manganese oxides; related to organic matter and sulphides; the rest (Tessier et al., 1979). As with other sequential extraction schemes, the availability of elements decreases over time extraction, so the first phase is the most labile and accessible to the plant, and the fifth phase represents the least mobile elements that cannot be mobilized in a normal period of time under natural conditions.

Samples were selected from the Port of Bar, specifically from the inner part of the port where the highest enrichment factor values were observed (56/05, 66/05), as well as from two other locations within the port (47/05, 48/05) where pollution is evident but less pronounced. Additionally, one sample (68/05) was taken as a referent location. The results of the sequential analysis, for five tested samples of sediment, are given in Table 15. Values that were below the detection limit of the method are presented as half the value of the detection limit.

Table 15. Sequential analysis results of sediment samples

		Cd	Pb	As	Cu	Ni	Cr	Zn
		mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg
68/05	Sum	0.279	22.7	14.4	27.6	125	142	82.5
	Extract 1	0.005	0.035	0.100	0.223	0.082	0.020	0.020
	Extract 2	0.039	5.41	0.050	1.72	1.60	0.530	2.54
	Extract 3	0.010	2.37	1.03	1.73	23.0	7.10	14.7
	Extract 4	0.010	3.00	2.75	9.30	11.2	6.40	8.30
	Extract 5	0.240	14.3	10.5	14.6	89.2	128	57.0
47/05	Sum	0.972	86.7	16.2	187	111	133	216
	Extract 1	0.005	0.135	0.135	0.625	0.070	0.020	0.148
	Extract 2	0.047	29.8	0.050	4.62	0.940	0.565	14.1
	Extract 3	0.010	28.5	1.00	1.40	13.6	5.60	38.1
	Extract 4	0.195	6.40	2.70	140	8.28	4.38	27.0
	Extract 5	0.730	21.9	12.4	40.0	88.2	122	137
48/05	Sum	1.350	122	28.6	477	127	142	308
	Extract 1	0.005	0.180	0.190	1.20	0.048	0.020	0.272
	Extract 2	0.055	40.2	0.079	7.10	0.774	0.570	19.3
	Extract 3	0.010	45.7	2.20	1.45	15.1	5.93	54.2
	Extract 4	0.196	10.9	4.50	386	8.20	4.91	36.0
	Extract 5	1.100	25.0	21.6	81.0	103	131	198
56/05	Sum	5.582	360	119	2728	119	161	1318
	Extract 1	0.079	0.830	0.565	1.91	0.090	0.020	2.44
	Extract 2	0.113	129	0.215	15.5	1.29	0.690	90.5
	Extract 3	0.010	150	7.010	2.350	14.8	6.300	162
	Extract 4	0.390	8.30	18.0	1675	7.40	4.40	121
	Extract 5	5.000	72.0	93.0	1033	95.0	150	942
66/05	Sum	2.110	492	40.0	673	90.9	126	549
	Extract 1	0.330	1.28	0.097	1.26	0.161	0.020	3.95
	Extract 2	0.180	141	<0.04	5.90	1.85	0.740	93.0
	Extract 3	0.010	236	2.40	1.38	13.9	8.72	118
	Extract 4	0.680	32.1	10.2	426	10.8	5.70	125
	Extract 5	0.920	81.2	27.3	238	64.2	111	209

Cadmium in all samples was mainly bound in the fifth fraction (Figure 66), indicating a stable form. In samples 56/05 and 66/05, where the enrichment factor values were the highest, a certain proportion of cadmium was also present in the second and fourth phases, which points to a higher potential mobility compared to the reference location (68/05). In particular, in sample 56/05, cadmium reached over 6% in the fourth fraction, while in sample 66/05, around 24% of the total content was found in the first and second fractions combined. This distribution confirms increased bioavailability in these port sediments compared to the referent site.

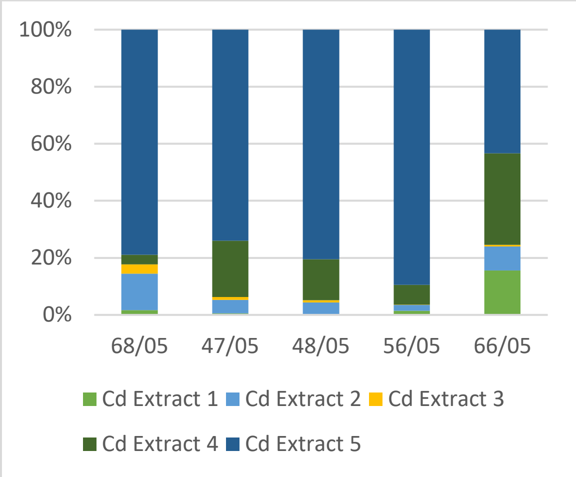


Figure 66. The percentage distribution of cadmium across extraction phases

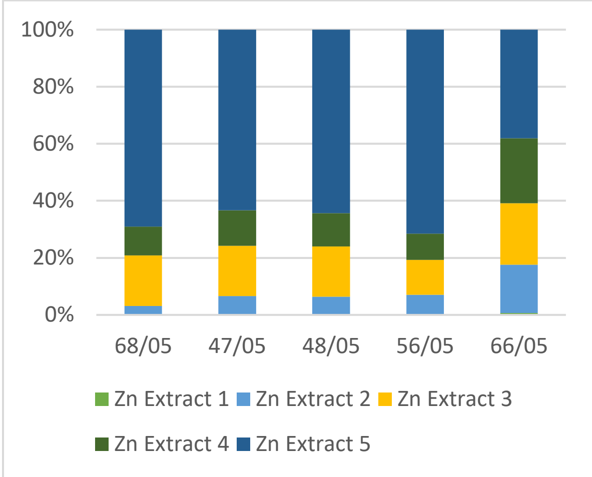


Figure 67. The percentage distribution of zinc across extraction phases

Zinc showed notable differences between the reference and inner port samples (Figure 67). While in the reference location (68/05) about 70% of Zn was bound in the residual fraction, in the most contaminated sediments (66/05) a significant proportion was found in the more mobile phases – particularly in the second and third fractions (up to 45%). This distribution suggests higher bioavailability of Zn in port sediments compared to the reference site.

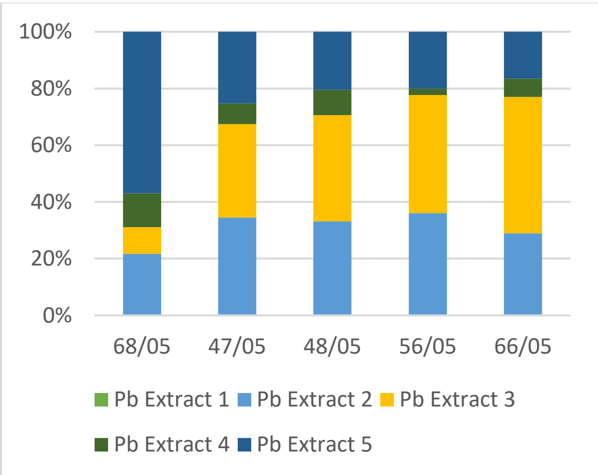


Figure 68. The percentage distribution of lead across extraction phases

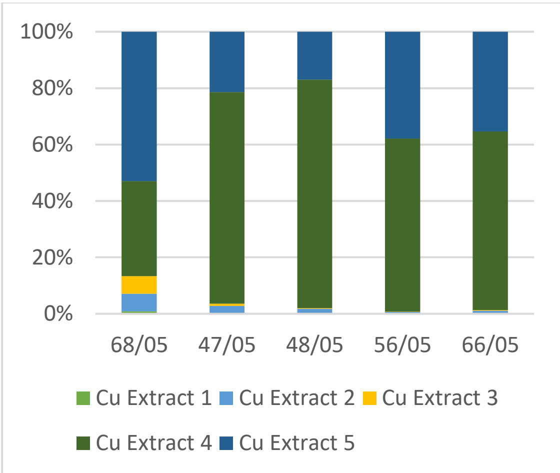


Figure 69. The percentage distribution of coper across extraction phases

The distribution of lead across fractions shows significant differences between samples. In the most contaminated samples (56/05 and 66/05), lead was predominantly associated with the third fraction (iron and manganese oxides), with 36–48% of the total content present in this form. In contrast, in the reference sample, the majority of lead was bound in the fifth fraction. Such distribution indicates a higher potential mobility of Pb in the inner port sediments, which correlates with the observed enrichment factors.

Figure 69 shows the percentage distribution of copper across extraction phases. Copper distribution patterns clearly differentiate the contaminated from the reference site. In samples 56/05 and 48/05, copper was predominantly bound in the fourth fraction, with 60–80% of the total content associated with organic matter and sulphides. In the reference sample, copper was more evenly distributed between the fourth and fifth fractions. This indicates that copper in the port sediments has a higher potential for remobilization compared to the background location.

The distribution of arsenic across the fractions shows that, although RAC values are low, its presence is not limited to the residual fraction (Figure 70). In several samples, arsenic is mainly associated with iron and manganese oxides, which implies that its stability depends on redox conditions. This suggests that arsenic may be remobilized under reducing conditions, indicating anthropogenic influence despite the low RAC classification.

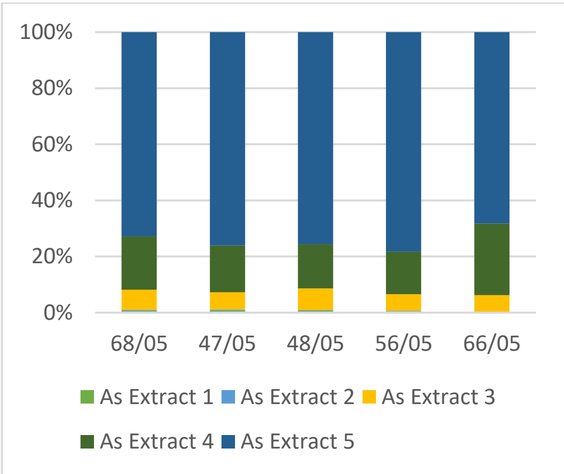


Figure 70. The percentage distribution of arsenic across extraction phases

Although the total concentrations of Ni exceeded the threshold values of the standards, sequential extraction results showed that more than 80% of Ni was bound in the fifth fraction in all tested samples, including the reference location (68/05). The similarity of distribution profiles (Figure 72) between contaminated and reference sediments indicates that nickel is of natural origin, with low potential bioavailability. Chromium followed a similar pattern to nickel (Figure 71). Despite exceeding the guideline values, chromium was predominantly present in the residual fraction, with more than 85% of the total content bound in the fifth fraction in all samples, including the reference site. This uniformity across sites confirms that Cr in these sediments is also of natural origin and unlikely to pose ecological risk.

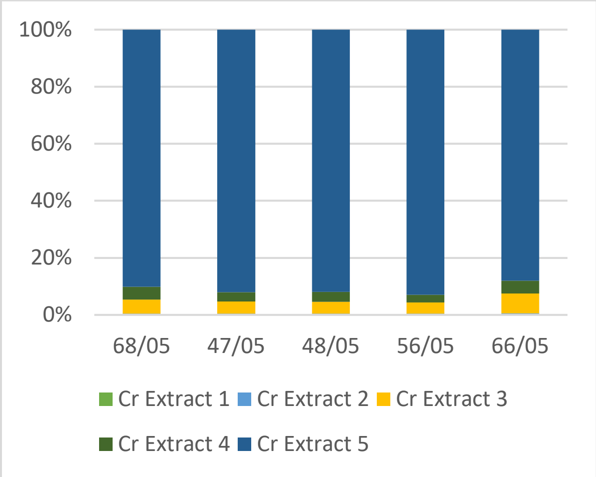


Figure 71. The percentage distribution of chromium across extraction phases

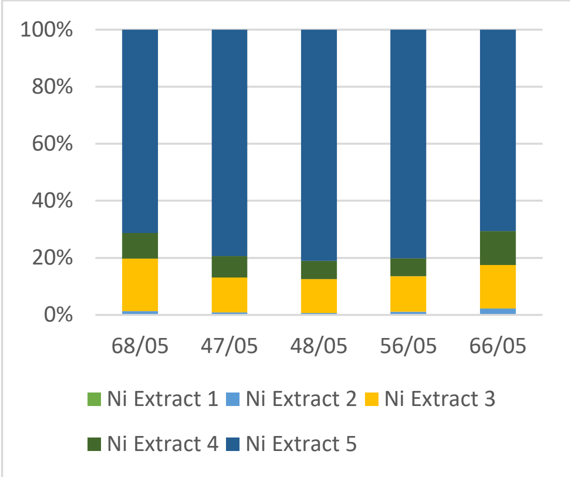


Figure 72. The percentage distribution of nickel across extraction phases

The sequential extraction results align well with the findings of the contamination factor (CF) and enrichment factor (EF). Metals that displayed the highest CF and EF values, such as copper, lead, and cadmium, were also predominantly present in the more mobile and potentially bioavailable fractions of the sediments. This confirms that their elevated concentrations are not only of anthropogenic origin but also pose an increased environmental risk due to their higher mobility. In contrast, chromium and nickel, which showed low CF values and EF close to 1, were mainly associated with the residual fraction, indicating their geogenic origin and limited ecological relevance.

The RAC evaluation provides additional insight into the potential mobility of metals in port sediments. Lead is the only element for which an anthropogenic origin is evident, with a substantial share found in the more mobile fractions. For copper, although the RAC values are not high, its availability cannot be simply interpreted through the percentage in the exchangeable and carbonate fractions. A significant proportion of copper, as well as lead, zinc, and arsenic, originates from ore concentrates, which are not in forms readily soluble in carbonates. This explains why the calculated RAC values for some metals may underestimate their environmental significance.

8.3 Indicators of potential ecological effects on the aquatic environment in Port of Bar

To evaluate sediment toxicity in the study area, French threshold values were applied, focusing on two principal indicators: ΣQN1 and QPECm. The ΣQN1 index is obtained by summing the ratios of individual contaminant concentrations to their respective French N1 threshold (PEC) values. This aggregate measure reflects the overall potential pressure exerted by multiple pollutants on the aquatic environment. The second indicator, QPECm, represents a generalized sediment risk quotient. It is calculated by taking the mean of the ΣQN1 values for a given sediment sample and dividing it by the number of pollutants considered, in this case, thirty-two. Equation (1) summarizes this approach, which is consistent with the methodology prescribed in French regulations for the management of marine dredged sediments.

$$QPECm = (\Sigma\ n\ i=1\ (Ci/PECi))/n \quad (1)$$

where QPECm is a general sediment risk quotient,
Ci is the contaminant concertation,
n is the number of measured contaminants,
PECi is the predicted effect concentration (French N1 level).

The resulting value acts as a screening tool for potential sediment toxicity. A QPECm value below one indicates that contaminant levels remain under the regulatory thresholds, implying non-toxic conditions. In contrast, values exceeding one highlight possible toxic effects and signal ecological risk for the marine environment under study.
Calculated QN1 and QPECm values for the anaysed sediment samples across the Port of Bar are presented in Table 16.

Table 16. QN1 and QPECm for sediment in Port of Bar

Zones	QN1	QPECm
68/05-Reference	7.71	0.24
45/05	11.00	0.34
64/05	13.18	0.41
46/05	14.69	0.46
47/05	16.11	0.50
65/05	18.38	0.57
54/05	18.79	0.59
53/05	20.11	0.63
55/05	21.34	0.67
60/05	22.61	0.71
48/05	24.66	0.77
59/05	31.82	0.99
49/05	35.18	1.10
58/05	36.49	1.14
51/05	36.97	1.16
66/05	42.42	1.33

50/05	46.59	1.46
52/05	55.15	1.72
57/05	67.16	2.10
56/05	103.6	3.24

QPECm values across the surveyed zones range from 0.24 to 3.24, reflecting a spectrum from low to high potential sediment toxicity relative to French N1 thresholds. Within the harbor, low QPECm values (0.34–0.99) dominate several zones (45/05–48/05, 53/05–55/05, 59/05, 60/05, 64/05–65/05), indicating sub-threshold contaminant levels. Copper (Cu) consistently represents the primary contributor, accompanied by substantial contributions from nickel (Ni) and chromium (Cr), with lead (Pb), arsenic (As), zinc (Zn), and cadmium (Cd) contributing at secondary or minor levels. Organic contaminants (PAHs, PCBs, TBT) are generally negligible, with only minor localized contributions (e.g., PCB-101/118 in zone 46/05; fluorene in zone 60/05).

Elevated QPECm values (1.10–1.72) are observed in zones 49/05–52/05, 58/05 and 66/05, indicating multi-constituent enrichment above N1 thresholds. Copper remains the dominant driver, often accompanied by substantial contributions from Ni, Pb, As, Zn, Cd, and Cr, depending on the zone. Organic compounds, while occasionally present at assessment-relevant concentrations (e.g., PCBs, fluorene), exert minor influence relative to the metal fraction.

The highest QPECm values occur in zones 56/05 (3.24) and 57/05 (2.10). In each zone, Cu accounts for the largest share of QPECm, with substantial co-contributions from Cd and Zn; As, Pb, Ni, and Cr provide additional secondary input. Regarding organics, fluorene (PAH) and PCB congeners occur at assessment-relevant levels but remain minor relative to the metals.
Overall, the spatial pattern demonstrates a metal-dominated sediment contamination profile, with Cu, Ni, Cr, and other analysed metals contributing most to potential toxicity, while organic pollutants play a secondary role. Low to moderate QPECm values prevail in edge areas, whereas elevated to high values cluster in central harbor areas.

Reference point: Zone outside the harbor influence, reference point - zone 68/05, displays the lowest contamination, with metal concentrations well below threshold levels and negligible organic presence. QPECm is calculated to be 0.24 which is roughly one quarter of the N1 thresholds. The composition is metal-led: Ni provides the largest share of QPECm, Cr is secondary**,** Cu is minor, and As**,** Zn and Cd remain very low. Organic compounds (PAHs, PCBs, TBT) are negligible, showing no signature of port-related inputs. Overall, this station serves as a robust a robust reference for background conditions for the harbour assessment.

The entire area of the port

The integrated evaluation of sediment quality across the Port of Bar provides a comprehensive overview on the cumulative contamination status.

The cumulative sum of individual risk quotients (∑QN1) for all analyzed pollutants across the port area is calculated to be 33.5. This sum represents the combined contribution of each of the 32 contaminants considered. The general sediment risk quotient, denoted as QPECm, is obtained by dividing this cumulative value by the total number of pollutants, yielding a QPECm of 1.05 for the Port of Bar. The mean ratio of measured concentrations to French N1 thresholds across all analytes and all zones is just above 1. This does not imply that every analyte or every zone exceeds N1; rather, it reflects the overall average and therefore masks spatial heterogeneity.

The calculated cumulative sum of individual risk quotients (ΣQN1 = 33.5) and the corresponding average sediment risk quotient (QPECm = 1.05) indicate that, on a port-wide scale, sediment contamination is generally moderate.

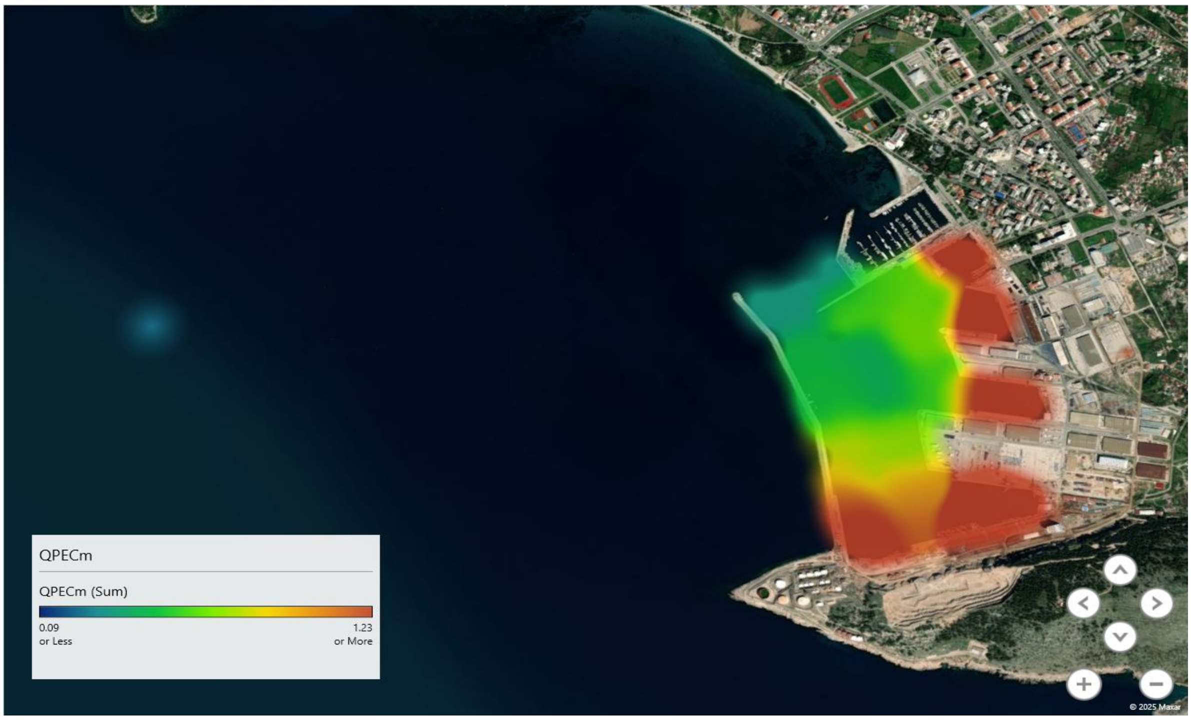
A spatially heterogeneous pattern of contamination emerges. The large majority of zones exhibit QPECm values < 1, signifying sediment quality that does not pose a significant toxicological risk. In these areas, contaminant levels are close to or below background thresholds, reflecting relatively limited anthropogenic input.

In contrast to these zones, there are areas within the harbor that exhibit clear enrichment of contaminants, with QPECm values exceeding 1 and reflecting stronger anthropogenic influence.

Among these, zones 56/05 (QPECm = 3.24) and 57/05 (QPECm = 2.10) represent the most critical sites. Their elevated QPECm values highlight substantial contamination by heavy metals, predominantly copper (Cu), cadmium (Cd), and zinc (Zn), with additional contributions from arsenic (As), lead (Pb), nickel (Ni), and chromium (Cr). Organic contaminants, including selected PAH and PCB congeners, were also detected at assessment-relevant levels but remained secondary to the metal-driven contamination profile. These hotspots are under the highest anthropogenic pressure, reflecting intense port activities.

Other zones with intermediate levels of contamination (QPECm between 1.1 and 1.7), such as 49/05, 50/05, 51/05, 52/05, 58/05, and 66/05, also indicate multi-element enrichment. While not as extreme as the hotspots, these areas collectively reinforce the conclusion that port-related activities exert a measurable ecological footprint, particularly through the accumulation of metal pollutants.

The spatial map of QPECm (Map 6) values presented in the report serves as a visual tool to interpret these findings. It demonstrates the concentration gradient, with low values at the outer reference points and peripheral areas, transitioning toward elevated and high values within the central basin of the port. This visual evidence provides clear insight into the spatial dynamics of contamination, directly linking the most polluted sediments to zones of intensive human activity.



Map 6. Spatial map of QPECm values in sediment

The comprehensive assessment of the Port of Bar sediments confirms a moderately contaminated aquatic environment, dominated by heavy metal inputs. While large portions of the port remain within safe ecological limits, localized hotspots exert a disproportionate influence on the port-wide average. Zones 56/05 and 57/05, in particular, stand out as areas of serious ecological concern and represent priority targets for future monitoring, management, and potential remediation measures. The cumulative evaluation highlights that the overall sediment quality in the Port of Bar is predominantly shaped by localized anthropogenic pressures, with the highest impacts concentrated in zones of intensive port activities and maritime operations.

9. Conclusion – Port of Bar Sediment Quality Assessment

The comprehensive investigation of sediments from the Port of Bar provides a multidimensional picture of sediment quality in an area that functions simultaneously as a strategic economic hub and a zone of heightened environmental vulnerability. By integrating chemical analysis, granulometric characterization, pollution indices (CF, MPLI, EF), sequential extraction procedures, and ecotoxicological indicators (ΣQN1 and QPECm), the study delivers a robust evidence base for evaluating ecological risks and regulatory implications.

Heavy metals dominate the contamination profile. Copper is clearly the most critical pollutant, with concentrations at numerous sites far exceeding the French N2 thresholds, Dutch Intervention Values, and, in more than ten stations, the 2024 French thresholds immersion values. Copper thus represents both a significant ecological risk and the primary regulatory constraint, as sediments from these zones cannot be disposed of offshore under any legal framework.

Zinc shows a similar pattern, with frequent exceedances of both French and Dutch limits, while lead and arsenic display localized but distinct hotspots surpassing intervention thresholds. Cadmium contamination is more diffuse, with widespread exceedances of N1 but limited N2 exceedances, indicating a persistent but moderate influence. Nickel and chromium, in contrast, exhibit elevated concentrations across the study area, including reference sites, strongly suggesting geogenic enrichment. Sequential extraction confirms this interpretation, as nickel and chromium are predominantly bound in residual, non-bioavailable fractions. Mercury concentrations remain low and uniform across all sites, confirming that this element is not of concern in the current setting.

Organic contaminants (PCBs, PAHs, TBT) play a secondary role relative to metals. PCBs are generally low, with sporadic exceedances of N1 thresholds (notably PCB-101 and PCB-118), though concentrations remain far below Dutch and French threshold limits. PAHs are predominantly negligible, with the exception of fluorene, which showed isolated N1 exceedances in three stations. Tributyltin (TBT) is uniformly below guideline values, and mineral oil concentrations are also far under Dutch Intervention thresholds, confirming the absence of petroleum-related sediment stress.

Indices of pollution (CF, MPLI, EF) clearly reinforce the metal-dominated profile. The Contamination Factor (CF) and Enrichment Factor (EF) analyses clearly identify copper, zinc, cadmium, and lead as pollutants of strong anthropogenic origin. Metal Pollution Load Index (MPLI) values above 1 across most port zones further confirm deterioration relative to reference conditions. Sequential extraction data further confirm that copper, lead, cadmium, and zinc occur in more mobile and bioavailable fractions, underscoring both their anthropogenic origin and elevated ecological risk. Conversely, nickel and chromium are primarily bound in residual fractions, consistent with natural geochemical sources and limited bioavailability.

Ecotoxicological indicators offer a holistic view of potential biological impact. The ΣQN1 results reveal widespread exceedances for Cu, Zn, and Pb, confirming their regulatory and ecological importance. QPECm values display marked spatial heterogeneity: while many peripheral sites remain below the toxicological risk threshold (QPECm < 1), several central harbor stations demonstrate high-risk profiles, with QPECm values exceeding 2 and in some cases above 3, particularly at zones 56/05 and 57/05. These findings confirm the presence of severe ecological hotspots, where multi-element contamination exerts cumulative stress on benthic organisms and could impair ecosystem functioning.

Integrated interpretation reveals that while large parts of the port remain within acceptable ecological limits, localized zones exert a disproportionate influence on overall sediment quality. The contamination profile is unequivocally shaped by port operations, particularly ore concentrate transshipment and industrial activities, which drive both the spatial distribution and intensity of pollution.

Conclusion

Port of Bar sediments display a contamination pattern typical of industrial and ore-transshipment harbors, where heavy metals—particularly copper—dominate, supported by lead, arsenic, zinc, and cadmium. Organic pollutants are of marginal importance, and their concentrations remains within acceptable limits. The combined evidence from chemical analysis, granulometry, enrichment indices, sequential extraction, and ecotoxicological evaluation demonstrates the strong anthropogenic imprint of port activities on sediment quality.

Management Implications

1. Continuous long-term monitoring of sediment quality to track spatial and temporal contamination trends.
2. Risk management of identified hotspots, particularly where copper concentrations exceed threshold values.
3. Integration of sediment quality management into port development planning, ensuring that dredging, transshipment, and waste handling follow strict environmental safeguards.
4. Promotion of best practices in industrial and maritime operations to minimize further heavy metal inputs.
5. Promotion of best practices in industrial and maritime operations to reduce further pollutant inputs, particularly of heavy metals.

Overall, this study provides a comprehensive diagnostic of the current contamination status of Port of Bar sediments and establishes a scientific and regulatory foundation for evidence-based decision-making. Implementing the recommended measures will be essential to mitigate further degradation, protect benthic ecosystems, and safeguard the ecological integrity of Montenegro's coastal and marine environment, aligning with the objectives of the MedProgramme and the Barcelona Convention.

10. Literature

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ANNEX 1 Tabular overview of results of analysis

RESULTS OF ANALYSIS OF CONTAMINATS IN SEDIMENT SAMPLES OF PORT OF BAR

Sample name		45/05/25	46/05/25	47/05/25	48/05/25	49/05/25	50/05/25	51/05/25	
Coordinates		42.097976° 19.081558°	42.095862° 19.079986°	42.093229° 19.079934°	42.091162° 19.079044°	42.089473° 19.077908°	42.087994° 19.077230°	42.095621° 19.089827°	
Sampling depth (m)		12	14	14	14	13	9	5	
Sampling date		18.06.2025	18.06.2025	18.06.2025	18.06.2025	18.06.2025	18.06.2025	20.06.2025.	
Parameter	Unit*	Results of analysis							Method
Metals:									
Cadmium	mg/kg	0.42	0.52	0.87	1.40	1.74	1.80	1.26	IAEA-MEL-LPB
Mercury	mg/kg	0.04	0.07	0.05	0.05	0.06	0.07	0.18	AMA-112
Copper	mg/kg	119	120	192	525	886	1293	949	IAEA-MEL-LPB
Nickel	mg/kg	94	90	104	108	117	94	85	IAEA-MEL-LPB
Iron	mg/kg	44784	44171	46613	48180	49110	49812	46362	IAEA-MEL-LPB
Lead	mg/kg	55	59	73	103	118	136	216	IAEA-MEL-LPB
Zinc	mg/kg	131	147	226	337	391	421	349	IAEA-MEL-LPB
Chromium	mg/kg	130	129	165	187	189	168	171	IAEA-MEL-LPB
Arsenic	mg/kg	14	15	17	28	47	62	45	IAEA-MEL-LPB
Polycyclic Aromatic Hydrocarbons									
Naphtalene	µg/kg	<1	<1	<1	1.2	4.1	55.6	37.4	EPA 8270D
2-methylnaphtalene	µg/kg	<1	<1	<1	11.5	8.5	74.2	41.6	EPA 8270D
1-methylnaphtalene	µg/kg	4.5	3.5	5.8	14.8	13.3	60.7	29.9	EPA 8270D
Acenaphtylene	µg/kg	<1	<1	<1	<1	<1	<1	<1	EPA 8270D
Acenaphtene	µg/kg	1.6	1.4	1.4	2.9	3.3	7.6	8.2	EPA 8270D
Fluorene	µg/kg	2.7	1.3	3.2	7.7	5.8	15.0	12.8	EPA 8270D
Phenanthrene	µg/kg	9.3	10.7	14.4	24.4	30.1	53.0	50.7	EPA 8270D
Anthracene	µg/kg	1.6	2.0	3.0	4.3	5.1	7.0	6.7	EPA 8270D
Fluoranthene	µg/kg	19.3	24.9	37.0	45.3	45.5	50.9	61.2	EPA 8270D
Pyrene	µg/kg	19.6	25.7	37.5	44.0	46.5	51.7	62.7	EPA 8270D
Benzo(a)anthracene	µg/kg	12.1	17.1	23.3	28.8	30.7	38.5	31.0	EPA 8270D
Chrysene	µg/kg	11.5	15.4	20.1	25.7	30.2	40.1	34.0	EPA 8270D
Benzo(b)fluoranthene	µg/kg	19.7	24.4	38.4	44.3	44.5	52.9	45.3	EPA 8270D
Benzo(k)fluoranthene	µg/kg	7.8	11.2	15.0	16.9	16.6	22.4	19.5	EPA 8270D

Benzo(a)pyrene	µg/kg	12.8	18.8	27.9	34.0	34.2	45.6	32.8	EPA 8270D
Indeno(1.2.3-cd)pyrene	µg/kg	12.6	17.4	22.7	27.5	27.4	34.4	35.1	EPA 8270D
Dibenzo(a.h)anthracene	µg/kg	2.2	3.7	6.0	7.3	7.7	9.6	5.3	EPA 8270D
Benzo(g.h.i)perylene	µg/kg	16.5	22.5	27.8	36.0	37.5	45.4	48.5	EPA 8270D
ΣPAHs	µg/kg	154	200	284	376	391	665	563	EPA 8270D
TPH	mg/kg	113	160	97	88	107	131	643	ISO 16703:2004
PCB congeners:	µg/kg								
PCB 18	µg/kg	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	EPA 8270D
PCB 31	µg/kg	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	EPA 8270D
PCB 28	µg/kg	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	EPA 8270D
PCB 52	µg/kg	<0.5	1.24	0.92	<0.5	<0.5	1.60	1.18	EPA 8270D
PCB 44	µg/kg	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	EPA 8270D
PCB 101	µg/kg	4.50	13.89	7.93	3.75	6.01	7.35	3.86	EPA 8270D
PCB 149	µg/kg	2.40	8.91	4.44	2.33	3.53	4.76	3.23	EPA 8270D
PCB 118	µg/kg	4.09	10.57	7.05	5.42	7.63	9.81	4.36	EPA 8270D
PCB 153	µg/kg	4.52	13.56	7.91	4.21	6.17	7.61	4.94	EPA 8270D
PCB 138	µg/kg	5.30	14.96	8.83	5.78	8.37	10.85	6.19	EPA 8270D
PCB 180	µg/kg	2.66	8.95	4.96	2.41	3.14	4.11	3.54	EPA 8270D
PCB 194	µg/kg	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	EPA 8270D
Organotin compounds:	µg/kg								
Monobutil-tin	µg/kg	<0.004	<0.004	<0.004	<0.004	<0.004	0.004	0.022	ISO 23161:2018
Dibutil- tin	µg/kg	<0.004	0.004	<0.004	<0.004	<0.004	<0.004	0.019	ISO 23161:2018
Tributil-tin	µg/kg	<0.004	0.007	0.007	0.004	0.009	0.005	0.034	ISO 23161:2018
Monooktil-tin	µg/kg	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	0.007	ISO 23161:2018
Tetrabutil-tin	µg/kg	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	ISO 23161:2018
Dioktil-tin	µg/kg	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	ISO 23161:2018
Trifenil-tin	µg/kg	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	ISO 23161:2018
Tricyclohexyl-tin	µg/kg	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	ISO 23161:2018
Organochlorine pesticides:	µg/kg								
HCB	µg/kg	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	EPA 8270D
Aldrin	µg/kg	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	EPA 8270D
α-BHC	µg/kg	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	EPA 8270D
β-BHC	µg/kg	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	EPA 8270D
Lindane	µg/kg	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	EPA 8270D
δ-BHC	µg/kg	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	EPA 8270D
α-Chlordane	µg/kg	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	EPA 8270D

γ-Chlordane	**μg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
4,4′-DDT	**μg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
4,4′-DDD	**μg/kg**	**0.44**	**0.61**	**0.42**	**0.26**	**0.39**	**0.29**	**0.26**	**EPA 8270D**
4,4′-DDE	**μg/kg**	**0.44**	**0.61**	**0.42**	**0.26**	**0.39**	**0.29**	**0.26**	**EPA 8270D**
2,4′-DDT	**μg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
2,4′-DDD	**μg/kg**	**0.12**	**0.14**	**0.10**	**0.06**	**0.14**	**0.07**	**0.09**	**EPA 8270D**
2,4′-DDE	**μg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Dieldrin	**μg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
α-Endosulfan	**μg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
β-Endosulfan	**μg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Endosulfan sulfate	**μg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Endrin	**μg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Heptachlor	**μg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Heptachlor epoxide	**μg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
PFAS:	**μg/kg**								
PFBS	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFDA	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFDoDA	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**0.078**	**EPA 1633**
PFDoS	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFDS	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHpA	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHpS	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHxA	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHxDA	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHxS	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFNA	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFNS	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFOA	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFODA	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFOS	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFPeS	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFTeDA	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**0.078**	**EPA 1633**
PFTrDA	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFUnDA	**μg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**

***dw**

Sample name		52/05/25	53/05/25	54/05/25	55/05/25	56/05/25	57/05/25	58/05/25	
Coordinates		42.093209° 19.088705°	42.095483° 19.087359°	42.095432° 19.084663°	42.093687° 19.085293°	42.086282° 19.082486°	42.086837° 19.083900°	42.087103° 19.080123°	
Sampling depth (m)		10	10	10	9	13	13	14	
Sampling date		20.06.2025.	20.06.2025.	20.06.2025.	20.06.2025.	25.06.2025.	25.06.2025.	25.06.2025.	
Parameter	Unit*	Results of analysis							Method
Metals:									
Cadmium	mg/kg	1.24	0.73	0.89	0.90	6.61	5.67	1.86	IAEA-MEL-LPB
Mercury	mg/kg	0.09	0.07	0.06	0.07	0.09	0.10	0.09	AMA-112
Copper	mg/kg	1708	396	348	391	2997	1559	857	IAEA-MEL-LPB
Nickel	mg/kg	92	93	90	94	108	113	97	IAEA-MEL-LPB
Iron	mg/kg	47197	48784	43058	47855	53159	51546	43806	IAEA-MEL-LPB
Lead	mg/kg	263	109	131	125	397	280	178	IAEA-MEL-LPB
Zinc	mg/kg	364	206	247	266	1371	1065	474	IAEA-MEL-LPB
Chromium	mg/kg	155	175	158	176	190	163	191	IAEA-MEL-LPB
Arsenic	mg/kg	84	29	24	26	111	65	47	IAEA-MEL-LPB
Polycyclic Aromatic Hydrocarbons Hydrocarbons									
Naphtalene	µg/kg	43.5	53.0	24.4	20.4	3.1	<1	27.5	EPA 8270D
2-methylnaphtalene	µg/kg	50.3	46.2	27.3	23.7	7.8	3.1	34.2	EPA 8270D
1-methylnaphtalene	µg/kg	38.0	35.1	21.8	19.0	9.4	3.9	31.5	EPA 8270D
Acenaphtylene	µg/kg	1.2	<1	<1	<1	<1	<1	<1	EPA 8270D
Acenaphtene	µg/kg	7.0	4.3	3.7	5.3	2.5	1.5	5.5	EPA 8270D
Fluorene	µg/kg	9.9	7.0	6.5	9.5	52.8	54.3	8.8	EPA 8270D
Phenanthrene	µg/kg	51.7	33.1	36.5	46.8	79.0	52.7	50.9	EPA 8270D
Anthracene	µg/kg	6.8	4.1	5.1	7.1	11.3	9.1	8.3	EPA 8270D
Fluoranthene	µg/kg	59.6	38.2	46.9	68.3	85.8	69.5	82.0	EPA 8270D
Pyrene	µg/kg	56.1	36.9	47.1	63.5	87.3	70.7	77.9	EPA 8270D
Benzo(a)anthracene	µg/kg	40.9	26.0	33.6	49.2	67.7	58.4	58.4	EPA 8270D
Chrysene	µg/kg	41.3	23.7	32.2	46.6	62.6	50.0	54.2	EPA 8270D
Benzo(b)fluoranthene	µg/kg	61.9	41.1	45.1	72.5	72.8	80.5	121.9	EPA 8270D
Benzo(k)fluoranthene	µg/kg	24.8	15.4	19.4	30.8	40.8	33.9	36.6	EPA 8270D
Benzo(a)pyrene	µg/kg	46.9	27.6	37.0	58.5	84.7	70.9	76.6	EPA 8270D
Indeno(1.2.3-cd)pyrene	µg/kg	42.6	26.2	30.1	46.4	77.8	61.6	56.3	EPA 8270D

Dibenzo(a.h)anthracene	**µg/kg**	**10.3**	**5.4**	**6.7**	**9.4**	**16.8**	**15.0**	**15.3**	**EPA 8270D**
Benzo(g.h.i)perylene	**µg/kg**	**54.6**	**31.1**	**36.8**	**53.3**	**78.3**	**64.8**	**66.6**	**EPA 8270D**
ΣPAHs	**µg/kg**	**647**	**454**	**460**	**630**	**840**	**700**	**812**	**EPA 8270D**
TPH	**mg/kg**	**263**	**121**	**88**	**126**	**205**	**140**	**152**	**ISO 16703:2004**
PCB congeners:									
PCB 18	**µg/kg**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**0.97**	**0.75**	**<0.5**	**EPA 8270D**
PCB 31	**µg/kg**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**2.59**	**2.30**	**0.54**	**EPA 8270D**
PCB 28	**µg/kg**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**3.80**	**3.97**	**0.98**	**EPA 8270D**
PCB 52	**µg/kg**	**1.01**	**0.59**	**<0.5**	**<0.5**	**4.76**	**6.09**	**1.13**	**EPA 8270D**
PCB 44	**µg/kg**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**2.66**	**2.96**	**0.55**	**EPA 8270D**
PCB 101	**µg/kg**	**2.86**	**1.90**	**1.73**	**2.99**	**19.25**	**23.44**	**5.54**	**EPA 8270D**
PCB 149	**µg/kg**	**2.43**	**1.98**	**1.29**	**2.48**	**8.15**	**8.48**	**3.25**	**EPA 8270D**
PCB 118	**µg/kg**	**3.32**	**2.44**	**2.07**	**2.86**	**18.73**	**18.38**	**6.34**	**EPA 8270D**
PCB 153	**µg/kg**	**3.80**	**2.70**	**2.55**	**4.05**	**13.67**	**14.16**	**5.42**	**EPA 8270D**
PCB 138	**µg/kg**	**4.75**	**3.42**	**2.78**	**4.26**	**19.18**	**19.59**	**6.95**	**EPA 8270D**
PCB 180	**µg/kg**	**2.85**	**1.97**	**1.74**	**2.69**	**6.59**	**6.52**	**2.76**	**EPA 8270D**
PCB 194	**µg/kg**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**EPA 8270D**
Organotin compounds:	**µg/kg**								
Monobutil-tin	**µg/kg**	**0.013**	**0.004**	**0.004**	**0.005**	**<0.004**	**0.008**	**0.005**	**ISO 23161:2018**
Dibutil- tin	**µg/kg**	**0.011**	**0.005**	**<0.004**	**0.004**	**<0.004**	**0.005**	**<0.004**	**ISO 23161:2018**
Tributil-tin	**µg/kg**	**0.021**	**0.014**	**0.007**	**0.01**	**0.013**	**0.028**	**0.009**	**ISO 23161:2018**
Monooktil-tin	**µg/kg**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**ISO 23161:2018**
Tetrabutil-tin	**µg/kg**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**ISO 23161:2018**
Dioktil-tin	**µg/kg**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**ISO 23161:2018**
Trifenil-tin	**µg/kg**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**ISO 23161:2018**
Tricyclohexyl-tin	**µg/kg**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**ISO 23161:2018**
Organochlorine pesticides:	**µg/kg**								
HCB	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Aldrin	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
α-BHC	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
β-BHC	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Lindane	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
δ-BHC	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
α-Chlordane	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
γ-Chlordane	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
4,4′-DDT	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**

4,4′-DDD	**µg/kg**	**0.61**	**1.03**	**0.61**	**0.96**	**0.34**	**0.32**	**<0.05**	**EPA 8270D**
4,4′-DDE	**µg/kg**	**0.36**	**0.57**	**0.32**	**0.42**	**0.74**	**0.45**	**2.20**	**EPA 8270D**
2,4′-DDT	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
2,4′-DDD	**µg/kg**	**0.16**	**0.27**	**0.15**	**0.23**	**0.12**	**0.09**	**<0.05**	**EPA 8270D**
2,4′-DDE	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**0.086**	**EPA 8270D**
Dieldrin	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
α-Endosulfan	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
β-Endosulfan	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Endosulfan sulfate	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Endrin	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Heptachlor	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Heptachlor epoxide	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
PFAS:	**µg/kg**								
PFBS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFDA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFDoDA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFDoS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFDS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHpA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHpS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHxA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHxDA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHxS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFNA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFNS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFOA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFODA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFOS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFPeS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFTeDA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFTrDA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFUnDA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**

* **dw**

Sample name		59/05/25	60/05/25	64/05/25	65/05/25	66/05/25	68/05/25	
Coordinates		42.088190° 19.080774°	42.090260° 19.080867°	42.093056° 19.083092°	42.091931° 19.084239°	42.090045° 19.086712°	42.10983° 19.05773°	
Sampling depth (m)		14	14	12	12	14	34	
Sampling date		25.06.2025.	25.06.2025.	30.06.2025.	30.06.2025.	30.06.2025.	30.06.2025.	
Parameter	Unit*	Results of analysis						Method
Metals:								
Cadmium	mg/kg	2.76	1.02	1.02	1.39	2.06	0.33	IAEA-MEL-LPB
Mercury	mg/kg	0.07	0.06	0.09	0.09	0.23	0.06	AMA-112
Copper	mg/kg	631	353	186	319	840	28	IAEA-MEL-LPB
Nickel	mg/kg	114	100	86	85	100	121	IAEA-MEL-LPB
Iron	mg/kg	49803	41568	42612	43479	43260	43576	IAEA-MEL-LPB
Lead	mg/kg	175	114	73	138	580	24	IAEA-MEL-LPB
Zinc	mg/kg	586	317	193	274	612	84	IAEA-MEL-LPB
Chromium	mg/kg	192	148	124	119	145	159	IAEA-MEL-LPB
Arsenic	mg/kg	35	24	17	22	43	14	IAEA-MEL-LPB
Polycyclic Aromatic Hydrocarbons:								
Naphtalene	µg/kg	7.6	<1	18.2	81.8	13.2	1.2	EPA 8270D
2-methylnaphtalene	µg/kg	8.5	<1	17.8	<1	14.4	<1	EPA 8270D
1-methylnaphtalene	µg/kg	6.6	<1	16.1	<1	11.5	2.7	EPA 8270D
Acenaphtylene	µg/kg	1.0	<1	<1	<1	<1	<1	EPA 8270D
Acenaphtene	µg/kg	3.5	<1	2.0	3.5	3.5	<1	EPA 8270D
Fluorene	µg/kg	7.5	65.5	4.1	12.3	2.1	<1	EPA 8270D
Phenanthrene	µg/kg	50.2	38.7	22.4	72.1	32.4	1.5	EPA 8270D
Anthracene	µg/kg	7.5	6.7	3.5	13.7	6.6	<1	EPA 8270D
Fluoranthene	µg/kg	61.4	46.7	39.5	141.7	64.8	9.1	EPA 8270D
Pyrene	µg/kg	59.1	43.2	38.9	131.4	59.1	9.0	EPA 8270D
Benzo(a)anthracene	µg/kg	44.7	36.4	27.0	86.5	40.9	7.2	EPA 8270D
Chrysene	µg/kg	41.4	33.8	26.6	102.7	43.5	6.0	EPA 8270D
Benzo(b)fluoranthene	µg/kg	63.6	42.0	39.6	120.2	56.5	10.5	EPA 8270D
Benzo(k)fluoranthene	µg/kg	29.3	20.5	16.5	62.0	26.3	4.4	EPA 8270D
Benzo(a)pyrene	µg/kg	57.3	38.8	30.9	118.1	49.2	7.0	EPA 8270D
Indeno(1.2.3-cd)pyrene	µg/kg	52.8	36.8	29.0	135.6	47.8	6.9	EPA 8270D

Dibenzo(a.h)anthracene	**µg/kg**	**11.7**	**8.3**	**7.3**	**23.7**	**8.7**	**1.3**	**EPA 8270D**
Benzo(g.h.i)perylene	**µg/kg**	**53.1**	**36.7**	**32.4**	**120.6**	**49.9**	**8.0**	**EPA 8270D**
ΣPAHs	**µg/kg**	**567**	**454**	**372**	**1226**	**530**	**75**	**EPA 8270D**
TPH	**µg/kg**	**66**	**41**	**39**	**71**	**50**	**18**	**ISO 16703:2004**
PCB congeners:								
PCB 18	**µg/kg**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**EPA 8270D**
PCB 31	**µg/kg**	**1.30**	**1.00**	**<0.5**	**0.54**	**<0.5**	**<0.5**	**EPA 8270D**
PCB 28	**µg/kg**	**1.75**	**1.67**	**<0.5**	**0.79**	**<0.5**	**<0.5**	**EPA 8270D**
PCB 52	**µg/kg**	**1.77**	**1.63**	**0.53**	**2.36**	**1.10**	**<0.5**	**EPA 8270D**
PCB 44	**µg/kg**	**0.84**	**0.61**	**<0.5**	**0.90**	**<0.5**	**<0.5**	**EPA 8270D**
PCB 101	**µg/kg**	**5.34**	**3.14**	**1.26**	**3.77**	**1.68**	**<0.5**	**EPA 8270D**
PCB 149	**µg/kg**	**2.61**	**1.57**	**0.95**	**5.01**	**1.60**	**<0.5**	**EPA 8270D**
PCB 118	**µg/kg**	**5.29**	**2.92**	**1.87**	**2.81**	**2.50**	**<0.5**	**EPA 8270D**
PCB 153	**µg/kg**	**4.58**	**2.83**	**1.80**	**7.65**	**3.11**	**<0.5**	**EPA 8270D**
PCB 138	**µg/kg**	**5.69**	**3.30**	**2.21**	**7.90**	**3.51**	**<0.5**	**EPA 8270D**
PCB 180	**µg/kg**	**2.37**	**1.46**	**1.19**	**8.33**	**2.34**	**<0.5**	**EPA 8270D**
PCB 194	**µg/kg**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**<0.5**	**EPA 8270D**
Organotin compounds:	**µg/kg**							
Monobutil-tin	**µg/kg**	**0.006**	**<0.004**	**<0.004**	**0.004**	**0.017**	**<0.004**	**ISO 23161:2018**
Dibutil- tin	**µg/kg**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**0.01**	**<0.004**	**ISO 23161:2018**
Tributil-tin	**µg/kg**	**0.013**	**<0.004**	**0.005**	**0.006**	**0.015**	**<0.004**	**ISO 23161:2018**
Monooktil-tin	**µg/kg**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**0.006**	**<0.004**	**ISO 23161:2018**
Tetrabutil-tin	**µg/kg**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**ISO 23161:2018**
Dioktil-tin	**µg/kg**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**ISO 23161:2018**
Trifenil-tin	**µg/kg**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**ISO 23161:2018**
Tricyclohexyl-tin	**µg/kg**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**<0.004**	**ISO 23161:2018**
Organochlorine pesticides:	**µg/kg**							
HCB	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Aldrin	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
α-BHC	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
β-BHC	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Lindane	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
δ-BHC	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
α-Chlordane	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
γ-Chlordane	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
4,4′-DDT	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**

4,4′-DDD	**µg/kg**	**0.35**	**0.27**	**<0.05**	**0.75**	**0.30**	**0.21**	**EPA 8270D**
4,4′-DDE	**µg/kg**	**0.33**	**0.23**	**<0.05**	**0.36**	**0.46**	**0.20**	**EPA 8270D**
2,4′-DDT	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
2,4′-DDD	**µg/kg**	**0.10**	**0.07**	**<0.05**	**0.22**	**0.09**	**<0.05**	**EPA 8270D**
2,4′-DDE	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Dieldrin	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
α-Endosulfan	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
β-Endosulfan	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Endosulfan sulfate	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Endrin	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Heptachlor	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
Heptachlor epoxide	**µg/kg**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**<0.05**	**EPA 8270D**
PFAS:	**µg/kg**							
PFBS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFDA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFDoDA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**0.095**	**<0.04**	**EPA 1633**
PFDoS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFDS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHpA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHpS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHxA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHxDA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFHxS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFNA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFNS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFOA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFODA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFOS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFPeS	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFTeDA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFTrDA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**
PFUnDA	**µg/kg**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**<0.04**	**EPA 1633**

***dw**