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Circular Ocean-bound Plastic

Spatial assessment of litter pollution along urban riverfronts

A comparative study of Aarhus, Gdańsk, and Rostock

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Spatial Assessment of Litter Pollution Along Urban Riverfronts in the Baltic Region - A comparative study of Aarhus, Gdańsk and Rostock

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Content

The COP project

This report is part of the EU Interreg South Baltic project Circular Ocean-bound Plastic (COP), which addresses the issue of ocean plastic in the South Baltic Sea. The COP project aims to reduce plastic waste entering into the sensitive ecosystem by identifying its sources and pathways. Over 80% of ocean plastic originates from land-based sources due to improper management or leakages, ending up primarily in rivers and water bodies in urban areas, making their paths to seas and oceans (WWF, 2024).

The project's overall goal is to investigate the collection, reuse, and recycling of ocean-bound plastic. The project is recognized as a "project of strategic importance" by the EU Interreg South Baltic Programme.

The project collaborates and cooperates with 10 partners from four different countries in the program specified region. The partner Clean – The Danish Water & Environmental Cluster serving as the lead coordinating partner. The selected pilot areas include Aarhus (Denmark), Rostock (Germany), and Gdansk (Poland) with Malmö (Sweden) as an associated area.

This report is deliverable 3.1.1 and a result of the activities within work package 3 'Ocean-bound Plastic Data analysis and demonstration' of the project.

1. Introduction

Marine litter is any persistent, manufactured or processed solid material discarded, disposed of or abandoned in the marine and coastal environment (UNEP, 2005). It includes items made or used by people that are either intentionally thrown into the sea, rivers, or onto beaches; carried to the ocean by rivers, sewage, stormwater, or wind; accidentally lost at sea—such as fishing gear or cargo during storms; or purposely left behind on beaches and shorelines (UNEP, 2005). Marine litter consists of many materials such as glass, paper, or metal but plastic represents the vast majority of it (Addamo et al., 2017; Reisser et al., 2013).

It adversely affects thousands of marine species (Law, 2017) and has detrimental impacts on key economic sectors such as tourism, fisheries, aquaculture, and shipping (UNEP, 2021). Most of the marine litter originates from land-based sources (Serra-Gonçalves et al., 2019) with rivers serving as a significant transport pathway; studies estimate that up to 80% of this litter is carried to the ocean via rivers (Meijer et al., 2021; Schmidt et al., 2017; Schwarz et al., 2019; Winton et al., 2020).
These findings are reinforced by long-term monitoring of macro-litter across various regions and rivers within the European Union, which showed that plastics accounted for between 56% and 89%—with an average of 75%—of all recorded litter (González-Fernández, et al., 2018).

Several studies conducted in Europe have identified, in addition to unidentifiable plastic fragments (González-Fernández, et al., 2018), single-use plastics—such as food wrappers, bottle caps and lids, cups, plastic bags, straws, cutlery, cigarette butts, and cigarette packaging—as the most frequently encountered litter items (Winton et al., 2020).

These single-use items are closely linked to human activities near river shorelines, highlighting the direct influence of local behavior on riverine litter pollution. They can enter the river through multiple pathways: being deliberately discarded, blown into the water by wind from overfilled or uncovered bins, scattered by animals such as seagulls, or left on the shore and subsequently washed or blown into the river.

Globally, small urban rivers have been identified as some of the most significant contributors to plastic pollution (Meijer et al., 2021). Due to their proximity to densely populated areas and short distance to the sea, as well as their limited capacity to retain or break down litter, small urban rivers play a key role in the transport of land-based litter into the marine environment. Understanding their role in this transport process is essential for developing effective, site-specific strategies to intercept and prevent plastic pollution at its source.

The goal of this report is to identify hotspots of personal, everyday human activities—such as recreation, commuting, and consumption—in the immediate surroundings of three urban rivers located in Aarhus (Denmark), Gdańsk (Poland), and Rostock (Germany). The objective is to determine where litter is most likely entering these river systems as a result of human activity. This Quantum Geographic Information System (QGIS) analysis focuses specifically on land-based litter linked to individual human behaviour, excluding contributions from sources such as wastewater overflows, shipping, industrial operations, and harbour-related activities.

2. Survey area

The Baltic Sea is a large, brackish, semi-enclosed inland sea bordered by nine countries—Denmark, Germany, Poland, Sweden, Finland, Estonia, Latvia, Lithuania, and Russia—and connects to the North Sea via the Danish Straits. Almost entirely land-locked, it has minimal water exchange, resulting in distinctive hydrographic conditions.

These unique geographical, oceanographic, and climatological features make the Baltic Sea ecosystem particularly sensitive to pollution and other environmental impacts caused by human activities (HELCOM, 2010; Rheinheimer, 1998). They also contribute to the sea's potential function as a sink for plastic pollution (Stolte et al., 2015). The structure and location of the Baltic Sea further increase its vulnerability to anthropogenic pressures.

The Baltic Sea drainage basin covers approximately 1.7 million km²—nearly four times the sea's surface area—and is home to around 85 million people, including 15 million living within 10 km of the coastline (HELCOM, 2023, 2018; Zalewska et al., 2021). Of these 15 million people, many live in large urban areas.

This study focuses on three urban river systems that have the potential to discharge litter into the sea (Figure 1).

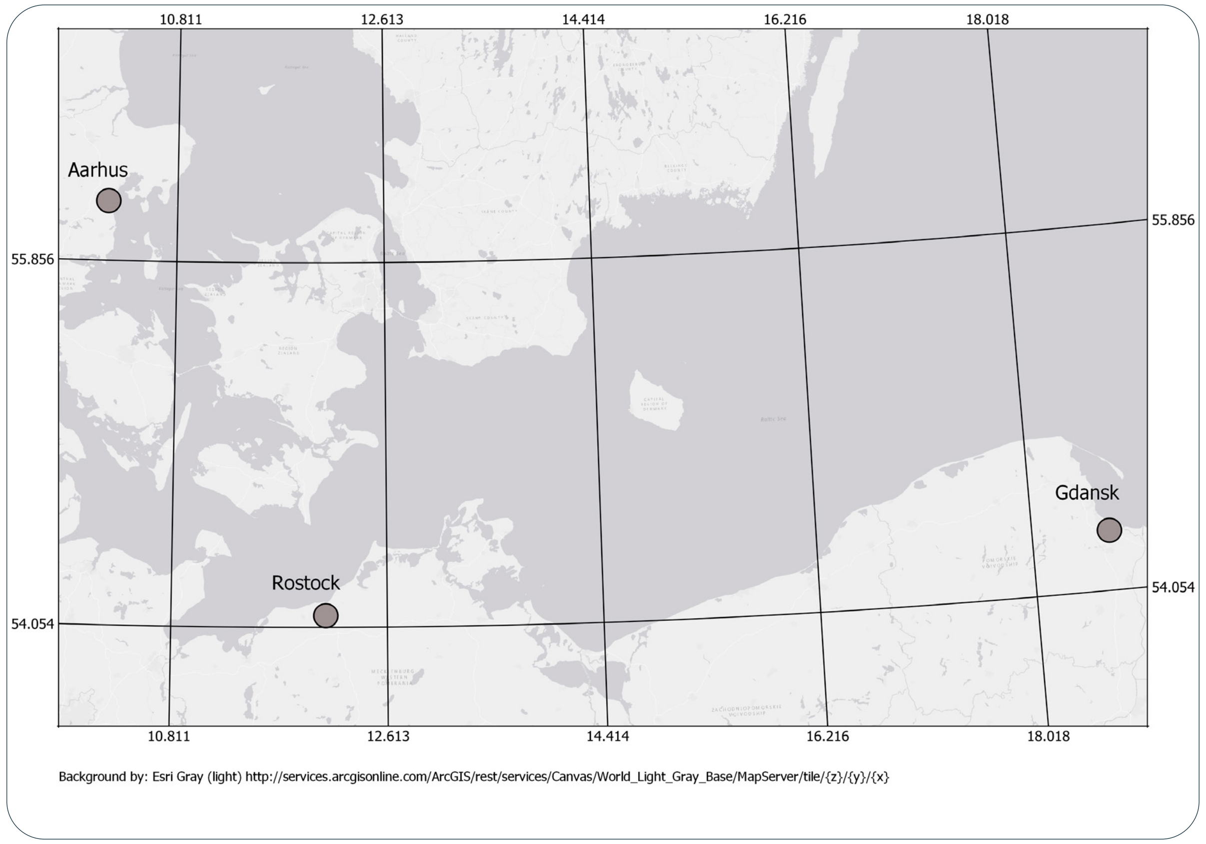

Figure 1: Geographic locations of the three pilot study cities: Aarhus (Denmark), Rostock (Germany), and Gdańsk (Poland). All three urban areas are located along rivers that discharge into the Baltic Sea.

2.1. Aarhus, Denmark

With an urban population of approximately 301,000, Aarhus is Denmark's second-largest city (Danmark Statistik, 2025). The Aarhus River, which is located in eastern Jutland, is around 40 km long and drains an area of 324 km² (Olsen, 2002).

For most of its course, the river flows through a rural landscape characterised by agricultural and wooded areas. Before reaching the city of Aarhus, it passes through Brabrand Lake and continues for around 6 km through an area that is predominantly urban — the designated research area of this study (Figure 2).

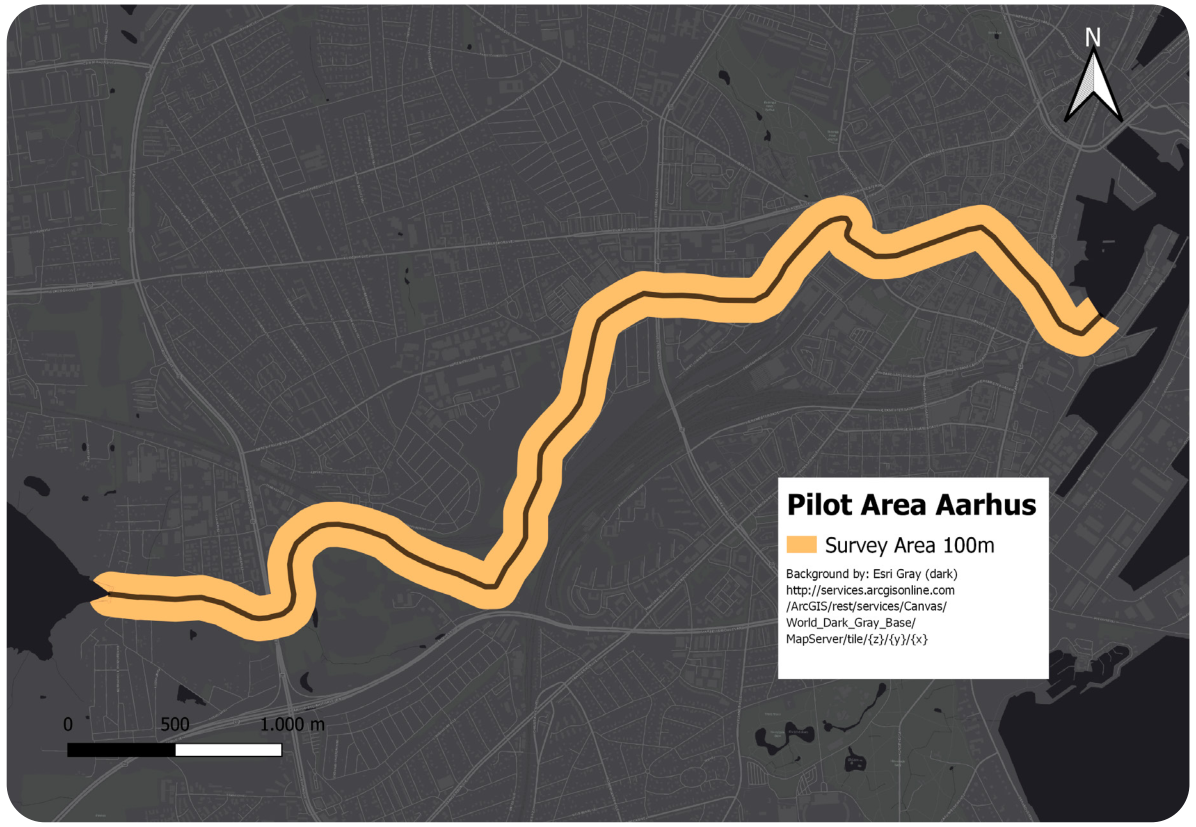

Figure 2: Pilot study area in Aarhus, Denmark. The 100 m buffer along the river served as the survey boundary for identifying potential litter sources near the waterbody. The area spans from Brabrand Lake (left) to the Aarhus harbour (right).

Here, it runs through an artificial channel averaging around 10 m in width before discharging into the city's harbour at Aarhus Bay, which is an embayment of the Kattegat. Lined with a vibrant mix of cafés, restaurants, shops, bars, parks and nightlife venues, the river that divides Aarhus into the northern and southern sections is a popular destination for locals and tourists alike. This makes it a central hub for social and recreational activity in the city.

2.2. Gdańsk, Poland

Gdańsk is the sixth-largest city in Poland, with a population of approximately 488,000 (Gdańsk City Council, 2025). The Motława River, located in Eastern Pomerania, originates near the village of Szpęgawa. It stretches for about 68 kilometers, flowing primarily through agricultural landscapes and forested areas. In its upper course, the river passes through several small lakes before continuing past several villages on its way to the city of Gdańsk, where it empties into the Martwa Wisła.

The research area covers the entire body of water located near the historic city center of Gdańsk, an area renowned for its lively atmosphere and rich cultural heritage (Figure 3). With its dense concentration of shops, bars, restaurants, and tourist attractions, it is one of the city's most popular and dynamic districts.

Its scenic waterfront and iconic Old Town architecture enhance its appeal, drawing both residents and visitors all year round.

Within the research area, the width of the river varies significantly—ranging from approximately 20 m to as much as 80 m—depending on the specific section.

Figure 3: Pilot study area in Gdańsk, Poland. The orange buffer represents the 100 m survey area for identifying potential litter sources on each side of the main urban river network, including the Motława River and adjacent canals.

2.3. Rostock, Germany

Rostock, with a population of approximately 210,000, is the largest city in the German state of Mecklenburg-Vorpommern (Rathaus Rostock, 2025). The research area is located along the Unterwarnow, the estuarine section of the Warnow River (Figure 4).
As the river approaches the city, its surroundings change from rural to highly urbanised. In this central area of Rostock, the riverside is characterised by mixed-use development, including commercial zones, residential buildings, and cultural sites.

The width of the waterway in the research area varies significantly, ranging from around 400 to 700 m in the south and narrowing to approximately 200 to 400 m in the north. An exception is the Breitling harbour area in the north-east, where the waterway extends over three kilometres from west to east.

The riverfront plays a particularly important role in the city's life in both Warnemünde (in the north) and the Haedgehalbinsel area (in the south), where the banks are lined with promenades, marinas, cafés, restaurants, and event spaces. These vibrant waterfront zones are major hubs for tourism, recreation, and daily urban activity.

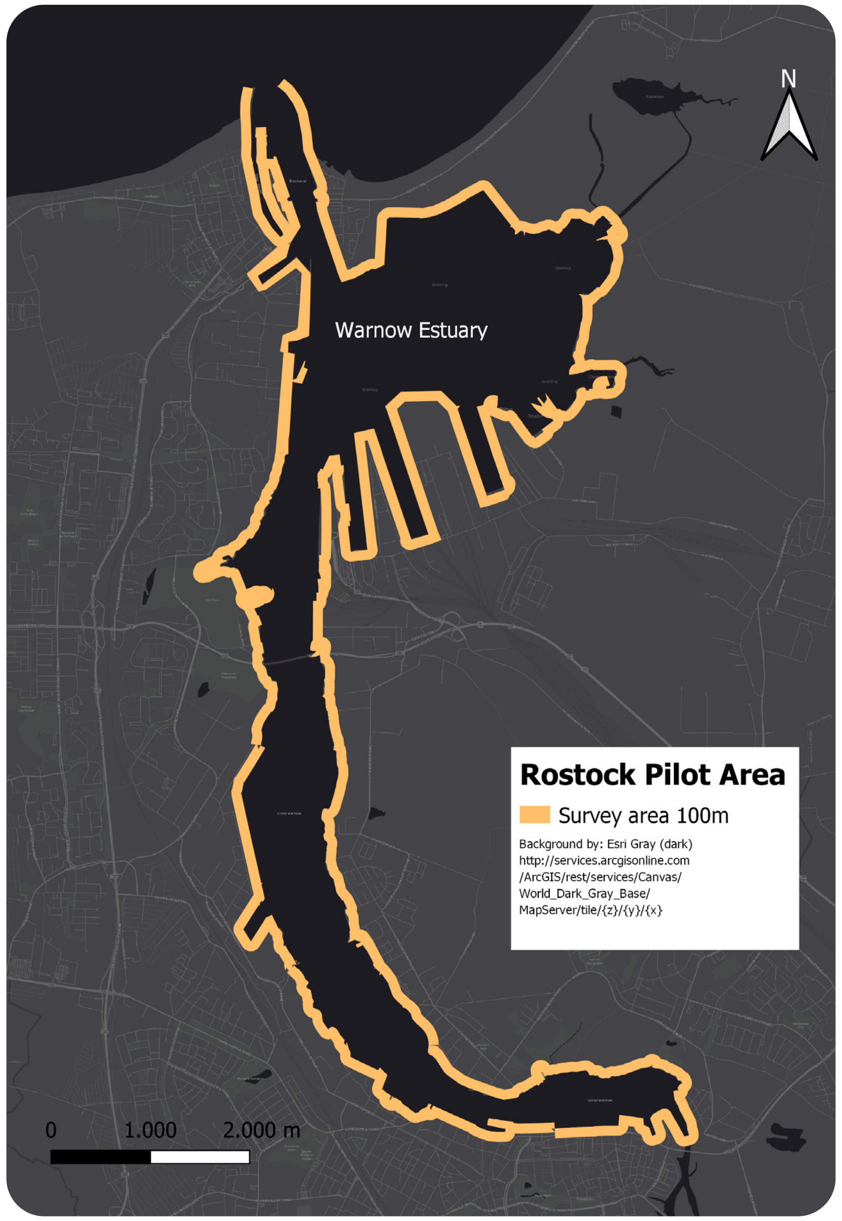

Figure 4: Pilot study area in Rostock, Germany, covering the Warnow Estuary. The orange buffer represents the 100 m survey area extending inland from the shoreline for identifying potential litter sources.

3. Method

A standardised GIS-based analysis was carried out in the three cities of Aarhus (DK), Rostock (DE) and Gdańsk (PL) to identify potential sources of litter linked to individual human behaviour in urban river basins. The methodological approach consisted of four steps: Data collection, data preparation, spatial restriction, and analysis.

3.1. Data acquisition via Overpass Turbo and manually

Primary geospatial data were collected using Overpass Turbo, a web-based query tool for the OpenStreetMap (OSM) database. For each city, the urban area was defined by a rectangular area with four corner coordinates, covering the central river research area.

The queries focused on OSM objects—both Points of Interest (POIs) and linear features—that are commonly associated with public space usage and represent potential sources of litter. In particular, the tag amenity=* was utilized, which represents a top-level category in OSM used to classify useful and important facilities for both visitors and residents — including bars, public toilets, cafés, benches, and others. In addition to amenity data, line features such as streets, pedestrian footways, paths, bike lanes, and informal desire paths were included.

Further, the pilot areas in all three cities were examined using Google Street View, satellite imagery and on-site observations to identify POIs that were not captured by OSM or Overpass Turbo queries. These missing features were then manually digitalised and added to the dataset (Figure 5 and Figure 6). This included piers, picnic tables or BBQ facilities, as well as outdoor seating areas associated with bars, restaurants, and fast-food establishments, such as tables, chairs, and benches, located near the waterbody.

Based on this process and related categories, the following types of amenities and features were extracted:

- Bar
- BBQ
- Bench
- Bicycle parking
- Biergarten
- Boat rental
- Boat sharing
- Bus station
- Cafe
- Community centre
- Dog toilet
- Event venue
- Exhibition centre
- Fast food
- Festival ground
- Food court
- Gas station
- Hospital
- Hotel
- Ice cream
- Lounger
- Marketplace
- Motorcycle parking
- Nightclub
- Parking
- Pub
- Recycling
- Restaurant
- Sanitary dump station
- Social centre
- Stage
- Toilets
- Vending machine
- Waste basket
- Waste disposal
- Waste transfer station

The following elements were partially added manually, based on satellite imagery, field observations, and Google Street View, where they were in direct proximity to the waterbody:

- Outdoor seating areas of bars, restaurants, and similar establishments
- Streets, pedestrian paths, paths, bike lanes, and informal desire paths
- Piers, recreational fishing spots, and bridges
- Picnic areas, BBQ spots, and other informal gathering spaces

Figure 6: Example of a pier observed shortly after use by a recreational fisherman that was manually digitalised and added to the dataset.

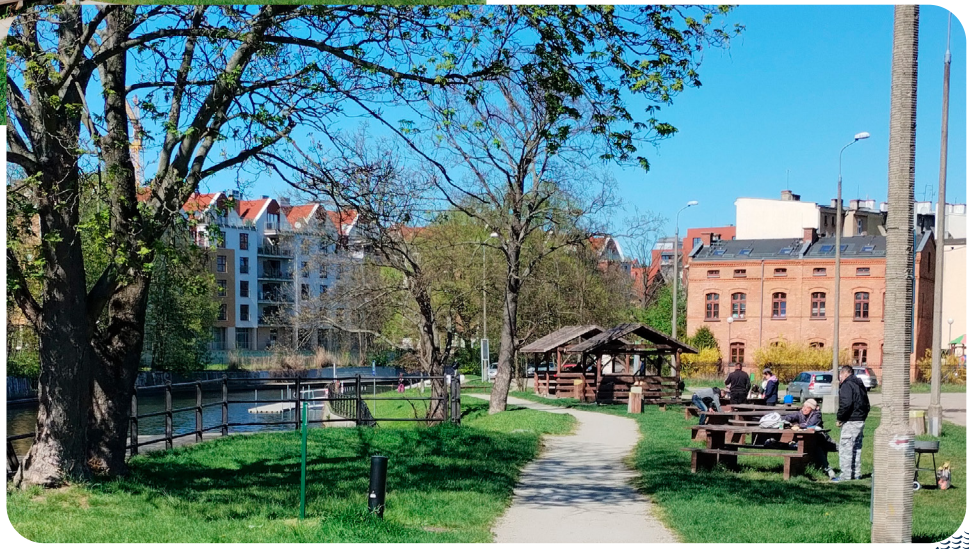

Figure 5: Example of a picnic area/BBQ spot in Gdansk close to the waterbody that was manually digitalised and added to the dataset.

3.2. Stakeholder engagement and local knowledge integration

To complement the data acquisition, stakeholder workshops were conducted in each of the three study cities. Participants included representatives from municipal authorities, environmental NGOs, community groups, and academic institutions.

The aim was to integrate local knowledge and practical insights into the identification of potential litter sources and high-risk areas. Stakeholders provided input on specific locations known for elevated pollution risk, such as areas used for public events, festivals, informal gatherings, or nightlife activities. This qualitative stakeholder input also resulted in the manual addition of POIs that were not fully captured by the spatial datasets.

3.3. Buffer creation around the river

In each city, the main urban river section was manually digitized as a line or polygon layer. To analyse areas with direct proximity to the river, a 100 m buffer polygon was generated on each side of the river using QGIS's buffer tool (Figure 7). This buffer represents the likely zone of increased litter input into the waterbody, e.g., via wind transport, surface runoff, purposely left behind, or direct use of the riverbank.

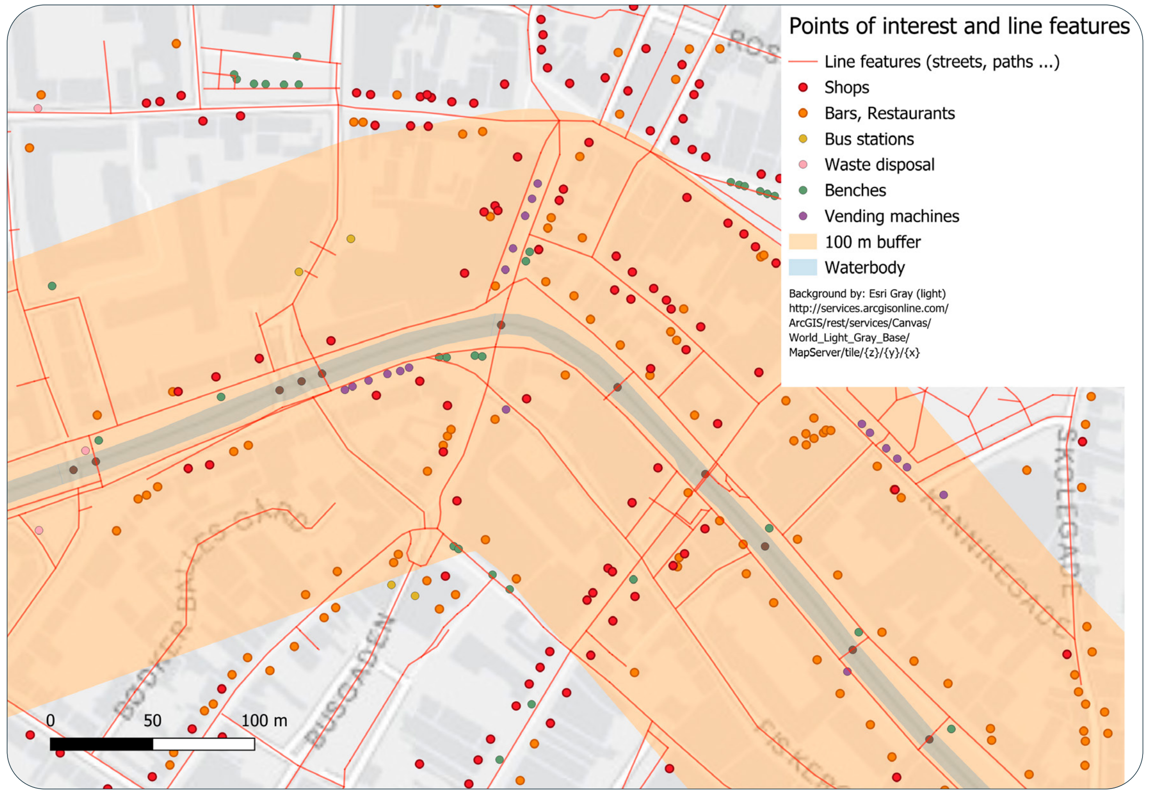

Figure 7: Example of categorized Points of Interest (amenities), like shops, bars, and restaurants and so on and of the line features (streets, paths, ...) displayed within a subsection of the Aarhus study area. In the middle in blue the waterbody with a 100 m buffer to both sides.

3.4. Spatial restriction of POIs and line features

The collected POI's and line datasets were spatially intersected with the river buffer, meaning that only POIs located within 100 m of the river were considered for further analysis. As a result, POIs and line features outside the buffer were excluded based on their geographic location. This spatial filtering was performed using QGIS tools such as "Clip" and "Select by Location." The outcome was a thematic subset of POI and line data for each city, focused specifically on the area immediately surrounding the river.

3.5. Hexagonal grid analysis of potential litter sources

The 100 m buffer zone along the river was subdivided into hexagonal cells spaced 25 m apart (center-to-center), and the number of POIs within each cell was calculated (Figure 8). These POI counts were used to classify the potential litter pollution risk associated with each hexagon. To account for the increased vulnerability of areas in direct contact with the river, the POI-based scores of hexagons immediately adjacent to the waterbody were doubled, reinforcing their relative importance in the overall risk assessment.

In addition to POIs, the analysis also considered whether linear features—such as public accessible streets, bike lanes, or paths—intersected hexagons directly adjacent to the waterbody. If a linear feature was present, further assessment determined whether it was in direct contact with the river or separated by a riparian buffer such as a vegetated strip or shrub layer. Where no buffer was present, the hexagon received an additional two points; if a natural buffer existed, one point was added. In cases where the riverfront was part of private property not accessible to the public—such as gardens, construction areas, or private paths—one point was also assigned. This reflects the reduced likelihood of public-generated litter, based on the assumption that residents are less likely to contribute to direct pollution. However, the possibility of indirect litter input—for example, through wind or runoff—was still acknowledged.

Unlike the POIs, these line feature scores were not doubled. They served as a supplementary indicator of accessibility and potential litter entry pathways.

No further weighting was applied to specific types of POIs or linear features. This decision was based on the recognition that the pollution potential of different POIs and line features can vary considerably depending on factors such as season, time of day, or day of the week. Due to this temporal variability and the absence of consistent usage data, the analysis focused solely on the presence and number of features per hexagon as a proxy for potential litter hotspots.

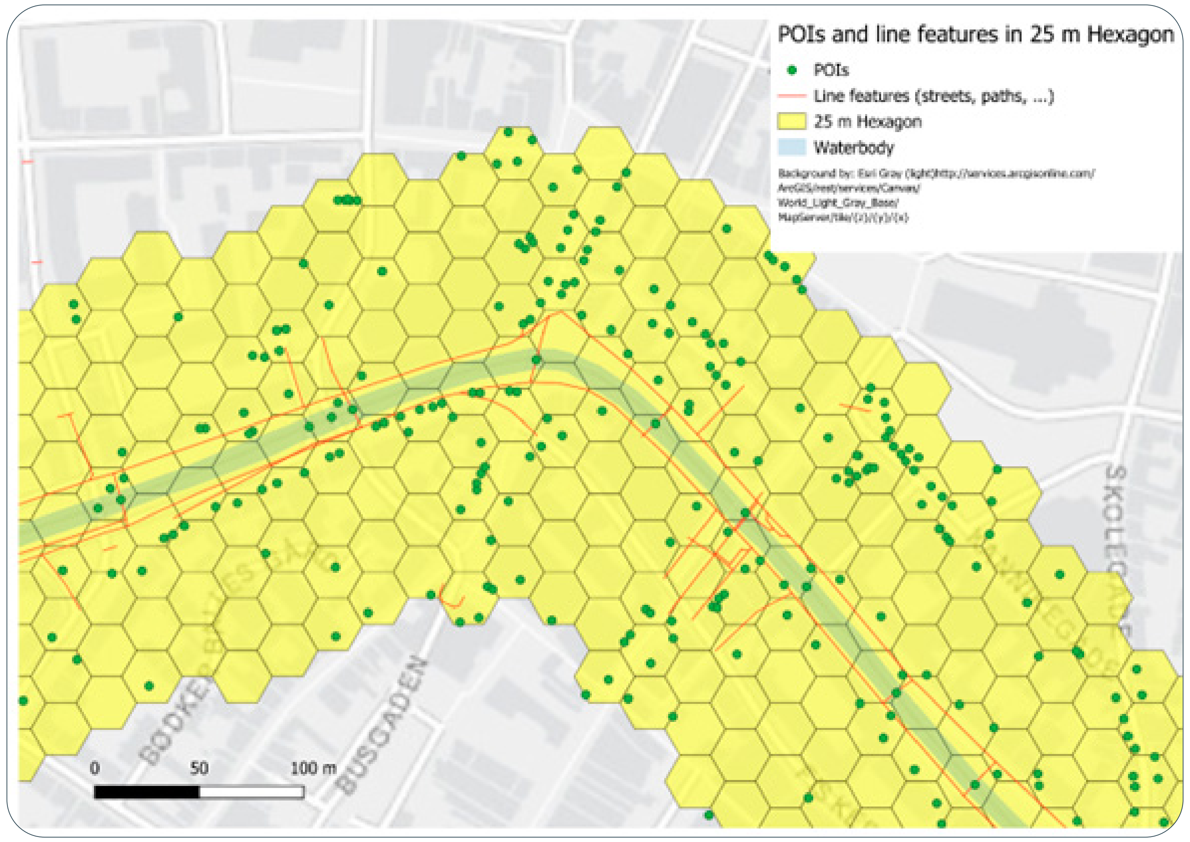

Figure 8: Example of merged Points of Interest (amenities), like shops, bars, and restaurants and so on and of the line features (streets, paths, ...) displayed within a subsection of the Aarhus study area. In the middle in blue the waterbody with the 100 m buffer divided into hexagons of 25 m each.

It should be noted that potential litter input from harbour areas, shipyards, industrial zones, and similar sites was not included in the analysis. These areas often have restricted access, lack public POIs, and may follow different waste management practices. Consequently, they were excluded from the Overpass Turbo queries, on-site observations, and subsequent spatial filtering. As a result, hexagons covering these zones were not assigned a pollution potential score, which may lead to a partial underrepresentation of potential litter sources in these specific areas.

The pollution potential score ranges from 0 to 14 (Figure 9), where a score of 0 indicates that no potential pollution sources were identified within the respective hexagon. This may result from an actual absence of relevant features, a lack of data from the Overpass Turbo query, limited visibility in Google Street View, or inaccessibility during field observations.

Higher scores in the range of 10 to 14 typically occurred in hexagons located directly adjacent to the waterbody, where multiple POIs were present and the pollution potential was doubled to reflect their proximity to the river. Additionally, the presence of linear features such as pedestrian paths or streets without a natural riparian buffer further increased the score, contributing one or two additional points depending on buffer presence. The combination of dense POIs, adjacency to the river, and accessibility via line features explains the occurrence of these elevated values.

Figure 9: Example of the pollution potential per hexagon with the pollution risk (scores 0–14).

4. Results

The analysis of the three pilot areas (Aarhus, Gdańsk and Rostock) revealed clear patterns of elevated pollution potential along central riverfronts and inner-city sections, where public amenities and accessible pathways are densely concentrated in close proximity to the water.
Hexagons in these zones often reached the upper end of the pollution potential scale (scores of 10–14), primarily due to the concentration of POIs, linear features such as pedestrian paths near the river and the lack of natural buffers.

Additionally, the scoring methodology doubled the values for hexagons immediately adjacent to the water, further amplifying scores in these high-activity zones.

In contrast, lower scores (0–4) were typically observed in outer urban and less developed waterfront areas, where fewer POIs, lower accessibility, and the presence of riparian vegetation—such as shrub layers or grass strips—reduce the potential litter input. Hexagons with medium scores (3–6) in these outer zones appeared only sporadically and were often associated with direct public access to the river. These included benches, piers, recreational fishing spots, picnic areas, BBQ sites, and other informal gathering locations.

Additionally, continuous stretches of low scores (1–2) often indicated the presence of a riverside path or street—i.e. a line feature—without many point-based amenities, but with some potential for litter input due to regular foot traffic or accessibility.

4.1. Aarhus

The highest pollution potential concentrations (scores up to 14) are found in the eastern part of the city centre, which is densely urbanised. This area is characterised by a high density of public amenities and frequent, direct access to the riverbank — factors that increase the likelihood of litter reaching the waterbody.

In contrast, the central and western sections of the river corridor mostly exhibit no or a moderate to low pollution potential. Isolated hexagons with scores (between 2 and 6) are usually found near access points, such as piers, e.g. litter bins or informal fishing spots. More continuous stretches of hexagons scoring 1 or 2, particularly in the central area, often indicate pedestrian paths running alongside or near the river. These lower-risk zones generally contain fewer POIs, benefit from greater vegetative buffering, and offer only limited public access to the shoreline. These factors collectively reduce the likelihood of pollution entering the aquatic system (Figure 10).

Figure 10: Pollution potential per hexagon along the Aarhus pilot area. The hexagons represent the spatially distributed pollution potential scores, which range from 0 (no identified sources) to 14 (a high density of litter-related features). High values are concentrated in the city centre, where multiple POIs and public pathways run directly alongside or intersect the river, indicating an elevated potential for litter input.

High pollution potential scores (up to 14) are concentrated along the central river in the eastern city centre. The cluster of dark red and orange hexagons indicates a strong presence of bars, restaurants, pedestrian paths, benches, and other amenities, in close proximity to the riverbank, often with limited natural barriers (e.g., shrub layers or fenced private areas). The frequent public use and festivities in these areas increase the likelihood of litter entering the waterway, either directly due to littering or via surface runoff or wind.

Surrounding zones with lower scores (1–4) still contain POIs but typically lie farther from the riverbank, have fewer features, or reduced pedestrian accessibility. The lower scores are therefore not only a reflection of lower POI density, but also of distance from the river, which reduces the immediate risk of litter entering the water. The three higher scores in the western part of the city centre are in Møllepark, where direct access to the river in combination with POIs of recreational activities lead to a higher pollution potential (Figure 11).

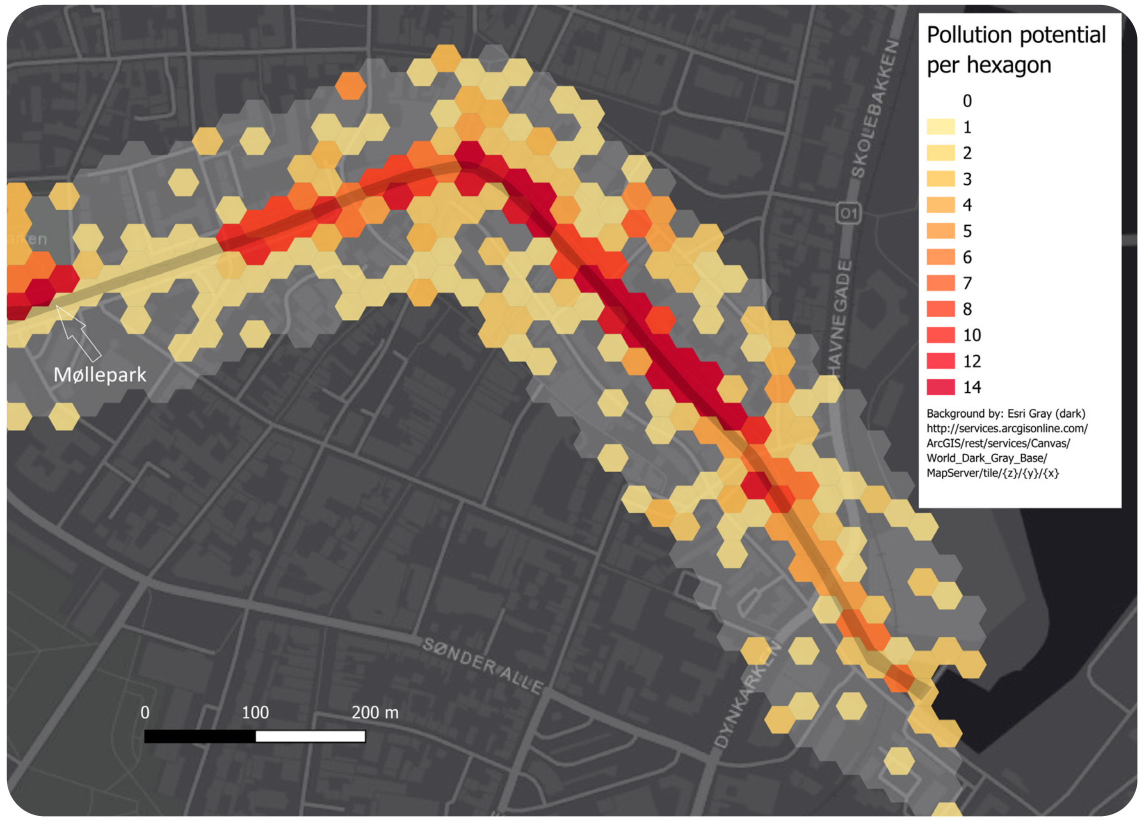

Figure 11: Detailed view of pollution potential in central Aarhus. This map highlights the dense cluster of high pollution potential scores (8–14) in the central section of this part of the river in Aarhus.

4.2. Gdańsk

The highest concentrations of potential pollution (scores 8–14) are concentrated along the central and northern sections of the mapped rivers, particularly where the waterways traverse densely urbanized and highly accessible public areas. These zones typically include clusters of bars, restaurants, benches, pathways, and other public-use amenities located directly along the riverbank—often with minimal or no riparian buffer. This close proximity to the water increases the likelihood of direct litter input into the river system (Figure 12).

In contrast, lower to medium scores dominate in the southern part of the Nowa Motława. In the less developed eastern part of the Opływ Motławy, where development is sparse, access is limited and natural barriers such as vegetation strips are common, the scores are usually low.

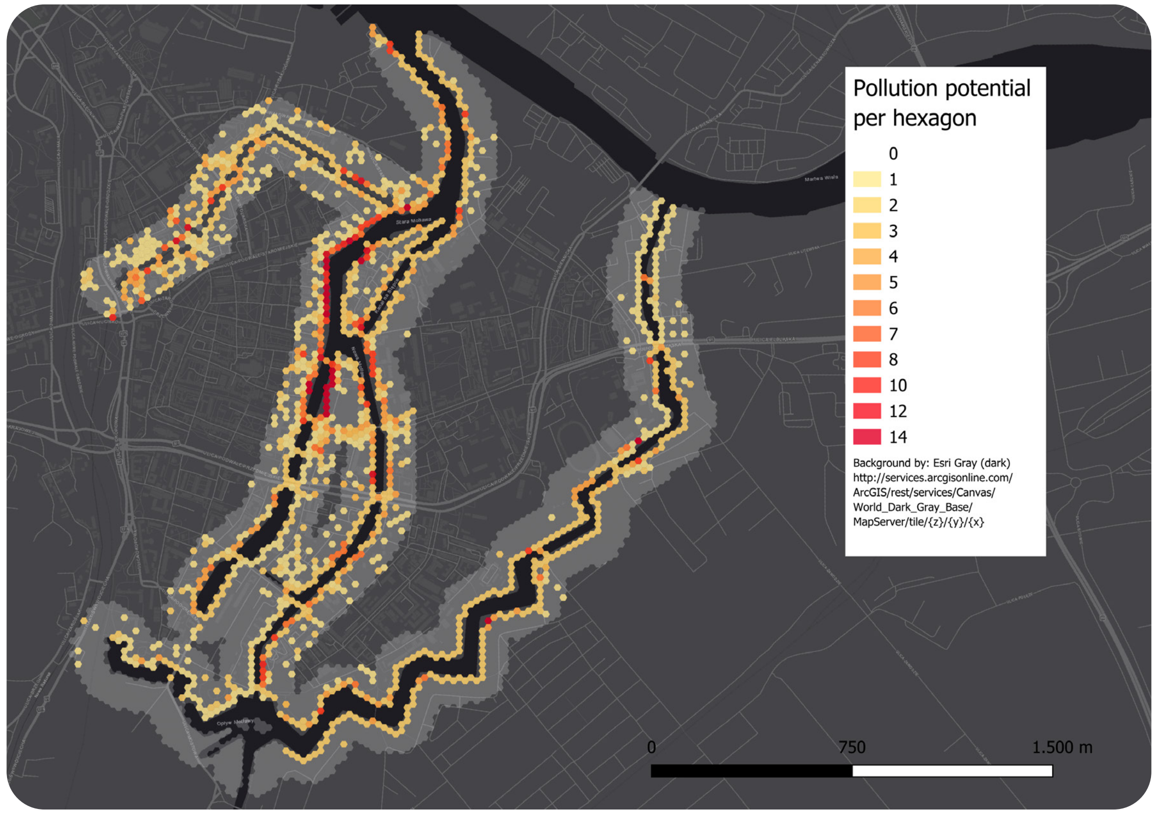

Figure 12: The spatial distribution of potential pollution input along the river corridors in Gdańsk. The highest scores (up to 14) are concentrated in the central and northern urban areas, where dense clusters of POIs coincide with minimal vegetative buffers and direct river access. Outer urban areas generally have lower scores, reflecting reduced human activity and more natural riverbank conditions.

The section of the river network in the area around Wyspa Spichrzów and the southern part of the Opływ Motławy shows moderate to high potential for pollution (Figure 13). Scores range from 0 to 12, with the highest values concentrated along the inner shores of Wyspa Spichrzów facing the river and along the edges of key canals with dense pedestrian access and public features. The higher-scoring hexagons are associated with direct river access, urban infrastructure, and informal gathering areas.

Further in the south at Opływ Motławy and to the south and west, the potential declines, though isolated medium and higher scores still appear, often near recreational features such as benches, BBQ and picn areas, or piers. Paths alongside the waterfront are reflected in linear sequences of low-scoring (1–2) hexagons, indicating maintained accessibility, but with fewer associated litter-generating POIs.

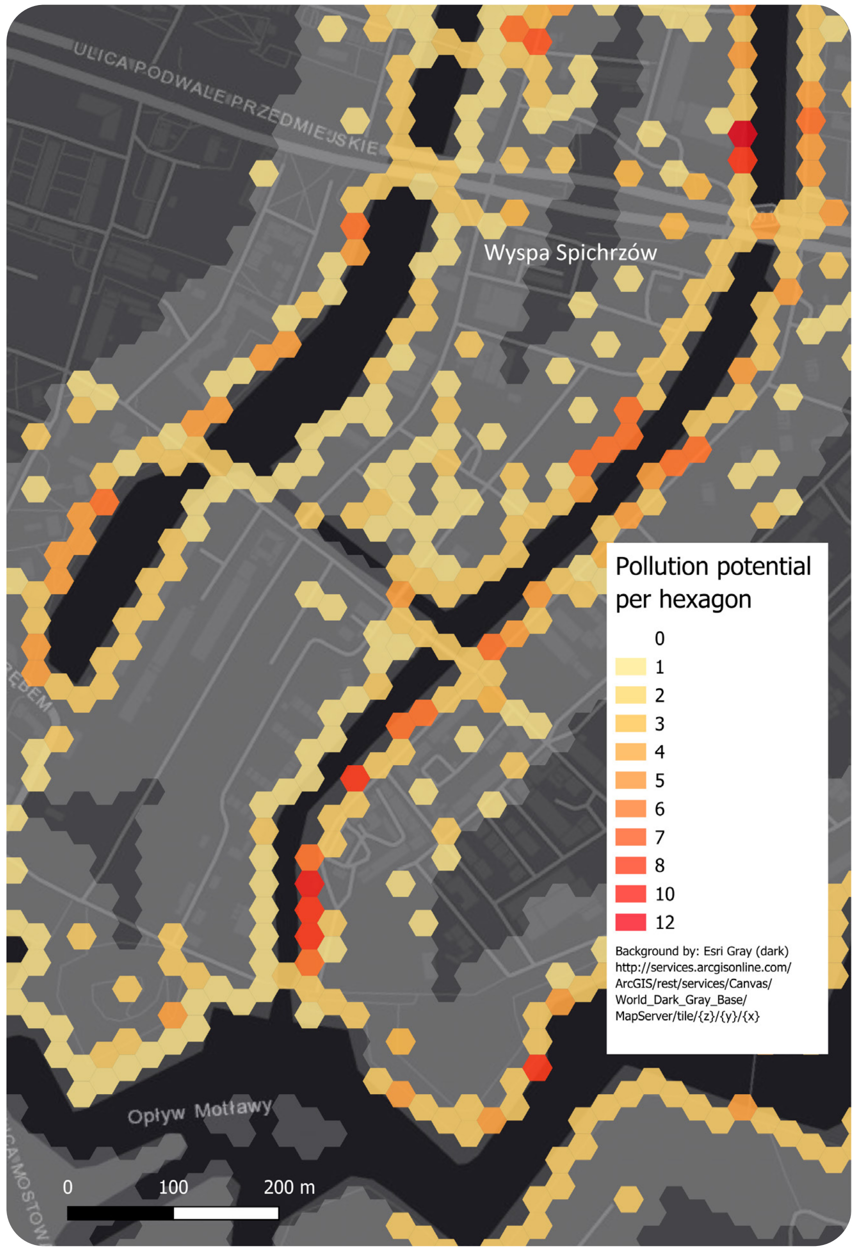

Figure 13: Pollution potential along the Opływ Motławy and the southern section of Wyspa Spichrzów, Gdańsk. Higher pollution scores are found along the urbanized waterfront of Wyspa Spichrzów and canal banks with direct access and dense human activity. Linear patterns of lower scores indicate accessible paths without strong clustering of litter-related POIs.

The central part of Gdańsk (Figure 14), specifically the western riverbank of the Stara Motława and Nowa Motława, has a high pollution potential, with several areas reaching the upper end of the scale (10–14). These elevated scores correspond to dense urban development and heavy public use of the riverbanks, including promenades, restaurants, and recreational piers, as well as minimal or no riparian buffers. Clusters of red and dark red hexagons on both sides of Wyspa Spichrzów and Ołowianka islands reflect intense human activity and continuous riverfront access. The Kanał na Stępce usually exhibits low scores as there are mostly pathways alongside the water with a few POIs. Some hexagons have higher scores due to localised POIs. Lower scores (0–3) appear slightly inland or in areas with vegetation, restricted access, or fewer mapped features (Figure 14).

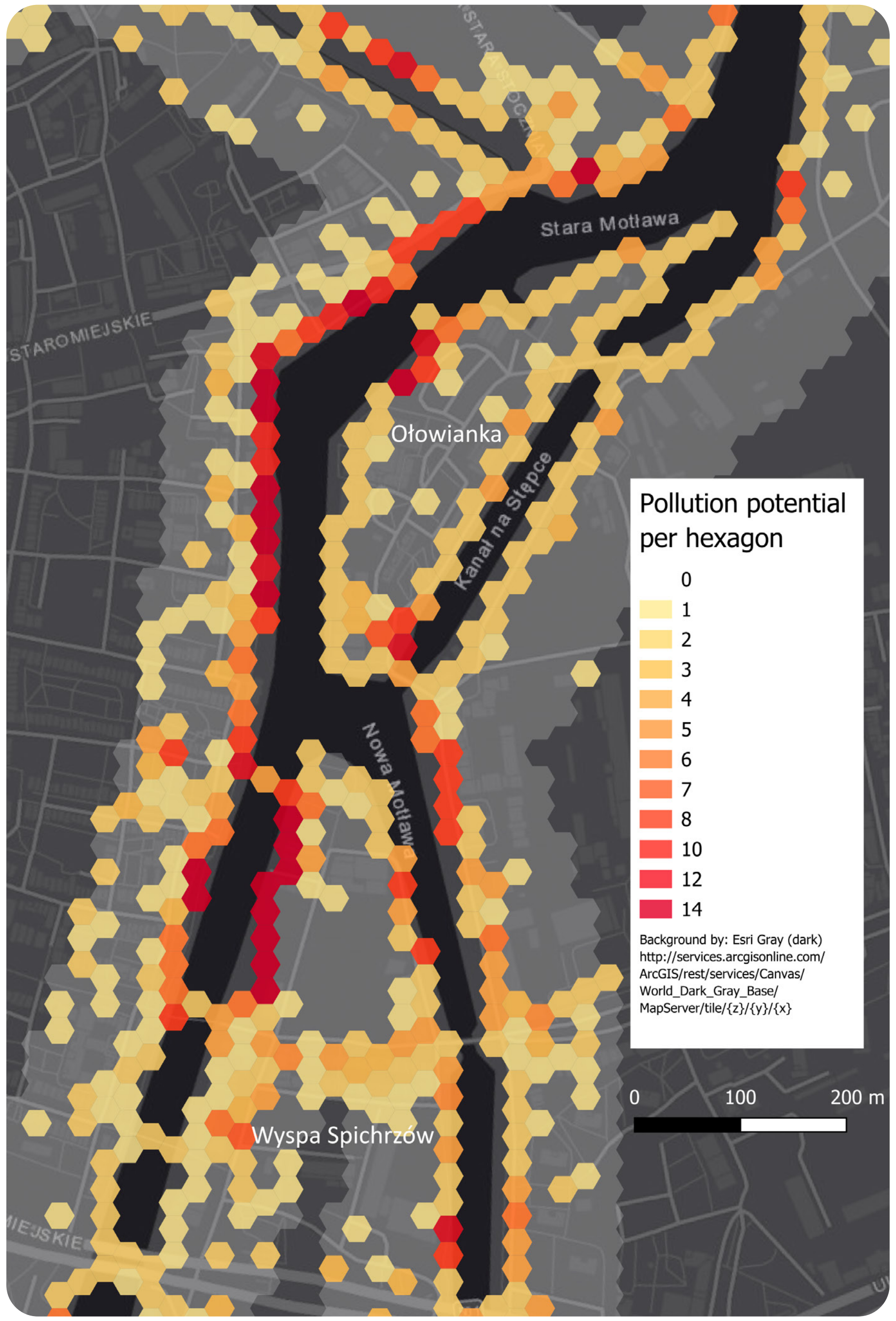

Figure 14: Pollution potential the central Gdańsk waterfront around the islands of Wyspa Spichrzów and Ołowianka.

Figure 14 shows the pollution potential in the central Gdańsk waterfront around the islands of Wyspa Spichrzów and Ołowianka. High pollution potential (up to 14) is found along both sides of the Nowa and Stara Motława rivers, and on the waterfronts of the islands Wyspa Spichrzów and Ołowianka. These areas feature dense public infrastructure, including promenades, cultural venues, and tourist facilities. Medium scores often align with pedestrian paths, while lower values indicate locations with limited access or greater natural buffering.

4.3. Rostock

The pollution potential analysis along the Warnow Estuary in Rostock reveals an overall low to moderate risk across most of the riverbanks. Most hexagons score between 0 and 2, particularly in the northern and southern stretches where access to the river is more limited and public infrastructure is sparse. However, isolated clusters of medium to high scores are visible, especially near the inner-city waterfront and harbour-adjacent zones. These areas feature more public amenities, accessible pedestrian paths, and built-up environments (Figure 15).

Most hexagons exhibit low pollution potential (scores 0–2), reflecting limited public infrastructure and access in many parts of the estuary. However, several localized high-risk areas are visible - particularly near the southern urban centre, around IGA Park in the midsection, and in the northwestern parts of Warnemünde, Rostock's main tourist hub. The harbour area indicated in pink was not part of the analysis.

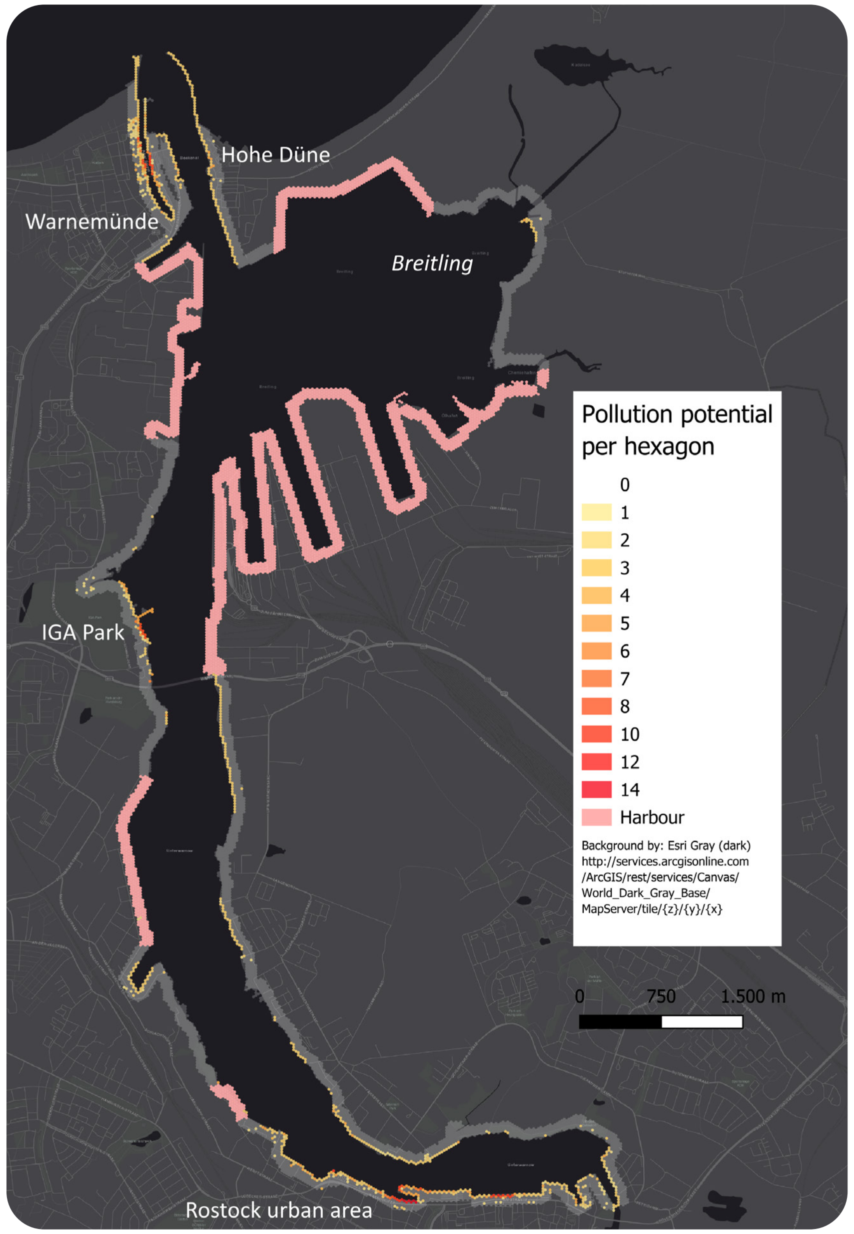

Figure 15: Pollution potential per hexagon along the Warnow Estuary in Rostock.

The map in Figure 16 displays the pollution potential along the northern part of the Warnow Estuary near Warnemünde. While most hexagons show low to moderate scores (0–3), a clear hotspot (Alter Strom) emerges along the west bank, where pollution potential reaches values of 8 to 10. This cluster corresponds with a dense area of public infrastructure, including tourist attractions, promenades, and mooring facilities, likely contributing to increased litter risk. The east bank (Hohe Düne) remains predominantly low-risk due to limited public access and the lack of major amenities. Only a narrow pedestrian path runs along the waterfront here, resulting in minimal human impact on the area.

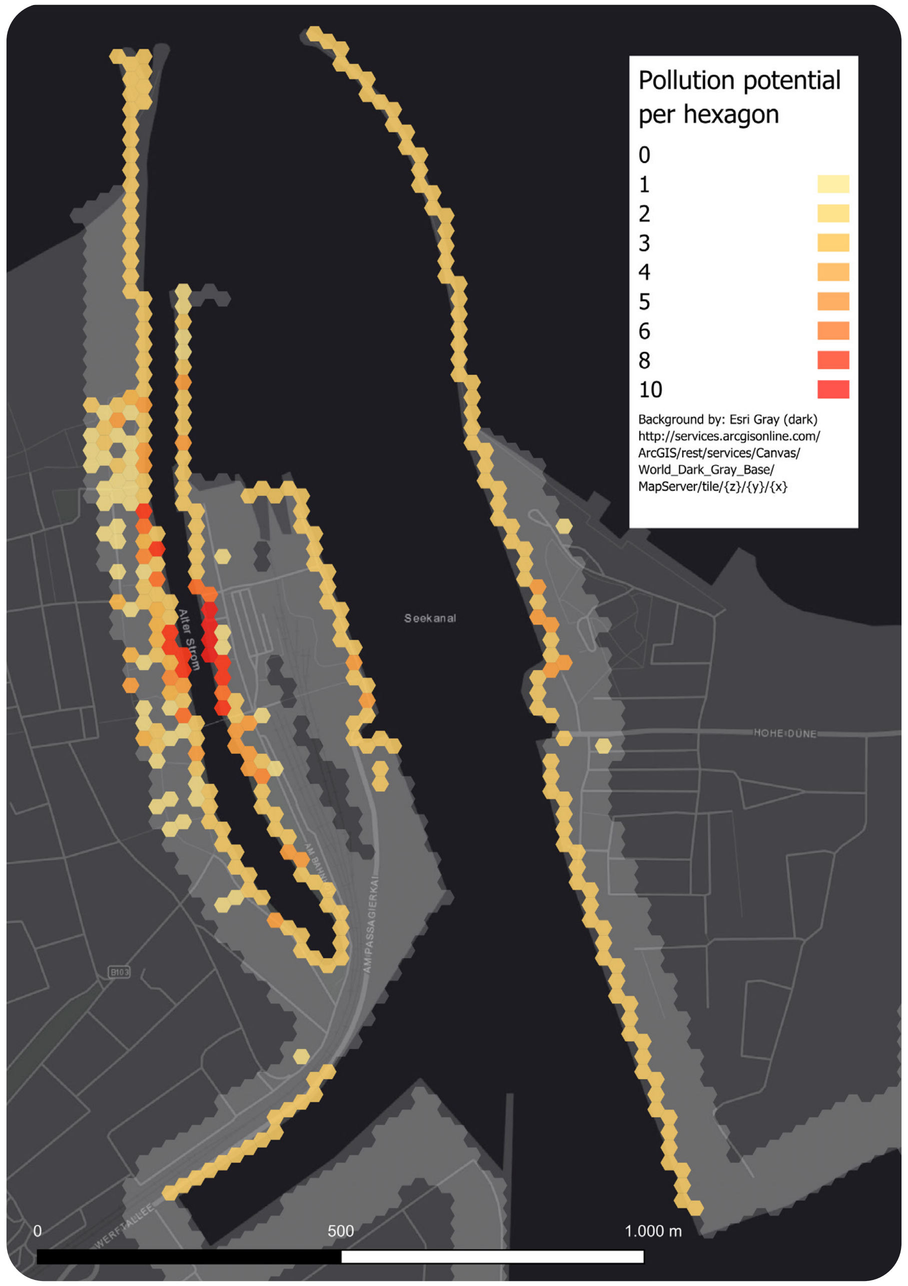

Figure 16: Pollution potential per hexagon along the northern Warnow Estuary near Warnemünde. A pollution hotspot is visible on the west bank of Alter Strom, associated with high tourist activity and riverbank access, while the east bank remains predominantly low-risk.

This map in Figure 17 shows a section of the eastern shoreline of Breitling, where the overall pollution potential is very low. Most of the hexagons in this area have a score of between 0 and 2, with only a small cluster reaching a score of 4, which is due to the presence of a small public beach, a narrow accessible path, and minor public infrastructure such as informal viewpoints and fishing spots. The broader area remains largely unaffected due to low levels of human activity and the absence of built-up or recreational features near the shoreline.

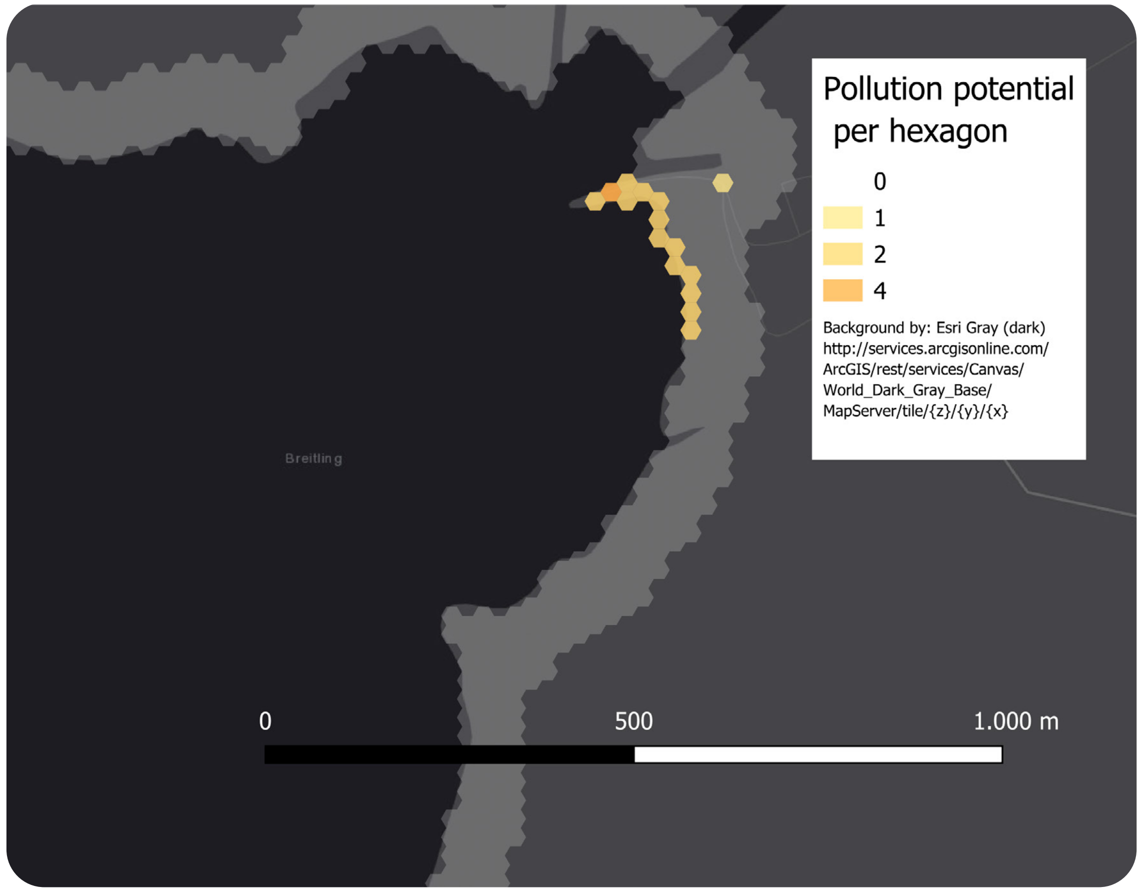

Figure 17: illustrates the pollution potential of each hexagon along the eastern shore of the Breitling. Pollution scores remain low (0–4), with only a small section displaying a moderate risk due to the presence of a beach and limited access paths.

This section (Figure 18) of the Warnow Estuary indicates a moderate potential for pollution along the western shoreline near IGA Park, especially to the north of the Warnow Tunnel. Several hexagons in this area have elevated pollution scores (4–8) and are located near a cluster of public amenities, paths, green spaces and a popular beach.

In contrast, the eastern shore remains largely low-risk, with pollution scores of 0–2 reflecting reduced accessibility and limited POIs. Large sections on both sides are designated as harbour areas and were excluded from scoring.

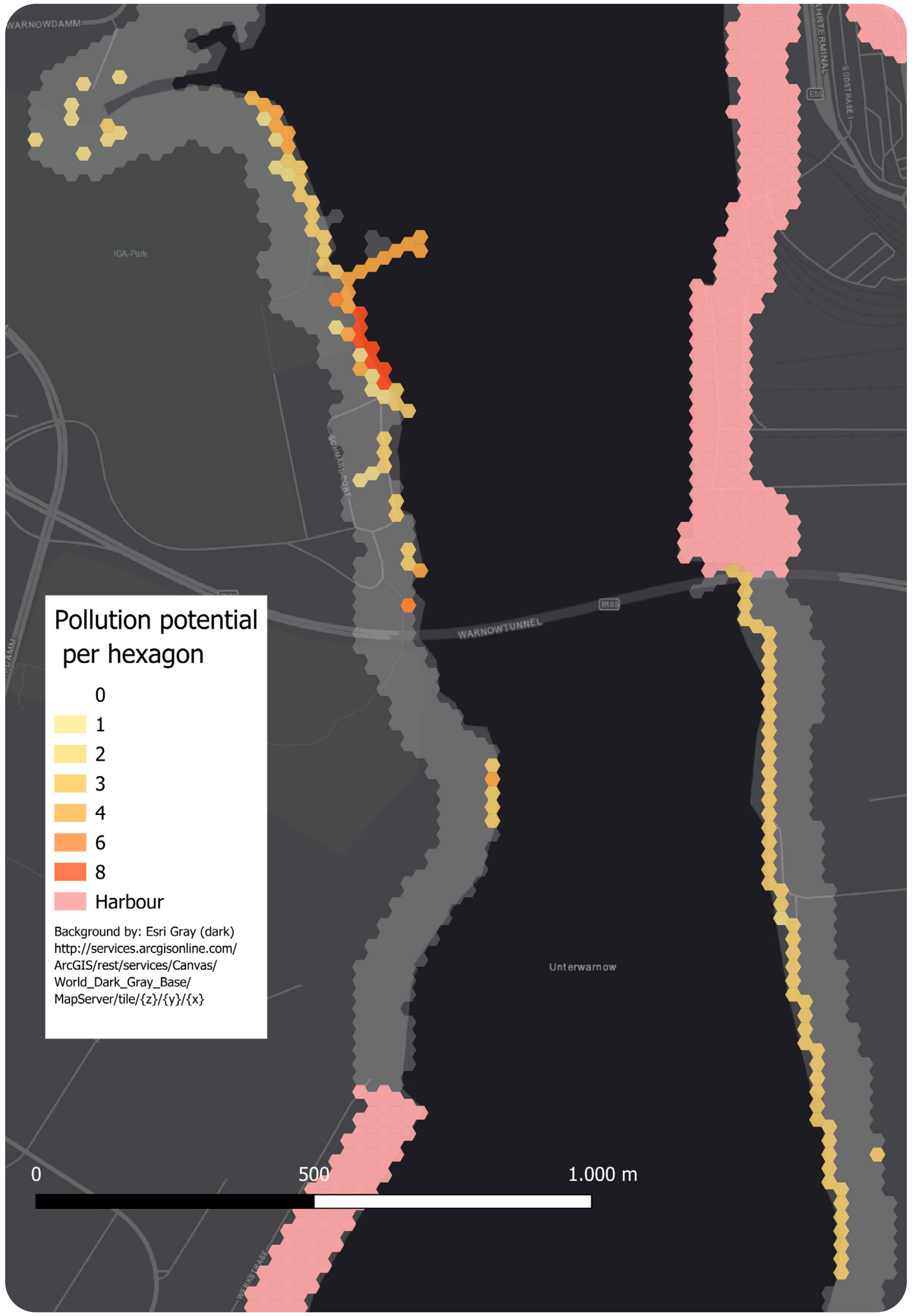

Figure 18: illustrates the pollution potential of each hexagon in the vicinity of IGA Park in the north-west and the Warnow Tunnel in Rostock. Moderate pollution potential (scores of 4–8) is concentrated along the western riverbank, adjacent to recreational areas. In contrast, the eastern riverbank shows minimal pollution potential. The harbour area was not included in the scoring of pollution potential.

There are several potential pollution hotspots in the southern section of the Warnow Estuary (Figure 19), particularly along the southern bank in the western half of the map. Here, hexagons with scores of up to 14 indicate areas with dense public infrastructure, such as promenades, benches, large camper van parking facilities, and leisure facilities with direct river access (e.g. BBQ areas, bars, restaurants, paths, seating areas, and event spaces). In contrast, pollution potential remains low (0–2) on the northern bank due to natural buffers, such as dense vegetation strips, and limited built-up access points. Moderate scores (3–6) also appear sporadically in the eastern half, reflecting occasional public use and accessibility.

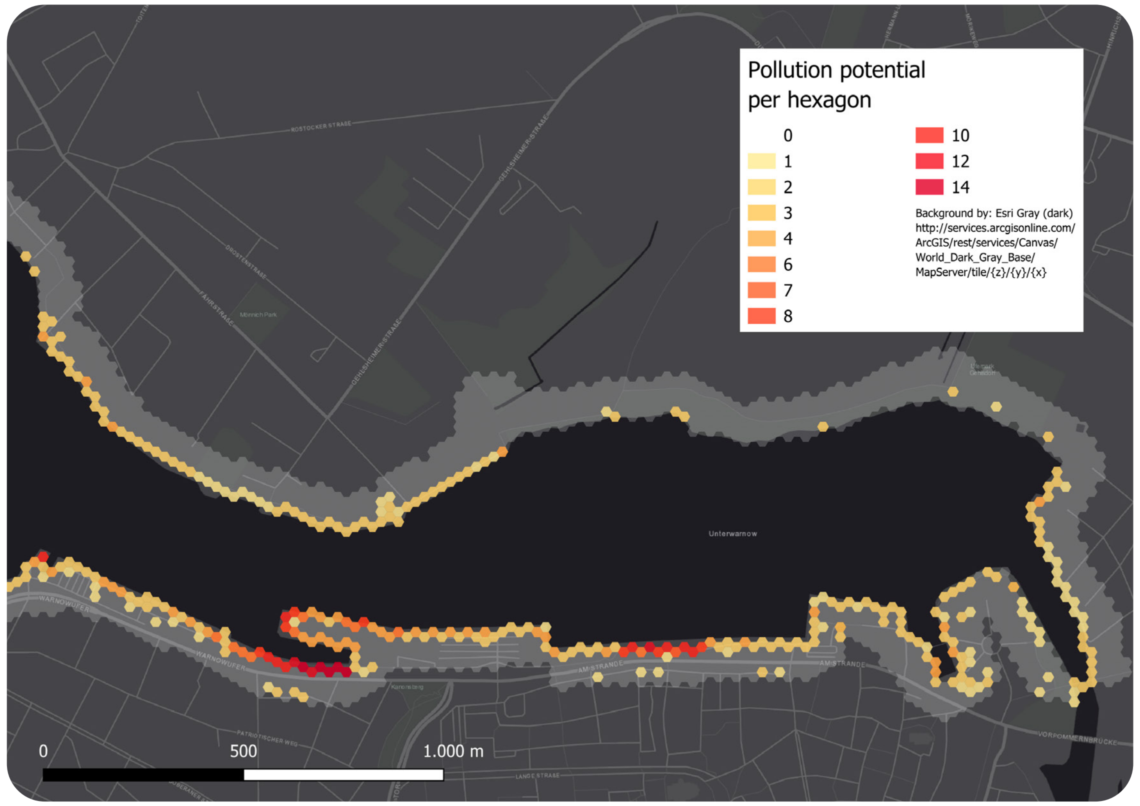

Figure 19: Pollution potential per hexagon along the southern and northern shores of the Unterwarnow. High-risk areas are concentrated along the southern bank in zones of high recreational activity, while the northern bank remains predominantly low-risk due to natural buffers and fewer access points.

5. Discussion

This section reflects on the key methodological decisions, limitations and contextual factors that influenced the spatial assessment of the pollution potential risk. Although the analysis successfully identified areas with a high potential for litter across the three study areas, it is important to critically evaluate the assumptions, simplifications, and data constraints of the approach. The following subchapters address the various aspects of the methodology that influence the interpretation and reliability of the results.

100 m buffer zones and 25 m hexagons

One methodological consideration concerns the choice of a 100 m buffer zone along the surveyed waterfronts. While this distance allows for the inclusion of broader urban structures and access features, it may also overestimate the relevance of distant elements in relation to litter input. Pollution potential is likely dominated by activities and public amenities located directly at or immediately adjacent to the water's edge. To address this, the implementation of the doubling factor for the first row of hexagons next to the riverbank, ensured that areas with direct connectivity to the water were appropriately emphasized in the final risk assessment. Additionally, the use of relatively small 25 m wide hexagons helped maintain spatial precision within the 100 m corridor, allowing for the distinction of fine-scale patterns even within a broad survey zone.

Considerations on POI selection and weighting

The selection of amenities (POIs) included in this study—such as restaurants, bars, cafés, shops, benches, waste bins, and many others—assumed that these features represent public space usage and are linked to potential litter pollution. However, it must be acknowledged that this selection is partly subjective. It was guided by personal expertise, input from local stakeholders, and supported by findings from previous research identifying the most common litter items in European rivers—primarily single-use plastics and consumer goods (González-Fernández, et al., 2018).
Different types of amenities may contribute to litter in varying degrees, depending on numerous factors such as function, foot traffic, location, and time of use (e.g., day vs. night, weekday vs. weekend, or seasonal differences).

While some amenities - like fast food outlets or nightlife venues - may pose a higher risk of generating packaging waste or beverage containers, others (e.g., loungers or benches) likely have lower direct litter potential. Given the absence of consistent, location-specific usage or littering data, no differentiated weighting was applied. Instead, all amenities were treated equally to maintain a standardised and replicable methodology.

The selection was made to the best of the authors' knowledge and experience, informed by field visits, expert workshops, and established urban environmental research practices.

Moreover, the POI dataset used for this study, while extensive, is not exhaustive. Certain features, especially informal or seasonal ones—like temporary kiosks, food trucks, or recreational fishing spots—may not have been captured. As a result, some key litter sources could have been missed. Additionally, the analysis did not account for temporal variability. POIs such as beer gardens, tourist piers, or public event spaces can have highly seasonal usage patterns. Their litter impact may spike during specific times of the year (e.g., summer or festival periods), which is not reflected in the static data used for this model.

To ensure a consistent and interpretable visual representation of pollution potential, the maximum score per hexagon was capped at 14. Although some hexagons could theoretically accumulate higher values—especially when combining a high number of POIs, adjacency to the waterbody (with score doubling), and the presence of additional linear features—this open-ended scoring risked distorting the overall visual impression. For instance, in Aarhus, where the stream is often only around 10 m wide, a single 25 m hexagon frequently included both sides of the river.

As a result, multiple POIs and line features from both banks were aggregated into one hexagon, potentially leading to scores above 20. Without capping, such outliers would have dominated the map's colour scale, making moderately high values (e.g., 6 or 8) appear visually insignificant.
The capping at 14 therefore improves comparability across sites and highlights a broader range of at-risk zones without overstating local extremes.

Natural buffer zones

It is important to acknowledge that riparian buffers, such as vegetated strips or shrub layers, are not static features and can change significantly over time due to natural growth cycles or human intervention. In areas where short-cut grass was present during the analysis, these zones were not classified as effective buffers; however, such areas have the potential to develop into shrub layers or denser vegetation over time, which could reduce the likelihood of litter entering the waterbody from adjacent paths or open spaces.

Conversely, existing shrub layers may be mowed or cleared, temporarily increasing the accessibility of the riverbank and, consequently, the risk of litter input. Additionally, reed belts along the water's edge may expand and act as natural barriers, both limiting human access and trapping litter before it reaches the river.
These dynamic processes highlight the need for temporal flexibility and caution when interpreting spatial data on vegetation as a fixed element in pollution risk assessments.

Limitations - Industrial and harbour areas

It should be noted that potential litter input from harbour areas, shipyards, and industrial zones was not included in the analysis. These areas often have restricted access, lack public POIs, and may follow different waste management practices. As a result, they were excluded from the Overpass Turbo queries and the subsequent spatial filtering. While these zones can clearly contribute to riverine pollution—through operational discharge, runoff, or accidental loss—they were considered outside the scope of this urban public-space-focused assessment. Future studies may incorporate such areas using targeted datasets or industrial site audits.

Limitations - litter drift and accumulation within the waterbody

While the analysis effectively highlights potential litter input zones along urban riverbanks, it does not account for the downstream transport or eventual accumulation of litter within the waterbody itself. Factors such as current velocity, stream direction, and local hydrodynamics were not included in this study. In addition, surface litter can be redirected by prevailing wind conditions, leading to accumulation in areas far from the original entry points. As a result, this assessment provides insights into likely litter sources, but not into the transport pathways or final deposition zones within the aquatic system.

6. Conclusion

Despite its limitations, this spatial approach provides a valuable foundation for identifying potential pollution hotspots along the urban riverfronts of cities in the Baltic Sea region. By identifying where public use, accessibility and proximity to water overlap, the methodology can guide more targeted clean-up strategies and preventive infrastructure planning. The results can inform practical action: near the identified high-risk zones, clean-ups can be organised or in-stream litter capture devices deployed to intercept litter before it disperses further downstream or into the Baltic Sea.

Furthermore, strategies to avoid litter input could be developed in cooperation with the owners and operators of POIs located directly along the waterfront, such as restaurants, bars, pubs, and cafes. These stakeholders can play a crucial role in minimising litter leakage from high-traffic areas, and they could be involved in awareness campaigns, infrastructure improvements (e.g. bin placement, small barriers along urban riverside railings to prevent windblown litter) and voluntary agreements to reduce waste generation and improve waste handling practices.

Future improvements should aim to integrate temporal dynamics, refine buffer calibration, and better incorporate harbour and industrial land uses to further enhance the accuracy and applicability of the model.

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