Microplastics and Nanoplastics

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Riverbank plastic distributions and how to sample them

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Abstract

As plastic pollution exists in aquatic ecosystems globally, monitoring its abundance and distribution has become crucial for understanding transport pathways, sources, sinks, and impacts. Riverbanks are accumulation zones for plastic, but the selection of monitoring methods is constrained by research goals, available resources, and site-specific conditions. This diversity in approaches has led to disparate datasets, highlighting the need for standardized monitoring protocols. Here, we study the spatial distribution of plastic at the riverbank scale, quantify the uncertainty of existing riverbank methods, and provide recommendations for improved monitoring based on the balance between uncertainty loss and increase in effort. We measured riverbank plastic abundance at eight Dutch riverbanks, categorizing the items using 108 item categories (River-OSPAR). For every riverbank, an area of 100 by 25 meters was subdivided into five-by-five-meter squares, resulting in 100 individual monitored sub-areas. We found riverbank plastic exhibited high spatial variability, with deposition patterns ranging from parallel to the waterline to clustered, random, or uniform (Moran's I between -0.050 and 0.301). Individual measurements from diverse sampling protocols are 5-49 times less accurate than estimates derived from extensive sampling, highlighting the diminishing impact of specific methods with increased data collection. Lastly, our findings suggest that increasing the sampling area quickly reaches diminishing returns in terms of accuracy. Reducing the sampled area by 80% only increases the uncertainty in estimating the true plastic density by 20%. While standardized protocols are essential for data comparability, a rigid, uniform sampling approach may be less efficient and resource-intensive than a flexible (step-wise) strategy that adapts to local conditions. By demonstrating that extensive sampling can mitigate the differences between unique sampling protocols, this study promotes a shift towards flexible and efficient riverbank plastic monitoring, ultimately accelerating global efforts to combat plastic pollution.

Keywords Monitoring method, Environmental pollution, Plastic debris, Protocol, Harmonization, Optimization, Uncertainty

Introduction

Plastic is entering water systems at an increasing rate [1, 2], with worsening negative impacts on aquatic ecosystems, fauna, and local economies which are potentially irreversible [3, 4]. Yet, the fate of mismanaged plastic waste is unclear, in which a recent estimate shows the majority of plastic waste can be retained within river systems for decades [5, 6]. Therefore, there is a strong need to assess the abundance and distribution of plastic in aquatic environments. In recent years, several approaches to understanding the sources, transport, and sinks have been developed [7]. Such methods are essential

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for understanding the abundance and fate of plastic in aquatic ecosystems [8]. Several examples include the monitoring of floating plastics in (urban) rivers [9, 10]; understanding transport dynamics using proxies such as water hyacinths [11], tracers, and/or GPS trackers [12, 13]; and riverbank plastic monitoring from estuaries [14–16] to upstream mountainous areas [17]. With plastic pollution rising and a high percentage persisting in rivers, assessing plastic abundance in aquatic environments is crucial [1]. Disparities in monitoring methods and data structure of existing riverine plastic research result in a lack of comparability, hindering design of mitigation measures and a global treaty on plastic pollution [18]. Therefore, harmonized methods and datasets or combining non-harmonized data in meaningful ways are required [18–20]. Subsequent efforts concerned developing guidelines for methodological harmonization [21, 22], creating frameworks to compare monitoring strategies [7, 8], and establishing baselines for large-scale assessments [23]. These efforts led to the harmonization of particular aspects of riverbank plastic monitoring, yet only on local or regional scales. For example, the River-OSPAR method developed by Schone Rivieren (Clean Rivers) [24] is now widely used to assess Dutch riverbank plastic by scientists [25–27], citizens [28], governments [29], and non-profit organizations [30]. The application of the River-OSPAR method on a large spatial scale and high density of measuring areas allows for comparable results on a national and local level. This approach shows the benefits of harmonized monitoring.

Although some level of harmonization has been achieved in river-bank plastic monitoring, the choice of methodologies remains highly dependent on situation-specific factors, leading to a range of approaches in practice. Trade-offs need to be made between the available resources and research objectives [8]. For instance, a detailed spatiotemporal analysis executed by trained experts at a few locations [31] inherently requires a different approach than a nationwide monitoring campaign with untrained schoolchildren [32]. Another factor concerns the strong heterogeneity in hydrodynamic conditions, land use/land cover types, and riverbank (geo) morphology and their influence on the spatial distribution of plastic on riverbanks [33, 34]. For instance, the presence of vegetation on riverbanks can result in patches of increased accumulation and retention compared to bare areas or areas with sparse vegetation [35]. The combination of these factors results in the application of situation-specific methodologies, which makes it difficult to compare results quantitatively.

The deposition and distribution of plastic on riverbanks are complex processes that are influenced by a myriad of factors, resulting in diverse spatiotemporal deposition patterns. For example, hydrological dynamics such as high flow velocities during floods can (re)mobilize plastic and amplify accumulation at specific points along the riverbanks [36]. Another aspect concerns the topography and morphology of riverbanks, in which features such as bends, meanders, and constrictions significantly influence plastic distribution [37]. Depositional zones created by these features can serve as hotspots for plastic accumulation, while areas with steep gradients may experience less plastic deposition due to rapid transport downstream [38]. Other features influencing deposition patterns are vegetation cover [39], or anthropogenic barriers and infrastructure such as bridges, fences, and ditches. Understanding these diverse spatial patterns could be crucial for plastic monitoring campaigns and subsequent pollution-mitigating strategies, which this work explores.

The aim of this paper is threefold. First, we explore the spatial distribution of riverbank plastic. As plastic pollution varies across different river systems, understanding the spatial distribution helps to direct cleanup efforts, identify potential sources, and contribute to the understanding of transport mechanisms. Eight locations along three Dutch river systems characterized by diverse morphological features and land use types were selected for monitoring. For each riverbank, we determined the level of clustering of plastics to explore the effect of vegetation, high water deposits, and infrastructure in retaining riverbank plastics. Secondly, to assess the impact of different monitoring methodologies on plastic density estimates, we compared five commonly used riverbank monitoring protocols using our high-resolution dataset. This analysis provides quantitative insights into the variability of plastic density measurements arising from different methodological approaches. Thirdly, we explore how the highest accuracy in riverbank plastic density values can be achieved. It is currently unknown how to balance effort (sample area/costs) and data accuracy. Optimizing this balance is helpful for reliable and efficient data collection, facilitating the development of effective strategies to address plastic pollution in rivers.

Methods

Study area

We measured riverbank plastic abundance at eight locations along the Dutch IJssel, Rhine, and Meuse rivers (Fig. 1) between 23 February and 18 March 2022. The selection of riverbanks along these major Dutch rivers represents various characteristics with diverse land uses (e.g. agriculture, recreation, built-up area), geomorphological features, orientation, and distance to upstream cities. We aimed to capture a representative subset of Dutch riverbanks, typically composed of sand, rocks,

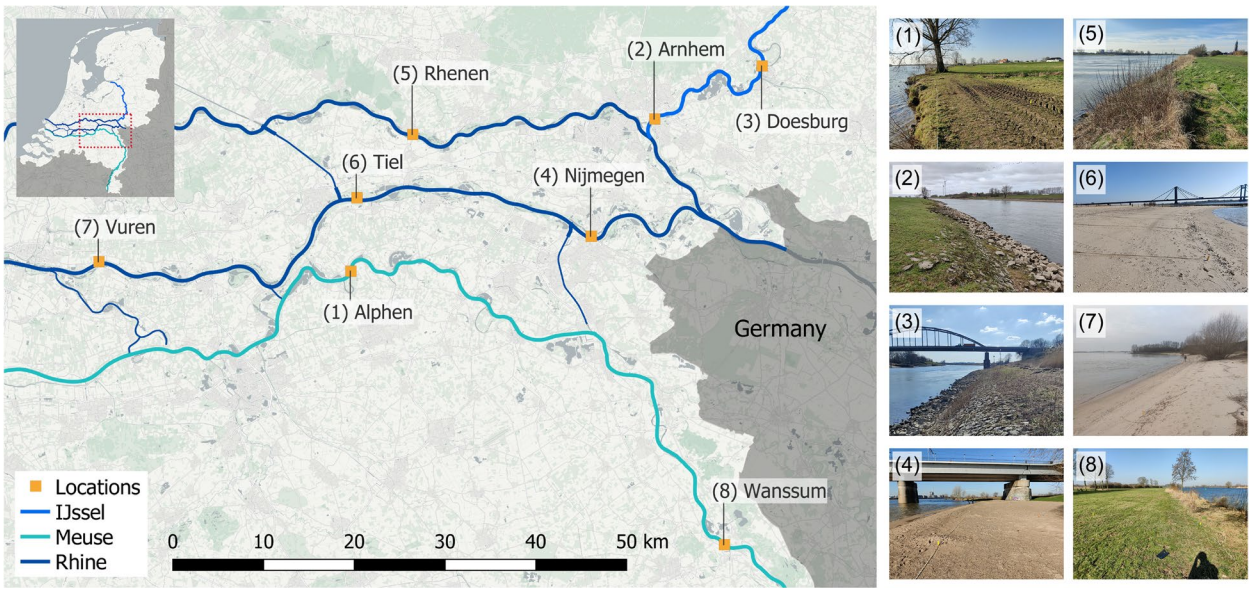

Fig. 1 Selected monitoring locations at the IJssel, Meuse, and Rhine rivers including pictures depicting the land cover characteristics at the time of the experiments

gravel, and various riparian vegetation types [40]. The timing of the data collection followed an annual high-water peak in winter, which ensured exposed riverbanks and deposited plastic items.

Sampling procedure and protocols

For each of the eight riverbanks, an area of 100 meters parallel and 25 meters perpendicular to the river was measured and delineated. A subdivision of 100-by-25-meter riverbank areas into 100 five-by-five-meter squares allows the establishment of a detailed data set describing the spatial distribution of riverbank plastics. The corners of these five-by-five meter squares were measured with a tape-measure and marked with colored flags to ensure correct sampling. For each of these squares, riverbank plastic items ($\geq$ 0.5 cm) were measured and categorized using the River-OSPAR method containing 111 unique item categories [15]. The data sheets used in the sampling are provided in the "Data availability" section.

The subdivision of the riverbank area into five-by-five meter squares allows testing four different protocols for collecting plastic samples (Fig. 2): (1) Battulga, (2) CrowdWater, (3) Plastic Pirates, (4), NOAA beach protocol. The protocol used by [41] samples a total area of 300 m^2, divided over three 10-by-10-meter squares without any other spatial restrictions (Fig. 2b). For instance, the squares can be adjacent to each other, next to the river, or at the boundaries of the 100 by 25 meter sampling area. The CrowdWater protocol [28] samples an area perpendicular to the river of 1, 2, 5, or 10 meters long, and covers the entire width of the riverbank (Fig. 2c). As the width of the protocol is variable, we assume the average width of the sample area to be 4.5 meters (with an equal distribution of 1, 2, 5, or 10-meter widths), resulting in an average sample area of 112.5 m^2. In the original protocol, discrete categories are used to count observed plastic items, but here we stick to the total item counts on a continuous scale. The Plastic Pirates protocol used by [32] takes samples in up to three transects, in predefined zones: the river edge (0-5 meters from the river), the riverbank (5-15 meters from the river), and the river crest (>15 meters from the river). For each sample, a circle with a radius of 1.5 meters is measured, in which all plastic is sampled, resulting in a total surface area of approximately 42.5 m^2. In our paper, we modeled the Plastic Pirates approach using two transects with circles in the 0-5 meter zone, the 10-15 meter zone, and the 20-25 meter zone (Fig. 2d) at random locations along the 100-meter riverbank length. The NOAA beach protocol [42] uses four randomly chosen transects five meters wide covering the entire width of the monitored area (Fig. 2e). Thus, the total area monitored in this protocol is 500 m^2, which is the largest out of the four protocols studied here.

Riverbank plastic distribution types

We identified five distinct plastic distribution types on riverbanks (Fig. 3) based on vegetation abundance, geomorphological features, anthropogenic structures,

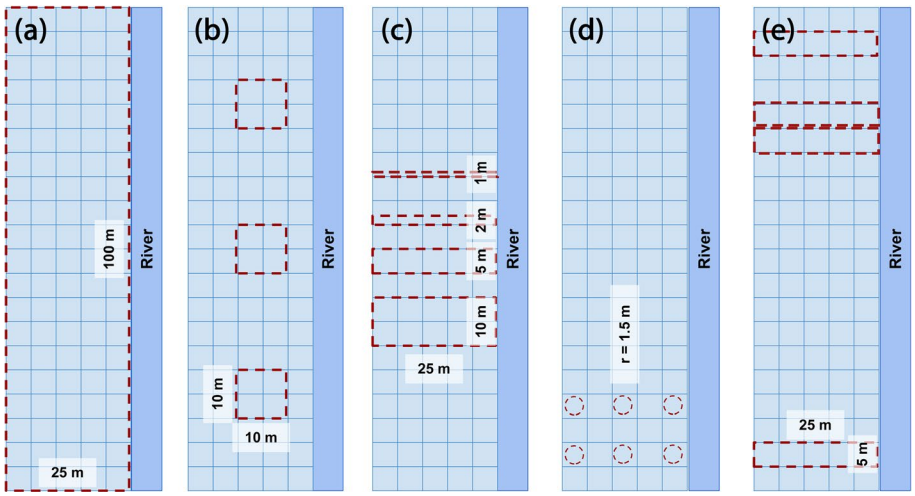

Fig. 2 Selected sampling areas for riverbank item density calculation, with (**a**) Clean Rivers; (**b**) Battulga; (**c**) CrowdWater; (**d**) Plastic Pirates; and (**e**) NOAA. For CrowdWater and Plastic Pirates, the underlying assumption was made that the item distribution within the five-by-five-meter squares is homogeneous

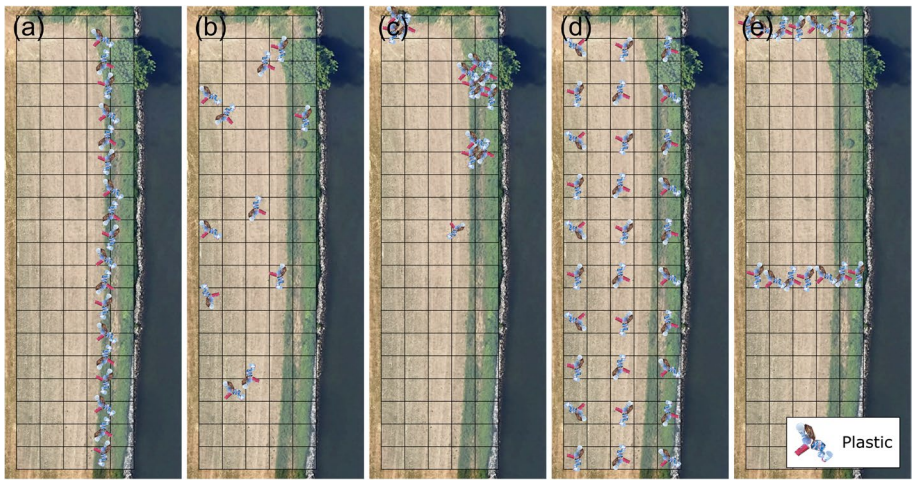

Fig. 3 Potential spatial distribution patterns of riverbank plastic, with (**a**) a deposition line parallel to the water line, (**b**) a random distribution, (**c**) clustering, (**d**) a uniform distribution, and **e** a deposition line perpendicular to the water line

hydrodynamic characteristics, or specific hydrologic events such as floods [33–37]. First, plastic can be distributed in a line parallel to the water line, when riverbanks or floodplains get inundated during floods or peak water events (Fig. 3a). Second, plastic can be distributed randomly across a riverbank, when no specific hydrologic events, vegetation, or morphology significantly influence the distribution (Fig. 3b). Third, plastic can be distributed in patches or clusters that are concentrated around vegetation, infrastructure, or preferential deposition zones because of morphological features (Fig. 3c). Fourth, plastic can be distributed uniformly, in which the plastic density is approximately equal for the entire riverbank (Fig. 3d). Lastly, distribution can be perpendicular to the waterline when fences or drainage ditches are present (Fig. 3e). A partial combination of two or more distribution types is possible when the riverbank is characterized by multiple unique features influencing deposition patterns. For each of the eight riverbanks monitored in this paper, we categorize the plastic distribution pattern in one of these five categories.

Estimating riverbank sampling uncertainty

In this study, we aim to quantify the accuracy, variability, and uncertainty of the Battulga, Crowdwater, Plastic Pirates, and NOAA sampling protocols. Using these

protocols, subsamples from the true plastic distribution density are taken. Here, the true density is defined as the total number of plastic items divided by the total sampling area of 2500 m^2. We randomly sampled, based on the respective protocol sampling areas, using Monte Carlo simulations with 10,000 runs. For each simulation, we calculated the difference between the protocol density and the true density, yielding a distribution of differences. By generating 10,000 random sub-samples, we aim to capture a wide range of sampling scenarios that might occur during actual sampling efforts, thereby estimating the true density distribution for each protocol. Similar to [31], we used the normalized standard deviation (σ/μ) as a metric for assessing accuracy. This metric measures the dispersion of each Monte Carlo run relative to the mean of all runs, providing insights into the consistency and reliability of the sampling protocols.

Optimizing sampling effort and accuracy

Another objective of our study is to assess how a balance between sampling accuracy and effort can be optimized. The relation between effort and accuracy may not always be linear. Therefore, we aim to uncover possible non-linear correlations between these variables, revealing instances where incremental increases in sampling effort yield diminishing results in terms of improving accuracy. We designed an additional Monte Carlo simulation using a random combination of 5-by-5-meter squares to achieve this. The simulation was initiated with a sampling area of 25 m^2, and increased incrementally in steps of 25 m^2 up to 2500 m^2. 10,000 Monte Carlo runs were conducted for each increment, showing variability in riverbank plastic density with increasing surface area. The additional squares are completely random and do not follow any rules that they need to be connected to one of the previously selected squares. A detailed MATLAB script is provided in the supplementary material for every simulation and statistical analysis. When the established protocols show less variability than true random sampling, it implies a protocol is more efficient than randomly sampling a similar surface area.

Determining spatial clustering

To determine the level of clustering, the global Moran's I value is calculated for each monitored riverbank [43]. A spatial perspective is useful to understand to what extent riverbank plastic is concentrated in clusters, and how they are affected by riverbank properties. High levels of clustering indicate concentrated pollution, which is valuable information for optimizing cleanups if specific riverbank features cause the plastic to accumulate in clusters.

The Moran's I is calculated according to Eq. 1, where:

- n is the total number of 5-by-5 meter squares,
- W is the sum of the spatial weights using a rook's case weighting ($\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}$),
- x_i is the plastic density value for spatial unit i,
- $\bar{x}$ is the mean of the plastic density values across all spatial units,
- w_{ij} is the spatial weight between spatial units i and j using a rook's case weighting.

$$I = \frac{n}{W} \cdot \frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij} \cdot (x_i - \bar{x}) \cdot (x_j - \bar{x})} \quad (1)$$

This value represents spatial autocorrelation statistics measuring the degree of clustering, dispersion, or randomness of spatial patterns. It assesses whether similar values are clustered together or dispersed across a geographic area. A positive Moran's I value close to 1 indicates strong positive spatial autocorrelation, meaning that similar values are clustered together ('Clustered distribution', Fig. 4c). A negative Moran's I value close to -1 indicates strong negative spatial autocorrelation, implying a dispersed or uniform checkboard distribution (Fig. 4d). Values close to 0 indicate spatial randomness, with no significant pattern of clustering or dispersion (Fig. 4b). A MATLAB script is provided in the supplementary material to compute the global Moran's I value for each monitored riverbank.

Results

Distribution of plastic on monitored riverbanks

The distribution of plastic along the eight studied riverbanks reveals considerable variability (Moran's I ranging between -0.050 and 0.301), indicating a diverse array of accumulation patterns. In Fig. 4a-h, the min-max normalized plastic counts for each riverbank are shown, highlighting the variability in the accumulation patterns. The distribution in Alphen (Fig. 4a), Doesburg (Fig. 4c), and Wanssum (Fig. 4h) mostly show a deposition line parallel to the water line (Fig. 3a). For these riverbanks, 82.9%, 58.9%, and 90.4% of all items are deposited in a 5-by-100-meter line parallel to the water line, respectively. The distribution of plastic in Rhenen (Fig. 4e) and Vuren (Fig. 4g) predominantly show high clustering, as depicted in Fig. 3c). For these riverbanks, 44.6%, and 29.3% of the total plastic is present in just 5% of the total sampled surface area, respectively. Even though this value for Alphen is higher (48.8% of items present in 5% of the total sampled surface area), the predominant distribution pattern is a deposition parallel to the water line. The Moran's I values for Rhenen (0.289) and Vuren (0.234) indicate a positive spatial autocorrelation, suggesting

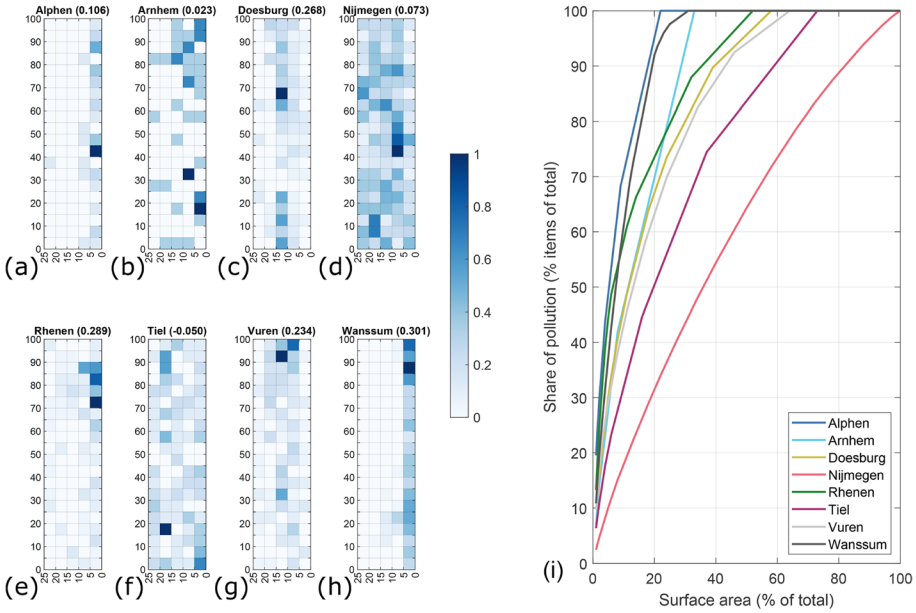

Fig. 4 Min-max normalized plastic counts (color bar) for **a** Alphen, **b** Arnhem, **c** Doesburg, **d** Nijmegen, **e** Rhenen, **f** Tiel, **g** Vuren, and **h** Wanssum. The values in brackets next to the riverbank locations are the Global Moran's I values for each riverbank. Panel (i) shows the share of pollution by the share of total surface area, indicating whether the plastic distribution is uniform and dispersed, or patchy and concentrated

some degree of spatial clustering. The distribution of plastic in Arnhem (Fig. 4b), and Tiel (Fig. 4f) predominantly show a random distribution, as depicted in Fig. 3b. For these riverbanks, the global Moran's I values are close to zero (0.023, and -0.050, respectively), implying spatial randomness with no significant pattern of clustering or dispersion. The distribution of plastic in Nijmegen (Fig. 4g) approaches a uniform distribution, as depicted in Fig. 3d. For this riverbank, the majority of every measured five-by-five meter square contains approximately 1% of the total pollution. The latter is discernible in Fig. 4i, in which the share of pollution over the share of the total surface area is significantly more linear and the closest to a 1:1 line for Nijmegen than for the other seven riverbanks. None of the riverbanks show a deposition pattern in a line perpendicular to the water line (Fig. 3e), as there were no morphological features or anthropogenic structures present promoting this distribution pattern.

Variability in monitoring protocols

The results show considerable variation in riverbank plastic density estimates for individual measurements using different monitoring protocols. The riverbank plastic density ranges between 0.052 and 0.123 items/m^2 for all riverbanks using different protocols (Table 1). The distribution of item densities for each protocol based on 10.000 Monte Carlo runs shows the difference per protocol can be large at the level of individual measurements (Fig. 5). For example, using the Battulga method in Wanssum (Fig. 5h), the item density ranges from 0.00 items/m^2 to 0.41 items/m^2 (Table 1). On the other hand, using the NOAA method for the same riverbank ranges from 0.05 to 0.18 items/m^2. Even though the range of both methods contains the true density value (0.10 items/m^2), a single measurement using the Battulga method can overestimate the density by a factor of 4.1, and fully misreport the item density when a specific sample area is chosen in which no items are present.

When the number of samples or the frequency of monitoring increases, the median values get closer to the true density. For assessing the variability, we use the median value instead of the mean value because of skewed distributions, which occur on multiple spatial scales within plastic pollution research [44]. The differences in median item densities per protocol can still vary when considering individual riverbanks but converge to the true item density when all the studied riverbanks are considered. For example, the median densities using the Battulga and NOAA methods in Wanssum are 0.05 and 0.10 items/m^2, respectively. Whilst this is still a factor two difference for two sampling protocols, this variability minimizes when more riverbanks are monitored. By comparing the average median value for each of the four protocols per riverbank to the true item density, this effect is even stronger (Table 1). Whilst the density resulting from the NOAA protocol approaches the true density by only a 3.3% median deviation, all protocols only have a factor 0.3

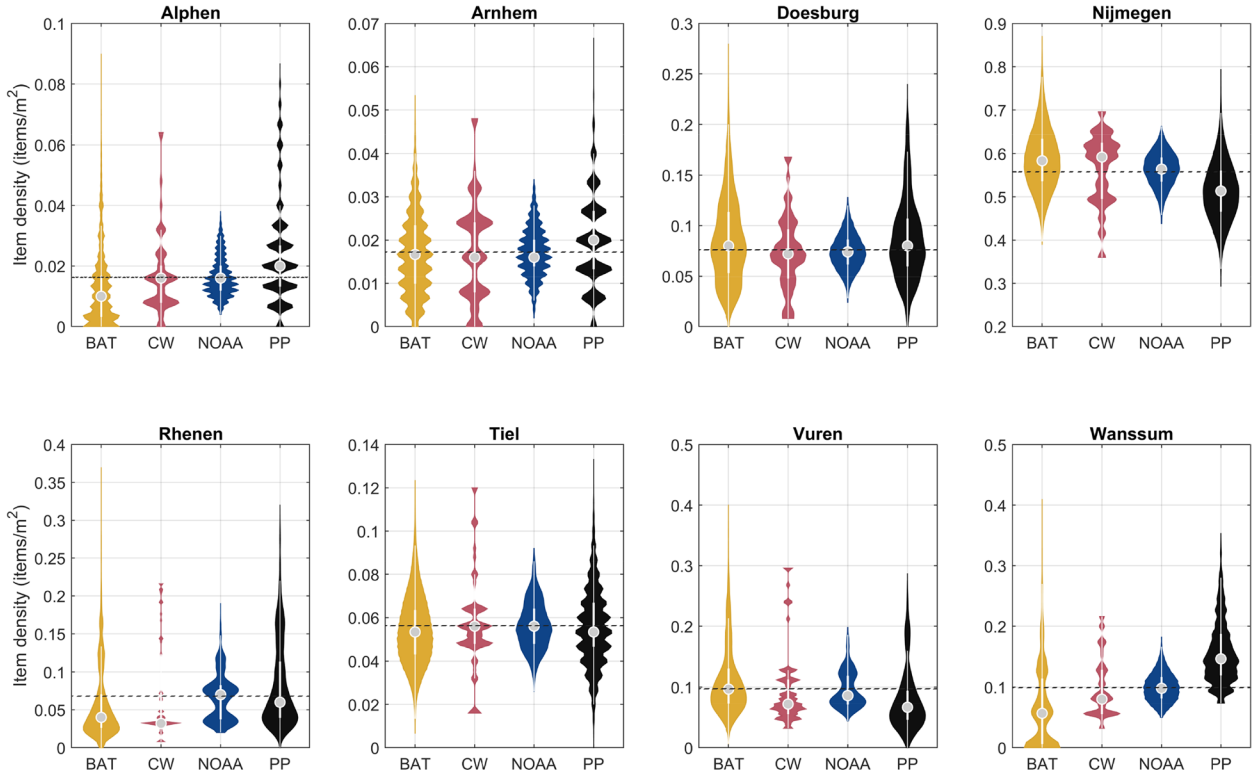

Fig. 5 Violin-plot distribution of item densities per sampling protocol for each monitored riverbank. The plots are based on 10.000 Monte-Carlo runs using a random configuration of the sampling areas according to the protocol. The dashed lines in the plots depict the true riverbank plastic density

Table 1 True item density for every monitored riverbank (in items/m^2), and the median item density values for the four protocols. The last four columns show the relative deviation between the true density and the protocol median item density values

	True density	Battulga	CW	NOAA	PP	Battulga	CW	NOAA	PP
Alphen	**1.64×10^{-2}**	1.00×10^{-2}	1.60×10^{-2}	1.60×10^{-2}	2.00×10^{-2}	39.0 %	2.4 %	2.4 %	22.0 %
Arnhem	**1.72×10^{-2}**	1.67×10^{-2}	1.60×10^{-2}	1.60×10^{-2}	2.00×10^{-2}	3.1 %	7.0 %	7.0 %	16.3 %
Doesburg	**7.40×10^{-2}**	8.00×10^{-2}	7.20×10^{-2}	7.40×10^{-2}	8.00×10^{-2}	8.1 %	2.7 %	0.0 %	8.1 %
Nijmegen	**5.63×10^{-1}**	5.83×10^{-2}	5.92×10^{-1}	5.64×10^{-1}	5.13×10^{-2}	89.6 %	5.1 %	0.1 %	90.9 %
Rhenen	**6.64×10^{-2}**	4.00×10^{-2}	3.20×10^{-2}	7.00×10^{-2}	6.00×10^{-2}	39.8 %	51.8 %	5.4 %	9.6 %
Tiel	**5.64×10^{-2}**	5.33×10^{-2}	5.60×10^{-2}	5.60×10^{-2}	5.33×10^{-2}	5.4 %	0.7 %	0.7 %	5.4 %
Vuren	**9.56×10^{-2}**	9.67×10^{-2}	7.20×10^{-2}	8.60×10^{-2}	6.67×10^{-2}	1.1 %	24.7 %	10.0 %	30.3 %
Wanssum	**9.96×10^{-2}**	5.67×10^{-2}	8.00×10^{-2}	1.00×10^{-1}	1.47×10^{-1}	43.1 %	19.7 %	0.4 %	47.3 %
Average	**1.24×10^{-1}**	**5.15×10^{-2}**	**1.17×10^{-1}**	**1.23×10^{-1}**	**6.22×10^{-2}**	**28.7 %**	**14.3 %**	**3.3 %**	**28.7 %**

difference from the true item density (Table 1). This ultimately implies the choice of a sampling protocol does not lead to significantly different results as long as extensive sampling takes place. The latter underscores the beneficial effect of extensive sampling, involving measurements at multiple locations and time intervals, in reducing variability and enhancing the reliability of findings.

Protocol accuracy compared to random sampling

When comparing the four protocols and their sample area to randomly sampled surface areas, it is evident that three out of the four protocols generally outperform random sampling in terms of uncertainty (Fig. 6). The Battulga method shows a lower accuracy (-9.5%), the Crowdwater method shows a higher accuracy (+11.8%), and the NOAA method shows a slightly higher accuracy

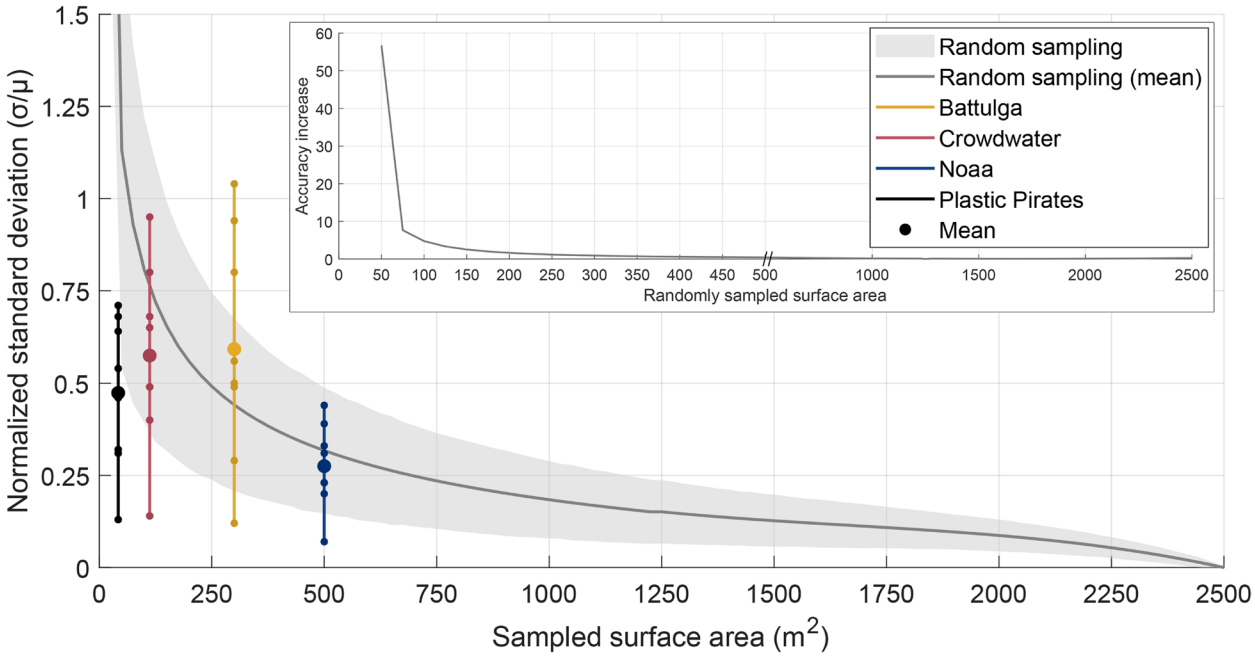

Fig. 6 Normalized standard deviation of randomly sampled surface area based on 10.000 Monte-Carlo runs. The vertical colored lines indicate the range of values from the four sampling protocols, in which the small dots show each monitored riverbank. When an observation or the mean value of all observations is below the random sampling curve, the sampling protocol performs better than random sampling. The inset shows the increase in accuracy for every additional 25 m^2 randomly sampled surface area. Note the scale difference in the x-axis beyond 500 m^2

(+2.7%) compared to random sampling. The "Plastic Pirates" protocol showed significantly higher accuracy than random sampling within the same area (+45.0%). However, the mean values of the Crowdwater, Battulga, and NOAA protocols (bold dots in Fig. 6) are close to the random sampling mean and fall within the range observed for random sampling. These findings imply minimal change in uncertainty compared to random sampling for the Crowdwater, Battulga, and NOAA protocols. In contrast, the Battulga method shows a much wider range in normalized standard deviation, exceeding that of random sampling for this surface area. This inconsistency indicates the Battulga protocol may deliver both accurate and inaccurate results.

Although increasing the sampled area consistently reduces uncertainty, the effect diminishes with each increment, suggesting a point of diminishing returns. The increase in accuracy (expressed as min-max normalized standard deviation) for every additional 25 m^2 is large with a small total surface area, but quickly levels off. Increasing the surface area from 75 m^2 to 100 m^2 results in an accuracy increase of 7.8%, from 175 m^2 to 200 m^2 results in an increase of 2.7%, and from 375 m^2 to 400 m^2 results in an increase of only 1.0% (Fig. 6, inset). The exact threshold where additional sampled surface area does not yield desired improvements in accuracy is flexible, depending on resources, the number of locations to be sampled, the required accuracy, and the measurement frequency.

Discussion

Plastic accumulation, distribution and impacts

Our study reveals that riverbank plastic exhibits distinct spatial distribution patterns, which we analyzed quantitatively. In previous studies, the monitoring of plastic on riverbanks often relied on bulk sampling across large sampling areas ranging from 25 m^2 - 2500 m^2, sometimes supported with detailed subsamples in randomly selected smaller areas (< 1 m^2) [8]. Smaller riverbank sampling areas are more prone to significant biases from observers, leading to a higher risk of inaccurately estimating true plastic densities compared to larger sampling areas [8, 45]. Although bulk sampling large areas represents an average plastic concentration across a riverbank, it can be time-consuming and miss spatial heterogeneity in local plastic distributions. Capturing spatial heterogeneity is essential to understanding the local transport and deposition mechanisms of plastic pollution along a riverbank. For instance, the subdivision and detailed monitoring revealed that the plastic on several studied riverbanks is concentrated in a line parallel to the waterline (Fig. 4a, c, h). This suggests high-water events, floods, or decreasing water levels under normal conditions have caused this localized accumulation of plastic [46, 47]. Other

riverbanks showed either a random, clustered, or uniform distribution of plastic, which suggests multiple mechanisms such as riverbank morphology, anthropogenic activity or the abundance of vegetation can each influence the local plastic distribution. We hypothesize that areas with gentle slopes and rocks experience increased plastic deposition [38]. This increased deposition might be further facilitated by the lack of obstacles between the river and a gentle slope, allowing for easier plastic accumulation [33]. Riverbanks near urban areas or industrial zones will likely have higher plastic concentrations due to littering and improper waste disposal in upstream cities or local recreational areas [48]. Similarly, recreational areas like parks or beaches may accumulate more plastic debris from activities such as picnicking, (un)deliberate littering, fishing, or tourism. Riparian vegetation acts as a storage ground for macroplastic [39]. The density and structure of these plants are crucial factors determining their trapping efficiency [49]. Therefore, we hypothesize that vegetated riverbanks exhibit a greater capacity to retain accumulated plastics compared to bare riverbanks. Riverbanks with patchy vegetation might therefore benefit from detailed insights into the spatial distribution of plastics.

As assessments of baseline pollution measurements are crucial to provide insights for long-term monitoring protocols, it is essential to accurately and efficiently estimate the local pollution of riverbanks [7]. The distinct patterns found in our study have implications for prevention and reduction measures, as riverbanks with natural accumulation due to floods might require different strategies compared to areas with other distribution patterns related to recreation or urban point sources of pollution [50]. This is key for targeted action. Flood-driven accumulation might require organized (community-driven) clean-up efforts to remove deposited plastic from floodplains. This can be a community-driven effort or involve dedicated teams. Identifying urban or industrial point sources might require stricter regulations regarding waste disposal or even mandating the use of less-polluting materials in manufacturing processes. By understanding the diverse pollution patterns on riverbanks caused by various actors, we can tackle the root causes and ultimately achieve cleaner floodplains and a healthier environment.

The role of frequent monitoring in riverbank plastic assessment

Our comparison of non-harmonized monitoring protocols with diverging sampling areas and methods suggests that the specific protocol details may not significantly impact plastic density estimates, provided frequent monitoring is conducted at many locations. Previous works emphasized the need for harmonized guidelines for monitoring plastic pollution in freshwater environments [21], marine environments [51], and riverine environments specifically [22]. While harmonized guidelines encompass more than sampling method and area selection, these choices are fundamental for determining the required resources and spatial resolution of data collection. Ultimately, these factors are crucial for designing an effective monitoring strategy. Our findings reveal that three out of four monitoring protocols yield results that closely resemble those obtained through random sampling across a similar surface area, with a large number of monitored locations. While the "Plastic Pirates" protocol emerged significantly more accurate (+45.0% compared to random sampling), others exhibited only slight improvements or a decrease in accuracy. This implies that, in the long run, achieving a large sample size through diverse yet representative sampling strategies might be more practical than enforcing strict protocols for large-scale riverbank plastic pollution assessments. This approach facilitates comparisons between existing plastic pollution datasets. It contrasts with the emphasis on strict protocol harmonization advocated in both foundational and recent literature [18, 19].

The future of riverbank plastic monitoring

While standardized metrics for measuring riverbank plastic pollution can facilitate (international) data comparison, a rigid approach to sampling methodology might hinder efficiency and resource allocation. Standardizing data collection and reporting (e.g. similar units of measurement) is still important, but the actual sampling method can be adapted to the specific riverbank being studied. This study demonstrates that four completely different sampling protocols yield statistically converging results toward the average true density of riverbank plastic, as long as enough samples are taken to achieve the required level of accuracy. All monitoring protocols have limitations, regardless of their categorization, spatial or temporal resolution, and the type of observers (e.g. citizens versus trained professionals) [8]. Therefore, we suggest applying a stepwise sampling design. Employing a low-effort method like Plastic Pirates initially provides a rapid estimate of riverbank plastic abundance. The sampling area can subsequently be increased to match the NOAA or River-OSPAR sampling areas when time and resources are available to meet specific research objectives. This way, the resource allocation can be optimized while still achieving the desired data quality. Our findings demonstrate that randomly sampling 500 m^2 yielded plastic density estimates within 20% of the true density for a much larger area of 2500 m^2. This suggests achieving a high degree of accuracy might not require sampling

riverbank areas in full, which allows the efficient use of resources. Still, to minimize bias, the sample area should accurately reflect the characteristics of the entire riverbank, and the sampling strategy ideally involves randomization. For example, [32] take subsamples randomly chosen in three different hydrological zones on the riverbanks. The NOAA protocol uses random number tables to determine the number and location of the monitored transects [42]. For frequent riverbank monitoring, targeted sampling strategies can be employed to optimize efficiency. These strategies leverage insights from previous studies or assumptions about plastic accumulation patterns to focus sampling efforts on areas likely to have representative plastic concentrations. For example, targeted sampling can avoid redundant measurements of areas with exceptionally low or high plastic accumulation, if frequent monitoring has shown specific areas are consistently characterized with representative plastic concentrations over time. Frequent sampling on riverbanks following established methods or the stepwise approach combining multiple methods is essential for obtaining ground-truth data on riverbank plastic pollution. Emerging remote sensing technologies using drones, cameras, and satellite imagery hold significant potential for future research, especially in areas where on-site monitoring is limited, dangerous, or impractical. While such techniques are promising, their current capabilities are still under development compared to established methods. As advanced techniques mature, a transition period between them and established traditional methods will likely emerge, in which data collection efficiency increases and spatial coverage is expanded. This allows us to leverage their complementary strengths, and ensure robust data collection for future monitoring, ultimately leading to a comprehensive understanding of plastic pollution dynamics.

Conclusion

In this paper, we characterized the spatial distribution patterns of riverbank plastic. The eight studied riverbanks exhibited considerable variation in their plastic distributions. Three riverbanks had a deposition line parallel to the waterline, while two showed highly clustered patterns (Moran's I = 0.234 and 0.289). The remaining two riverbanks showed random distributions (Moran's I $\approx$ 0), and one showed a uniform distribution (Moran's I = 0.073). These plastic distribution patterns result from a combination of processes influenced by the topography, morphology, hydrological dynamics, vegetation cover, and anthropogenic barriers or infrastructure. Understanding these diverse spatial patterns is crucial for (1) fate, transport, and impact assessments, (2) more efficient plastic monitoring, and (3) optimizing pollution mitigating strategies.

We explored the variation between five riverbank sampling protocols in estimating the true riverbank plastic density. We highlight the importance of increasing monitoring frequency over rigidly following standardized monitoring protocols. For individual measurements, the different protocols can yield extremely diverging results. Here, the uncertainty is 5 to 49 times larger than the uncertainty in the range of large-repetition medians. Yet, when the spatial or temporal sampling resolution increases, the different sampling protocols converge to the true item density with only a 3.3-28.7% difference. This implies increasing the sampling frequency across either large areas or extended periods can reduce the impact of the chosen sampling protocol on data comparability. This is particularly important for long-term trends in time-series analyses.

We investigated how to minimize uncertainty and optimize the balance between effort and uncertainty reduction in riverbank plastic monitoring approaches. Our investigation highlights a diminishing uncertainty decrease when increasing the sampling area. While the accuracy increases with a larger sampling area, the gains become smaller as the area increases. Reducing the sampled surface area by 80% (500 m^2 compared to 2500 m^2), only increases the deviation from the true riverbank plastic density by 20%. This suggests that prioritizing efficient sampling strategies over sampling riverbank areas in full can be valuable for optimizing resource allocation in monitoring and cleanups.

We have two key recommendations for future riverbank monitoring. First, we recommend prioritizing data quality and relevance by adapting sampling methods to suit specific goals, objectives, and local conditions. For large-scale studies, harmonized protocols can be effective and useful in comparing data across different regions. For small-scale studies, the harmonization should not overshadow the importance of sampling strategies and datasets tailored to specific goals, such as localized informed decision-making. With increased sampling frequency, the results from different protocols tend to converge, providing valuable insights regardless of standardized or harmonized protocols. Second, we recommend a step-wise sampling strategy. We suggest starting with a coarse baseline, based on a simplified protocol using a small but representative sample area to gain a preliminary understanding of the riverbank plastic distribution. This initial understanding can help to allocate available resources more effectively and adapt the sampling frequency and sampling area to meet specific objectives. With these recommendations, we encourage a future of strategic, cost-effective riverbank

plastic monitoring that informs broader efforts to combat plastic pollution in aquatic ecosystems globally.

Supplementary Information

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Supplementary Material 1

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Authors' contributions
Conceptualization: PT, MB, WdW, TvE; Methodology: PT, TvE; Formal analysis: PT, TvE, MvdP; Investigation: PT, MB, WdW, PV; Data Curation: PT; Writing - Original Draft: PT; Writing - Review & Editing: All authors; Visualization: PT; Supervision: TvE, MvdP; Project Administration: PT, TvE; Funding acquisition: TvE. All authors have given approval to the final version of the manuscript.

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Data availability
The datasets generated and/or analyzed during the current study and all the MATLAB scripts and files used for these analyses are available in the 4TU. ResearchData repository, https://doi.org/10.4121/3f5d76d4-c361-4158-84f9-fef02b2db898.

Declarations

Ethics approval and consent to participate
Not applicable.

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Competing interests
The authors declare no competing interests.

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