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Measuring riverine macroplastic: Methods, harmonisation, and quality control

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ABSTRACT

River systems are a key environmental recipient of macroplastic pollution. Understanding the sources of macroplastic to rivers and the mechanisms controlling fate and transport is essential to identify and tailor measures that can effectively reduce global plastic pollution. Several guidelines exist for monitoring macroplastic in rivers; yet, no single method has emerged representing the standard approach. This reflects the substantial variability in river systems globally and the need to adapt methods to the local environmental context and monitoring goals. Here we present a critical review of methods used to measure macroplastic flows in rivers, with a specific focus on opportunities for methods testing, harmonisation, and quality assurance and quality control (QA/QC). Several studies have already revealed important findings; however, there is significant disparity in the reporting of methodologies and data. There is a need to converge methods, and their adaptations, towards greater comparability. This can be achieved through: i) methods testing to better understand what each method effectively measures and how it can be applied in different contexts; ii) incorporating QA/QC procedures during sampling and analysis; and iii) reporting methodological details and data in a more harmonised way to facilitate comparability and the utilisation of data by several end users, including policy makers. Setting this as a priority now will facilitate the collection of rigorous and comparable monitoring data to help frame solutions to limit plastic pollution, including the forthcoming global treaty on plastic pollution.

1. Introduction

Plastic debris is now well-established as a global pollutant. In the environment, its occurrence can extend across a wide size spectrum – from several meters down to the nanometre scale – where macroplastic refers to the larger, tangible pieces of plastic litter. There remains a lack of internationally accepted definitions on what is included within the term plastic pollution, such as size boundaries or relevant material compositions that are considered to be plastic (Hartmann et al., 2019); however, macroplastic typically includes plastic items down to a few centimetre in size (e.g. 2.5 cm; González et al., 2016) and may comprise common plastics, such as polyethylene or polypropylene, as well as bio-based or biodegradable polymer types. As such, macroplastic pollution is typically characterised as a heterogeneous assemblage of plastic waste items, exhibiting a range of properties that exert variable influence on fate and possible risks.

Several modelling studies point to river systems as a key environmental recipient of plastic and an important pathway to other environments, including wetlands, lakes, estuaries, coastal ecosystems, and the oceans (e.g. Lebreton et al., 2017; Meijer et al., 2021; Schmidt et al., 2017). Macroplastic pollution in river systems is a cause for concern as it can interact with organisms, increase flood risk, reduce amenity value, and fragment into microplastics (Al-Zawaidah et al., 2021; van Emmerik and Schwarz, 2020; Lechthaler et al., 2020). Understanding the sources

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of plastic to rivers and the mechanisms controlling riverine transport efficiency is key to identify measures that can effectively reduce pollution, such as source control, clean-up technologies, and shoreline/riverine infrastructure designs (Black et al., 2019; Rochman, 2018). By mass, macroplastic represents the dominant component of river plastic pollution (Mai et al., 2020); yet, riverine macroplastic monitoring activities are hindered by lack of consolidated methodologies (van Emmerik and Schwarz, 2020).

Emphasising the urgency, 175 countries endorsed a historic resolution at the UN Environment Assembly (UNEA-5.2) aiming at developing a legally-binding agreement on plastic pollution by 2024. Understanding the sources and riverine loadings of plastic pollution is instrumental for both the design and the implementation of the policy (Rognerud et al., 2023). Currently, riverine plastic loading estimations are conducted with non-validated coarse model frameworks (e.g. Lebreton et al., 2017; Meijer et al., 2021; Schmidt et al., 2017). Field data are required to consolidate these estimates and assess the future success of policy implementation. Developments in monitoring design, including the coordination of monitoring activities and their methodological approach, are central to success for this goal.

The majority of riverine macroplastic studies specifically aim to quantify the movement of plastic waste in the river channel. Thirty nine published studies have measured macroplastic flows in rivers globally within the scope of this review (Fig. 1), utilising five main methodological approaches (Table S1). These methods can be divided into observation-based and physical interception-based techniques. Observation-based sampling refers to the surveillance, quantification, and categorisation of macroplastic that is visible in the river without collecting the detected items, whilst physical interception-based sampling instead involves the active entrapment and collection of macroplastic from the river for the quantification and categorisation step. There is significant variability in the methodological approaches adopted in existing published studies. This includes discrepancies in the specific conditions of method deployment, as well as the specific component of the total macroplastic load that is measured – for example floating versus submerged items – thus hampering the potential to compare between datasets, globally (Winton et al., 2020).

Several guidelines have been developed that describe and promote different methods for analysing riverine macroplastic (e.g. Barnardo and Ribbink, 2020; González et al., 2016; González-Fernández and Hanke, 2017; Miliute-Plepiene et al., 2018; UNEP, 2020); yet, no single method has emerged representing the standard (van Emmerik and Schwarz, 2020). This reflects the difficulties in establishing a global 'one size fits all' approach for all river systems and monitoring goals. There is significant variability in river hydrology and geomorphology across the world. Macroplastics also vary considerably in size, morphology, and other physical properties, where there is a current lack of harmonisation regarding this characterisation. These differences will require substantial improvements, adaptations, or even the development of entirely new approaches to accurately assess macroplastic pollution in rivers, globally. Better understanding plastic fluxes in a range of different fluvial settings is important. Meijer et al. (2021) demonstrated that over 1000 rivers account for 80% of global plastic release to the oceans, so targeting action on a small number of catchments may not be sufficient to tackle global plastic contamination. Moreover, according to the same study, more than 98.5% of the total mismanaged waste is not transported into the sea and remains within river catchments. Monitoring is therefore crucial to better understand the fate of plastic waste in rivers.

There is, in addition, a wide range of different operational objectives connected to riverine macroplastic monitoring linked to, for instance, assessments of plastic inputs (e.g. recharge or affluent points loading), flows (e.g. baseline vs high flow assessments; focused vs time aggregated observations, etc.), or accumulations in specific parts of a river (e.g. sediment bed, bank, riparian vegetation, etc.) (UNEP, 2020; van Emmerik et al., 2022b). Different monitoring foci require different solutions and may necessitate the collection of data in different forms. No single method is capable of measuring the total macroplastic load for all riverine settings, in a single deployment. Instead, methods are capable of characterising specific fractions defined by size, buoyancy behaviour, or other characteristics which must be interpreted or combined with other measurements to obtain a more complete picture of plastic contamination in a given catchment. Herein lies the importance of establishing

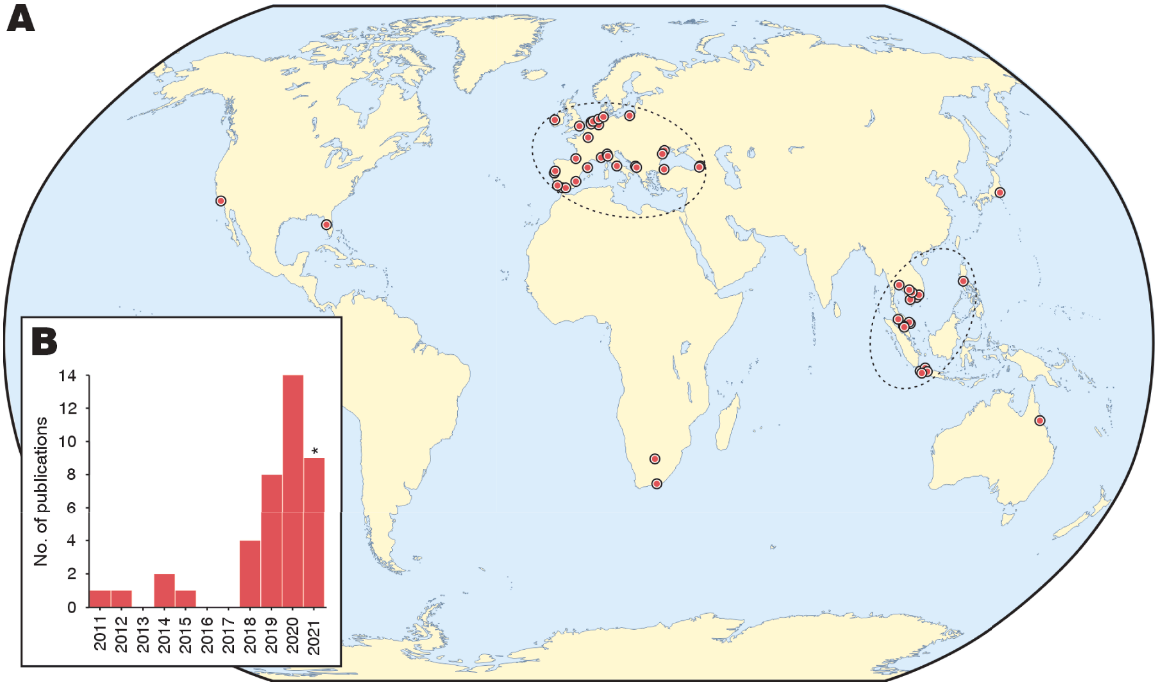

Fig. 1. Map of river catchments sampled for macroplastic flows globally (A). Two main geographical clusters are evident and are highlighted by dashed circles: Europe and South East Asia. The total number of publications released each year reporting environmental monitoring of riverine macroplastic flows are shown in panel B. *This figure is based on the 39 studies included in the critical method review up to 01.12.2021 (see Supplementary Information for details).

well-defined frames and methods with due consideration for what they are capable of accurately measuring and what the generated data can inform about plastic pollution across different spatial and temporal scales.

For these reasons, harmonisation of methods is likely to be more important than standardisation in this context. Harmonisation can be defined as an effort to achieve cross-comparability and interoperability in data outputs from different surveys. Operationally, harmonisation includes an initial recognition and explanation of potential differences between datasets and the definition of a set of tools enabling conversions for comparability or interoperability. Harmonisation can be achieved through method testing, validation, and quality assurance and control (QA/QC). Respectively, these actions can clearly define the limits, thresholds, and optimal deployment of a method (methods testing), establish the precision and accuracy (validation), and ensure data quality, comparability and interoperability (QA/QC). Harmonisation of data reporting is also important.

The present paper critically reviews the methods adopted by published studies of macroplastic flows in river systems. This refers to macroplastic actively transported in the river channel, and does not include a review of methods to measure stocks or temporary stores of plastic within or along the river. Through this, the aim is to support ongoing international policy processes (such as the proposed Global Agreement on Plastic; UNEP/EA.5/Res.14) by identifying priority knowledge gaps related to method development and optimisation and defining opportunities for method testing, validation, and harmonisation that will facilitate a convergence of existing approaches. The different applications of riverine macroplastic data are also considered, to further optimise methods towards providing data that can be used by a wide range of end users, including policymakers.

2. Measuring riverine macroplastic flows

A total of 39 studies were identified as part of the critical method review for this paper, following a systematic approach. A full description of the review methodology is provided in the Supplementary Information. Briefly, a series of Boolean search strings were used for Web of Knowledge, ScienceDirect, and Google Scholar to identify relevant papers, which were further assessed based on the following criteria: 1) a specific macroplastic focus; 2) reporting of measurements of active macroplastic transport under field conditions and in river systems; and 3) publication of data and methods in peer-reviewed literature or technical reports. The final list of 39 studies identified utilise five main methodological approaches, which are depicted in Fig. 2A-E. In the following sections, each method will be evaluated with regard to ongoing needs for method testing and opportunities for validation and harmonisation.

2.1. *Observations of riverine macroplastic*

2.1.1. *Visual observation*

Visual observation is the most commonly utilised technique for measuring macroplastic flows in rivers (17 out of 39 publications; Table S1). Briefly, human analyst(s) observe and record the visible macroplastic load passing a cross-section of the river channel – or a portion of it –during a predefined measurement period.

A prerequisite is the availability of a vantage point for viewing the river: this is typically a bridge or other infrastructure that passes over the river, but surveys can also be performed from the riverbank for narrower streams (e.g. Crosti et al., 2018; Tasseron et al., 2020). Visual observation is therefore limited to locations where such a vantage point exists and can be safely accessed (van Emmerik et al., 2020b). In wider channels, it will not be possible to observe the full width of the river from a single point and, in this case, it is necessary to define a cross-section portion or observation track that represents a proportion of the river width (González-Fernández and Hanke, 2017). van Emmerik et al. (2018) recommends dividing the channel cross-section into several portions and observing each of these for a measurement period that allows all defined portions to be observed in under one hour (termed a ‘sweep’), deemed to be a time lag where stream conditions will be relatively stationary. Where the full river width cannot be monitored within an appropriate time window, the results from the measured

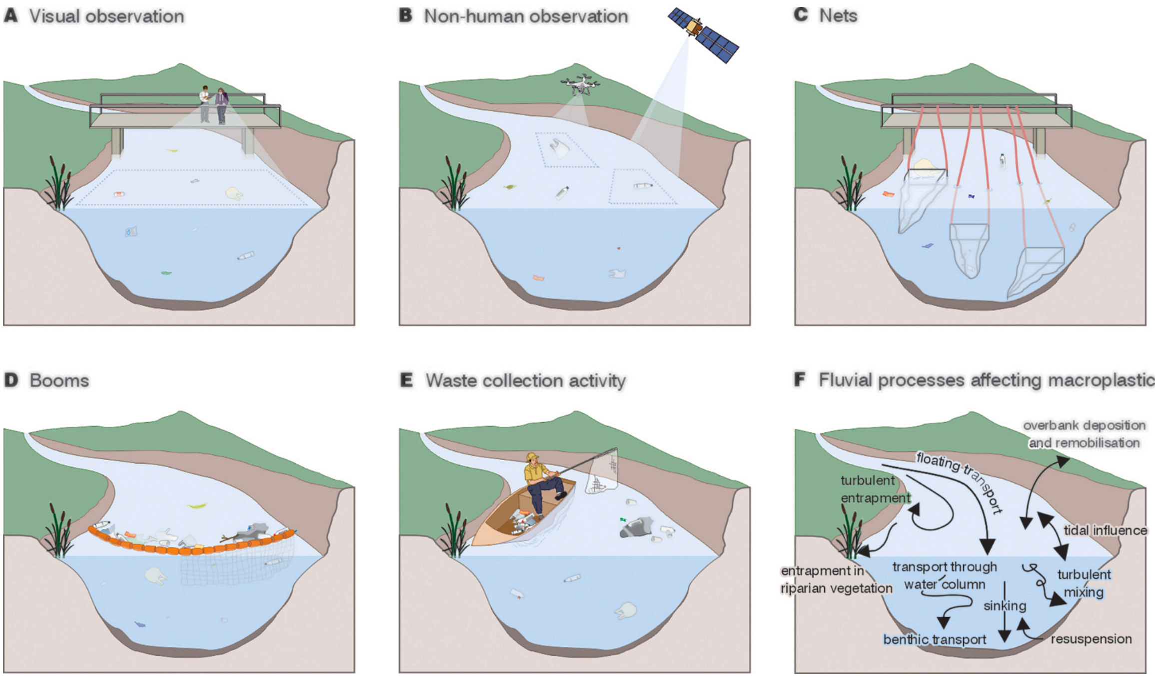

Fig. 2. Depictions of the five main methodological approaches identified in the critical method review: A. visual observation using human analysts; B. non-human observation, such as the use of unmanned aerial vehicles (UAVs) or remote sensing; C. use of nets, such as trawl nets; D. use of booms, including an example of a boom with a net extending below the floating component; and E. waste collection activities that can be adapted for monitoring. Fluvial processes relevant for the fate and transport of macroplastic in rivers are described in panel F.

portions will be extrapolated to the full river width to estimate total transport. An appropriate portion width will depend on a number of factors, for example vantage point height, flow velocity, plastic load, and weather conditions. Some guidelines recommend that analysts face upstream to obtain a better view of arriving litter items (e.g. González-Fernández and Hanke, 2017); however, several studies have also opted to view downstream in response to the specific environmental setting, such as to avoid sun glare (Table S2). Commonly, a minimum of two analysts are required to perform this task: one to observe the river and the other to record the data; although, this will depend on the plastic flux and flow velocity. All macroplastic items that are observed during the measurement period are recorded. Additional categorisation of observed macroplastic can range from no categorisation to polymer category (e.g. van Calcar and van Emmerik, 2019) or item specific categorisation (e.g. González-Fernández et al., 2021).

The visual observation method allows for the rapid and inexpensive collection of data without the need for specialised equipment, extensive training, or permits. This can facilitate the generation of several datapoints covering a range of spatial and temporal scales, representing an important asset of this technique. However, this method is not capable of assessing the total riverine macroplastic load, but only items visible from a position above the surface. It also presents limitations or challenges that need to be carefully acknowledged and addressed. These are:

Selection of cross-sectional spatial resolution of observations: The optimum river cross section dimensions that can be reliably observed by a single analyst or team under a range of flow and plastic load conditions should be assessed. This is likely to vary case by case and in relation to the contingent river flow conditions. This includes an investigation into the upper thresholds for flow velocity and total plastic loads: in cases where the total plastic flowing past the observation portion becomes too high, it is no longer possible to reliably record (and categorise) all macroplastic items (Geraeds et al., 2019; van Emmerik et al., 2018). Moreover, turbulent flows, particularly in highly turbid rivers, can potentially reduce the proportion of the total macroplastic load that can be reliably observed. In this case, river currents may drag buoyant plastic items below the river surface and out of the visible range. Hence, the visual observation method is likely to be more challenging to accurately measure and categorise plastic flows during flood conditions or during periods of high suspended sediment load.

Single observer cross-sectional portions range from 2.5 to 65 m in width (Table S2). This factor can affect the lower size limit of macroplastic that can be identified. For example, Schöneich-Argent et al. (2020) selected a maximum 20 m segment width for their analysis of three German rivers, as this facilitated assessment of >2–2.5 cm particles under different light and weather conditions. Additionally, Castro-Jiménez et al. (2019) noted that whilst 2.5 cm particles could be identified directly below their selected vantage point, only >7 cm particles could be reliably detected at the distal edges of their 65 m segments in the Rhone River. The use of cross sectional portions to facilitate visual observation can also have an impact on the representativeness of the data generated. Many studies do not visually observe the full river width and, in some cases, the portion(s) observed may represent <1% of the river width at the site in question (Table S2). This can create problems when extrapolating observation results to the full river cross-section (e.g. in connection with the statistical representativeness of the observations which is a function of the total density of visible floating items, the percentage of the total cross section covered by the observers, and the cross-sectional distribution of plastic items, turbulence, and stream velocity). Method testing and validation exercises – for example, using tracers and measurement standards (Newbould, 2021) or video footage (van Lieshout et al., 2020) – would help to establish what conditions facilitate effective measurement of riverine macroplastic (e.g. bridge height and lower size limit) and what the minimum requirements are for achieving accurate and representative measurements of macroplastic flows (e.g. proportion of channel width measured or need for replication).

Elevation of the observation point from water surface: The distance of the observer from the water surface will also influence the lower size limit that can be reliably observed, and the selection of the cross-sectional domain covered by each observer. Reported vantage point heights vary between 0.5 and 20 m (Table S2). Method testing should assess the realistic lower size limit for a range of vantage point heights to establish what can be defined as a suitable site for visual observation-based monitoring. This could be performed using items of a known size that are released upstream or by running the visual observation method in parallel with a physical interception technique to verify what was present in the water and was successfully detected. van Emmerik et al. (2020a) established a size limit of 1 cm for observation heights of up to 12 m when using human analysts. A slightly different approach is outlined by González-Fernández and Hanke (2017), who recommend the selection of a monitoring site on the basis that it is possible to detect plastics >2.5 cm in size. The latter facilitates more harmonised data collection, but it is important to note that no such location may available in some river catchments. Incorporating data reporting in size bins may help to better compare between datasets with different minimum item sizes.

Establishing an adequate lower observable size limit: The lower observable size limit is, in principle, a function of the observer elevation and sensitivity, the width of the cross-sectional observation domains, and stream flow. It can be argued that lower observable item size is smaller than the lower size of items that can be reliably detected (i.e. the lower size of quantifiable items) because of the difficulty for a human operator to maintain an elevated level of attention over long observation periods and because different operators deployed along different cross-sectional portions of the channel may have different sensitivities and concentration abilities. The distinction between lowest detectable size and lowest size of quantifiable items is rarely discussed.

The lower size limit of plastics applied by the studies ranges across an order of magnitude: from 0.5 to 5 cm (Table S2). This limits the potential for comparability between different studies. Using a common lower size limit or reporting in defined size categories could help to overcome this shortcoming; however, accurately assessing size when an item is in flux can be challenging. For this, measurement standards placed in line of sight may be needed. Unfortunately, often the size limit is dictated by contingent aspects, such as the elevation of the infrastructure (e.g. a bridge, river side, etc.) used for the observations. Schöneich-Argent et al. (2020) included an additional size category down to 0.5 cm to capture an important source of macroplastic litter (cigarette butts) that was detectable and below their initial lower size limit. Validating the accuracy of human analysts in detecting the lowermost sizes of macroplastic under a range of conditions is also necessary to ensure good data quality. Effective training of analysts is essential to avoid under-reporting of some sizes classes of riverine macroplastic.

Visibility depth vs channel depth: The visibility of submerged plastics is likely to vary between monitoring sites and river catchments, and in response to factors such as turbidity, turbulence, wind speed, sun glare, and the colour and size of the plastic items (van Emmerik et al., 2018). The extent of visibility is only detailed in 5 out of 17 published studies (Table S2) and has been reported as 10 cm in the Saigon river (van Emmerik et al., 2018), Manila rivers (van Emmerik et al., 2020b), and Dutch canals (Tasseron et al., 2020) and 20 cm in the Seine (van Emmerik et al., 2019c) and Klang rivers (Geraeds et al., 2019). These studies do not report the total depth of the river, so the proportion of the river that was observable cannot be discerned, hindering the scaling of observations for the total water column depth. In only very rare cases, it may be possible to observe the total plastic load, due to clear waters and very shallow rivers. Difficulties in accounting for variability in visibility represents a major challenge for harmonisation; although reporting the visibility associated with each measurement along with the depth of the observed cross sections should represent a minimum data reporting requirement (Section 4.1).

Human error: The potential for human error and bias should also be assessed within future methods testing and validation exercises (Geraeds et al., 2019; Vriend et al., 2020b). The time for a single measurement ranges from 1 to 63 min (Table S2). It is important to consider what is reasonable with regard to the concentration limit of a human analyst, which will in turn be connected to the plastic load at a given site. It may be preferable to take several short measurements in channels with a high flow velocity and/or plastic load, versus fewer, longer measurements where the reliability of the human analyst(s) could be called into question. The concept of fatigue has already been raised in other fields that rely on human observation-based approaches (e.g. Rankin et al., 2020). Some studies report the use of binoculars to improve the confirmation of object identity (e.g. Crosti et al., 2018; Schirinzi et al., 2020; Weideman et al., 2020). This may help to verify that a piece of debris is composed of plastic and what category it falls into; although, whilst using binoculars the field of view is significantly narrowed, so they may not be suitable in circumstances where the plastic load is high or is spread across the river cross-section. Moreover, some particles may be preferentially under-reported due to their characteristics, for example being small in size or transparent (Vriend et al., 2020b). Further validation tests to verify what can be reliably identified by human analysts – under a range of conditions and for a range of plastic sizes and types – are required to establish the real significance of these factors for generating accurate and reliable monitoring data and setting important thresholds in monitoring guidelines. The influence of human error bias can be assessed and reduced by replicating (e.g. two or more observers working independently from the same vantage point) or randomising observations (e.g. repeating observations by randomising the locations of individual observers in different cross-sectional portions during consecutive sweeps).

Using citizen science as a means to obtain larger datasets of visual observations for macroplastic flows has been discussed (Kiessling et al., 2021; van Emmerik et al., 2020a). This should consider the potential implications for data quality (e.g. imprecise measurements, human bias) and balance the uncertainties of any given single reported measurement within a dataset. For example, problems associated with low motivation of citizen scientists has been reported for scenarios where plastic loads were low or the weather conditions were unfavourable (Kiessling et al., 2021). Based on the potential limitations set out for visual observation, the extent to which citizen science represents the optimal use of this methodological approach should be explored. This does not preclude the use of trained analysts for undertaking monitoring activities but – through setting thorough monitoring and data reporting guidelines – the uncertainties associated with visual observation data could be outweighed by the size of the datasets generated. Thus, general trends could be more rapidly identified, despite the potential lower quality of any single measurement within a citizen science-generated dataset (van Emmerik et al., 2020a).

The influence of the analyst, as well as the environmental setting, should be assessed routinely during the monitoring programme as part of a QA/QC procedure. This includes checks to evaluate: i) the total proportion of floating (or visible) macroplastic that is successfully recorded (recovery rate), for example through the use of "dummy" items intentionally released in the upstream; ii) the degree of variation in the categorisation of plastics between analysts; iii) the successful identification of litter items as plastic; iv) the successful categorisation of macroplastic litter items; and v) agreement between analysts regarding categorisation. Many of these factors can be assessed by running a parallel method which includes the physical interception of macroplastic, such as the deployment of nets (Geraeds et al., 2019; van Emmerik et al., 2019a, 2019b).

2.1.2. Non-human observation

Non-human observation approaches follow a similar principle as for visual observation (Section 2.1.1) but replace human analysts with technological solutions. Current applications include the use of cameras (Kataoka and Nihei, 2020; Onoi and Nihei, 2012; van Lieshout et al., 2020) and unmanned aerial vehicles (UAVs); Geraeds et al., 2019; Rocamora et al., 2021; Schreyers et al., 2021a; Wolf et al., 2020). As for the visual observation approach, these methods are capable of assessing the visible macroplastic at the water surface; namely, what is floating and what is visible beneath the surface within a certain visibility depth (relative to the optics and device used). In addition, sonar has been applied to detect below the water surface (Broere et al., 2021). Sensor-assisted observations present many of the same limitations affecting human-based observations but also offer some advantages. Similar to human-based approaches, turbidity and the distance from the water surface will define both the proportion of the total macroplastic load that can be recorded and the lower size limit that can be detected by a camera. For example, Geraeds et al. (2019) noted that macroplastic could no longer be classified at heights of 8–18 m above the water surface. In the case of sonar, echo sounding devices can permit observations of submerged – including non-visible – plastics below the water surface (Broere et al., 2021); however, sonars cannot currently concretely discriminate whether a detected item is made of plastic or another material.

Benefits of these techniques include the potential to measure over longer durations with high levels of consistency – for example in the case of mounted cameras – or in river reaches that are not easily accessible – in the case of UAVs. They are able to handle higher plastic loads and flow velocities, especially when footage can be replayed, or the analysis is automated with the use of a visual processing algorithm (Geraeds et al., 2019; Kataoka and Nihei, 2020). Although, the influence of turbulent flow on the buoyancy – and therefore visibility – of plastics should be assessed. If cameras are equipped with night vision capability, then measurements of plastic flows during the night may be possible. However, in this case, due to a potential different visibility depth, a correction factor is necessary to harmonise data with day-time observations. It can also be possible to assess the size or 2D area of plastics, with the use of a measurement reference or by registering deployment criteria (e.g. height and angle) to establish the spatial resolution (Geraeds et al., 2019; Rocamora et al., 2021).

Image-capture based-methods can be limited by factors such as the file size of data outputs – e.g. in the case of large video files – or the battery life of devices (Geraeds et al., 2019). The field of view (i.e. the total area observed by the camera or UAV, etc.) will define the area of river that can be measured. Where the field of view is relatively small, this may not cover the full width of the river and, therefore, may not assess the total visible floating and sub-surface macroplastic load of the river in a single deployment. This can be solved as for human-based observations: by considering well-defined portions of the river cross-section. Some technologies, e.g. UAVs, are limited to quite specific weather conditions, such as sufficiently low wind speeds or a lack of precipitation (Geraeds et al., 2019). Despite significant potential, these approaches require testing and likely optimisation prior to routine deployment based on the limited application of these techniques thus far. This includes testing what can be accurately detected with these technologies associated with different deployment conditions.

Studies have already begun to compare human and technological approaches to plastic observation in rivers. van Lieshout et al. (2020) found that 34.6% more plastic was detected when using a camera and visual processing algorithm than with human analysts in several Jakarta rivers. There was high variability associated with counts derived from both methods. The camera and algorithm approach appeared to be better suited to handle high plastic loads, where human observers were not able to count and classify as many items at the highest loadings. However, the study did not verify results with physical interception-based sampling, so it is difficult to conclude regarding the accuracy of each approach. Geraeds et al. (2019) also recorded discrepancies between human and UAV-derived counts. The potential for human analysts to be overwhelmed by high plastic loads and high flow velocities was observed; however, the occurrence of sun glints or shadows in UAV images also lead to some classification errors using that technique.

Validation and QA/QC for non-human observation approaches could be performed in a similar way to that for visual observation; namely, the deployment of a parallel physical interception sampling methodology to verify what proportion of total plastic is identified and assess the accuracy of item characterisation or facilitate assessment of mass conversions. The efficacy of these techniques relies upon the quality and breadth of the training data for visual processing algorithms, or the ability of human analysts to detect plastics in recorded images (Geraeds et al., 2019; van Lieshout et al., 2020). This relates to the ability to reliably distinguish plastic items from other materials in the river. An additional QA/QC protocol should be put into place to confirm the quality of matches established. Ideally, algorithms and associated training data should be provided as open source or made available through data/code sharing platforms, to allow for harmonisation in data collection. Where different programmes are used for different techniques, facilitating interoperability should be a priority. Methods testing for these approaches should aim to identify the optimal range of working conditions, as well as aspects related to the lower size limit of detection or the proportion of the river reach that can be studied. Additionally, methods testing should address new and emerging technologies that can replace human analysts, such as the potential use of underwater drones.

2.2. Physical interception of riverine macroplastic

2.2.1. Nets

Nets comprise mesh screens or bags that are lowered into the water and used to intercept macroplastic that is flowing in the river (Fig. 2C). They are typically deployed from a fixed point, such as a bridge, but they may also be used from a boat (e.g. Haberstroh et al., 2020; Schöneich-Argent et al., 2020) or from the riverbank or bed (e.g. Munari et al., 2021; Taryono et al., 2020). Nets can be utilised to measure floating, sub-surface, or even benthic transport of macroplastic using buoys and weights to position them in the desired location within the water column (e.g. Moore et al., 2011; Morritt et al., 2014). They can also be deployed in fleets (several nets connected to the same frame) to sample different parts of the water column simultaneously (e.g. van Emmerik et al., 2019a, 2019b). Nets are deployed for predefined measurement times or until the net becomes full or clogged with debris. In published studies, this ranges from 30 s to 3 days (Table S3). Once the measurement period is over, the nets are retrieved from the water. The contents are then inspected to isolate, count, categorise, and weigh the macroplastic component. The use of nets represents the mostly commonly utilised physical interception-based technique for measuring macroplastic flows (Table S1).

The proportion of the total riverine macroplastic load captured by this method depends on the parameters of the net and its deployment. First, the size of the net opening (aperture) will determine both the proportion of the river cross-section and the volume of water that can be sampled during the measurement period. Second, the mesh size of the net establishes the lower size of plastic that is retained. Third, the location and depth of deployment in the river cross-section will define the transport pathway (floating, sub-surface, benthic) that is assessed by this technique. Factors such as the selected mesh size, the length of the net, the flow velocity of the river, and the total suspended load will also impact the length of the useful deployment time in a given environmental setting, based on the clogging of the net. Harmonisation between these many factors is dependant upon a thorough description of the specific methodological details. Some studies do not report important criteria that can define what a given deployment specifically measured. For example, only six out of fifteen studies that deploy nets at the water surface describe the extent to which the nets were submerged in the water (Table S4) – a factor which dictates the volume of water sampled and has potential implications for the sampling of floating macroplastic of different sizes. Minimum reporting requirements should form the basis of harmonised methods, and this is addressed in more detail in Section 4.1.

The thresholds associated with the deployment of nets with different configurations and under different flow and plastic load conditions requires testing. This testing will help to optimise the technique and ensure safe deployment in the field. A submerged net produces drag, a force with an orientation opposite to that of the water flow. Drag results in additional turbulence in water and the reduction of the downstream transport of plastic in the vicinity of the net mouth upstream. This in turn lowers the likelihood that an item will be captured be the net. Drag (and hence turbulence) is linearly proportional to the stream flow velocity at low flow velocities, while it increases quadratically at high flow velocities. Drag force also depends on the drag coefficient imposed by the geometry of the net, which increases as the net accumulates material. Flow velocity immediately upstream of a clogged net can even approach zero, rendering further sampling ineffective. Maintaining adequate control of operational conditions of nets with a given geometry and mesh, and in given river conditions is therefore essential to enable quantitative and reliable assessments and comparable and interoperable data generation.

The selection of mesh size should also be considered. For, example, Weideman et al. (2020) reported that flow velocities up to 3 m s^{-1} were manageable for a 0.6 × 0.3 m net with a 300 μm mesh set at the water surface in the Orange-Vaal River System, South Africa. Under lower flow conditions (reported as <0.002 m s^{-1}), the presence of the net introduced turbulence that prevented some plastic items from entering the net and being captured; the debris instead flowed around. At higher velocities, the potential for damaging the net increases and the drag force acting on the nets becomes too great for safe manual deployment and retrieval. This was noted by Geraeds et al. (2019), who selected a 2.5 cm mesh to ensure safe deployment of a 0.67 × 0.67 m net in the Klang River, Malaysia (flow velocity between 0.5 and 1 m s^{-1}). Changes in one variable (flow velocity, mesh size, deployment duration, etc.) will affect other variables, so this technique should be adapted to the specific research questions and conditions in the river. This will determine the total length of time (temporal scale) that a single measurement can account for and the representativeness of the net as a sampling technique.

Nets represent the second most commonly utilised technique for assessing macroplastic flows (Table S1). Yet, there is currently very little harmonisation between monitoring efforts that utilise this method. For example, only two studies use the same net configuration with regards to aperture, mesh size, degree of submersion (for surface nets), or depth/location of deployment (Fig. 3; Haberstroh et al., 2021, 2020). Given the lack of a standardised description of which nets are appropriate for macroplastic monitoring in different contexts, it is likely that the choice of the net characteristics adopted in the different studies is at least partly contingent to what was locally available or had precedence in a research group. It is unlikely that a single net configuration can be recommended for all rivers, as several of the above mentioned factors are tailored to the conditions in the river. Instead, method calibration, aiming to define the operability window of a given net in a given environmental setting, should proceed deployment. Results of such calibration should be presented along with monitoring results and constitute a set of parameters and knowledge to increase confidence in the comparability and interoperability of data. Rather than being based on a set of technical specifications, standardisation in this area should be achieved through a shared set of quality criteria relative to pre-calibration of the net operability. A venue to achieve this type of standardisation could be through the deployment of nets in artificial flumes during ad hoc calibration experiments that aim to test what net parameters (e.g. mesh size) are optimal for different hydrological conditions and plastic loads. This could provide model parameterisation to predict behaviours of macroplastic capturing devices under different conditions, reduce calibration effort prior to monitoring, and produce guidelines for the types of nets to be used in riverine macroplastic monitoring. This should also comprise a quantitative assessment of the errors associated with net design and operation. In addition, harmonisation efforts should address the data

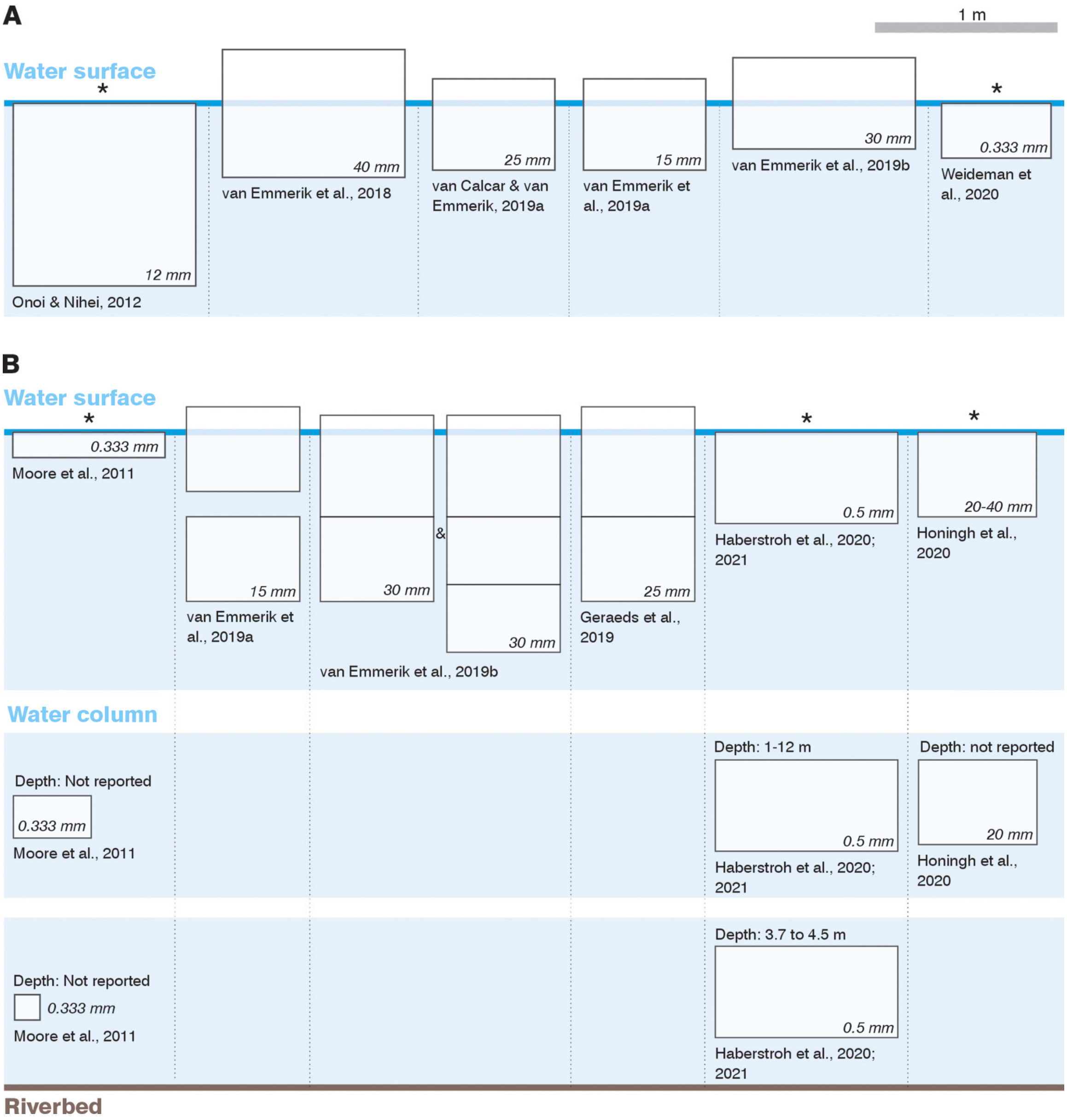

Fig. 3. Trawl net aperture (opening) sizes, deployment depths, and mesh sizes reported in published studies of macroplastic flows for single nets (A) and multiple nets or fleets of nets (B). In panel B, fleets of nets which are connected to surface nets are shown in the Water surface section, nets deployed at greater depths in the Water column section, and nets deployed at the riverbed in the lowermost section. The scale for all net aperture sizes (A, B) is given at the top of the figure. For surface nets (A, B) the degree of submersion (the proportion of the net aperture that was submerged under water) is shown with the corresponding relative height from the defined water surface line. For studies that do not report what proportion of the net was submerged, the top of the net is placed directly at the water surface line and marked with *. Only trawl-type nets are depicted, other net types are not shown (e.g. fyke nets).

collection and reporting to ensure that critical differences between studies are described and can be accounted for.

2.2.2. Booms

Booms are floating barriers that extend across all or part of the channel and collect buoyant debris, including macroplastics, as they accumulate at the water surface upstream (Fig. 2D). They are typically used as clean-up or pollution prevention measures but may also be used as a sampling methodology by adding a procedure to isolate, count, categorise, and weigh the macroplastic component of collected debris. Booms are emptied by carefully dragging the floating accumulation to the bank or other suitable location for retrieval. Some more advanced installations include automated collection, for example by lifting debris from the water or directing it towards a collection container (e.g. Vriend et al., 2020b). Booms may also include a mesh or screen that extends below the floating line to collect near-surface debris flows (Vriend et al., 2020b). Booms can measure the macroplastic load that is transported in the uppermost part of the water column, across the full or partial river width (depending on the nature of deployment), for the duration of boom deployment. If a net or screen is present below the floating component of the boom, the coverage of the total cross-section of course increases. The mesh size used for this net/screen will determine the lower size limit that can be captured from this near-surface flow.

Only six studies have thus far utilised booms as a sampling method (Table S5). All of these use structures that were already established as part of ongoing clean-up or debris removal schemes before being used in monitoring. It is notable that studies rarely report important criteria about the structure of the device or the parameters of any given measurement. Specifically, this includes sparse reporting of the dimensions of the boom, the presence of any mesh or screen, the depth of the submerged part, the rate at which the boom was emptied, the proportion of the channel width intercepted by the boom, or the capacity of the boom structure (Table S5). These represent crucial details for interpreting data derived from this methodological approach, and the lack of reporting is a barrier to harmonisation. Without these details, it is difficult to conclude on the efficacy of booms as a sampling method for measuring macroplastic flows.

In order to transform this approach into a validated sampling methodology, methods testing is required. For example, Malik et al. (2020) established that this method is best suited to slower moving water as the capture rate is highest. This was further explored by Roy et al. (2021) for the specific context of Covid-19 related floating waste. They found that the structure design can influence the surface streamflow dynamics, affecting how waste can be channelled into a collection device or how it could potentially bypass the boom structure – particularly in the case of configurations that only partially cross the river width. Yet, based on their study, it was not possible to observe significant differences between the trapping efficiencies of different structures for the plastic types investigated. The authors also noted that plastic items may slip under the boom structures during periods of high flow (Roy et al., 2021).

Further methods testing should specifically assess the capture rate of different boom structures under different deployment conditions. This includes the maximum working conditions in terms of the maximum flow rate or maximum working load (i.e. the maximum amount of floating debris that can be retained by the boom) and how this changes over time (e.g. as the boom fills up). The influence of high flow conditions should also be further studied, for example the thresholds above which plastics could pass over or under the boom structure and be lost. The retention capacity of the boom as it nears full capacity should also be investigated, as this could set important guidelines for the duration of deployment. As booms are typically deployed over longer time periods, the variability in flow conditions in this time should be accounted for within the final measurement; for example, the potential losses that may have occurred whilst the boom was in operation. This information can transform the data from the deployment of a boom into a number that represents a known proportion of the riverine macroplastic load over a given timescale.

One further aspect relates to the potential for non-plastic material to complicate measurements. Much of the debris collected by a boom may be non-plastic in composition. Gasperi et al. (2014) found that 92.0–99.1% of the mass of debris collected by a network of 26 booms on the Seine River in Paris was vegetal, where the percentage of plastic ranged between just 0.8% and 5.1%. Such sample composition introduces new challenges for the isolation of the plastic component, particularly for smaller particles sizes, and handling of waste, in terms of personnel requirements and infrastructure for removing the sorted debris. This should form the basis of further study, to help identify the optimal conditions for boom deployment and interpretation of results.

2.2.3. *Waste collection activities*

Riverine macroplastic flows may also be measured using data from waste collection activities, which include both litter clean-up actions (from the river channel, banks, or beaches) and operations linked, for example, to the maintenance of gauges or dams or dredging activities. Litter clean-up was utilised by Lahens et al. (2018) for the Saigon River in Vietnam and Bauer-Civiello et al. (2019) for the Ross River in Australia (Table S6) as an approach to estimate riverine macroplastic transport. Both studies manually cleared floating debris from the water surface. Lahens et al. (2018) used data from a public clean-up company that employ nets with 2 cm mesh towed from the side of boats to clear 0–10 cm depth of debris in channels with slow moving water. Five subsamples were taken from the total load to assess the composition. Bauer-Civiello et al. (2019) instead present data from complete clearance by hand, by 2–3 people on kayaks, of a defined sampling area.

Utilisation of waste collected data as a method for measuring macroplastic flows hinges upon the successful harmonisation of data collection and reporting. Standard data collection forms should be developed in parallel with the delivery of training or development of detailed protocols to describe how macroplastic data should be collected and reported. This include details such as: i) the spatial extent that was covered during the clean-up activity; ii) an estimate of the total capture rate of the activity; iii) basic river morphological and hydrological data to enable scaling for total flow assessment; iv) the time elapsed since any previous clean-up activities; v) the approaches to categorising macroplastic and separating plastic from other waste types; and vi) how to report macroplastic counts or weights.

2.3. *Other approaches*

In addition to the methods identified during the critical review of studies (Table S1), other approaches could also serve as a means for measuring macroplastic flows as part of monitoring activities. Remote sensing has been proposed as a promising new approach to observation-based monitoring; although, the spatial resolution may be too coarse to detect small macroplastics unless they are accumulated or entrapped in vegetation patches, for example (Al-Zawaidah et al., 2021; Schreyers et al., 2021b; Tasseron et al., 2021). Trash racks – a coarse screen or gridded cage that is placed across a channel to catch large debris – represent a relatively common form of riverine infrastructure that is used to capture litter (Carleton and Nielsen, 1990). Several other devices have also been specifically designed for the purpose of intercepting plastics in river or estuarine systems (Helinski et al., 2021). These techniques could theoretically be adapted to provide measurements of macroplastic flows, in a similar way as has already been done for booms or waste collection activities. Such adaptations should be accompanied by a process of method testing and validation to ascertain what such a method can accurately measure and any associated thresholds or limitations.

The selection of methodological approach(es) to be included in a given study should be based on the specific objectives of the study, a consideration of the local environmental context, a clear definition of what constitutes macroplastic pollution in the study, and the outcome of methods testing and validation related to an understanding of what each method is capable of measuring. In addition to this, more general selection criteria could include the time and cost efficiency of methods.

3. Towards a holistic assessment of riverine macroplastic flows

3.1. *Measuring total macroplastic flux*

There are some scenarios in which the total macroplastic flux could be discerned using a single approach: for example if the visibility is very good and observation-based methods can be used to view all plastics flowing in the river, or if the water level is low (paired with low flow velocities or plastic loads) and a physical interception technique can safely isolate plastics from the whole river cross-section. However, these descriptions do not marry well with the realities of most river systems globally. In more complex settings, no single measurement can be taken to assess the total macroplastic flux. Instead, it is more common to combine multiple techniques or deployments (e.g. Haberstroh et al., 2020; van Emmerik et al., 2018) and/or undertake statistical extrapolations to upscale measured values (e.g. Taryono et al., 2020; van Emmerik et al., 2019b). This creates an urgent need to understand exactly what fraction of the total macroplastic load each method can sample, both theoretically (through method testing and validation exercises) and practically (as part of a QA/QC procedure). Such efforts can improve the accuracy of estimates of the total macroplastic flux in rivers.

Not covered in this review, methods for assessing macroplastic concentrations in other parts of the river system should also be developed and optimised (van Emmerik et al., 2022a). This includes establishing the storage of macroplastic on the riverbed, in riverbanks or floodplain environments, and in riparian vegetation (Liro et al., 2020). It should be noted that many of these environments are subject to discharge conditions – for example, during flood events – and macroplastic stored in these zones may be introduced to or resume active transport in the river channel. The methods required to measure stores of macroplastic in the river system differ from those used to assess active flows and, as such, should be addressed in further review and critical evaluation. An important goal of such work should be to identify opportunities to report data in units that can be combined with outputs from different methods: data on riverine macroplastic storage should be combined with measurements of flows to establish a more holistic perspective of riverine macroplastic dynamics and provide more accurate flux calculations, as well as shed light on the processes that govern the partitioning between different components of the river.

3.2. Quantifying variabilities

Thus far, the majority of studies of riverine macroplastic flows have concentrated on two main geographic regions: Europe and South East Asia (Fig. 1). Whilst there is significant variability in catchment characteristics, hydrogeomorphology, and flow regimes within these regions, the uneven geographic distribution of study sites thus far may omit additional unique challenges elsewhere in the world where current methods may be unsuited for macroplastic monitoring. Some examples include anastomosing or braided channels or ephemeral streams. Methods that can be applied in a wide variety of settings can ease efforts towards harmonisation. Optimisation of methods should prioritise approaches that have greater geographic applicability and do not preclude use in globally important river channel types or flow regimes. This is also relevant on a finer scale, where methods should be adaptable to different river environments within regions or catchments, for example with differing river widths, tidal effect, flow velocity variation, anthropogenic modification or activity, extent of vegetation, or with different geomorphological profiles (González et al., 2016). Any specific factors which rule out the deployment of different methods in different settings should be evaluated to help identify study sites within regions or catchments which represent the optimum locations for undertaking sampling.

Understanding spatiotemporal variability in macroplastic flows forms a key focus within ongoing monitoring and research. Several studies have, together, begun to identify some important trends, for example the occurrence of higher macroplastic flows during wet seasons or flood events (Roebroek et al., 2021; van Calcar and van Emmerik, 2019). There are also additional factors – which may impart an important control on macroplastic flows – that remain poorly understood (Roebroek et al., 2022). The variability across short term temporal scales such as day-night cycles, the occurrence of a ‘first flush’ response during flooding, or the dynamics of macroplastic accumulation and flushing associated with ephemeral streams represent three such examples related to temporal variability. Vriend et al. (2020b) point out that rivers typically exhibit a unique plastic footprint, which is tied to spatial and temporal trends in source dynamics and fate and transport processes. Understanding the variability in macroplastic typologies across time and space is essential for tailoring and refining policy instruments or remediation actions to reduce riverine pollution. For example, more data on the spatial variability of macroplastic within a river system could help to identify plastic sources and identify hotspots associated with potential risks posed by macroplastic pollution, such as interaction with organisms, impacts on amenities, or impact on flood risk.

Consideration and, where possible, quantification of uncertainties is also critical to better understand macroplastic riverine flows and how they vary across space and time. For example, high flow events have been highlighted as periods of increased macroplastic transport due to the greater connectivity with land-based sources to rivers and flushing of plastic stored in the catchment, as a result of increased surface runoff and discharge (Roebroek et al., 2022). Yet, these events also impose additional challenges to effectively monitor macroplastic in rivers due to safety aspects, higher flow velocities, and increased turbulence and/or turbidity that can affect visibility. As such, there is a current lack of data globally to effectively measure macroplastic fluxes across an entire hydrograph and in different local environmental contexts. Model estimates provide some preliminary data to quantify the potential magnitude of flood events on macroplastic flows (Roebroek et al., 2022); further research is now needed to refine these estimates using monitoring and experimental investigations to more accurately assess the errors associated with riverine macroplastic data.

3.3. Fate and transport of riverine macroplastic

3.3.1. Fate and transport processes

The majority of studies conducted thus far concentrate on how much macroplastic moves through rivers, rather than the transport dynamics that govern this movement (Newbould, 2021). No clear pattern related to density, size, or morphology has emerged in the current evidence to detail specifically how these factors influence the way in which macroplastic debris moves through riverine environments. Yet, there are indications that they represent important controls on how plastic is transported. For example, several studies point towards the dominance of the floating component of riverine macroplastic (e.g. Haberstroh et al., 2021; van Emmerik et al., 2019b, 2019a); however, in other river systems a more complex pattern of transport has been observed throughout the river cross-section, including dominant flows at greater depths (e.g. Broere et al., 2021; Haberstroh et al., 2020).

In studies of macroplastic flows in rivers, movement of the litter is implicit. Yet, this is often not the case. Several papers report that plastic litter follows a complicated journey (Lechthaler et al., 2020; Liro et al., 2020; Newbould et al., 2021; Schreyers et al., 2021a; van Emmerik et al., 2022a; Williams and Simmons, 1997). Transport of litter is discontinuous and stranding in sediments, vegetation, or turbulent eddies is common and can occur repeatedly and for varying durations as a plastic item travels downstream (Cesarini and Scalici, 2022; Schreyers et al., 2021a; Williams and Simmons, 1997). Characteristics such as size, morphology, and density play an important role in controlling this temporary trapping or deposition and the thresholds for remobilisation (Williams and Simmons, 1997), but this has not yet been specifically established for a range of different litter types. The spatial and temporal scales over which these processes operate are also essentially unknown.

This complexity is highly relevant when designing sampling programmes and interpreting results: plastic flows in the river may reflect source dynamics (proximity, magnitude of release, etc.) but they are also a net result of the processes that facilitate transport or remobilisation. Studies utilising plastic litter tracers that are representative of a range of different sizes, shapes, and polymer composition are needed to support monitoring and modelling assessments, to better quantify and predict the movement of plastic in rivers. This has been performed for plastic bottles (Duncan et al., 2020; Newbould, 2021; Tramoy et al., 2020a) and plastic films and sanitary products (Williams and Simmons, 1997), but more knowledge is needed regarding the fate of different items, including those that represent the most abundant types in river systems.

3.3.2. Riverine discharges of plastic to the ocean

There is often an assumption that all plastic that is released into rivers eventually reaches the marine environment. In some cases, rivers are described as conduits for plastic to the ocean, with the implication that they represent smooth pipelines delivering plastic along their course; however, this does not account for the high level of complexity inherent in riverine environments, the global diversity in catchment characteristics, hydrology, and fluvial geomorphology, and the inherent and variable characteristics of macroplastics affecting transport efficiency (Kallenbach et al., 2021). The time at which a macroplastic item that is inputted into a river could be expected to theoretically be released into the marine environment remains a persistent knowledge gap. This gap has the potential to undermine estimates of plastic release to the marine environment that utilise, for example, waste (mis)management data or quantify specific sources to rivers.

In fact, there is now increasing evidence that substantially less than 100% of the plastic that enters a river is released into the ocean (van Emmerik et al., 2022a). This was initially observed as a marked discrepancy between estimates for plastic emissions based on waste (mis)management data versus the results from monitoring activities: revealing a difference of up to 98.5% (Meijer et al., 2021; van Emmerik et al., 2019a). The potential for macroplastic to enter temporary sinks within river catchments has already been stated. An additional factor includes the removal of plastic through pollution remediation efforts (e.g. Sidek et al., 2016), although data on the total volumes collected or the efficacy of different technologies remains sparse (Helinski et al., 2021). On the other hand, the extent to which discrepancies between measured and estimated values could be explained by, for example, the accuracy of estimates of mismanaged waste, item-to-mass conversions, model uncertainties, or the difficulties associated with accurately measuring macroplastic emissions during flood events remains unknown (Roebroek et al., 2022).

This issue is also confounded by the influence of estuarine environments. Estuaries represent complex and dynamic systems that sit at the interface of riverine and marine environments. Practically measuring flows of macroplastic in these settings introduces an additional level of complexity compared to riverine methods, and it has been recommended to focus on downstream sections of the main river channel to overcome this issue (González et al., 2016). Movement within the estuarine environment is complicated by factors such as bidirectional flow dynamics (Tramoy et al., 2020a; van Emmerik et al., 2020b), which can also bring marine-derived plastic litter upstream (Ryan and Perold, 2021), and salinity gradients which can affect the transport of macroplastics. Estuarine beaches and vegetated areas such as mangroves represent sinks for macroplastic (do Sul et al., 2014; Gonçalves et al., 2020), with residence times in the order of several decades (Tramoy et al., 2020b). The fate of plastic entering estuarine environments remains a persistent knowledge gap (Dris et al., 2020). Based on this, measurements of macroplastic flux taken in the downstream zone of a river may not represent the actual emission to the ocean (van Emmerik et al., 2020b). The role of estuaries as macroplastic sinks requires further scrutiny to better establish the fate of riverine macroplastic debris and its potential for release into the oceans across different temporal scales (Schernewski et al., 2021).

4. Optimising monitoring data

4.1. Harmonisation of data collection and reporting

Harmonisation is a necessary task to facilitate comparability and interoperability of data generated in different studies and different geographical contexts. This applies to both the method(s) used and the way in which data is collected and reported. A hindrance to harmonisation efforts include the lack of detail in reporting methodological parameters and results; future studies should aim to converge methods and data reporting. For example, standard data collection forms should be generated in parallel with the delivery of training or the development of detailed protocols to describe how macroplastic should be quantified and categorised and how data should be reported. Mobile applications, such as CrowdWater (Tasseron et al., 2020; van Emmerik et al., 2020a) or the Floating Litter Monitoring app (González-Fernández and Hanke, 2017) have been developed with this goal. Flexibility is still important – especially given that rivers often present a unique plastic footprint (Vriend et al., 2020b) – but this should be nested within broader, standardised categories to allow for interoperability. Standardisation of the definitions for macroplastic sizes and types and methods for establishing the quantity (number, weight) is important.

Reporting units should also be addressed within the context of riverine macroplastic pollution. Several different units have been used to quantify macroplastic fluxes thus far, many of which are not comparable (exemplified in Table S7). Where possible, studies should report in multiple units to assist in harmonisation efforts and facilitate wider utilisation of data outputs, for example reporting totals relative to river discharge or time. To further improve the potential for comparing between datasets (or even datapoints), reporting in units that account for additional factors should be considered. For example, reporting data in a way that accounts for the width of the river at a site or the total discharge can help to avoid drawing false conclusions when comparing two sites that have different characteristics, even within the same study. Some monitoring methods – typically observation-based approaches – generate data in the form of counts. For establishing policy and regulations, mass-based data may be the preferred option. This has already been recognised by some researchers, who have used a combination of approaches to help establish a conversion (van Emmerik et al., 2018) or applied an assumed conversion factor (Castro-Jiménez et al., 2019; Kataoka and Nihei, 2020). The need for data in particular forms may dictate what is the most suitable monitoring method for a given study, and this detail should form part of the ongoing optimisation of monitoring methods.

To facilitate data reporting and interpretation of results, additional parameters associated with practical measurements must also be recorded. Table 1 presents a summary of different details related to the method and the environmental conditions that represent critical information for interpreting and contextualising macroplastic data. For

Table 1
Details of ancillary data that should be recorded and reported alongside macroplastic data. Some criteria relate to specific method(s) only; this has been highlighted in the table using parenthesis. This does not represent an exhaustive list, due to the variability in river catchments globally. Other site specific information or details of method deployment that are relevant should also be reported.

	Observation-based methods	Physical interception methods
Measurement parameters	Location Duration of observation Date and time of observation Section of the river analysed Distance from water surface/height of vantage point Lower size limit of detection Parameters of deployment, e.g. flight height, angle, camera/filters used, processor, field of view, flight duration (non-human observation) Name and details of visual processing algorithms used (non-human observation)	Location Duration of measurement/deployment Date and time of observation Deployment depth and location (relative to river cross-section) Net aperture Mesh size Degree of submersion (surface nets) Spatial extent (clean-up activity) Time elapsed since previous cleaning activities (booms, clean-up activity) Estimate of capture rate (clean-up activity)
Environmental conditions and location context	Meteorological conditions for duration of measurement Antecedent conditions Flow velocity and discharge Water level Visibility (turbidity) Measurement/estimate of total suspended load Waste management practices Plastic consumption patterns Relevant social or cultural factors	Meteorological conditions for duration of measurement Antecedent conditions Flow velocity and discharge Water level Measurement/estimate of total suspended load Waste management practices Plastic consumption patterns Relevant social or cultural factors

example, it is important to record the flow velocity in the river alongside each plastic measurement that is taken. Changes in velocity, even on short temporal scales, can affect the number of plastic items flowing past a measurement point and it therefore represents a useful parameter for interpreting results. It can be measured using different techniques, such as with flow meters or the simpler 'Pooh sticks' approach (Moss et al., 2021). Alternatively, monitoring could be conducted in locations where routine hydrological monitoring is already undertaken, such as close to gauging stations. Many studies do not provide important variables that can affect the interpretation of results (Tables S2-S6), such as the lower size limit detected, the visibility conditions, the location and duration of net deployment in the river cross-section, and the proportion of the total river cross-section that each measurement relates to. This further hinders the potential for harmonisation, as it becomes more difficult to account for potential differences in methods or compare results. Future monitoring should report measurement parameters and environmental conditions as a standard requirement of the data reporting.

Several studies report macroplastic data with reference to the polymer type (e.g. Lahens et al., 2018; van Calcar and van Emmerik, 2019; van Emmerik et al., 2018). A standardised approach is needed to ensure that categorisation by composition is undertaken in a verifiable or reproducible manner. For example, the ASTM International Resin Identification Coding system represents a useful resource in this case (e.g. Blettler et al., 2019); although, a physical interception-based method is needed to facilitate inspection for such codes and, in some cases, degradation may lead to a loss of this information. Many studies report polymer type based on the function of the litter item: for example, plastic bottles are recorded as polyethylene terephthalate (PET). Data generated through this approach should indicate the potential for uncertainty here, based on the diversity of polymer types used for some applications. To facilitate harmonised data collection and reproducible results, a standardised set of polymer categories with explicit definitions should be established. This should aim to increase the convertibility of existing categorisation lists to translate item or polymer-based information (Vriend et al., 2020a). Specific polymeric data – if analysed experimentally, such as with infrared spectroscopy techniques – should be collected and verified using validated methods. Reference libraries or library search algorithms should be used to confirm polymer type and minimum requirements for data reporting should be observed.

4.2. Tailoring methodologies to different data applications

4.2.1. Estimates of riverine emission to the ocean

Establishing the release of macroplastics from a river is an important goal for many monitoring campaigns. This is linked to a strong marine focus in the plastic pollution domain, and is often in response to modelling studies that report substantial releases of plastics from many river catchments globally (e.g. Lebreton et al., 2017; Meijer et al., 2021; Schmidt et al., 2017). Yet, there are several potential shortcomings inherent to flux estimates calculated from monitoring data (Section 3.3.2). Namely, they may not represent real releases to the marine environment, for example by overlooking macroplastic sequestration in rivers or estuaries.

This matter aside, efforts to tailor monitoring activities for the purpose of calculating estimates should focus on increasing the accuracy and representativeness of data generated. The data should represent, where possible, the full river cross-section and account for temporal variability. Selecting a location that is furthest downstream will generate an estimate that is closest to reality; although, this introduces challenges associated with handling tidal influence. Finally, efforts should be paid towards harmonising how flux estimates are reported. At present, several different approaches to describe release have been presented in the literature (Table S7), undermining potential comparability. Selected units should conform to the resolution of the monitoring data: for example, data from a short temporal frame will render a high level of uncertainty in annual-scale estimates. Reporting in multiple units may enhance the utilisation of flux estimates for different purposes.

4.2.2. Hydrological models

Riverine macroplastic modelling studies thus far have focused on upscaling estimates of plastic masses emitted from land to sea – at the catchment, national, or global scale (Lebreton et al., 2017; Meijer et al., 2021; Sakti et al., 2021; Schmidt et al., 2017). These have utilised data sources related to waste management practices, consumption patterns, land use or population density, and catchment characteristics to generate outputs. The resolution of models and the description of riverine macroplastic transport mechanisms can be further improved by focusing on processes occurring within the catchment to predict inputs and transport of plastic of different types, such as the hydrological models established for micro- and nanoplastics (e.g. Besseling et al., 2017; Nizzetto et al., 2016).

For hydrological models, macroplastic monitoring data – mainly mass-based – is needed to validate outputs. Ideally, the resolution of the data should fit with the model frame and it is important to establish what the monitoring data represents – i.e. what the selected method was able to accurately measure. Thus, quality controlled data from validated methods are preferable. Monitoring campaigns that encompass both spatial and temporal variability are needed to improve the accuracy of models. In particular, monitoring efforts should span a range of representative hydrological conditions including hot spots and hot moments, e.g. capturing flush effects, when estimating seasonal or annual emissions. Additional insights into quantified inputs of plastics across space and time, partitioning of plastic (of different typologies) in different components of the river system, and dominant fate and transport processes represent critical data to parameterise models, particularly at the catchment scale. Plastic typologies relevant for modelling purposes do not necessarily fit with those relevant to other applications. While shape, size, and polymer are common and relevant characteristics, degree of buoyancy is often lacking despite its control on transport processes and settling likelihood (Kooi et al., 2018). Hence, reporting data from the water surface and below, as well as ancillary information on net deployment depth and degree of submersion, becomes essential.

4.2.3. Policy and governance

Governments worldwide have recognised plastic pollution as an urgent environmental, social, and political issue (Rognerud et al., 2021). National and international regulations have already been proposed, particularly for some components of the problem, such as single use plastics (e.g. Patrício Silva et al., 2020; Sun et al., 2021; Syberg et al., 2018). At the resumed session of UNEA 5, 175 countries endorsed a historic resolution to start the negotiations of a legally-binding agreement on plastic pollution. High modelled plastic emissions occur at the intersection of i) increasing economic prosperity and material consumption, and ii) inadequate regulation or (mis)management of waste. The collection, analysis, and reporting of plastic data detected in various environmental compartments is an essential source of information for developing targeted and efficient policies in all countries (van Emmerik et al., 2022b). However, government action is also dependant on other data such as technological innovation, policy assessments, and the existence of less harmful or environmentally sustainable alternatives.

Of particular importance to policy and governance is establishing the scale of the problem, its origin or temporal frame, the behaviour of the problem, its impacts, and interlinkages with other pressures. Data that can help to highlight potential solutions or evaluate the impact of mitigation or remediation actions are also relevant. Monitoring data tailored towards policy and governance should include typical descriptors of the debris, such as the category of plastic or polymer type. Mass-based data is typically preferred in the context of setting regulations. Additional identifying information such as brand name or provenance data can also be useful in identifying specific sources or release pathways that could be targeted through policy. Additional ancillary data includes anthropogenic factors such as waste management systems, consumption patterns, or cultural events occurring in spatial or temporal proximity to the sampling, which can help to better understand observed plastic fluxes (Table 1).

Extending beyond the frame of a single study, achieving harmonisation in riverine macroplastic monitoring globally is a critical task for setting appropriate, well-framed, and realistic policy instruments, ensuring comparability, assessing the impact of concerted action, and sharing of best-practices and technological advances. As the UNEA 5.2 resolution indicates a global legally-binding agreement is expected to materialise in 2024, the agreement may include an effectiveness evaluation requirement for the parties of the agreement which requires time series of comparable data of plastic flux to prove the effectiveness of the measures taken by the parties. This stresses the need for coherent standards, definitions, and a harmonised monitoring system across the different geographic locations in the world. The current limited comparability between datasets represents a major hindrance. Promoting international collaboration on defining criteria, converging methods towards interoperability, and setting guidelines for data collection and reporting should represent important priorities for academics and policy-makers alike.

5. Conclusions

Riverine macroplastic monitoring has already revealed numerous important findings. This includes the scale of pollution in different regions, dominant sources of plastic to river environments, the role of seasonality and source dynamics in governing observed concentrations, and indications of several fate and transport processes relevant for understanding how plastic waste moves through the environment. Yet, the lack of comparability between several reported data from different studies sets limitations that prevent concrete conclusions from being drawn. Expanding upon the testing of methods, undertaking method validation, implementing QA/QC protocols in sampling, and reaching agreements internationally to set standards for harmonisation are urgently needed to progress in this arena.

This critical review has highlighted several opportunities for achieving this aim. By reviewing the current utilisation of different methods, aspects that require further testing have been identified. In many cases, this relates to better understanding the thresholds or limits of a given method. This should be paired with QA/QC procedures, which will help to elucidate the suitability, reliability, and consistency of each methodology. Beyond this, each monitoring study should understand what exactly is being measured and what the obtained data can reliably reveal.

Similar effort directed towards stranded or sequestered plastics in riverine or estuarine settings is also needed – a topic which was outside the scope of this present review. Fewer studies have investigated freshwater plastic sinks than flows of plastic litter; yet, this presents a crucial opportunity to harmonise methods before several different – and potentially poorly comparable – approaches emerge. Understanding the mechanisms and scales associated with the accumulation of plastic in freshwater environments is critical to gain a holistic perspective of plastic pollution. Accumulation zones may represent ideal sites to intercept pollution and target clean up actions. Plastic accumulation may be dependant on factors such as macroplastic size, buoyancy, or morphology. Therefore, surveys that sample plastic flowing out from a river may underestimate a significant source of plastic to rivers that is preferentially retained due to its characteristics.

Harmonisation is an ongoing task. Decisions need to be made internationally to set defining criteria and research priorities; however, early progress can be made towards the goal of harmonisation by facilitating comparability wherever possible. Practically, this refers to undertaking QA/QC during sampling and data analysis, reporting data in multiple units or forms, and providing ancillary data to enable effective interpretation of the data. This should keep in mind the potential utilisation of data beyond the primary goal of the study, and reporting should facilitate this where possible.

Riverine macroplastic research is at a critical early stage. Establishing quality and harmonisation as a priority now will facilitate the collection of rigorous and comparable data from ongoing and future monitoring efforts. This will provide essential information to help frame local, national, and international solutions to limit pollution and its associated impacts. A legally-binding global agreement on plastic pollution will emerge by 2024, and thereafter countries will prepare for ratification and implementation. This imposes a time pressure on further advancing this field of research. Establishing a consensus on harmonised monitoring standards for riverine macroplastic could strengthen the agreement by providing solutions for compliance checks.

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.

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Data availability

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Supplementary materials

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