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Macrolitter budget and spatial distribution in a groyne field along the Waal river

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ABSTRACT

Current research on riverine macrolitter does not yet provide a theoretic framework on the dynamics behind its accumulation and distribution along riverbanks. In an attempt to better understand these dynamics a detailed field survey of three months was conducted in which location of macrolitter items within a single groyne field along the Waal riverbanks was tracked. The data provided insight into the daily changing patterns of spatial item distribution with respect to the waterline. Furthermore, the rates of item uptake and deposition were monitored and related to hydrologic fluctuations. Uptake was initiated by rising water levels and was generally higher when the water level increased faster. Deposition occurred continuously, despite hydrologic fluctuations. This caused the riverbank macrolitter budget to be positive during stable or dropping water levels and negative during rising water levels. Although the results show clear patterns an extended monitoring duration is required to fully understand the fate of plastic objects.

1. Introduction

Plastics have benefited society greatly (Lebreton et al., 2017). Durability and low production costs make plastics not only suitable as packaging for food and medicines, but also as engineering component in many products and construction work (Zalasiewicz et al., 2016). Unfortunately, its widespread use has led to a global increase of plastic waste in the environment (Lebreton et al., 2017), posing a threat to ecosystems and human health (van Emmerik and Schwarz, 2020). Also, plastic debris causes clogging of hydraulic structures and urban drainage sewer systems which increases flood risk (van Emmerik and Schwarz, 2020).

The majority of studies on plastic pollution focuses on the marine environment (Blettler et al., 2018; González-Fernández et al., 2021). Current understanding of pollution in freshwater systems is limited. Evidence indicates that the microplastic concentration in freshwater ecosystems is comparable to that of marine ecosystems (Blettler et al., 2018), but the dynamics of riverine macrolitter (> 2.5 cm along the length) remain largely unknown. It is often suggested that rivers act as pathways for litter from land to ocean (Lebreton et al., 2017; Schmidt et al., 2017). Some studies proposed the concept of rivers acting as macrolitter storage reservoirs (Tramoy et al., 2020b; van Emmerik et al., 2022), which are filled and emptied by extreme events. More recent studies conducted in the Rhine found that the macrolitter concentration in the watercolumn increases with higher discharge (Vriend et al., 2023; Oswald et al., 2023).

Current monitoring strategies mainly focus on either riverine transport or riverbank storage (Kiessling et al., 2021; Schone Rivieren, 2021a; Tramoy et al., 2020a, 2020b; van Emmerik and Schwarz, 2020, Vriend et al., 2023). Widely used practices include quantification by visual observation of floating items from bridges and analysis of riverbank litter items through large scale clean-up initiatives. Each of these methods focus on a specific aspect of riverine macrolitter dynamics. Counting from bridges yields information on macrolitter fluxes. Data gathered using this method was used by González-Fernández et al. (2021) to estimate the annual release of riverine macrolitter into the ocean in Europe. Riverbank monitoring studies emphasise on item quantity and detailed item descriptions. In the Netherlands, riverbank monitoring campaigns are often carried out twice a year, thus giving information on seasonal variability and allocation of different types of litter (Schone Rivieren, 2021a).

Data from the Netherlands showed that macrolitter hotspots can be

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identified along certain parts of the riverbanks (Schone Rivieren, 2021a). Though it is not certain why hotspots occur at these locations, various suggestions are made in scientific literature. Kiessling et al. (2021) related an increase in riverbank macrolitter to proximity of polluting sources. Garello et al. (2021) suggested that hydrodynamic fluctuations are the main control in macrolitter variability, while Roebroek et al. (2021) found only little relationship between hydrometeorologic processes and macrolitter variability. These theories may hold to some extent, but a fully satisfying answer is yet to be given.

Developing a better understanding of the factors that determine macrolitter accumulation is necessary to map macrolitter pathways and come up with efficient clean up strategies. Monitoring and data acquisition are key in this effort. There are still many aspects of macrolitter behaviour yet to be studied. Current literature does not provide insight into how macrolitter is distributed on a riverbank with respect to the waterline. Furthermore, movement of riverbank macrolitter and the exchange with the river itself have not yet been studied on fine spatiotemporal scale (e.g. daily and cm level accuracy).

To contribute in filling this gap, we repeatedly counted, identified and localised macrolitter items within a single groyne field along the river Waal. We chose the river Waal as Rijkswaterstaat aims to reduce the macrolitter pollution in this river. Surveys were carried out several times per week for over a period of three months. We used the detailed spatial and temporal data we gathered to thoroughly investigate the distribution of macrolitter along the riverbank. Furthermore, we studied the transfer dynamics of macrolitter between the river and riverbank (uptake and deposition) under varying hydrological conditions.

The scope of the study was to relate the variability of riverbank macrolitter to natural processes. The effect of anthropogenic controls on riverbank macrolitter, such as clean-up activities or on site littering, was outside the scope of this study. We expected to observe that macrolitter accumulates on the riverbank during prolonged periods of lowering water levels, as suggested by Garello et al. (2021). By surveying during both high and low hydrologic conditions, a better view on the behaviour of macrolitter under hydrologic fluctuations was established.

2. Materials and methods

2.1. Study area

From November 12, 2021 to January 27, 2022, we carried out an in-situ monitoring campaign in a groyne field in the Waal river (see Figs. 1 and 2). We excluded the groynes themselves and areas of the riverbank with dense grass matt from our monitoring. We selected this specific groyne field, located at 51.893500 N, 5.685803 E, for its remote location to eliminate the impact of secondary clean-up activities by volunteers or passers-by. A wildlife camera (Stealth Cam 2020 DS4K Max) confirmed the absence of such activities during our study.

2.2. Survey methodology

During the visits to the study area, the terrain was covered by walking in parallel, straight lines along the width of the riverbank. For every macrolitter item (> 2.5 cm) encountered, its location was recorded using RTK GPS (Polaris S100 RTK Receiver) and a picture was taken with a smartphone camera (Samsung A10). The item itself was left untouched. The position of the waterline at maximum wave run up was measured with RTK GPS at the beginning of every survey, allowing for referencing item positions towards the waterline for each day. Additionally, the floodmark position was measured in order to define the sample area. The surveys took an average of 3 h to perform. During these surveys it was assumed that no major changes in the position of the waterline, the position of the floodmarks and the macrolitter budget would occur.

The elevation data from all RTK GPS measurements was used to create a depth elevation model (DEM) of the local morphology. It was assumed that the morphology did not change during the course of this study. At the end of the monitoring campaign, all macrolitter items were removed.

Throughout the monitoring campaign three important assumptions were made: (1) item uptake and deposition only occurred between the waterline and the nearest floodmarks, (2) items located above the flood marks remained immobilised[1] and (3) changes in riverbank morphology during the monitoring period were neglectable. Hence, the area between the flood marks and the waterline was monitored several times a week whereas the area above the initial flood marks was only monitored during the onset of the monitoring campaign. The flood marks were identified by lines of accumulated, fine debris and marked the boundary of the sample area for each survey. As floodmarks moved upwards or downwards due to water level fluctuations, the sample area also shifted. Data presented per sampling day was a combination of the data collected on that day between the flood marks and the waterline and the data relating to items above the flood marks that were not measured on the same day. Older items situated below (i.e. north of) the flood marks were deleted.

2.3. Temporal planning

The timing of surveys was decided based on the expected water level. Surveys were carried out at the peaks of the hydrograph (Fig. 4). The water levels were measured at the Doodewaard gauging station (Fig. 1) and retrieved from Rijkswaterstaat (Rijkswaterstaat Waterinfo). Also, the frequency was increased with rapidly changing hydrologic conditions. During inundation of the study area, no surveys were carried out due to inaccessibility of the site. A total of 21 surveys were performed in the period between the 12th of November 2021 and the 27th of January 2022.

2.4. Post-processing

The raw data obtained from surveys consisted of a list of coordinates (WGS84) and an accompanying set of pictures. Item properties based on physical attributes and item locations were deduced from the pictures. Each object was assigned: 1) an item category according to the OSPAR protocol adjusted by Schone Rivieren (2021b), 2) location (latitude, longitude and elevation) and 3) mobilisation indication (yes/no).

2.5. Definitions and estimation of item uptake and deposition

In defining the movement of macrolitter within a groyne field, we conceptualised the idea of three domains in which items can be situated: water, (riverbank) surface and sediment. Items can be moved between these domains due to external forces. The movement between domains is depicted in Table 1. In this study we only considered movement between water and surface, defined as uptake and deposition. We assumed that item storage under sediment is limited as it is likely a slow process which is induced by geomorphic processes.

Item balance is defined by Eq. (1.1). The amount of items present at the riverbank depended on the magnitude of uptake and deposition:

$$N(s) = N(s-1) + \Delta N^{+} - \Delta N^{-} \tag{1.1}$$

where:

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[1] The effect of wind on items deposited on the riverbank was assessed by empirical observations and found to be limited, probably due to macrolitter being wet and partially buried when washed ashore. Items which are very susceptible to wind mobilisation may not have been observed often due to their high mobility. Almost all items encountered on the riverbank are somehow immobile, either due to weight, wetness, sediment or physical obstructions from the environment. Please see Appendix B for Supporting information.

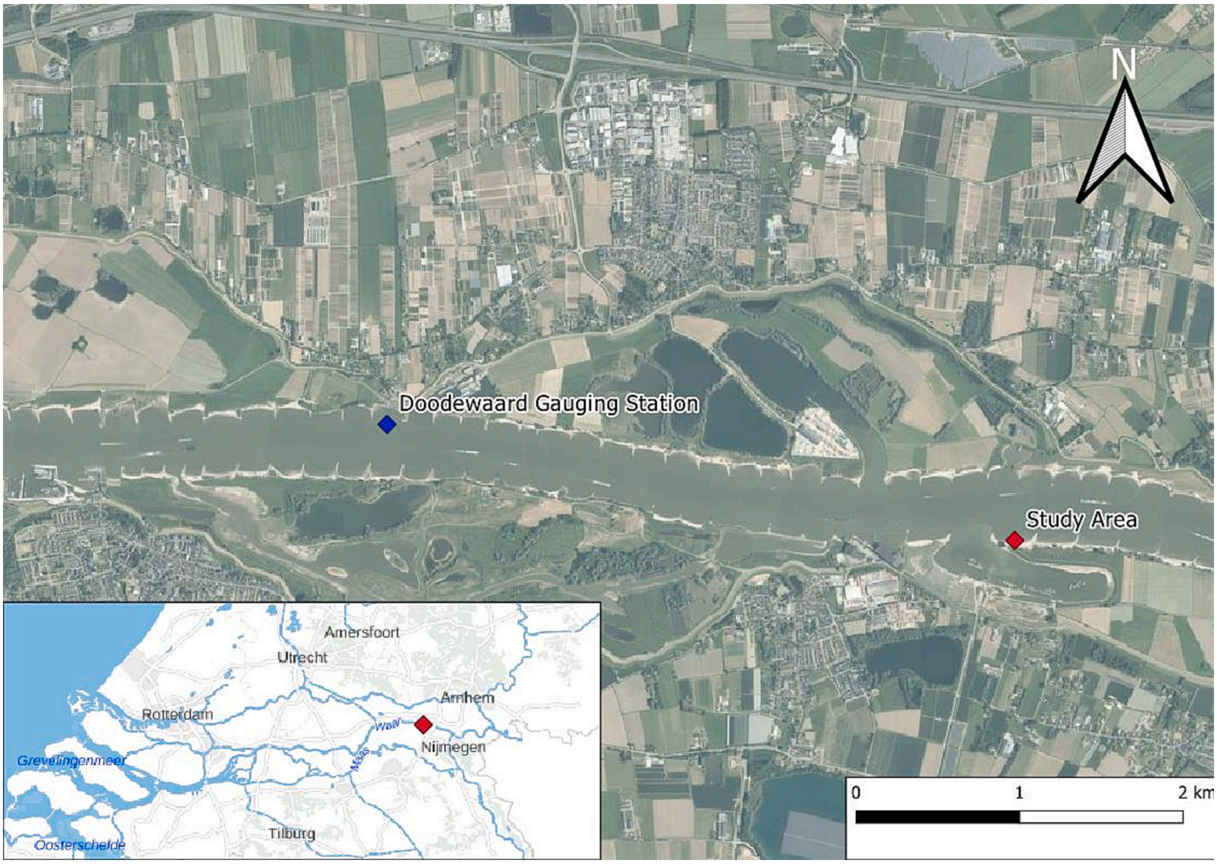

Fig. 1. Location of the study area and the Doodewaard gauging station in the Waal river (Netherlands).

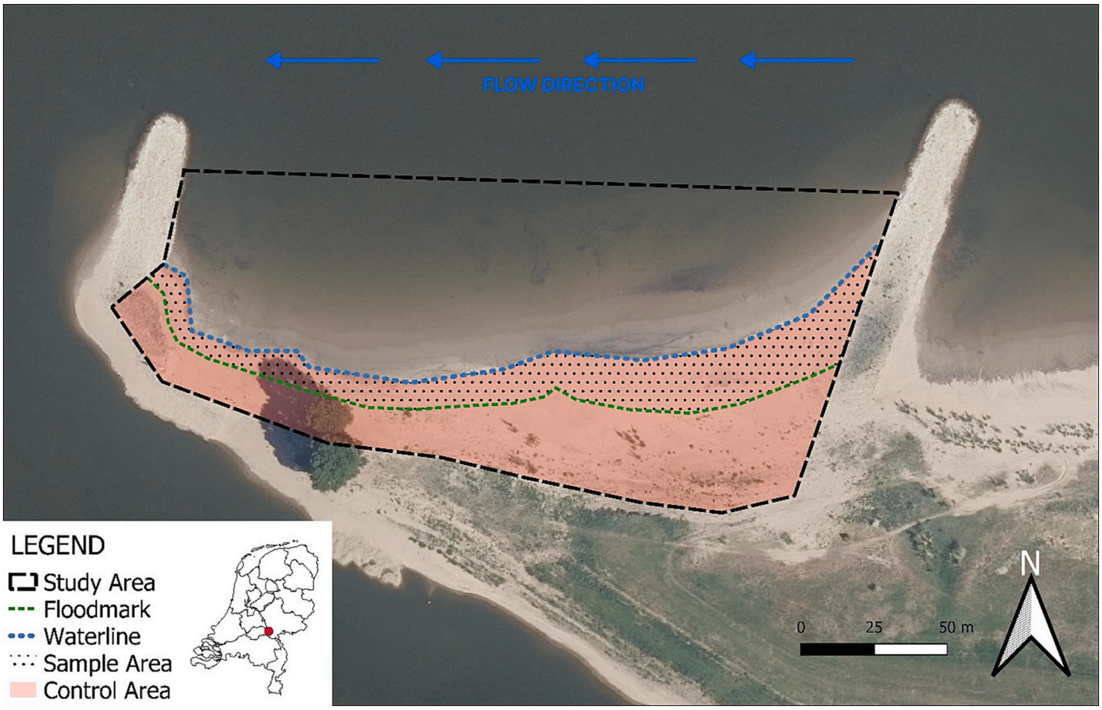

Fig. 2. The study area and area boundaries of monitoring. The control area is defined as the riverbank area which is not submerged and contains litter items. No data is available outside the control area. The sample area is the location where daily monitoring takes place. Two trees are located near the study area, the most northern of which is positioned at the border of the study area.

Table 1

Movement of macrolitter between domains.

		Destination		
		Water	Surface	Sediment
Origin	Water	–	Deposition	Storage
	Surface	Uptake	–	Storage
	Sediment	Mobilisation	Mobilisation	–

N : Amount of items present at the riverbank [items]
s : Number of survey
ΔN^{+} : Magnitude of deposition between surveys [items]
ΔN^{-} : Magnitude of uptake between surveys [items]

ΔN^{+} and ΔN^{-} could not be obtained directly from the data. Uptake and deposition were estimated by counting the net differences of the amount of items per OSPAR category (Eqs. (2.1) and (2.2)). Uptake and deposition within one OSPAR category could not be accounted for.

$$\Delta N^{+} = \sum_{j} min\{0; N_j(s) - N_j(s-1)\} \tag{2.1}$$

$$\Delta N^{-} = \sum_{j} max\{0; N_j(s) - N_j(s-1)\} \tag{2.2}$$

In which:

j : Item OSPAR category
N_j : Number of items for OSPAR category j

In order to account for items which resurface on the riverbanks after being washed away, a total of 90 distinguishable items were tracked individually based on the photographs. Additionally, 16 indistinguishable items (mostly wet wipes and sanitary towels) were marked yellow with waterproof spray paint. The (re-)occurrence of this subset of items was tracked. This gave an indication of the share of items which reappeared on the riverbank after being taken up, thus yielding information about the residence time of items within a groyne field.

2.6. Correlation analysis

Possible correlations between the rate of uptake/deposition and water level variations were investigated using Spearman's Rho correlation (performed with the Scipy 1.0 (Virtanen et al., 2020) package in Python). Spearman's Rho is chosen as it is a robust, non-parametric method for analysing correlation between two variables.

Uptake and deposition were regarded as different processes. Therefore, the analysis was performed for each process separately. In line with Garello et al. (2021), the following hypotheses were tested:

1. Deposition (ΔN^{+}) is negatively correlated with change in water level (ΔH)
2. Uptake (ΔN^{-}) is positively correlated with change in water level (ΔH)

Although the physics behind uptake and deposition are unknown, we assumed that uptake/deposition of an item during rising water levels was driven by similar physics as uptake/deposition of an item during dropping water levels. These physics were thought to be mainly waves, of which the majority is induced by inland navigation. Climo et al. (2022) observed that inland navigation induced waves can cause macrolitter (re-)mobilisation in the Waal river. Due to the fact that the Waal is intensely navigated (Reeze et al., 2017), we considered weekly variations in wave intensity to be limited.

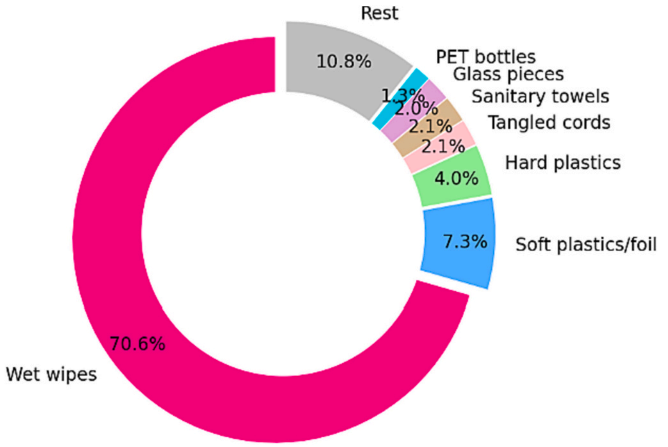

Fig. 3. Most common items categories. The categories are comprised of the following OSPAR codes: Wet wipes (102.2), Soft plastics (46.2, 117.2, 81), Hard plastics (46.1, 117.1), Tangled cords (35.1), Sanitary towels (99), Glass pieces (93), PET bottles (4).

3. Results

Items of 54 OSPAR categories were found. 7 OSPAR categories made up 89.2 % of all items (Fig. 3). The reason why few categories comprised the majority of the items can be attributed to the fact that many items are fragmented pieces of plastics, either hard or soft. The vast amount of wet wipes found in this area is remarkable when compared to the data from Schone Rivieren (2020, 2022). This is illustrated in Table 2. We found that the number of items varied throughout time. This is depicted in Fig. 4.

We found macrolitter items to have been accumulated along lines parallel to the waterline (Fig. 5a1, b1 and c1). During the first three weeks of surveying, the water level was relatively stable. An older floodmark was already present. Deposition of macrolitter during this period caused accumulation along a newly formed floodmark, closer to the waterline (Fig. 5a1). Thereafter, the water level rose, pushing the macrolitter higher on the riverbank. The two floodmarks merged (Fig. 5b) and subsequently the number of items reduced from 535 to 342 due to item uptake (Fig. 2c1). In the centre part of the riverbank the number of items decreased, whereas in the corners of the groyne field accumulation occurred. Hereafter, the water level dropped. During dropping water levels (Fig. 5d) it was observed that items were deposited equally over the area of the groyne field.

The rates of item uptake and deposition in relation to water level

Table 2

Item quantity per category compared to data from Schone Rivieren (2020, 2022).

Category	Mean quantity per 100 min study area (rounded)	Max. quantity per 100 min study area (rounded, including date of survey)	Mean quantity per 100 m(according to Schone Rivieren)
Wet wipes	133	226 *at 05-12-2021*	12 (when present)
Soft plastic pieces (<50 cm)	14	27 *at 28-12-2021*	32
Hard plastic pieces (<50 cm)	7	21 *at 18-11-2021*	15
Tangled nets/cords	4	14 *at 02-12-2021*	7
Sanitary towels	4	7 *at 04-12-2021*	9 (when present)
Glass pieces	4	7 *at 28-12-2021*	Not mentioned
Plastic Bottles	2	5 *at 01-12-2021*	9

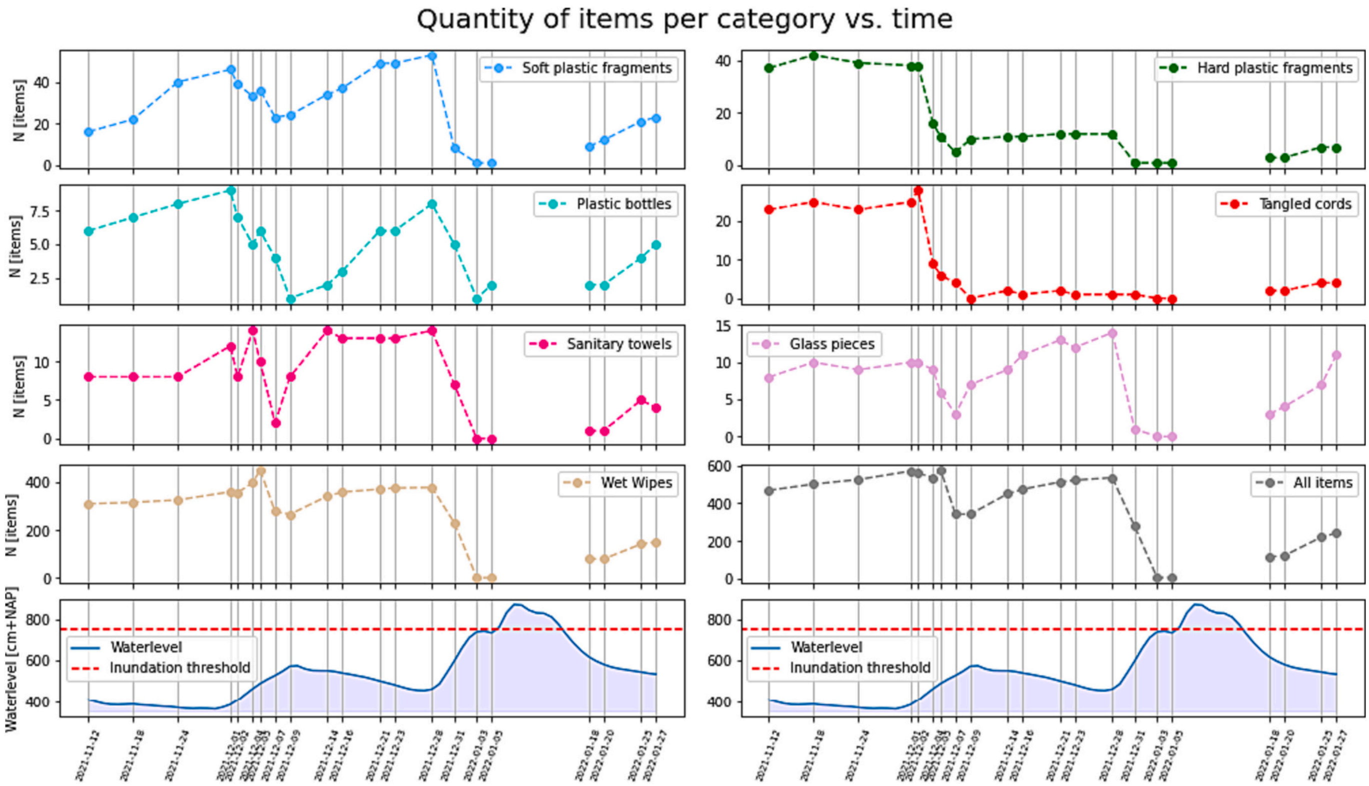

Fig. 4. Quantity of items per category throughout time for every day of survey plotted above the water level measured at Doodewaard.

revealed interesting patterns (Fig. 6). The observed hydrologic peaks were below the threshold of 1030 cmNAP (Normaal Amsterdams Peil, the vertical reference datum used in the Netherlands), which is considered to be high and has a return period of $T = 5$ years (Rijkswaterstaat Waterinfo). Deposition occurred as an almost continuous process during the period of monitoring, resulting in a smooth cumulative frequency curve. The uptake curve, on the other hand, is more erratic. Uptake during dropping water levels was minimal. During rising water levels, it was very profound. Fig. 6 also reveals that uptake and deposition may take place simultaneously. The magnitudes of uptake and deposition define the net increase/decrease of the amount of items found on the riverbank.

The scatterplot (Fig. 6b, left) for deposition shows little indication of a relationship between deposition and change in water level at this temporal scale. Spearman's Rho is performed on all datapoints. The test results in a correlation coefficient of rho $= -0.06$ with a p-value of 0.813.

Item uptake was found to be minimal during dropping water levels. The magnitude of uptake increased with rising water levels. The scatterplot (Fig. 6b, right) depicts a relationship which seems linear, with the exception of the outlier at dH = 20 cm/day. Spearman's Rho test resulted in a correlation coefficient of rho = 0.71 with a p-value of 0.001.

Not all items left the groyne field after uptake. A share of items resurfaced again when water levels dropped. Two hydrologic peaks occurred during the period of monitoring. The first occurred on 9-12-2021 and the second in 7-01-2022. In order to estimate the share of resurfacing items, a subset of the tracked items which were present on 02-12-2012 was followed. The categories to which items of this subset belonged to are depicted in Table 3. Fig. 7 depicts the percentage items which resurfaced after the two hydrologic peaks respectively. Almost all tracked items had left the groyne field at the end of the study; only 2 items have been recovered. It should be noted that the water level at 27-01-2022 is above that of 02-12-2021. The water level is more similar to that of 16-12-2021. Nevertheless, the amount of tagged items found on the final day is also less than the amount of items found on 16-12-2021.

4. Discussion

The data visually describes the movement of macrolitter with respect to changing water levels. With increasing water levels, a large part of the items were not directly taken up but were pushed higher on the riverbank. For some categories, net deposition occurred during the first rising limb of the hydrograph (Fig. 4). Whether items were taken up or pushed higher on the riverbank could be a consequence of several factors. First of all, items with different shapes, sizes and densities may behave differently in the surf- and wave run up zones of a riverbank (Luccio et al., 1998). While there is little research available on the behaviour of macrolitter items in the surf zone, studies on sediment transport and microplastic beaching found that item shape and weight can influence susceptibility of an object to either wave forcing or return flow (Luccio et al., 1998; Forsberg et al., 2020). Luccio et al. (1998) showed that large sediment objects ($D = 6.4$–25.6 cm) are mobilised with swash due to turbulence in the surf zone as a result of breaking waves. In their experiments, increased item density limited the length of the on-shore transport induced by waves. Therefore, high density macrolitter items would be pushed less high on the riverbank and thus are more prone to uptake. Similar observations were made for microplastic particles by Forsberg et al. (2020). Heavy particles tend to accumulate in the breaking zone due to the balance between wave forcing and return flow. Lighter particles are advected across the surf zone. The study also found that sheet shaped microplastic particles were less prone to beaching compared to pellet shaped particles, as they were carried off-shore by the return flow. In macroplastic experiments, similar behaviour was found for plastic bags, which tend to be influenced much by turbulent flow (Zaat, 2020).

Secondly, item location may affect uptake as it was visually observed to be more profound in the centre part of the groyne field. The data does not provide a solid answer as to why this was observed. It is possible that this is due to the difference in riverbank slope, which was steeper in the

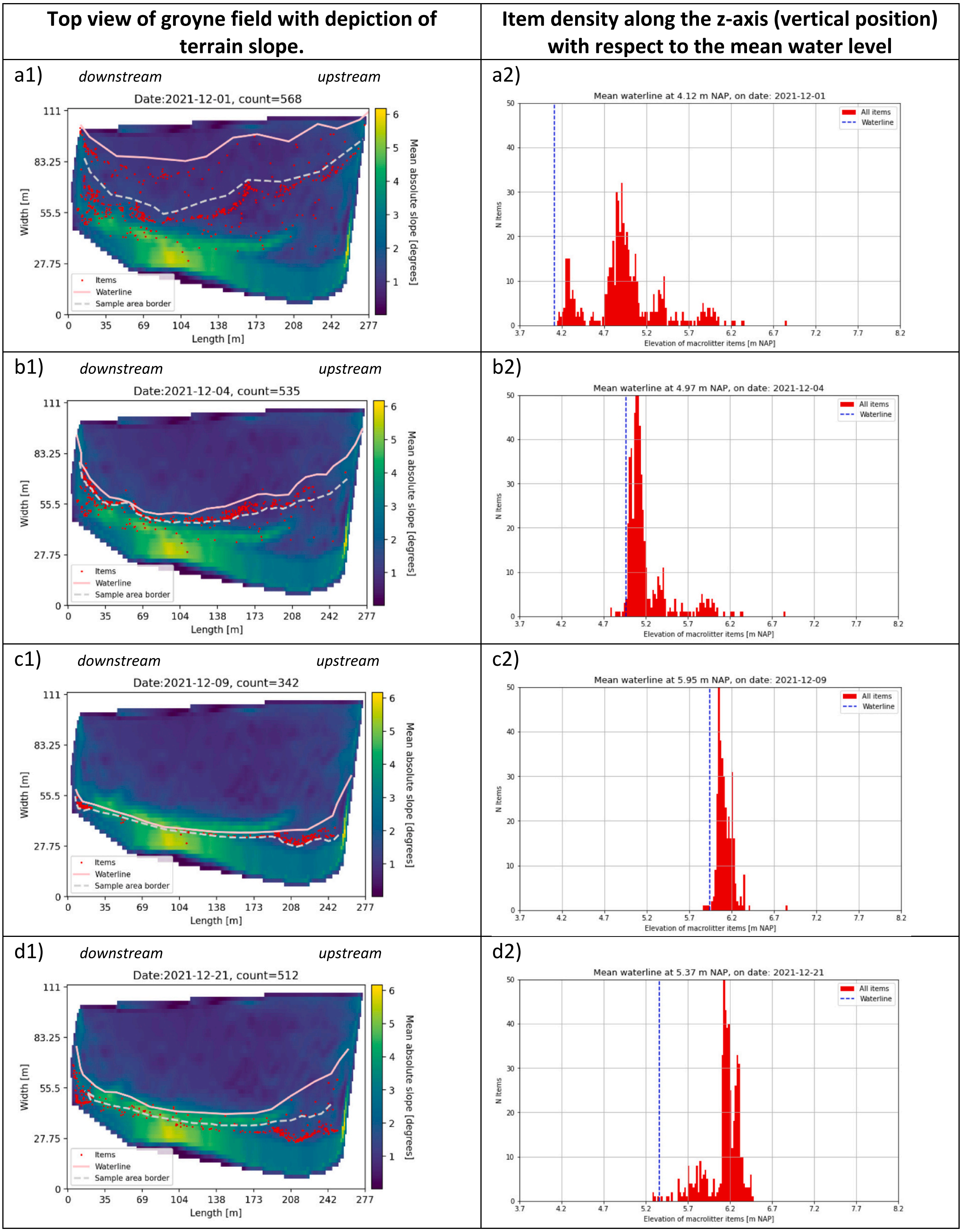

Fig. 5. The spatial distribution of macrolitter at certain dates, giving an impression on how items move due to rising water levels. The data is shown only for a selection of surveys in order to illustrate macrolitter distribution throughout time. The complete set of figures for all surveys can be found in Appendix A.

In the left column, a top view of the groyne field is presented. The location of every item (red dots) and the waterline at maximum wave run up (pink line) are depicted. The slope of the terrain of the study area is visualised in yellow to blue colour grading. Every subfigure depicts the locations of macrolitter within the groyne field at a certain date.

In the right column, the vertical distribution of the items is depicted in a histogram, together with the water level (calculated from the mean vertical position of the waterline). Thus the histogram depicts the elevation of the items in mNAP with respect to the waterline at the time of survey. The peak of the histogram shows at which elevation the item density is highest. This coincides with the elevation of the macrolitter flood marks. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

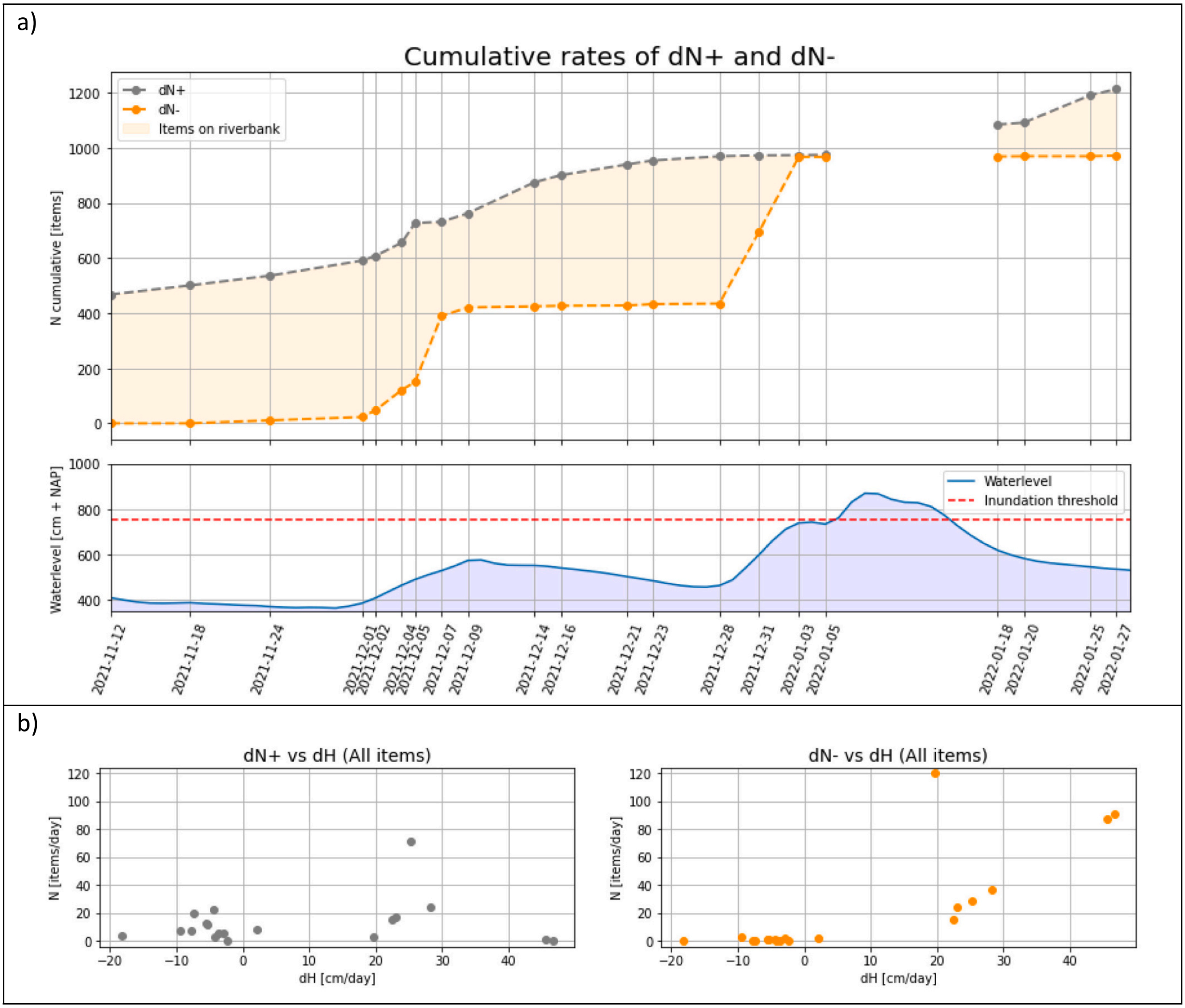

Fig. 6. a) dN+ (deposition) and dN− (uptake) represent item uptake and deposition respectively. The plot depicts the cumulative number of items which were taken up or deposited. The line slope represents the rate of deposition (grey) and uptake (orange). Substracting the deposition curve from the uptake curve will give the number of items present at the riverbank. Note that no data was interpolated for the period during which the study area was inundated (from 5 January until 18 January).The amount of items at the riverbank is determined by the space between the curves. The bottom graph shows the water level measured at Doodewaard. Between 05-01-2022 and 18-01-2022 the groyne field was entirely inundated. No surveys could be carried and therefore no uptake and deposition is depicted in the figure for this period. b) The daily mean deposition and uptake rates are plotted against the daily mean change in water level (dH).

Table 3
Categories of tracked items.

Categories	Frequency	OSPAR codes
Wet wipes	12	102.2
Soft plastics/foil	4	46.2 & 81
Hard plastics	5	46.1 & 117.1
Foam sponge	4	45
Container/tubes	2	103
Tangled cords	2	35.1
Sanitary towels	2	99
Glass pieces	1	93
PET bottles	7	4
Rest	31	–

centre part compared to the corners of the groyne field. An item situated on a steep inclined riverbank would hypothetically be less prone to move onshore due to incoming waves. This is in line with the study from Luccio et al. (1998), in which the riverbank slope acts as a limiting variable in the displacement of cobbles in the on-shore direction. Alternatively, uptake in the centre part of the groyne field could be a consequence uptake being promoted by stronger currents in the centre of the groyne field. Water in groyne fields commonly flows in gyres, with the strongest current located in the centre part of the groyne field and flowing in contrary to the stream direction of the river (Ten Brinke, 2003).

The behaviour of uptake and deposition, as well as the outcome of the Spearman's Rho analysis, reveal that hydrologic fluctuations play a role in the magnitude of macrolitter found at riverbanks. In our observations it was found that especially uptake was controlled by hydrologic fluctuations. During stable or dropping water levels, uptake was minimised. This resulted in periods where item deposition was the dominant process, leading to macrolitter accumulation. Uptake only became dominant when the water level was rising which resulted in a reduction of riverbank macrolitter.

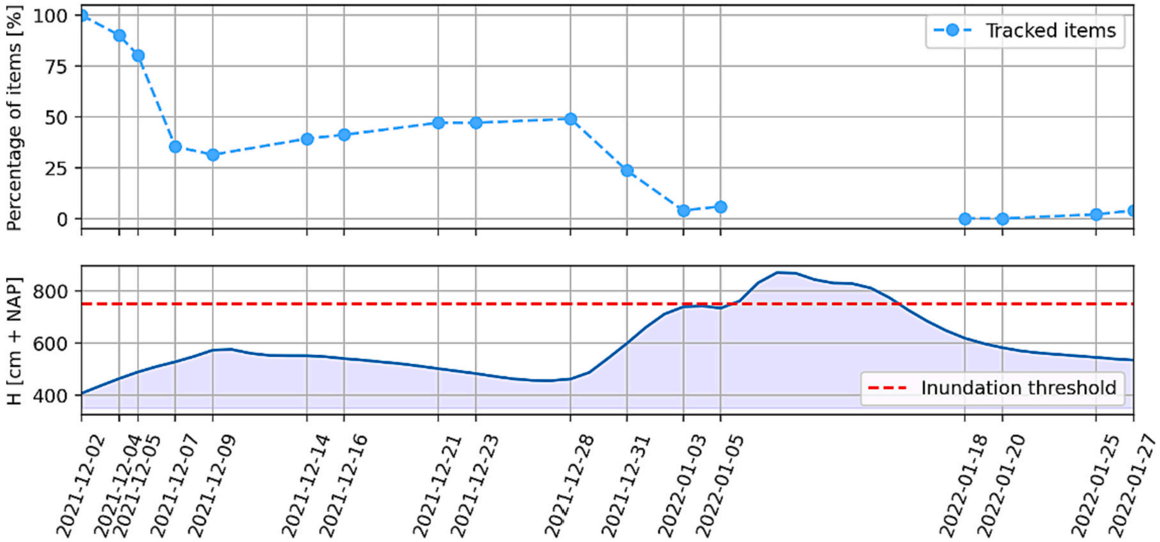

Fig. 7. A total of 106 items were tracked during the entire study. Of these items, 64 were tracked from 02-12-2021 until the end of the monitoring campaign. The figure depicts the percentage of tracked items found at the riverbank which were also present on 02-12-2021. After the first hydrologic peak, 31 % of the tracked items remained. When the waterlevel dropped, another 18 % of the tracked items resurfaced again. At the end of the monitoring period, only 4 % of the tracked items present at the beginning of the study were found.

The found correlation between dN- and dH suggests that the faster the water level rises, the larger the uptake will be. This correlation should be interpreted with caution though. There are several factors which may influence the actual uptake. First of all, the rate of uptake is limited (or promoted) by the amount of items in reach of fluvial processes. This can cause deviating observations. For example, the daily rate of uptake may vary under steadily rising water levels if items are not evenly distributed over the riverbank. Secondly, physical item properties such as shape and density are expected to affect the susceptibility for uptake. Therefore, allocation of different item types along the riverbank may also influence observed uptake. Studies on the behaviour of sediment and microplastic in the swash zone support this idea (Luccio et al., 1998; Forsberg et al., 2020). Thirdly, vegetation at certain places along the riverbank may act as litter traps (Liro et al., 2020; Newbould et al., 2021; Cesarini and Scalici, 2022). Uptake can therefore be lower than expected if rising water levels reach the vegetated zones of a riverbank. This study was carried out in an area with very sparse vegetation.

In this particular groyne field, deposition was almost continuously observed. The fluctuations in deposition were small compared to the fluctuations in uptake. Deposition rates did not seem to respond to changes in water level. This leads to believe that there are other factors influencing deposition which were not considered in this study. The rate of deposition may be location specific and/or controlled by processes which act on another spatial/temporal scale. Examples of possible location specific controls which may promote deposition are proximity to pollution source (Kiessling et al., 2021) or the riverbank location within meander bends, which may increase the chance of a single item to be deposited (Newbould et al., 2021). Seasonality, for example, may be a control which can either increase or decrease deposition rates (van Emmerik et al., 2019). Tidal influences can act as a dynamic barrier preventing macrolitter to leave an estuary (Tramoy et al., 2020b), which could increase deposition rates. At the same time, tides can lead to significant water lever fluctuations. This may result in a simultaneous increase in uptake rates on a daily basis. As Tramoy et al. (2022b) coined, this may result in an uptake/deposition cycle for macrolitter items.

The rates of both uptake and deposition show one outlier. The outliers were observed on subsequent surveys. A sudden increase in deposition was measured on 05-12-2021 and an increase in uptake was measured on 07-12-2021. It is not entirely clear what the reason for this outlier was. A possible explanation could be that the rising water levels caused an increase in macrolitter flux due to increased uptake further upstream, perhaps even in one of the adjacent groyne fields. This could have resulted in an increase in deposition at the study area.

The data gathered in this study also give insight into the residence time of macrolitter in groyne fields and the magnitude of items passing by within a three months period. The method used, however, has a few inaccuracies which should be taken into account. First of all, the Eqs. (2.1) and (2.2) which were used to estimate uptake and deposition may underestimate their true values. This is because uptake and deposition within one category is not accounted for. For example, an item may have been flushed away and replaced by a very similar, but different item. It should also be noted that $\Delta N-$ does not represent the amount of items have left the groyne field. It only corresponds with the amount of items that left the riverbank. Items may still be present within the limits of the study area, though under water. On the longer term, however, it might be safe to assume that the total rate of items travelling further downstream is similar to the observed rates of uptake. This holds when assuming that underwater accumulation within the groyne field does not occur over long periods of time.

Furthermore, the data shows that almost all tracked items present (96 %) on 02-12-2021 were taken up at the end of this study, even though reappearance of macrolitter items was observed shortly after hydrologic peaks. This leads to believe that this location does not act as a macrolitter storage reservoir which is only emptied after extreme events (van Emmerik et al., 2022). Thus, downstream transport of riverbank microliter was initiated by moderate water level fluctuations. Moderate hydrologic fluctuations therefore determine the residence time of riverbank macrolitter.

5. Concluding remarks and recommendations

This paper presents a unique dataset on the movement of macrolitter in a riverine groyne field, as well as a methodology used to obtain such a dataset. The data gives insight in the short term variability of riverbank macrolitter and can be used by researchers to get an impression of how items behave with respect to changing waterlevels and riverbank morphology. The data can also assist in hypothesis generation for future research initiatives.

Analysing spatiotemporal representations of the data reveals that macrolitter accumulates in floodmarks and can be pushed higher on the riverbanks if the waterlevel rises. The data was also used to estimate uptake and deposition rates. We observed that item uptake and deposition could occur simultaneously. Hydrologic fluctuation had a prominent role in the riverbank macrolitter budget. Uptake was initiated by rising water levels and was generally higher when the water level increased faster. When the water level decreased uptake was negligible. Deposition occurred with an almost constant rate despite hydrologic fluctuations. This caused the riverbank macrolitter budget to be positive during stable or dropping water levels and negative during rising water levels. These observations confirm the suggestions made by Garello et al. (2021). It should be noted that behavioural patterns presented in this paper are based on a limited number of observations. Therefore the conclusions we made are not yet fully proven.

Abbreviations

RTK **R**eal **T**ime **K**inematic
GPS **G**lobal **P**ositioning **S**ystem
DEM **D**igital **E**levation **M**odel
NAP **N**ormaal **A**msterdams **P**eil (Vertical reference datum used in The Netherlands)
WGS84 **W**orld **G**eodetic **S**ystem **84**

CRediT authorship contribution statement

J.J. Grosfeld: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **M.M. Schoor:** Project administration. **R. Taormina:** Supervision. **W.M.J. Luxemburg:** Supervision. **F.P.L. Collas:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data can be accessed through the link below:
Macrolitter in Riverine Groyne Field (Original data) (Figshare)

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2024.116110.

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