

A feasible method for riverine macro litter monitoring

A case study of the Warnow River

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Identifying a feasible method for riverine macro litter monitoring

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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 among the most significant contributors to plastic pollution (Meijer et al., 2021). Due to their proximity to densely populated areas and their 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 transporting land-based litter into the marine environment (González-Fernández et al., 2021). Understanding their role in this transport process is essential for developing effective, site-specific strategies to intercept and prevent plastic pollution at its source. It has been estimated that 69.000 to 198.000 litter pieces enter the Baltic Sea yearly via the Warnow River (González-Fernández et al., 2021). But these estimations are based on short-term visual observations of floating macro-litter in other comparable rivers. Further, other studies on riverine (plastic) pollution support the hypothesis that most litter is retained in and around rivers rather than flowing into the oceans (Tramoy et al., 2020; van Emmerik et al., 2022).

The Interreg South Baltic project Circular Ocean-bound Plastic (COP) contributes to reducing plastic pollution by strengthening the evidence base on riverine macro-litter in the South Baltic Sea region. COP aims to identify challenges and opportunities related to monitoring, collecting, recycling, and reusing plastic captured in rivers and their surrounding environments. It also supports pilot activities in coastal cities to test collection approaches and improve understanding of how litter enters aquatic systems. The Warnow River was selected as a case study due to its connection between potential inland sources and an urban estuary and port environment, which is highly relevant for land-based plastic pathways.

This research report aims to assess and compare different field-based methods for monitoring riverine macro-litter along the Warnow River. Specifically, it aims to quantify the amount, composition, and, to some extent, the spatial distribution of litter recorded in different compartments (floating, stranded on riverbanks, and retained in vegetation or interception devices). A further objective is to evaluate each method and to identify the most suitable approach for long-term monitoring based on its potential for standardization, effort requirements, and selectivity. Ultimately, the report provides an evidence-based recommendation for a robust monitoring strategy that can be applied consistently over time and compared across studies.

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 is connected to the North Sea via the Danish Straits (Figure 1). Almost entirely landlocked, 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).



Figure 1: The Baltic Sea and the geographic location of the Warnow River (blue line) and its catchment area (light blue) in north-east Germany.

2.1. Warnow River and catchment area

The Warnow is a river in Mecklenburg-Vorpommern in north-eastern Germany (Figure 2). It rises near the village of Grebbin (district of Ludwigslust-Parchim) and flows north for approximately 155 km before reaching the Baltic Sea at Rostock (Warnemünde). In the lower reaches of the Warnow, the long-term mean discharge is approximately $19 \text{ m}^3 \text{ s}^{-1}$, with an average specific runoff of about $6.37 \text{ L s}^{-1} \text{ km}^{-2}$. The river drains a catchment area of roughly $3,304 \text{ km}^2$ (Schulz et al., 2023). Along its course, the river passes through (or close to) settlements including Bützow, Schwaan and Rostock, as well as several smaller municipalities (e.g., Zölkow, Bülow, Warnow, and Weitendorf). The Warnow also traverses lake sections, notably Mickowsee and Barniner See, before entering the Rostock estuary. Within the Warnow catchment, arable agriculture is the dominant land use, accounting for around 58% of the area. Forests form the second largest share (about 21%), followed by grassland (approximately 13%). By contrast, wetlands represent only a small fraction (around 4%), while settlements cover roughly 3%. Open water surfaces make up less than 1% of the catchment (Schulz et al., 2023). Rostock is by far the largest settlement along the Warnow River and, together with Bützow and Schwaan, represents the most likely source of concentrated riverside activity, with populations of 203,470, 7,549, and 4,945, respectively (Statistisches Bundesamt, 2022).

In this report, the study area extends from Klein Raden, 2 km south of Eickhof, to the mouth of the Warnow River where it flows into the Baltic Sea. This section contains the main urban and peri-urban areas along the Warnow River. It is therefore expected to generate the greatest pressure in terms of potential litter inputs. The research area was further subdivided into three functional zones: (1) the riverine section from Klein Raden to Bützow (2) the riverine section from Bützow to Rostock, and (3) the estuarine section within Rostock leading to Warnemünde (Figure 2).

These zones were created to account for differences in hydrodynamics, land use, and potential litter retention processes. By contrast, the upper (southern) Warnow, stretching from Grebbin to Eickhof, is predominantly rural. There are fewer settlements here, and waterfront use is less intensive. For this reason, it was considered less likely to be the primary source of macro-litter within the scope of this project.



Figure 2: Course of the Warnow River from its source near Grebbin to its mouth at Rostock/Warnemünde. The catchment area is shown in light blue and the city of Rostock in grey. The study area was divided into three functional zones: (1) the upstream riverine section from Klein Raden (≈1 km south of Eickhof) to Bützow; (2) the downstream riverine section from north of Bützow to Rostock; and (3) the estuarine section within Rostock extending to Warnemünde.

3. Methods

Riverine litter was monitored using a set of different field methods targeting litter in various compartments. These included:

- collection of floating litter from a stand-up paddleboard along a predefined section of the river.
- accumulated litter within reed-belt areas along the shoreline of the estuary.
- interception of floating litter using a litter boom.
- interception of floating litter with a driftwood barrier that was emptied at regular intervals.
- standardized shoreline surveys along a 100 m transect of the riverbank, and
- drone observations.

These methods were used together to capture both accumulated and floating litter, enabling a comparative evaluation of their performance.

3.1. Visual observation from stand-up paddleboard

Visual observations were conducted five times across September and October 2024, spanning the entire length of the river from Bützow to Rostock (Figure 3) before the river reaches the estuary. The general procedure was to put in the stand-up paddleboard at an available entry spot and to take it out at the selected endpoint; these locations were Bützow, the bridge connecting Kassow and Kambs, Schwaan, Papendorf and Rostock (Figure 4). The stand-up paddleboard provided the versatility and portability required for solo travel to reach entry points that are usually inaccessible by car.

Once on the river, paddling downstream with the current was usually done, but on days with a particularly strong northerly wind (over 16 km/h), paddling upstream was necessary. While paddling, the stand-up paddleboard was kept in the center of the 50-meter-wide river to offer the best views on both sides. Whenever litter was spotted, the board was navigated to collect or at least photograph the piece of litter. All pieces were collected unless they posed a significant risk to the surveyor (biologically or physically) or to the environment (e.g., if something was buried deep in the reeds, it was not disturbed to retrieve it), and unless the pieces were too large to collect (very large items, such as a sunken loveseat, were photographed but not collected).

Once collected and/or photographed, the litter pieces were entered into a Garmin GPSMap 66s handheld GPS, which marked the coordinates of the piece. It was noted whether the litter was free-floating, sunken, on the riverbanks, or trapped in the flora, and a description of the piece of litter was provided. Collected litter pieces were placed in plastic bags for transportation.

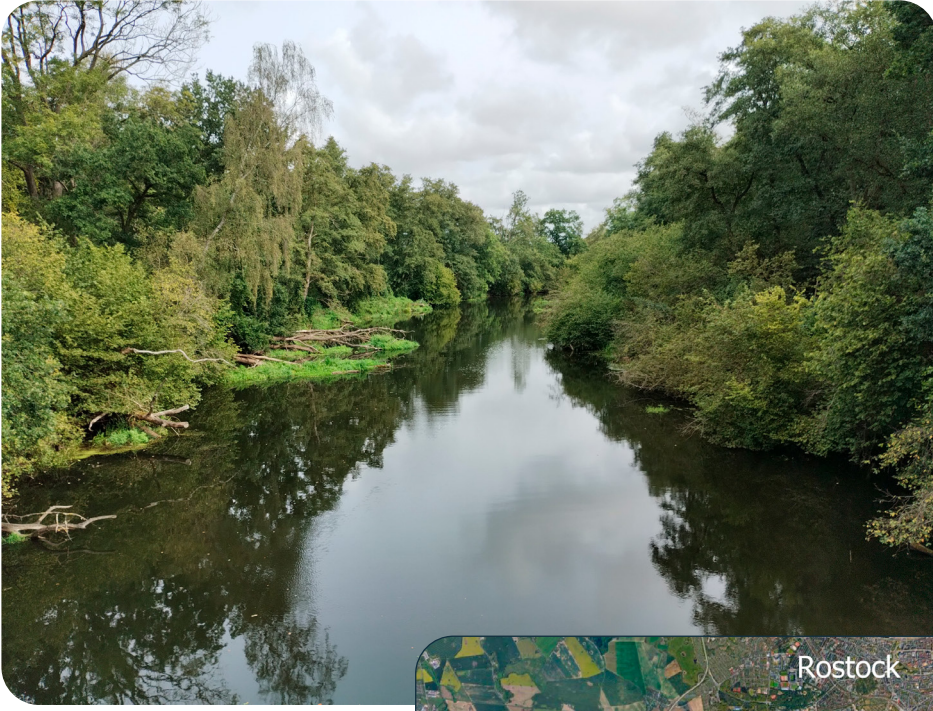


Figure 3: Example view of the Warnow River from the stand-up paddleboard near Kassow Bridge.



Figure 4: The stretch of the Warnow River between Bützow and Rostock (via Kassow Bridge, Schwaan, and Papendorf), which was surveyed visually from a stand-up paddleboard.

3.2. Reed Investigation

Reed belts are a common sight along the Warnow River and its estuary, and many of these belts are up to several meters wide, with only the first meter or so being reachable from the water. However, litter can become entangled much further into the reeds than this. Therefore, six reed investigations in the Warnow estuary (Figure 5) were carried out between 17.10.2024 and 11.11.2024.

The species, *Phragmites australis*, is a cosmopolitan species known as the Common Reed and grows in dense stands (as many as 200 stalks per square meter) up to six meters tall and is very resilient and hardy (Engloner, 2009). All reeds sampled were of this species. To survey these parts of the river, a novel method had to be implemented. Many parts of the river are less than 2 meters deep along the banks, particularly in the outer reaches of the reed belts on the land side. This gives the opportunity for actual wading observations of the reed belts. Using chest-high waders along several sites of the river, visual observations were completed from within the reed belts (Figure 6).

Due to wind and previous travelers, both human and otherwise, passing through the reeds, there are many small, trampled paths. These paths and their surroundings were examined. While the paths were the primary route taken within the belts, the area was also circumnavigated, including outside the belts and in the river itself, where the depth permitted. This method resulted in rather cohesive coverage of most of the belts. Every few minutes, a GPS coordinate was taken to later calculate the area (m²) covered during the surveys. All visible litter was collected in plastic bags and then later analyzed.



Figure 5: The Warnow estuary study area showing the shoreline sections where reed-belt surveys were conducted to assess litter accumulation and entanglement in riparian vegetation.



Figure 6: Visual Example of reed wading in the Warnow estuary in July 2024.

3.3. Litter Booms

Three sites were chosen to test the litter booms (Figure 7). Here, the river had a width between 10 and 15 m, so it was possible to cover roughly a third of the river width with the 5m long litter boom. The sites needed to be accessible by car due to the weight of the litter boom and further equipment (around 15-20 kg).

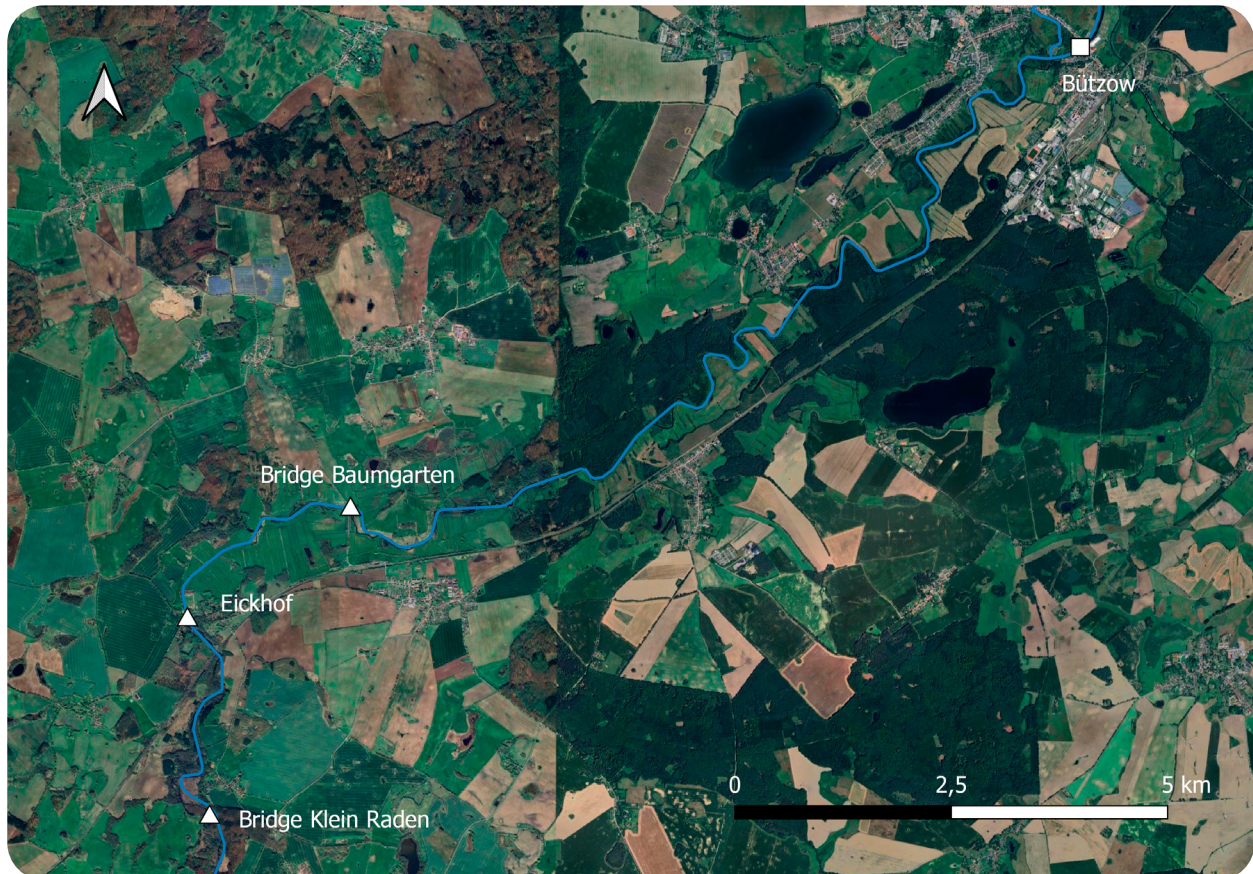


Figure 7: Locations where the litter booms were employed (white triangles) and the location of the driftwood barrier in Bützow (white square).

The booms are made of plastic-coated polyester carrier fabric (900 gr/m²), five meters in length, 100 mm Ø in diameter, immersion depth approx. 100 mm, weight approx. 2.5 kg/m. If needed, several booms can be connected to each other to increase the length. The ends of the booms can be connected to a cylindrical-shaped part that can be moored in the water or on the shore by using ropes and/or metal pins. Underneath the boom is a skirt of 5 cm to prevent litter from slipping under.

To deploy and operate the boom system, the following equipment was required: boom segments, connector pieces, mooring gear (ropes, pegs/pins, cable ties), a hammer (for securing pegs), printed field sheets (on a clipboard/cardboard backing) and pencils, a smartphone or camera, a GPS device (or smartphone GPS where adequate), a measuring tape, a measuring stick, a landing net, and plastic bags for collected litter. Further, the following requirements were set: The flow rate of the river (m/s) is not too strong (water flow is too strong when the shape of the boom changes, is damaged,

or cannot be secured), the water flows downstream and flows continuously, and the water stream is not disturbed.

At the site of the pedestrian bridge in Klein Raden and the bridge in Baumgarten, the boom was attached in the middle of the stream by using ropes on both ends. The ropes were secured on the piles of the bridge. In Eickhof, the boom was moored on the side of the river using a metal pen and attached to a tree on the same side using ropes (Figure 8). In each of the three locations, the litter boom was used for three hours: in Baumgarten on 27.03.2024 (11 am – 2 pm); in Klein Raden on 11.02.2024 (11 am – 2 pm); in Eickhof on 25.03.2024 (2 pm – 5 pm).



Figure 8: The three locations where the litter boom was tested. (Top left) At the pedestrian bridge in Klein Raden. (Top right) Before the waterfall in Eickhof. (Bottom left) At the Warnow bridge in Baumgarten. Bottom right picture shows a sketch of the litter boom – eagle eye perspective.

3.4. Driftwood barrier in Bützow

A driftwood barrier was installed in Bützow (Figure 7) as part of the replacement construction of the Warnow Bridge. The barrier serves to protect the bridge structure and hydraulic engineering structures from flotsam that can flow through the Warnow. The barrier consists of a metal chain to which several tree trunks (approx. 20-30 cm radius; length 2-3 m) are attached, which float on the surface (Figure 9). There are gaps of 10-20 cm between the tree trunks. The barrier runs from the north to the south bank. The tree trunks protrude only a few cm out of the water. For flexibility of the barrier, the first meter on both sides is only covered by the metal chain without tree trunks. In total, twenty-two meters of the twenty-four-wide river is covered by the tree trunks (91.6%).

Between March 2024 and September 2024, the material captured by the barrier was pulled ashore from the riverbank using a long telescopic pole fitted with a rake. This work was carried out weekly by official public-sector staff, with a few exceptions when no worker was available (e.g., illness or vacation). The collected material was then searched for macro-litter. Any pieces of litter found were given to us and subsequently sorted and analysed by our team.



Figure 9: The driftwood barrier in Bützow. In the front is the metal chain visible that connects several tree trunks (approx. 20-30 cm radius; length 2-3 m), which are floating on the surface. There are gaps of 10-20 cm between the tree trunks. The barrier runs from the north to the south bank.

3.5. 100m Riverbank method

Riverbank litter was collected on 40 sites for one month between 21 March 2024 and 18 April 2024 using the OSPAR method (Lacroix and Vriend, 2025). This method is based on the OSPAR Commission’s beach litter identification method and has been modified to make it suitable for riverbanks. A survey unit is defined as a 100 m stretch of riverbank, measured along a line running parallel to the waterline. The two sides of the unit are marked by perpendicular lines extending inland from the water’s edge to the flood line, with a maximum width of 25 m (Figure 10). In practice, the entire 100 m section is surveyed from the waterline up to the flood line. To ensure systematic coverage, the section is worked through in parallel strips (approximately 1–3 m wide), and all visible litter pieces (> 2.5 cm) are collected. Afterwards, the litter was analysed.

The 40 sites investigated were spread across five locations along the Warnow: the bridge at Klein Raden, the Eickhof area, the Baumgarten bridge, Schwaan and Bützow. Detailed site maps and coordinates can be found in Appendix 1. Each site was 100 m long and ranged in width from 3 to 15 m. For each site, the vegetation type in the riparian zone was noted (unvegetated, herbaceous, reed, shrubby, or arboreal). The arboreal type is defined as trees over 5 m in height, while the shrubby type is defined as trees less than 5 m in height. 38 of the sites were vegetated, and two were not. The land use types of the areas varied, ranging from agriculture to forestry.

To carry out the OSPAR riverbank method, the following equipment was required: a field recording sheet (ideally mounted on a clipboard or cardboard backing) and pencils, string/lines to mark transects, pins or pegs to secure the lines, a measuring tape, a camera or smartphone for photo documentation, and plastic bags for collecting the litter.

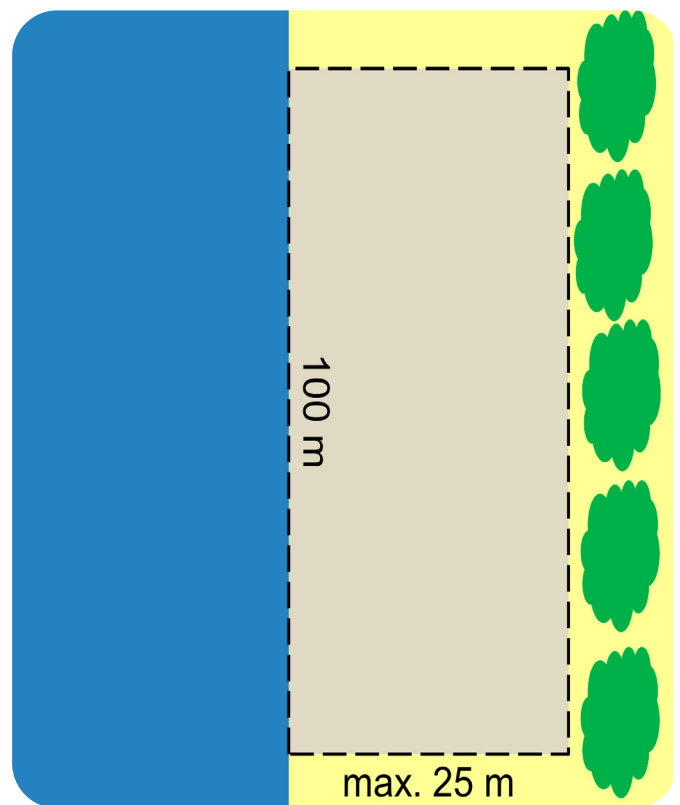


Figure 10: Schematic layout of the OSPAR-based riverbank survey unit: a 100 m riverbank section surveyed from the waterline to the flood line, with a maximum inland width of 25 m.

3.6. Litter analysis

All litter collected (or photographed during the visual observation from the stand-up paddleboard) was analyzed using the hierarchical system of the “Joint List of Litter Categories for Marine Macrolitter Monitoring” (J-List) developed by the EU (Fleet et al., 2021). The J-List is useful in this context as it is explicitly designed to be applicable across different environmental compartments—such as the coastline/riverbank, surface layer of the water column (floating litter), and the bottom/seabed, and it can also be used for biota-related assessments—thereby facilitating consistent comparisons of litter composition and patterns between compartments within the same study area.

In practice, each piece of litter found was assigned in the highest level (5) of detail possible to the most appropriate J-code category, as defined in the Joint List of Litter Categories and the accompanying Online Photo Catalogue the list can also (European Commission, 2026; Fleet et al., 2021). Litter was further categorized into single-use plastic (SUP) and categorized as plastics, glass/ceramics, metal, processed wood, paper/cardboard, textiles, rubber, and others.

3.7. Additional Drone Observation of the Reed Belts

An aerial drone by DJI P4 Multispectral was used for the investigation of the reed belts as a means of collecting data without having to access areas that would otherwise be difficult or inaccessible. Six different altitudes were used to investigate litter in the reed belts: 3 m; 4 m; 5 m; 10 m; 15 m; and 20 m (Figure 11). The drone was flown over selected areas while recording video of the area below.

This footage was then analyzed visually to identify any litter. Therefore, each video was uploaded to Labelbox and then run through their video labeling tool software. This tool was used to play the recorded videos at a slower speed and add bounding boxes to any litter pieces visible. When possible, the marked litter pieces were identified by material as well. Using landmarks from the videos, polygons of the areas were created in QGIS Release 3.22 (Białowieża) to determine the size of the scouted sites.

The length of the recordings and the time taken to analyse them were used to calculate the time required to search an area and the number of litter pieces found per unit of time. Based on these two factors, an approximate estimate was made of how much litter could be found by searching larger areas, assuming a homogeneous litter distribution around the reed belts.



Figure 11: Visual Example of Drone footage at 15 m height. The white specks to the left of the footbridge are pieces of plastic foam waste.

3.8. Evaluation Matrix for long-term monitoring suitability

To evaluate the tested monitoring methods, a semi-quantitative evaluation matrix was developed to compare their suitability for long-term application. The methods were scored for their potential of standardization, effort, and bias/selectivity based on the practical experience of the field team members who implemented each approach during the monitoring campaign. This included their observations on how easy it was to apply the method consistently, how much time and logistics were required under real conditions, and which types of litter were more likely to be detected or missed. The scoring, therefore, reflects method performance as experienced in the field rather than purely theoretical considerations. To make the assessment transparent, the individual scores were combined into a weighted overall score using predefined weights.

4. Results

The following sections summarize the main results of the field campaigns and compare the outcomes across the different monitoring and collection approaches applied along the Warnow River. The results provide an overview of litter quantities, composition, and spatial patterns, and they form the basis for evaluating the practical performance of each method.

4.1. Floating litter collected by stand-up paddleboard

A total of 84 litter pieces were found over the course of 15 hours of field work. Of these 84 litter pieces, 71 could be collected, while 13 were not reachable from the board; these pieces were noted but not collected. The litter (collected and noted) was composed of 23 different litter items (J-Code). Plastics were the most commonly found category of litter (n=37) with 44.0 %, followed by glass/ceramics (n=26; 31.0 %), metal (n=15; 17.9 %), wood (n= 2; 3.6 %), paper (n=2; 2.4 %), and textile (n=1; 1.2 %). Of all litter found, 52 pieces (61.9 %) were entangled in plants, 17 pieces (20.2 %) were found on riverbanks, 12 pieces (14.3 %) were floating, and 3 pieces (3.6 %) were found on the bottom (sank) (Figure 12). The top ten litter items found were responsible for 79.8% of all litter (Table 1).

Table 1: top ten litter items collected and noted with the stand-up paddleboard with their litter category, in total numbers, percentage, and cumulative percentage.

	J code	J list type code	SUP	Litter item	Category	Quantity	%	Cumulative %
1	200	gc_nn_b&c_bott_		Bottles incl. pieces	Glass/ceramics	26	31.0	31.0
2	92	pl_fi_bte_		Bait containers/packaging	Plastics	12	14.3	45.2
3	175	me_fc_b&c_cans_bevg_		Cans (beverage)	Metal	6	7.1	52.4
4	8	pl_fc_b&c_dbot_lage_	SUP	Drink bottles > 0.5 l	Plastics	5	6.0	58.3
5	176	me_fc_b&c_cans_fcan_		Cans (food)	Metal	5	6.0	64.3
6	7	pl_fc_b&c_dbot_sml_	SUP	Drink bottles <= 0.5 l	Plastics	3	3.6	67.9
7	30	pl_fc_wrp_cwls_crsp_	SUP	Crisp packets/sweet wrappers	Plastics	3	3.6	71.4
8	172	wo_nn_owo_larg_		Other wood > 50 cm	Processed/ worked wood	3	3.6	75.0
9	227	pl_fc_tab_cups_hpcp_	SUP	Cups and cup lids	Plastics	2	2.4	77.4
10	27	pl_sm_but_		Cigarette butts and filters	Plastics	2	2.4	79.8

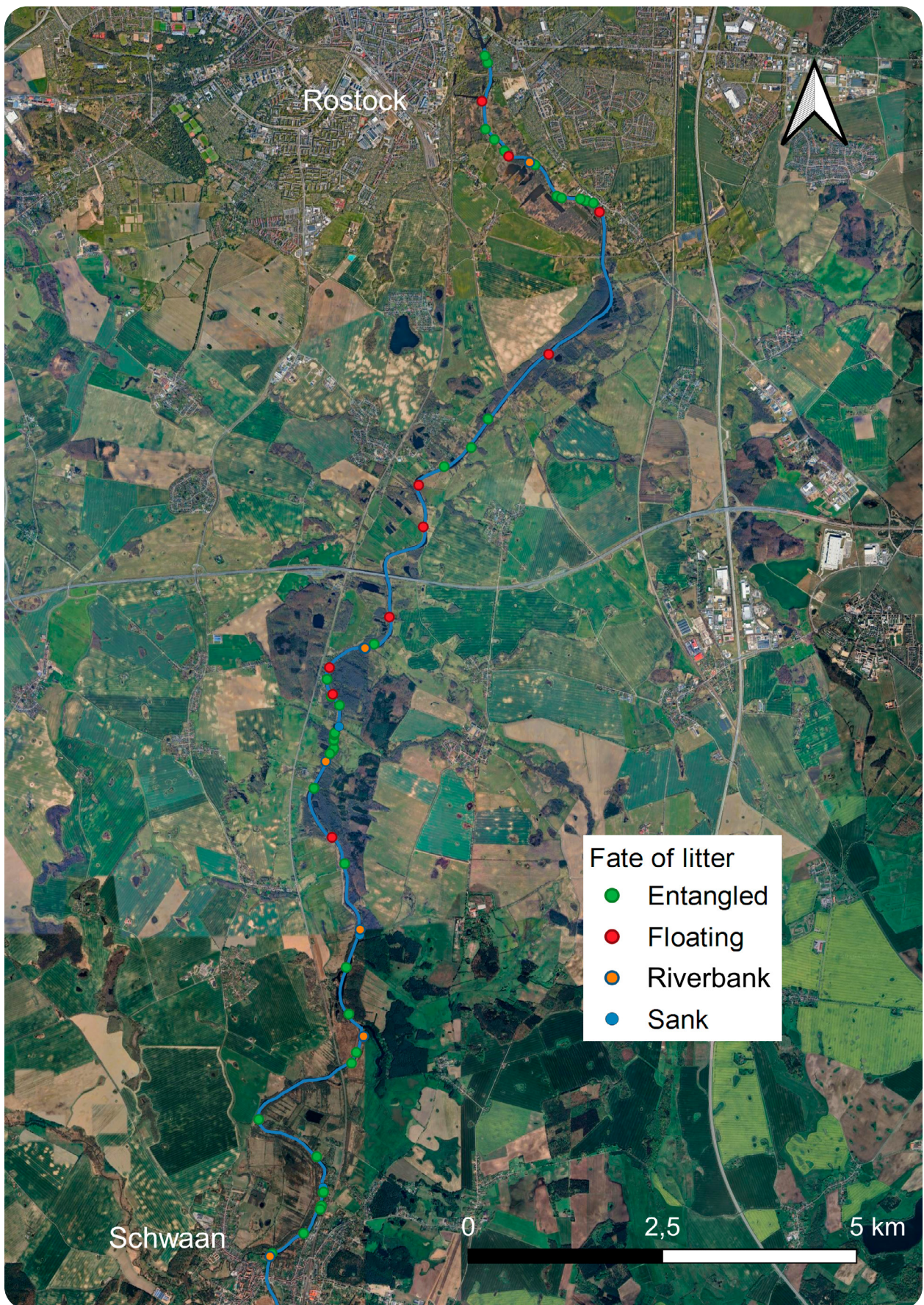


Figure 12: The location of litter pieces found with the stand-up paddleboard method and their fate: entangled, floating, on the riverbank, or sank to the bottom.

4.2. Reed investigations

Of the total 400 pieces of litter found and collected during the reed investigations, 86.9 % were plastic, followed by glass (6.8 %), metal (2.3 %), and other materials (4.0 %). A total of 54 different litter items were found. Across the total surveyed area of 7895 m², the average pollution was 0.05 litter pieces/m² ± 0.03 / median 0.05. The top ten litter items were responsible for 71.6 % of all litter found (Table 2).

Table 2: Top ten litter items found during the reed investigations with their litter category, in total numbers, percentage, and cumulative percentage.

J code	J list type code	SUP	Litter item	Category	Quantity	%	Cumulative %
1	30	pl_fc_wrp_cwls_crsp_	SUP Plastic crisps packets/ sweets wrappers	Plastics	72	18.0	18.0
2	82	pl_nn_frg_fopy_smal_	Fragments of foamed polystyrene 2.5 cm >=<= 50 cm	Plastics	51	12.8	30.8
3	67	pl_nn_cpa_shet_	Plastic sheets, industrial packaging, sheeting	Plastics	40	10.0	40.8
4	79	pl_nn_frg_nofp_smal_	Fragments of non-foamed plastic 2.5cm >= <= 50cm	Plastics	31	7.8	48.5
5	200	gc_nn_b&c_bott_	Glass Bottles incl. pieces	Glass/ceramics	27	6.8	55.3
6	8	pl_fc_b&c_dbot_lage_	SUP Drink bottles > 0.5 l	Plastics	15	3.8	59.0
7	4	pl_nn_bag_smbg_	SUP Small plastic bags, e.g. freezer bags incl. pieces	Plastics	14	3.5	62.5
8	225	pl_fc_b&c_pfoc_	SUP Plastic food containers made of hard non-foamed plastic	Plastics	14	3.5	66.0
9	21	pl_fc_b&c_lids_drnk_	SUP Plastic caps/lids drinks	Plastics	11	2.8	68.8
10	241	pl_nn_idp_idnf_	Other identifiable non-foamed plastic items	Plastics	11	2.8	71.6

Most litter was found on the western part of the Warnow estuary opposite the industrial harbour area around the reed belts of IGA Park. Lower amounts but still high were found north and south of IGA Park (western shore), and lower amounts on the eastern reed belts below the harbour area. In the southern area of the estuary in Gehlsdorf and the area of the old landfill site, the pollution found was lowest (Figure 13 and Table 3).

Table 3: Pollution in total litter pieces and litter pieces/m² found during the Reed investigations.

Location	Total litter	Area in m ²	Litter pieces/m ²
IGA Park North	96	883	0.11
IGA Park	118	2023	0.06
IGA Park South	93	1274	0.07
Harbour area	66	1999	0.03
Gehlsdorf	20	1495	0.01
Old landfill	7	221	0.03

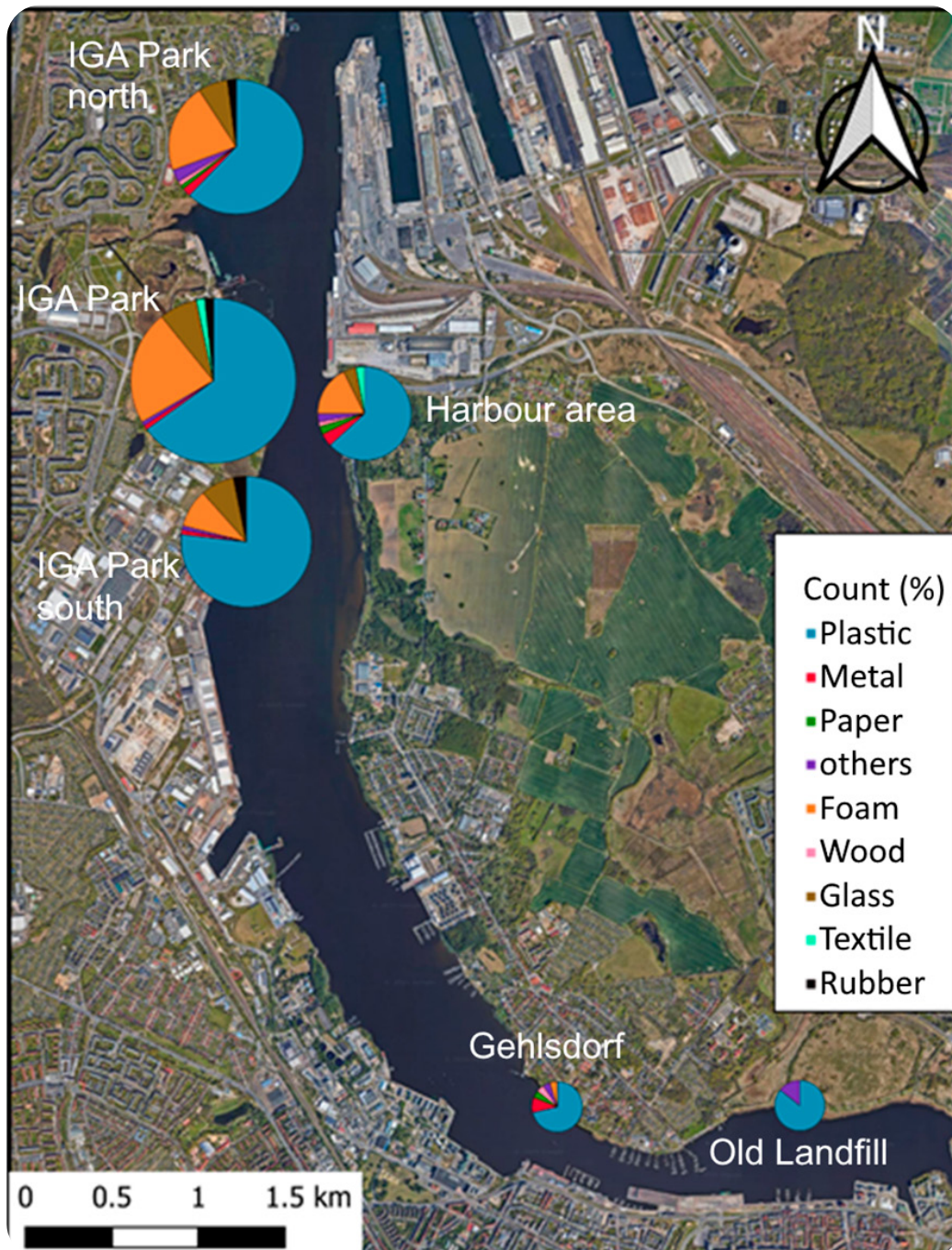


Figure 13: Quantity of litter found in the reed belts in the Warnow estuary.

4.3. Litter booms results

During the three days with a total of nine hours of sampling litter on the water surface, no litter pieces were collected, nor was any litter visible that was not caught by the litter boom.

4.4. Driftwood barrier Bützow

A total of 228 litter items were collected from the driftwood barrier in the Warnow River at Bützow. Litter was not recovered at every emptying event. Across the 28-week observation period, litter was recorded in 10 weeks. For weeks with no recorded litter, it is not always possible to distinguish whether (i) no litter was captured by the barrier, or (ii) the barrier was not emptied or documented (e.g., due to limited staff availability). Accordingly, the data record is not fully continuous, and consistent reporting (information flow) was not always guaranteed throughout the study period.

The composition of litter was composed of 47 different litter items (J-Code) and seven categories. Plastics were the most commonly found category of litter (n=141) with 61.8 %, followed by metal (n=37; 16.2 %), paper (n=31; 13.6 %), glass (n=13; 5.7 %), textiles (n=4; 1.8 %), rubber (n=1; 0.4 %) and processed wood (n=1; 0.4 %). The top ten litter items were responsible for 65.8 % of all litter found (Table 4).

Table 4: The top ten litter items found in the driftwood barrier in Bützow with their litter category, in total numbers, percentage, and cumulative percentage.

J code	J list type code	SUP	Litter item	Category	Quantity	%	Cumulative %
1	27	pl_sm_but_	SUP Tobacco products with filters (cigarette butts with filters)	Plastics	31	13.6	13.6
2	30	pl_fc_wrp_cwls_crsp_	SUP Plastic crisps packets/ sweets wrappers	Plastics	27	11.8	25.4
3	4	pl_nn_bag_smbg_	SUP Small plastic bags, e.g. freezer bags incl. pieces	Plastics	18	7.9	33.3
4	225	pl_fc_b&c_pfoc_	SUP Plastic food containers made of hard non-foamed plastic	Plastics	18	7.9	41.2
5	178	me_nn_b&c_lids	Metal bottle caps, lids & pull tabs from cans	Metal	15	6.6	47.8
6	61	pl_fi_ofi_	Other plastic fisheries related items	Plastics	10	4.4	52.2
7	200	gc_nn_b&c_bott_	Glass Bottles incl. pieces	Glass/ceramics	9	3.9	56.1
8	156	pp_nn_frg_	Paper fragments	Paper/cardboard	8	3.5	59.6
9	176	me_fc_b&c_cans_fcan_	Metal food cans	Metal	7	3.1	62.7
10	148	pp_nn_box	Cardboard (boxes & fragments)	Paper/cardboard	7	3.1	65.8

4.5. 100 m Riverbank

In total, 544 litter pieces were collected during the riverbank surveys along the Warnow River. The composition of litter was composed of 53 different litter items (J-Code) and numerous categories. Plastics were the most common category of litter (n=334) with 61.2 %. Followed by glass (n=108; 19.9 %), paper (n=48; 8.8 %), metal (n=46; 8.5 %), and textile (n=8; 1.5 %). The average pollution was 0.02 litter pieces per m² ± 0.02 / median 0.02. The top ten litter items found are shown in Table 5.

Table 5: The top ten litter items found on the riverbanks with their litter category, in total numbers, percentage, and cumulative percentage.

J code	J list type code	SUP	Litter item	Category	Quantity	%	Cumulative %
1	200		gc_nn_b&c_bott_	Glass/ceramics	105	19.3	19.3
2	30	SUP	pl_fc_wrp_cwls_crsp_	Plastics	75	13.8	33.1
3	27	SUP	pl_sm_but_	Plastics	60	11.0	44.1
4	225	SUP	pl_fc_b&c_pfoc_	Plastics	36	6.6	50.7
5	158		pp_nn_opp_	Paper/cardboard	32	5.9	56.6
6	7	SUP	pl_fc_b&c_dbot_sml_	Plastics	27	5.0	61.6
7	178		me_nn_b&c_lids_	Metal	23	4.2	65.8
8	3	SUP	pl_nn_bag_cabg_	Plastics	19	3.5	69.3
9	8	SUP	pl_fc_b&c_dbot_lage_	Plastics	19	3.5	72.8
10	82		pl_nn_frg_fopy_smal_	Plastics	16	2.9	75.7

4.6. Drone Observation results

The drone was flown at 6 estimated altitudes. Figure 14 summarizes extrapolated detection rates (litter pieces per hour) by altitude. The highest rates occur between 5 and 15 m (with a peak at 15 m), and altitude has a significant effect (ANOVA, $p < 0.001$). At 20 m, the detection rate drops markedly. This could reflect genuinely lower litter density in the area flown at that height, but it may also be methodological (reduced visibility of small litter pieces due to fewer pixels per litter piece, and/or litter pieces may have been more difficult to see due to the reeds). At very low altitudes (3 and 4 m), image detail is high, but far less ground is covered per unit time, which reduces the overall chance of encountering litter.

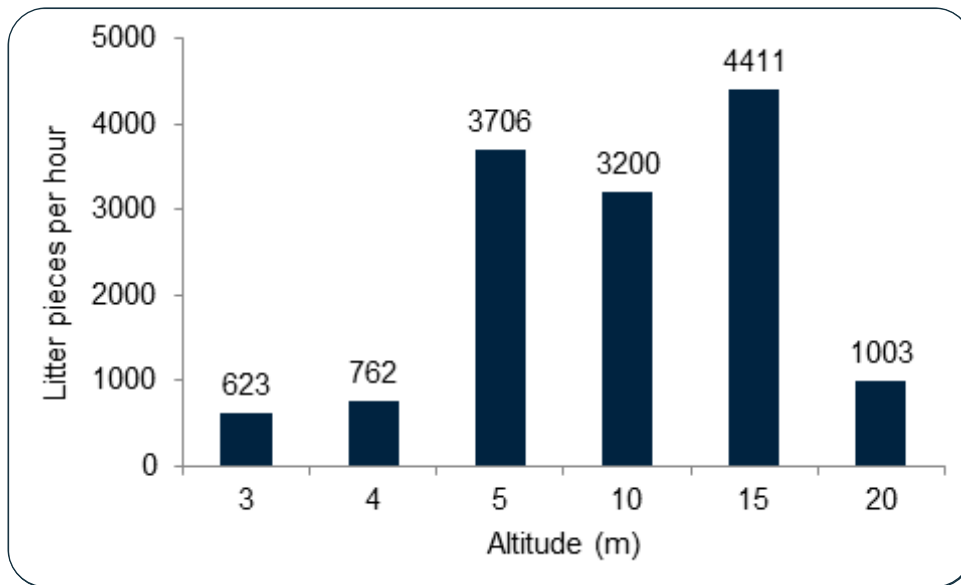


Figure 14: Extrapolated litter detection rate (litter pieces per hour) across estimated drone flight heights (3–20 m).

Figure 15 shows litter density (litter pieces per m²). Altitude is again statistically significant ($p = 0.002$), and post-hoc tests indicate that the pattern is largely driven by the substantially higher densities recorded at 5 m. Overall, the trend suggests that lower altitudes increase detection rates, especially of smaller litter pieces. However, several biases may contribute: low-altitude flying can encourage more intensive visual scanning and may also lead to unintentional drifting toward visible pollution clusters rather than maintaining a strict transect. Finally, differences may partly reflect spatial heterogeneity in litter distribution across the areas flown at each height.

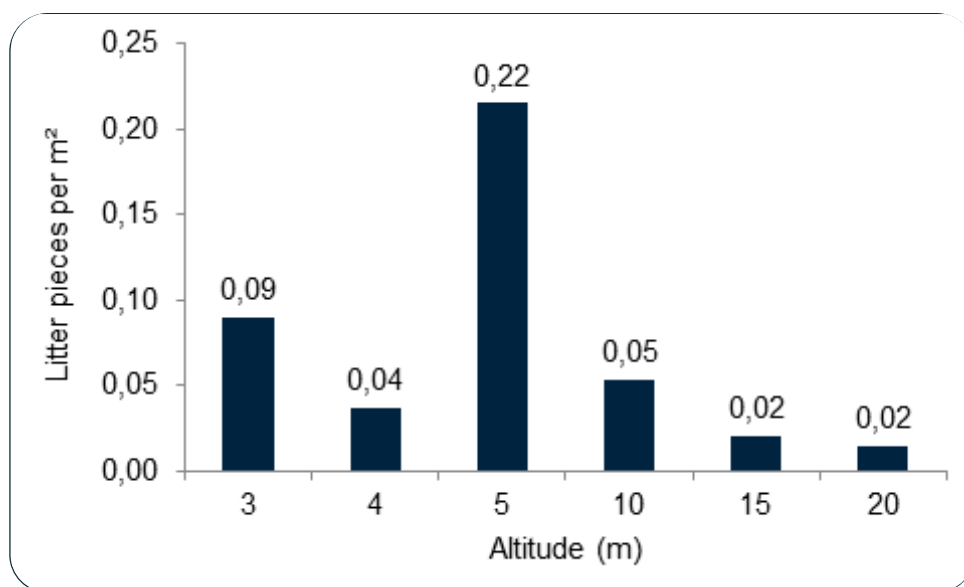


Figure 15: Litter density (pieces per m²) across different drone flight heights (3–20 m), showing the highest densities at low altitude.

Beyond litter counts, identifiability is crucial for monitoring. In Figure 16, the percentage of identifiable litter pieces declines clearly with increasing altitude (significant, $p = 0.007$): identifiability is high at 3–5 m, but much lower from 10 m upward. The small increase at 20 m height likely reflects an outlier and/or a size-selection effect, where mainly larger and easier to identify litter pieces remain detectable at that height.

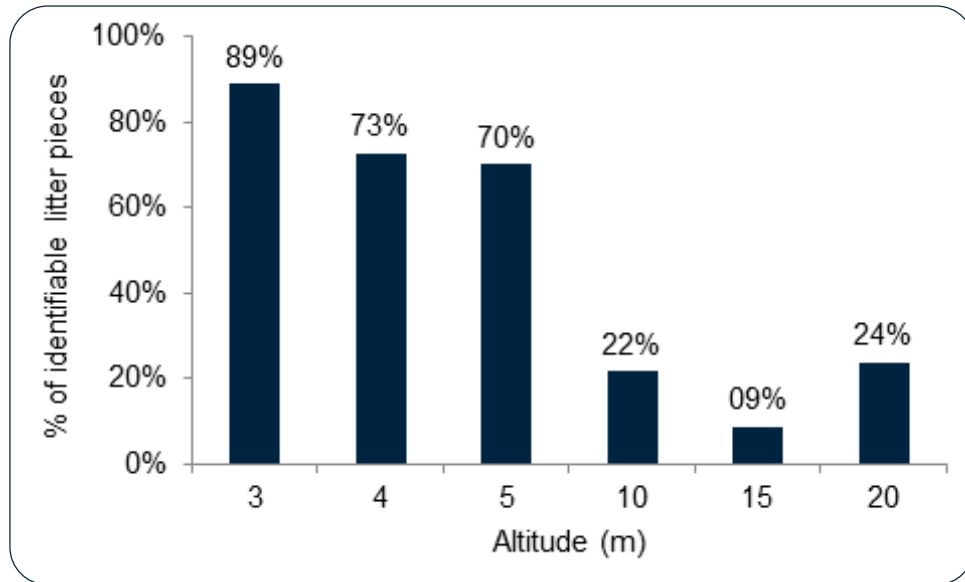


Figure 16: Proportion of litter pieces that could be identified/classified (%) across different drone flight heights (3–20 m), generally decreasing with increasing altitude.

5. Comparison of methods

For the purposes of comparison, the methods were divided into active and passive monitoring methods. Active methods involved direct visual searches and manual collection, such as riverbank transects, reed-belt surveys, and stand-up paddle surveys. Passive methods, such as litter booms and driftwood barriers, collected floating litter and were emptied at defined intervals. This distinction helped separate effort-based collection efficiency from time-integrated capture rates.

5.1. Efficiency of active methods

To evaluate the efficiency of the actively implemented collection methods, catch rates were calculated as litter collected per hour (pieces collected per person-hour). The median was used as a robust measure of central tendency and was complemented by a 95% bootstrap confidence interval to account for skewed distributions and small sample sizes (Table 6). The highest catch rates were recorded along the riverbank (100 m) and within reed belts: for the 100 m riverbank transects ($n = 40$), the median was 58.0 items/h (95% bootstrap CI: 42.0–71.0), and for the reed belts ($n = 6$) it was 61.6 items/h (95% bootstrap CI: 16.7–81.5). The confidence intervals overlap substantially, meaning that, based on the available data, no clear difference in efficiency between riverbank and reed belt surveys can be statistically supported.

The small sample size for reed belt surveys also results in higher uncertainty, reflected in the wider interval. In contrast, the stand-up paddleboard method ($n = 5$) showed much lower efficiency, with a median of 3.3 items/h (95% bootstrap CI: 2.86–6.76). Stand-up paddleboard surveys mainly target visible pieces of litter on the water's surface, and are limited by visibility, flow conditions and manoeuvrability.

Furthermore, of all the litter found during stand-up paddle surveys, only 14.3% was free-floating, while most pieces of litter were stranded or entangled in some way. Therefore, many of these pieces could have been more easily collected using one of the on-foot methods (riverbank or reed-belt surveys). This suggests that riverbank and reed-belt surveys are effective at removing stranded and retained litter, whereas stand-up paddle surveys are less effective, as most floating litter accumulates or becomes entangled quickly, resulting in lower catch rates for floating litter per unit of field effort.

5.2. Efficiency of passive systems

For the passive systems (driftwood barrier and litter boom), catch rates were calculated as a time-integrated collection rate over the emptying interval, i.e., the number of captured pieces per hour between two emptying events (pieces per deployment hour) (Table 6). This metric does not represent efficiency per working hour; instead, it serves as a proxy for the transport and input of floating litter over time. For the driftwood barrier ($n = 28$), the median was 0.000 pieces/h (95% bootstrap CI: 0.000–0.039), while the mean was 0.048 pieces/h.

The combination of a near-zero median and a higher mean indicates a strongly skewed distribution of litter pieces per interval: many intervals show zero catches, whereas peaks of pollution were found. For the litter boom ($n = 3$), only zero catches were recorded (median 0.000; CI 0.000–0.000), though interpretation is limited due to the very small dataset. Passive interception systems are therefore particularly useful for detecting episodic transport events and integrating floating-litter transport over time.

However, due to their selectivity (capturing only the floating litter pieces) flowing into the device and their dependence on hydrological conditions, they are not suitable as a standalone method for representing litter in the overall river environment, as most litter accumulates quickly and is not free floating for long period of times (as discussed in chapter 5.1). But combined with active riverbank or reed belts surveys, passive systems enable a complementary assessment of retention/accumulation on riverbanks and in reed belts and time-integrated transport dynamics at the water surface.

Table 6: litter pieces collected per hour per method used.

Method	n	Median	95%-Bootstrap- CI low	95%-Bootstrap- CI high	Avg.	Standard deviation
Stand-up paddleboard	5	3.3	2.86	6.76	4.38	1.72
Litter boom	3	0	0	0	0	0
Reed belts	6	61.6	16.7	81.5	53.26	31.88
Riverbank 100 m	40	58	42	71	64.21	53.44
Driftwood barrier	28	0	0	0.039	0.048	0.083

5.3. Suitability of Monitoring Methods for Long-Term Application

Finding more litter with a given method does not automatically mean that this method is “best,” because long-term monitoring also depends on factors such as potential of standardization, logistical effort, safety, cost, and systematic bias. Table 7 compares the tested methods in terms of potential of standardization, effort (lower is better), and bias/selectivity (lower is better), highlighting differences in their suitability for consistent long-term monitoring across multiple seasons and years. Since the drone surveys were based on visual detection only and did not involve collecting litter pieces, the drone method was not included in the evaluation matrix.

Stand-up paddle surveys score lower for long-term monitoring because they are comparatively difficult to standardize and are strongly affected by external conditions. Strengths include the ability to target the floating litter compartment directly and to cover longer river sections, which can be valuable when the monitoring objective is floating litter. However, weaknesses for long-term use include dependence on visibility, wind, current, water level, safety constraints, and higher logistical requirements (vessel access, trained personnel).

Standardized 100 m riverbank transects performed best overall for long-term monitoring (the highest weighted score in the matrix). Their main strengths are the high repeatability (fixed length and clear protocol), low logistical complexity (no specialized equipment beyond basic sampling gear), and good feasibility for regular sampling at consistent intervals. This makes the method well-suited to detect temporal trends and to compare sites. Key limitations are that riverbank surveys primarily represent stranded/accumulated litter and can be influenced by hydrological conditions (e.g., high flows that redistribute litter, recent flooding, wind-driven stranding). Therefore, riverbank data should be interpreted as monitoring shoreline accumulation rather than real-time in-stream transport.

Reed belt surveys provide important information on retention and entanglement in shoreline vegetation, which is often missed by stand-up paddle monitoring and can represent longer-term accumulation. Their main strengths are that they are sensitive to litter that becomes trapped and stored in vegetation, and they help to identify spatial hotspots along vegetated shorelines. For long-term monitoring, however, reed surveys are typically harder to standardize than riverbank transects because access, vegetation density, and the surveyable area can vary a lot, and the required effort is often higher and less predictable. Walking through reed belts may also cause ecological disturbance. In addition, the litter collected likely reflects some observer bias, as larger and more colourful items are easier to spot, and there may also be a bias towards items that are more likely to get entangled, although this was not tested. Overall, reed-belt litter, similar to riverbank litter, mainly represents shoreline accumulation rather than real-time in-stream transport, but in a different compartment that is more sensitive and harder to access.

Finally, passive interception methods (litter boom and driftwood barrier) can be useful for long-term monitoring when the goal is to approximate the transport/flux of floating litter integrated over time. Their main strengths are that they can intercept litter continuously between servicing events and that the sampling interval can be fairly standardized if emptying is done regularly. However, their weaknesses are mostly practical: they require installation and maintenance, permits, safe and robust anchoring, and a reliable routine for emptying and documenting the material. They are also selective by design, because they only capture the floating fraction that is actually routed into the device by the local flow field, which can change with discharge, wind direction, and channel shape. In addition, there is likely some detection bias during sorting, as larger and more colourful items trapped in the boom/barrier are easier to notice, while small fragments may be missed - especially when a lot of vegetation or algae are collected at the same time. Consequently, passive devices work best as a complementary long-term tool alongside shoreline transects, rather than as a standalone monitoring method.

Overall, the results point to 100 m riverbank transects as the most practical “backbone” for long-term trend monitoring, because they are easy to repeat and keep consistent over time. Where possible, this can be complemented with passive interception (boom or barrier) if information on floating-litter transport is needed. Reed-belt surveys are best for identifying retention zones and hotspots, but since reeds are hard to access, often protected, and small litter is easy to miss on foot, a drone-based approach is the better option, so that hotspots can be mapped without disturbing this sensitive habitat.

Table 7: Semi-quantitative evaluation of the tested river-litter monitoring methods for long-term application. Methods are grouped into active (direct observation/collection) and passive (interception devices). Each method was scored on a 1–5 scale (potential of standardization: 1 = poor, 5 = excellent; effort: 1 = low effort/best, 5 = high effort/worst; bias/selectivity: 1 = low bias/best, 5 = high bias/worst). Scores were combined into a weighted overall score using the following weights: potential of standardization = 0.35, effort = 0.35, and bias/selectivity = 0.30.

	Method	Potential of standardization	Effort (lower is better)	Bias / selectivity (lower is better)	Weighted score	Short rationale
Active	Stand-up paddleboard	2	4	4	2.0	Depends on visibility/wind/flow; paddle board logistics; width of river; shipping or other boat activities; selective for larger visible floating litter.
	Riverbank 100 m	5	1	2	4.7	Fixed transect; easy logistics; some bias from water level/stranding.
	Reed belts	2	3	4	2.4	Area/access vary; higher disturbance/effort; litter is difficult to detect; Reeds could be damaged by trampling.
Passive	Litter boom	4	4	3	3.4	Emptying interval can be standardized; low field time per emptying; selective for larger fraction; smaller litter can be hard to detect; often high amounts of biomass collected; Wind or upper flow reversal can push out litter; if river must be kept open not applicable; permits required
	Driftwood barrier	4	5	3	2.7	Emptying interval can be standardized; field time per emptying depends on width of the barrier; selective for larger fraction; smaller litter can be hard to detect; often high amounts of biomass collected; Wind or upper flow reversal can push out litter; if river must be kept open not applicable; permits required

6. Discussion

The comparison of methods showed strong differences in performance depending on the targeted litter compartment. Active, on-foot methods (100 m riverbank transects and reed belt surveys) achieved the highest catch rates per person-hour and therefore represent efficient approaches for quantifying and removing accumulated litter.

The riverbank method performed particularly well for long-term monitoring because it is highly repeatable and logistically simple, enabling systematic trend analysis across sites and seasons. At the same time, the riverbank pollution is influenced by hydrological processes (e.g., flood events, wind-driven stranding, and remobilisation), so results should be interpreted primarily as shoreline accumulation rather than instantaneous in-stream transport.

Reed-belt surveys add a complementary way by capturing litter retained in vegetation, which may represent longer-term storage and help identify hotspot areas, but they are harder to standardize and can be associated with ecological disturbance and stronger detectability bias (especially for small litter pieces). Together, these findings argue for separating monitoring goals: if the objective is to describe overall litter presence and accumulation, riverbank transects (and, where relevant, reed-belt assessments) are more informative than surface-only approaches.

The stand-up paddleboard approach was comparatively inefficient in this study when evaluated as catch per person-hour. For the Warnow, the results suggest that floating litter may be small during many periods, or that floating litter quickly accumulates on banks and in vegetation. This implies that floating-litter monitoring should ideally be coupled with hydrological context (e.g., discharge, wind direction/speed, and rainfall) and timed to periods when transport is expected to peak (e.g., after heavy rain, high discharge), rather than relying on a small number of opportunistic surveys.

For passive interception systems (litter boom and driftwood barrier), the near-zero median capture rates but occasional peaks indicate a strongly episodic transport pattern, where many intervals show no capture of litter, but certain events contribute disproportionately. This is consistent with the idea that transport of floating macro-litter can be event-driven (storms, high flows, or specific human activity patterns).

The drone-based approach provides an important methodological contribution for monitoring litter in reed belts and other difficult-to-access habitats. The results demonstrate a clear trade-off between coverage and detectability/identifiability with flight altitude: lower altitudes increase the likelihood of detecting small items and improve item identification, while higher altitudes increase area coverage

but reduce resolution and thus detectability. For long-term monitoring, this suggests that drone surveys could be standardized with (i) a fixed or narrow altitude band tailored to target litter sizes, (ii) consistent transect design for clear comparison of pollution (iii) transparent reporting of detection limitations.

The semi-quantitative evaluation matrix used to compare the long-term monitoring suitability of the tested methods was developed to complement the quantitative results. Scores for potential of standardization, effort, and bias/selectivity were assigned based on the practical experience of the field team members who applied each method during the monitoring campaign. This approach makes it possible to include operational aspects that are difficult to capture with a single numerical metric—such as access constraints, safety considerations, permit requirements, weather dependence, and the feasibility of applying a protocol consistently over time. At the same time, the scoring inevitably includes an element of professional judgement and is therefore context-specific; ratings could differ under other river settings, staffing levels, or management conditions. To ensure transparency, we used a clearly defined 1–5 scoring scale, applied predefined criterion weights, and documented the main reasons for each score in short rationales. The matrix should therefore be understood as a structured decision-support tool rather than a precise quantitative measurement.

7. Conclusion

The results of this study highlight that riverine macro-litter in the Warnow is not predominantly transported as freely floating material but rather becomes stranded on riverbanks or trapped in shoreline vegetation/reed belts over relatively short distances. This supports the broader hypothesis that rivers can act as retention zones and temporary or long-term reservoirs for macro-litter, where accumulation along banks and in vegetation may dominate over continuous downstream export. In practical terms, this means that a monitoring strategy that focuses only on floating litter risks underestimating the total litter loads present in the river corridor, because a large share of litter is stored outside the active transport pathway at the water surface. Overall, the combined findings support a tiered monitoring strategy. Standardized 100 m riverbank transects should form the backbone for long-term trend monitoring because of their repeatability and feasibility. Where information on floating-litter transport is required, passive interception (boom or barrier) can be added as a complementary, time-integrating tool—ideally with regular emptying and periodic calibration of capture efficiency.

Finally, pollution hot spots in vegetation, such as reed-belts, are best monitored using drone surveys to reduce disturbance and improve spatial coverage.



8. Reference



Reference

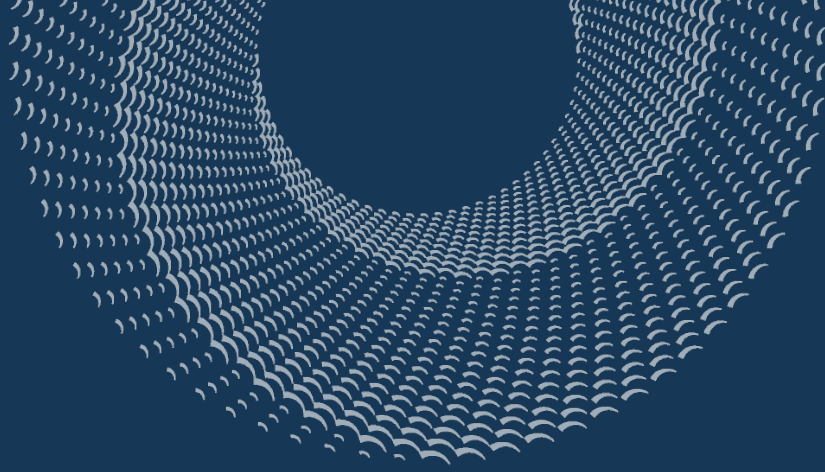
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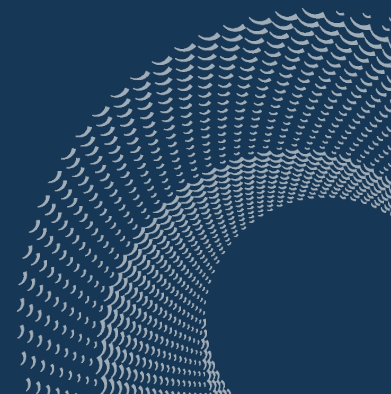
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Appendix



8. Appendix 1



Figure 17: Riverbank survey sites (n = 13) in Bützow, centred approximately on 53.840473, 11.990399 (coordinates indicate the approximate midpoint of the mapped survey area).

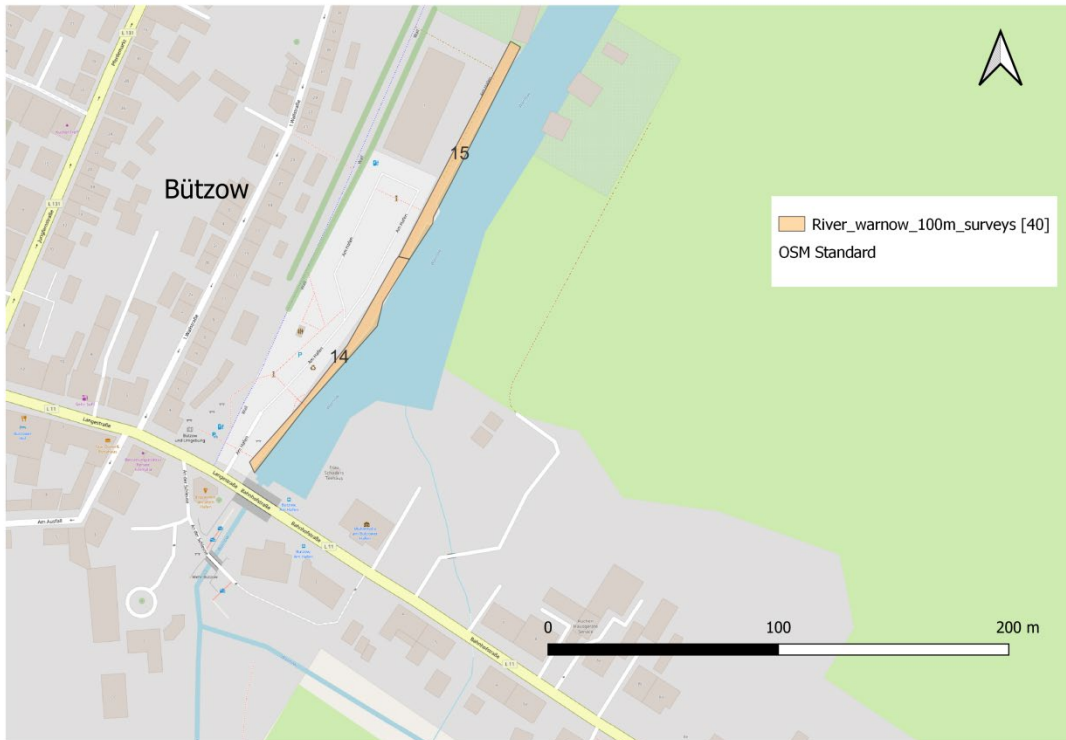


Figure 18: Riverbank survey sites (n = 2) in Bützow, centred approximately on 53.848567, 11.989658 (coordinates indicate the approximate midpoint of the mapped survey area).



Figure 19: Riverbank survey sites (n = 10) in Schwaan, centred approximately on 53.937920, 12.117509 (coordinates indicate the approximate midpoint of the mapped survey area).



Figure 20: Riverbank survey sites (n = 3) in Eickhof, centred approximately on 53.783592, 11.841395 (coordinates indicate the approximate midpoint of the mapped survey area).

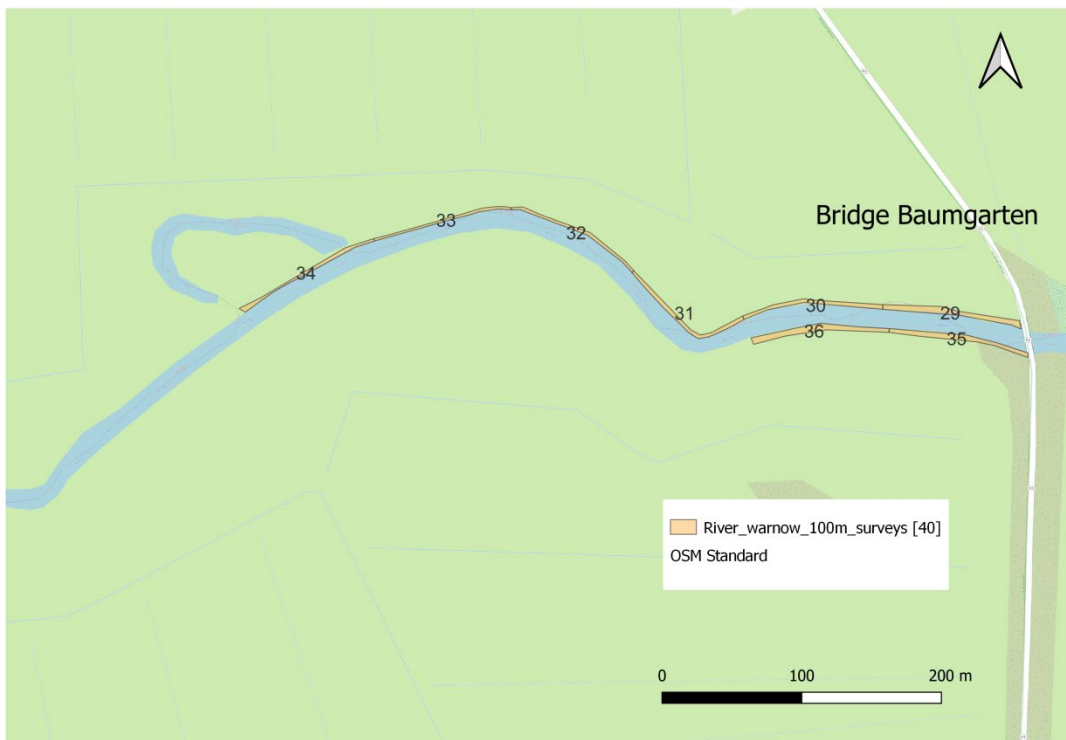


Figure 21: Riverbank survey sites (n = 8) close to the bridge Baumgarten, centred approximately on 53.795428, 11.863019 (coordinates indicate the approximate midpoint of the mapped survey area).

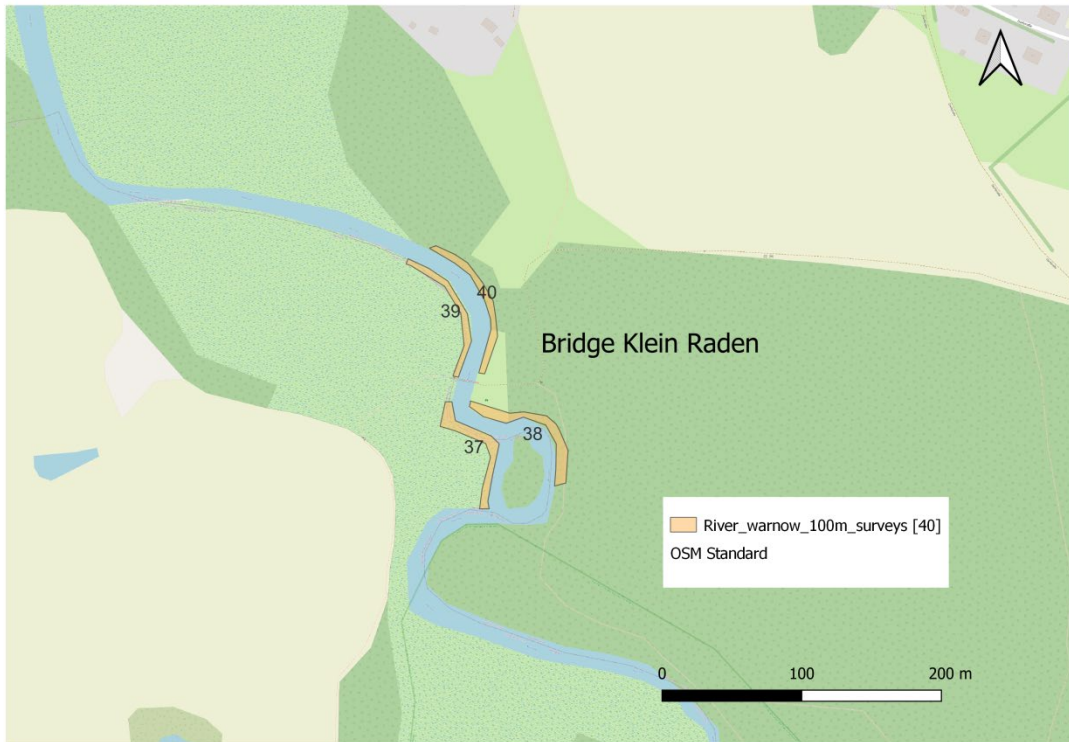


Figure 22: Riverbank survey sites (n = 4) close to the bridge Klein Raden, centred approximately on 53.762954, 11.842090 (coordinates indicate the approximate midpoint of the mapped survey area).

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