MONITORING PLASTICS IN RIVERS AND LAKES

Guidelines for the Harmonization of Methodologies

TECHNICAL SUMMARY FOR POLICY MAKERS

UN environment programme

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Executive summary

To date, more than 8,000 million metric tons of plastic have been made since the beginning of large-scale plastic production in the 1950s. As a consequence, combined with insufficient waste management and handling practices, plastic debris is present in all ecosystems, including remote locations such as mountain lakes and polar sea ice. Oceans are the most prominent example of widespread environmental plastic pollution, and research, societal awareness and action have long focused on marine plastics.

Current knowledge indicates that the majority of marine plastics originate from land-based sources. Research and action have therefore been expanded to freshwater and terrestrial environments. Rivers have been identified as major pathways that connect land-sourced plastics with the marine environment. Other freshwater bodies, such as lakes and reservoirs, are also threatened by plastic pollution.

Despite the growing body of data and knowledge regarding freshwater plastics, current understanding of the transport processes, loads and impacts is limited. Most published data stem from individual projects that apply different sampling and analysis techniques. This lack of harmonization hampers the comparison and synthesis of these data.

The guidelines outlined here build on the large body of knowledge and experience gained from marine plastic monitoring. Methods of sample processing and instrumental analytics for particle characterization are mostly the same for freshwater and marine systems. However, sampling techniques and the design of monitoring programmes used in marine environments often require adaptation to specific freshwater conditions, such as the typically high content of coarse particulate material that naturally occurs in rivers and the wide range of plastic concentrations driven by river flow variation.

These guidelines present methods to support freshwater monitoring and assessment programmes as well as the most current procedures for analysing plastic debris in rivers, lakes, reservoirs and wastewater treatment plants.

The recommendations reflect stakeholder input from two workshops, which revealed that developing and developed countries face similar challenges in implementing freshwater plastic monitoring and assessment programmes. The type and intensity of hurdles to overcome in setting up such programmes may differ by country. So, the guidelines are designed to assist with their timely development and application and can be tailored to various starting conditions.

Freshwater plastic monitoring programmes are needed to better assess the state of and trends in plastic pollution and to prioritize land-based sources of freshwater and marine pollution and achieve target 14.1 of the Sustainable Development Goals: “By 2025, prevent and significantly reduce marine pollution of all kinds, particularly from land-based activities, including marine debris and nutrient pollution”.

Chapter 1: Introduction

The most prominent sign of the widespread and increasing problem of plastic pollution is the occurrence of plastic debris in the marine environment. Research, public awareness and action so far have primarily focused on oceans. However, an estimated 80 per cent of plastic debris input to the oceans originates from land-based sources. The amount of land-based plastics entering the oceans each year is estimated to be ~9 million metric tons (Jambeck and others, 2015). Rivers are one of the major pathways, with a likely annual contribution of ~2 million metric tons (Lebreton and others, 2017; Schmidt and others, 2017). This kind of estimate is subject to many uncertainties, since programmes for monitoring plastics in fresh water are small and sporadic and use heterogeneous methods. Current knowledge about plastic pollution in fresh water suggests that it is as ubiquitous as it is in the marine environment. An urgent call is therefore needed for a harmonized system of sampling, measuring and analysing plastic debris in freshwater systems.

Chapter 2: Scope

These guidelines detail the most advanced ways to monitor plastic debris of all sizes in fresh water, ranging from whole items to microsized fibres and fragments. Sampling techniques and monitoring strategies for freshwater environments are generally not too different from those applied in marine settings. So, this report builds on *Guidelines for the Monitoring and Assessment of Plastic Debris in Marine Environments* by the Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP, 2019). To avoid redundancies, overlapping aspects are kept brief. At the same time, the similarities and differences in plastic input, distribution and effects between marine and freshwater environments are discussed. Recommendations for improved reporting, increased stakeholder involvement, expanded data availability and preventive action and intervention are presented.

This report is intended to be a cornerstone of work towards harmonized methodologies for monitoring and reporting plastic debris in freshwater systems. It will aid in developing and implementing monitoring programmes for rivers, lakes, reservoirs and wastewater treatment plants. Such programmes are needed in order to prioritize land-based sources of marine pollution and achieve target 14.1 of the Sustainable Development Goals: "By 2025, prevent and significantly reduce marine pollution of all kinds, particularly from land-based activities, including marine debris and nutrient pollution".

Chapter 3: Definitions and terminology

The term "plastic debris" as used in this report applies to plastic particles of all sizes. Although similar terminology is used in science and policymaking, there is as yet no agreed-upon or official directive on how plastic debris should be categorized. The terminology in the report therefore follows GESAMP (2019).

3.1 Plastic debris

Plastics are synthetic organic polymers with thermoplastic or thermoset properties (synthesized from hydrocarbon or biomass raw materials), elastomers (e.g., butyl rubber), material fibres, monofilament lines, coatings and ropes. Many plastics are a mixture of different polymers and various plasticizers, colourants, stabilizers and other additives. About 80 per cent of plastic production consists of polyethylene (both high and low density), polypropylene, polyvinyl chloride, polyurethane, polystyrene and polyethylene terephthalate. Packaging is the dominant market sector for plastics (39.9 per cent), followed by building and construction (19.8 per cent) and automotive (9.9 per cent) (PlasticsEurope, 2019).

3.2 Size categories

Sampling and analysis should capture the sizes of plastic particles, and the procedures must be appropriate for the targeted size. Particles smaller than 5 mm are commonly referred to as "microplastics"; "mesoplastics", "macroplastics" and "megaplastics" describe larger particles (table 1). Microplastics are often further separated into size classes, especially during sample preparation for mass-based analyses.

3.3 Shape categories

The shapes of plastic debris are important indicators of their origin and state of fragmentation or disintegration. Shape definitions are mainly important when particles are <1 cm in size. Larger particles often occur as whole items or larger fragments, so it may be possible to categorize them according to their original shape (e.g., bottles, bags, straws). As with size, no standardized categorization exists for plastic debris shape. For these guidelines, shape type is based on the United Nations Environment Programme guidelines for marine litter (see annex III in GESAMP, 2019), namely fragments, fibres and filaments, beads and spheres, foams and sheets, and pellets (table 1).

Table 1. Commonly used microplastic characterizations

Microplastic characterization	Classes	Description
Size	mega	> 1 m
	macro	25 mm-1 m
	meso	5 mm-25 mm
	micro	< 5 mm
Shape	fragments	irregularly shaped particles, crystals, fluff, powder, granules, shavings
	fibres	filaments, microfibres, strands, threads
	beads	grains, spherical microbeads, microspheres
	foams	polystyrene, expanded polystyrene
	pellets	resin pellets, nurdles, pre-production pellets, nibs

Source: Lusher and others, 2017.

3.4 Colour

The colour of a particle can provide information about its origin. In a biological context, it can also provide information about whether organisms have a feeding preference based on colour. However, in general, colour is not regarded as a crucial parameter for the categorization of plastic debris (GESAMP, 2019; Hartmann and others, 2019).

3.5 Monitoring

The term "monitoring" as used in this report indicates the intention to measure the current status of an environment or to detect trends in environmental parameters with respect to space or time. Freshwater plastic monitoring programmes should be performed systematically, using harmonized sampling methods and consistent data and metadata management procedures. This is further discussed in chapter 4.

Chapter 4: Designing monitoring programmes for freshwater environments

This chapter discusses the applicability of established marine sampling and analysis protocols to freshwater environments and preventive measures that can be taken to minimize sample contamination.

4.1 Similarities and differences between monitoring marine and freshwater systems

Research and public interest have long focused on plastic pollution in oceans and coastal areas. Studies continue to investigate the sources of ocean plastics, which are considered to be mostly land based. Rivers have been shown to deliver considerable amounts of plastic debris into the marine environment, so these and other freshwater systems may also be contaminated. In particular, drinking water reservoirs could be susceptible to elevated plastic concentrations.

Plastic debris monitoring in freshwater systems can and does rely on the expertise gained in ocean monitoring programmes. For example, sample preparation and subsequent analytical methods used in marine settings can also be used in fresh water. This is encouraged, as it will improve the comparability of data between these different environments. However, some marine sampling techniques may need to be adapted. For example, sampling from a vessel is not possible in small rivers. Instead, sampling devices must be installed on riverbanks or lowered from bridges. Further, concentrations of particulate material are typically higher in fresh water than in the marine environment due to mostly organic material originating from the shoreline (e.g., leaves, branches), blooms of phototrophic organisms (e.g., algae, cyanobacteria) and high suspended sediment.

4.2 Precautions concerning sample contamination

An important aspect of analysing microplastics is the risk of trace contamination. Because microplastics have been detected almost everywhere, those from an outside source will likely contaminate the sample during sample preparation and analysis. In general, the smaller the particles to be detected, the more critical the procedures must be to avoid (or at least track and document) contamination.

Various preventive measures can be taken to minimize contamination. Those conducting sampling should ensure their clothing is made of natural fibres and should use cotton lab coats and nitrile gloves in the laboratory. Lab materials should be made of metal such as aluminium or stainless steel. If any plastic must be used, it should be a relatively uncommon polymer. All sampling equipment should be kept closed as much as possible, and filtered water or ethanol should be used to clean or rinse equipment. The filter size should correspond to the desired detection level (e.g., use at least 0.45 μm filters to detect particles as fine as 1 μm). Reagents used to treat samples also must be filtered. Installing air cleaners, such as portable dust boxes, is advised.

Even when the above guidance is followed, it is nearly impossible to avoid sample contamination. It is therefore recommended that procedural blanks be run to track how much and where contamination has occurred. This means the whole sampling and extraction procedure is imitated without a real sample. For example, when sampling drinking water, ultrapure water can be used as the blank sample; it is then analysed at the same time as the contaminated sample. Regardless of the result, concentrations and types of contamination must be documented, and possible sources must be examined.

Chapter 5: Sampling freshwater

Figure 1. Limnological plankton nets. *Left: small net with 55 µm mesh size and a metal cod end; middle: large net; right: cod end of the large net.*

Photographs: Yvonne Rosenlöcher, UFZ

5.1 Sampling rivers

This chapter covers plastic sampling procedures for the high diversity of compartments and matrices present in freshwater systems. It discusses sampling with regard to rivers, lakes and reservoirs, including their water, sediment and shores, as well as sampling of the organisms living in freshwater systems. Basic sampling procedures for drinking water systems and wastewater treatment plants are also outlined.

5.1.1 Water surface and water column

Macroplastics

Macroplastics are a key component of plastic transport from land to ocean. However, observation and an understanding of the process remain limited. Various methods have been developed in recent years to monitor macroplastics in rivers. An overview of these is presented, including tracking, net sampling, visual observation and passive sampling techniques (van Emmerik and Schwarz, 2020). For each method, key parameters that can be adjusted to optimize its application are described. Global examples of these applications are given, along with a brief discussion of the results. The outlook for future methods and those currently under development is also presented.

Micro- and mesoplastics

The methods used to sample micro- and mesoplastics in rivers are similar to those used for macroplastics. Manta trawls or neuston catamarans are smaller than those used in marine studies, and most freshwater investigations use nets with mesh sizes of ~300 µm. Samples are typically large, so that with a 30 cm manta trawl, ~20–50 m3 of water can be sampled in 10–30 minutes. Finer nets collect more particles, especially fibres, but sample volumes will be lower if such an approach is used. Studies targeting very small particles in rivers or streams have been rare so far, but one catchment-wide assessment using 1-litre bottles combined with 0.45 µm filtration was recently published (Barrows and others, 2018). The project included major contributions from trained citizen scientists. This strategy should be developed further to obtain a better perspective on spatial and temporal distributions of microplastics in fresh water.

Studying the transport of microplastics in situ is difficult. Current estimates are based to a large extent on theoretical considerations. Generally, the lateral and vertical structure of large rivers requires that existing sampling equipment be modified in order to sample different depths at the same time (Liedermann and others, 2018). Liedermann and others (2018) also reveal a slight tendency towards near-bank microplastic accumulation.

5.1.2 River sediment

The consequences of river flow are that the extent of shore sediment and the water depth above riverbed sediment are variable. The width and accessibility of the river shore area for the beaching of particles and sampling also vary with flow. While pulse flows may mobilize erodible material (both shore sediment and plastic debris) and transport it downstream, high-flow events may induce the mobilization of this material (Hurley and others, 2018). An assessment of plastic debris content in river sediment should therefore consider hydrological conditions before the sampling programme.

River sediment is less stable than lake sediment, so it is difficult to sample, and sediment thickness cannot be related to sedimentation time. Therefore, no standard methodology for obtaining layered sediment from riverbeds has been established. Riverbed samples are frequently obtained using metal spoons (as in the case of shore samples) or grab samplers, usually the top 10–15 cm of sediment. These samples are large enough (in the kilogram range) to obtain meaningful microplastic concentrations.

5.2 Sampling lakes and reservoirs

There are a number of factors to consider when planning a sampling study of lakes and reservoirs. The following is a general list of conditions that can affect the likelihood that plastic particles will settle, undergo sedimentation or be transported through these freshwater systems:

- shape and depth
- zoning (vertical and horizontal)
- stratification (as a function of season/temperature)
- wind direction
- biological processes (bioturbation or gas bubble formation)

5.2.1 Water surface and water column

For small lakes and lakes with a simple (close to circular) shape, the deepest point is generally considered representative. Large lakes, especially those with complex morphometry, need several sampling points. Lake inflow areas should also be sampled (Vaughan and others, 2017). In reservoirs, where there is often horizontal zoning, all zones should be sampled to observe any gradient of plastic concentration. Many reservoirs possess a pre-dam, built to keep sediment and nutrients from reaching the main dam. This spot can also be sampled to analyse the possibility of effective plastic reduction. It is recommended, if possible, that lake modelling or simulations be used to predict transport routes and hotspots of plastic pollution.

In large lakes, samples representing large parts of the near-surface water can be obtained using manta trawls or neuston nets. However, as with river sampling, the mesh size (typically 330 µm) limits the detection of microplastic particles. Plankton nets have finer mesh sizes (as fine as 100 µm for oceanographic nets) and can be used for horizontal and vertical sampling. The standard mesh size for a limnological plankton net targeting phytoplankton is 55 µm, but even finer nets are available.

Pumping technology is suitable for surface water sampling (top 0.5 m depth), where, for example, one method traps small particles (>10 µm) in a stainless steel cartridge. In some cases, it is worthwhile to combine the pumping apparatus on-site with prefiltration. Generally, electricity (e.g., provided by a diesel generator) must be available for pumping. A stable boat to hold the equipment and at least two people are needed to perform the sampling. If water from deeper parts of a lake or reservoir is to be sampled, submersible pumps must be used (e.g., Setälä and others, 2016). However, the surface layer should be sampled first to gain an impression of the prevailing contaminates.

Sieving or filtering samples ex situ is generally not suitable for lakes or reservoirs, as a minimum of hundreds of litres of water is needed for reliable quantification of microplastics. There are alternative sampling options if microplastic fibres are of interest. Samples from nets and sieves must be processed on-site, with consideration given to minimizing contamination. To analyse the organic content, the sample should be kept cool (<4°C). Depending on the number of particles in the sample, density separation may also need to be included.

Figure 2. Examples of the use of sampling nets in a wadable river *(left, Baldwin et al. 2016) and from the bank and a crane (right, Moore, Lattin and Zellers 2011)*

5.2.2 Lake sediment

Lake sediment can be considered an archive of material input from the catchment. The concentrations of plastics in this type of sediment can be expected to vary over time much less than water-based concentrations. Therefore, a high temporal resolution of sampling is not necessary. Similar to water sampling, the sediment sampling strategy is determined by lake morphometry and hydrology. The lake bottom structure should be investigated with a bathymetric map or transects of depth measurements.

Soft sediment samples (i.e., those without large debris or vegetation) can be obtained by rod-operated or cable-operated Ekman grabs. These typically extract the top 15 cm of sediment and provide a large sample in a single step. As the sediment surface is disturbed, however, the exact depth cannot be determined. Alternatively, gravity coring can be applied, whereby the core length depends on sediment structure and compaction. It is recommended that three cores per site be taken to determine possible variation. If an intact water-sediment interface is not required for other study purposes, a metal box corer can be used. The sediment itself can be recovered undisturbed and subsampled with small tubes.

Figure 3. Sampling a large river (the Danube) by crane from a bridge. *An array of nets is positioned to sample the water surface and the water columns simultaneously (Hohenblum et al. 2015).*

5.3 Sampling lake and river shores

Shorelines of aquatic ecosystems are (temporary) accumulation zones for plastic debris. Quantifying this debris yields insights into the sources, sinks and pathways of plastic pollution through river catchments. The deposition and mobilization of plastic debris on shores depend on water level and flow velocity. Understanding the dynamics of shoreline plastics can help identify potential sources of additional plastic debris (remobilized shoreline plastics) in response to extreme events such as floods.

Riverbanks have been monitored extensively around the world, and several examples of strategies and their results are given. For quantification on riverbanks, data are often collected using a citizen science–based approach, and several such efforts have been compared.

Lake shores are less studied than riverbanks. Those studies that are available are used to discuss the role of shores in plastic mobilization through catchments and to provide examples of reported monitoring efforts.

5.4 Sampling drinking water

Microplastics in drinking water have a much smaller size range than those in surface water (1–10 μm particles are most frequent, with those >50 μm almost absent; Pivokonsky and others, 2018). Since drinking water is already treated, it also generally contains low plastic concentrations. Therefore, sampling and detection methods are specialized. To confirm not only the presence of microplastics in the drinking water supply but also the source(s) of contamination, samples should be taken at different stages along the supply chain, such as the raw water supply (e.g., groundwater, surface water, recovered water, some mix of these), the purification step (e.g., drinking water treatment plant), the transport, and the final supply to the consumer (e.g., household tap, bottled water).

Contamination of drinking water supplies by plastic particles can come from various sources, even pipes, fittings and packaging (see sect. 4.2). Because there are low concentrations of microplastics and smaller particle sizes in drinking water, a relatively large volume of water should be sampled, as is also suggested for raw freshwater sampling. In addition, there should be consideration of the sampling sites, the frequency of sampling, and the sources (e.g., raw water, treated water, bottled water) to ensure that results are representative. Collected samples should be filtered through a series of µm-scale mesh size filters (studies used between 5 and 0.2 µm). To identify the small particles in drinking water as plastic, spectroscopic techniques are needed. Most analyses in the literature use Fourier-transform infrared (FTIR) microscopy to determine microplastic content. Research methods use micro-Raman spectroscopy to detect smaller sizes.

5.5 Sampling at wastewater treatment plants

Raw sewage and storm water contain plastic debris in a variety of sizes. During the treatment process, a substantial proportion (~95 per cent) of particles in raw sewage is retained. The goal of monitoring plastics at wastewater treatment plants is often to quantify the efficiency of particle removal both throughout the treatment steps and with different treatment technologies. To date, the comparison of data on the fate of plastics at wastewater treatment plants is hampered by the wide range of sampling and analysis methods. Guidance is therefore provided on sampling and analysis techniques, from raw sewage to treated wastewater effluents.

5.6 Sampling freshwater biota

Sampling freshwater biota in situ to obtain information about their microplastic content is not generally practicable. To retrieve a representative sample, a large number or mass of organisms – and in many cases, specialized analytical procedures – is required. In addition, not all organisms can act as bioindicators for plastic pollution and identifying those that are indicators is still at an early research phase. Nonetheless, it is important to consider the size, life history, age and developmental stage of the organism. The life stages of many freshwater organisms have strong seasonal and diurnal patterns of activity that must be considered. Further, ingestion of microplastics typically occurs along with food uptake, so organisms' feeding strategies (e.g., filter feeding, suspension feeding, deposit feeding, predation, scavenging, grazing) must also be known.

Selected organisms should be typical of the studied ecosystem and fulfil the criteria for good indicator species (GESAMP, 2019). Possible invertebrate indicator species are the Asian clam, *Corbicula fluminea* (Su and others, 2018), and the oligochaete worm, *Tubifex* (Hurley and others, 2018). These are recommended by the Organization for Economic Cooperation and Development (OECD) for testing bioaccumulation of chemicals in endobenthic animals (OECD, 2008).

Freshwater fish and birds are also affected by plastic pollution. Any vertebrate monitoring programme should avoid killing animals not intended for consumption. For example, the study of bird faeces and feather brushings provides a non-destructive and ethically sound sampling approach (Reynolds and Ryan, 2018).

Monitoring or assessment strategies that use samples from commercial suppliers, such as fish markets, are pragmatic and resource efficient. However, any conclusion about plastic pollution in a specific freshwater system is impossible, and results can only be interpreted when related to the species itself. If field-collected specimens are analysed, water and sediment samples from the same site in the freshwater body should also be taken. In addition to the assessment and monitoring of microplastics, typical plastic-associated chemicals are also of interest.

To prepare biota for polymer analysis, removing loosely attached particles, recording the dimensions and weight of the organism and quickly preserving or defining depuration periods are crucial.

Indirect effects on biota might be related to the use of plastic surfaces as a habitat or to feeding on plastic-colonizing biofilms.

Figure 4. Typical freshwater biota used for microplastics assessment. *Top: Corbicula fluminea, a group of clams and an individual; bottom:* Tubifex *sp. (left) and chironomid larva (right). Photographs are not at the same scale.*

Photograph: Mario Brauns, UFZ

Photograph: Sven Bauth, UFZ

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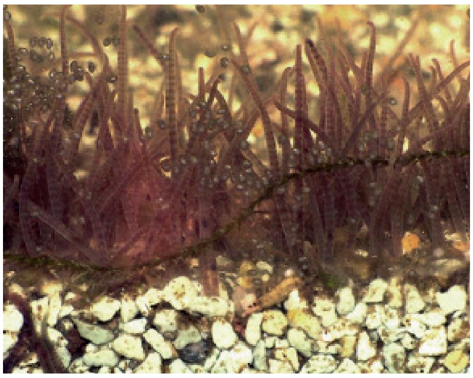


Thunderclap - Eigenes Werk, CC BY 3,0 https//commons.wikimedia.org/w/index.php?curid=6099484

Chapter 6: Sample preparation for different environmental matrices

The processing of particles obtained from water column samples requires the removal of natural organic debris, which is typically achieved using acids, bases or oxidants (hydrogen peroxide or Fenton reagent) or enzymes. Care must be taken to not destroy polymer fibres or weathered plastic fragments with aggressive reagents. Although enzyme treatments are time-consuming, they are the safest way to obtain representative microplastic samples. Density separation is not always necessary for processing water column samples.

Sediment generally has a large ratio of natural and mostly inorganic particles to potential microplastic particles. Therefore, density separation is usually required. This is typically accomplished using concentrated or saturated salt solutions. If mass-based analyses are planned, size fractionation of sediment is necessary, which is best achieved by wet sieving before density separation. The use of sodium chloride (NaCl) is currently recommended by both the Marine Strategy Framework Directive (MSFD) technical subgroup (Galgani and others, 2013) and the United States National Oceanographic and Atmospheric Administration (Masura and others, 2015). NaCl is widely available, cheap and non-toxic, but only light polymers can be reliably recovered. Other salt solutions require recycling because of cost and hazardous waste constraints. Recycling includes filtration – through pore sizes smaller than the microplastic particles to be detected – and density adjustment (e.g., by evaporation). These guidelines follow Prata and others (2019), who recommend sodium iodide as a technically superior and safe alternative.

Biota contain relatively little inorganic material. Their natural organic content hinders microplastic detection; lipids, especially, may interfere with the spectroscopic identification of plastic polymers. It is therefore necessary in most cases to use thoroughly digested whole organisms, the digestive tracts or specific tissues. Although published protocols using acids or bases may work well, the possibility of conserving fibres and small fragile particles is the clear advantage of enzymatic treatments.

Chapter 7: Sample analysis – sizes, shapes, polymer types, polymer mass and associated chemicals

Distinguishing between plastic and non-plastic particles is easy for macroplastics and feasible for microplastics >1 mm in size. With smaller particles, visual and microscopic inspection have a high error rate (~70 per cent) compared with spectroscopic identification. They are also time-consuming and subjective. Auxiliary low-cost methods, such as touching particles with a hot needle or staining them with Nile Red, can be helpful. Although these methods do not allow identification of polymer type, they can be applied to preselected particles for later chemical characterization, which is often limited by high cost, availability of sophisticated equipment and skilled personal and complexity of data processing and evaluation.

If the polymer types in a sample are to be determined, particle-based (spectroscopic) or mass-based (thermoanalytical) approaches can be used. The latter does not require complete separation of the plastics from the surrounding matrix. However, it cannot give information on shape or surface characteristics, as the details of particle dimensions depend on how finely the sample was size-fractioned. Thermoanalytical methods are also destructive, so the plastic material cannot be recovered after analysis. Sample masses must be recorded at every preparatory step in order to report final results.

Mass-based analysis methods include pyrolysis-gas chromatography-mass spectrometry and thermoextraction and desorption coupled with mass spectrometry (TED-GC-MS). The advantage of TED-GC-MS is that higher sample masses (milligrams instead of micrograms) can be processed. Single samples are therefore more likely to be representative. As acceptable thresholds of contaminants will likely be defined in regulations based on mass concentrations, these methods have great potential for future assessment or monitoring of sediment and sewage sludge.

The particle-based methods FTIR and Raman spectroscopy are those most widely used to identify plastic polymers in environmental samples. Both produce spectra based on the interaction of light with the presumptive polymer molecules and so are non-destructive. The measurements are, however, time-consuming, so often not all particles in a sample can be analysed. The MSFD subgroup (Galgani and others, 2013) recommends analysing all particles in the size range of 20–100 µm and at least 10 per cent of particles in the range of 100–5,000 µm. Subsequent extrapolation to the total particle number will, however, produce considerable uncertainty.

The specific configurations of both spectroscopic and thermoanalytical methods have different prerequisites for sample characteristics, detection limits, measuring times and potential for additional information and are based on Braun and others (2018) and Prata and others (2019).

The chemical characterization of plastic polymers in environmental samples requires a comparison with the reference databases of known polymers. The information provided by instrument manufacturers is often insufficient, and considerable time and expert knowledge are needed to process the raw data. Only recently, freeware for quick microplastic identification has been provided by Aalborg University, Denmark, in collaboration with the Alfred Wegener Institute in Germany (https://simple-plastics.eu/).

Chapter 8: Assessing sources, pathways and categories of plastics in freshwater

To understand the movement of plastic debris over land, through rivers and eventually into oceans, a holistic, catchment-scale approach can give insights into its sources, sinks and pathways. Once these are identified and characterized, a consistent dataset that allows for comparison of plastic pollution over time and space can be created. Strategies to prevent and reduce plastic fluxes and stocks can then be optimized.

Plastic debris comes in different shapes, colours, sizes, polymer types, stages of degradation and so on. The most commonly used plastic polymer and size categories are presented. Some examples of categorization protocols applied in the field and lab are also given.

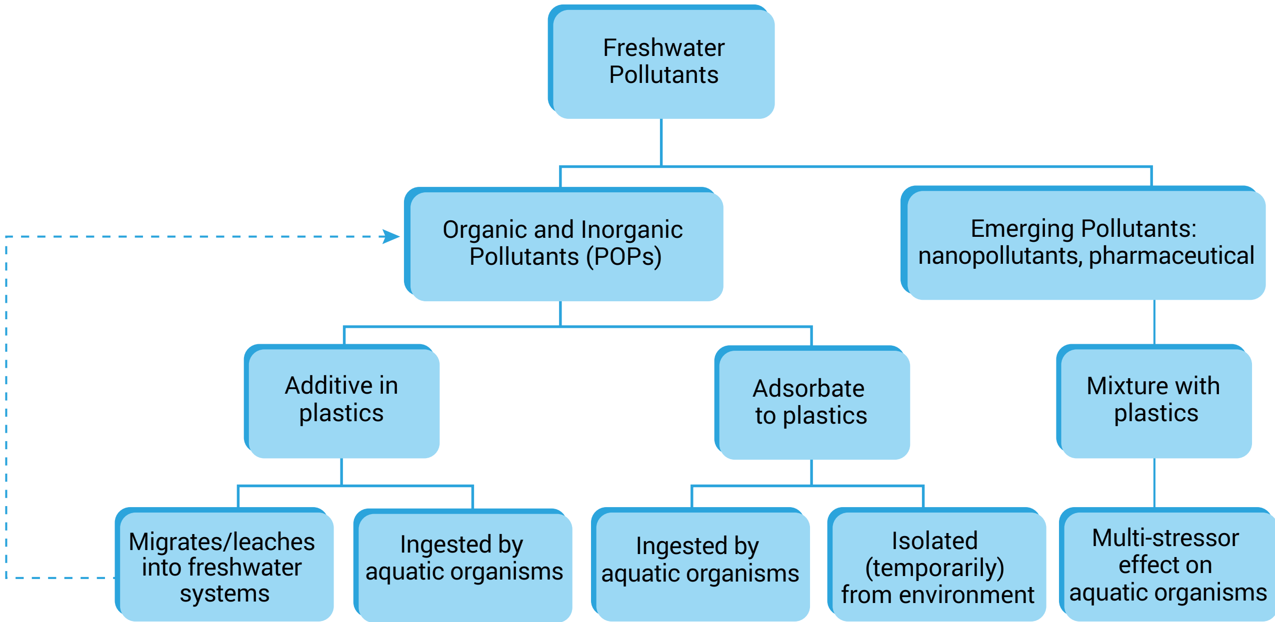
Once plastics are in the environment, transport on land and within freshwater bodies is mainly governed by natural processes. An overview is given of studies that link observed plastic transport rates and concentrations to hydrometeorological variables (e.g., wind, rainfall, surface run-off, river discharge, flow velocity). Such specific links between plastic transport and catchment characteristics allow for optimal design of efficient monitoring campaigns.

This chapter also gives several examples of catchment-scale assessments that provide valuable information about the movement of plastic debris through a catchment area towards the oceans. Two microplastic cases (the Ebro River in Spain and catchments in the United Kingdom) and two macroplastic cases (the Jakarta waterways in Indonesia and the Rhône River in France) are discussed.

Chapter 9: Relationship between plastic contamination and other forms of dissolved and particulate contamination

Figure five is a visual representation of contaminant-plastic interactions. Plastic contamination may interact with other forms of contamination in various ways. In this chapter, three modes are recognized: (1) contaminants that are part of the chemical makeup of plastics, (2) contaminants that sorb to plastics, and (3) contaminants that mix with plastics.

Figure 5. Visual representation of contaminant-plastic interactions



In the first case, the primary concern is toxic additives, some of which are priority contaminants (e.g., plasticizers, flame retardants; see table 2). These additives, which are associated with hormonal disruption and stressed behaviours, can be ingested or absorbed dermally, providing a direct route of exposure. They may also leach into the surrounding aquatic medium.

In the second case, plastic contamination has been recognized as a carrier for other contaminants due to the hydrophobicity of certain persistent organic pollutants and metals, which allows contaminants to more easily attract and adhere to other non-polar materials such as plastics. Similar to the exposure pathways described above, plastics carrying sorbed hazardous compounds may be ingested or otherwise interact with freshwater organisms and their environment.

The last interaction is the effect of plastic contamination as an amplifier or moderator of the toxic effects of nearby contaminants. The chapter gives examples of newer contaminants such as pharmaceuticals and nanoparticles. There is little indication thus far that plastics contribute to overall toxicity, but this kind of interaction is relatively unstudied and therefore should continue to be monitored.

Table two provides a list of additives by category from Hahladakis and others, 2018, those of most concern are italicized based on Hermabessier and others, 2017.

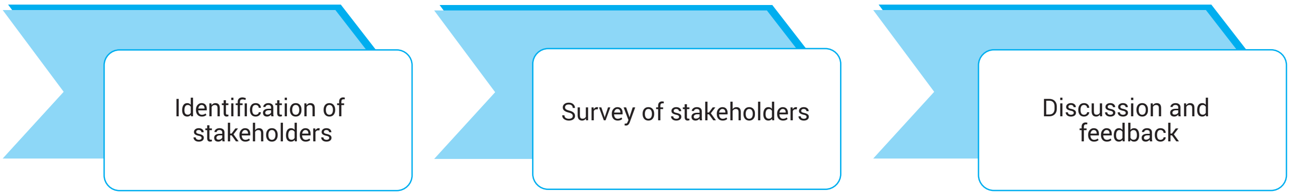
Table 2. List of plastic additives by category (Hahladakis *et al.* 2018). *Those of most concern are italicized (Hermabessiere et al. 2017)*

Category	Type of Additive
Functional	UV stabilizers
	antioxidant stabilizers (nonylphenol)
	heat stabilizers
	antistatic agents
	flame retardants (brominated flame retardants)
	plasticizers (phthalates)
	lubricants
	slip agents
	lubricants
	curing agents
	blowing agents
	biocides
Colourant	pigments
	soluble azo dyes
Fillers	mica
	talc
	clay
	calcium carbonate
	barium sulphate
Reinforcement	glass fibres
	carbon fibres

Chapter 10: Stakeholder feedback on existing monitoring and assessment activities in freshwater systems

Figure six below shows the three consecutive steps in stakeholder involvement:

Figure 6. Three consecutive steps in stakeholder involvement



To ensure the global applicability of these guidelines, the involvement of potential user groups during their development was pivotal. Therefore, stakeholders representing various sectors and nationalities were invited to answer an online survey containing 12 questions on their background, current and future plastic monitoring practices and what they consider to be perceived drivers and limitations of plastic monitoring in freshwater environments. Twenty-three individuals from 14 countries at different levels of development responded to the survey between 9 July and 9 August 2019.

Although most of the interviewees indicated they had little to no experience with plastic monitoring, most perceived it to be necessary. The reasons given were to ensure the preservation of the environment and maintain its recreational value and to guarantee the provision of safe drinking water.

Stakeholders reported that in the past, plastic monitoring projects had mostly been pursued in rivers and (to a limited extent) in lakes or reservoirs. In many cases, the assessment consisted of a combination of sampling and laboratory analysis. Monitoring of plastics on the water surface or the shoreline, however, was often complemented by a visual assessment.

In the future, the majority of interviewees would like to perform more regular sampling and laboratory analysis for various environmental compartments. However, they are constrained by a lack of funds and technical equipment. Legal hurdles and unclear responsibilities are also major inhibitors to further develop and implement plastic monitoring projects in fresh water.

Table 3. Stakeholders in freshwater monitoring and their functions

Main types	Sub-types	Function in the monitoring process
Public sector	international actors such as organizations, commissions and financial institutions	supporting knowledge exchange and in-depth monitoring, giving financial support
	local, regional and national authorities	performing freshwater monitoring
	waste management agencies and water providers	performing plastic monitoring to ensure the quality of their service
Private sector	waste management companies and water providers	performing plastic monitoring to ensure the quality of their service
	agricultural companies and fisheries	performing plastic monitoring to ensure the quality of their product
	environmental monitoring companies	providing technical know-how on plastics monitoring
Civil society	scientific societies and institutes	research on plastic monitoring in freshwater
	NGOs and citizen science projects	raising awareness, gathering data on plastics in freshwater and addressing contamination through various activities, gender related dimensions

Chapter 11: Recommendations for more effective mapping, monitoring and assessment

Assessing the occurrence of plastics of all sizes and shapes (or measuring them in all environmental compartments) is desirable. However, as noted in the previous chapter, stakeholders perceive a lack of funds and technical equipment to be among the main limitations to setting up plastic monitoring programmes in fresh water. Hence, it is recommended that monitoring methods be systematically prioritized depending on the goal of the programme (e.g., drinking water protection, assessment of sources and pathways).

The stakeholder survey also demonstrated that clear responsibilities and ascertaining legal frameworks are mostly missing in plastic monitoring in freshwater environments. It is therefore also recommended that responsibilities be clarified and legal obstacles be addressed.

Table four provides a scoring scheme for the sampling and observation methods covered in the main report (https://wedocs.unep.org/bitstream/handle/20.500.11822/35405/MPRL.pdf)

Table 4. Scoring scheme for the sampling and observation methods covered in main report
Cost of the equipment for observation, sampling and analysis, the infrastructure to run and maintain the equipment, the efforts required for installing the equipment, and requirements in terms of skilled female and male personnel

1	Low
1.5	Low-Medium
2	Medium
2.5	Medium - High
3	High

		Equipment cost	Infrastructure	Staff training level	Installation effort	Comments
Micro						
Sampling						
River Water Surface	Drift net	1.5	2	2	2.5	Driftnet installation in larger rivers (e.g. by lowering equipment from bridges) may require more effort and equipment than sampling smaller, wadable rivers
	Pump and Filtration	2	2	2.5	2.5	
River Water Column	Drift net	1.5	2	2	2.5	Basically the same equiment as for water surface sampling
	Pump and Filtration	2	2	2.5	2.5	
River sediment	Grab sampling	1.5	1	1	1	
Shorelines (Lake + River)	Grab sampling	1	1	1	1	
Lake surface	Trawl net and vessel	2	2.5	2.5	2	Additional effort if the same vessel is used at various lakes, must be transported
	Pump and Filtration mounted on vessel	3	2.5	2.5	2	
Lake water column	Trawl net and vessel	2	2	2	2.5	Depending on the depth of the lake additional equipment might be needed to lower the trawl or the pumping hose to the required depths
	Pump and Filtration mounted on vessel	3	2.5	2.5	2.5	
Biota	Collect from drift nets, trawls, catching with nets	1.5	2	2.5	2.5	Requires skilled staff
	Electro fishing	1.5	2	2.5	2.5	Additional equipment needed, requires skilled staff
Analysis						
Microscopy		2.5	2	2	2.5	
Microscopy and spectroscopy (FTIR, Raman)		3	3	3	3	Requires high-end analytical labs
Alternative instrumental analytical methods (e.g. Pyro-GC/MS)		3	3	3	3	
	Meso					
Sampling						
River Water Surface	Drift net	1.5	2	2	2.5	
	Pump and Filtration	2	2	2.5	2.5	
River Water Column	Drift net	1.5	2	2	2.5	
	Pump and Filtration	2	2	2.5	2.5	
River sediment	Grab sampling	1.5	1	1	1	
Shorelines (Lake + River)	Grab sampling	1	1	1	1	

1	Low
1.5	Low-Medium
2	Medium
2.5	Medium - High
3	High

		Equipment cost	Infrastructure	Staff training level	Installation effort	Comments
Lake surface	Trawl net and vessel	2	2.5	2.5	2	
	Pump and Filtration mounted on vessel	3	2.5	2.5	2	
Lake water column	Trawl net and vessel	2	2	2	2.5	
	Pump and Filtration mounted on vessel	3	2.5	2.5	2.5	
Biota	Collect or Catching with nets/electro-fishing	1.5	2	2.5	2.5	Mesoplastics will be ingested only by larger organisms where the particles are in the size range of their typical food food. Requires skilled staff.
Analysis						
Visual observation		1	1	2	1	
Spectroscopy (FTIR, Raman)		3	3	3	3	For polymer identification
	Macro					
Sampling						
River Water Surface	Visual counting	1	1	1.5	1	
	Camera automated camera counting	2.5	2.5	2.5	2	Bridge mounted or via UAV
	Drift net	1.5	2	2	2.5	
River Water Column	Drift net	1.5	2	2	2.5	
River sediment	Grab sampling	1.5	1	1	1	
Shorelines (Lake + River)	Grab sampling	1	1	1	1	
Lake surface	Trawl net and vessel	2	2.5	2.5	2	
Lake water column	Trawl net and vessel	2	2.5	2.5	2	
Biota	Collect or catch with nets/electro-fishing					Only very large organisms will contain macroplatics, it will be challenging to sample these
Analysis						
Visual observation		1	1	2	1	
Spectroscopy (FTIR, Raman)		3	3	3	3	For polymer identification

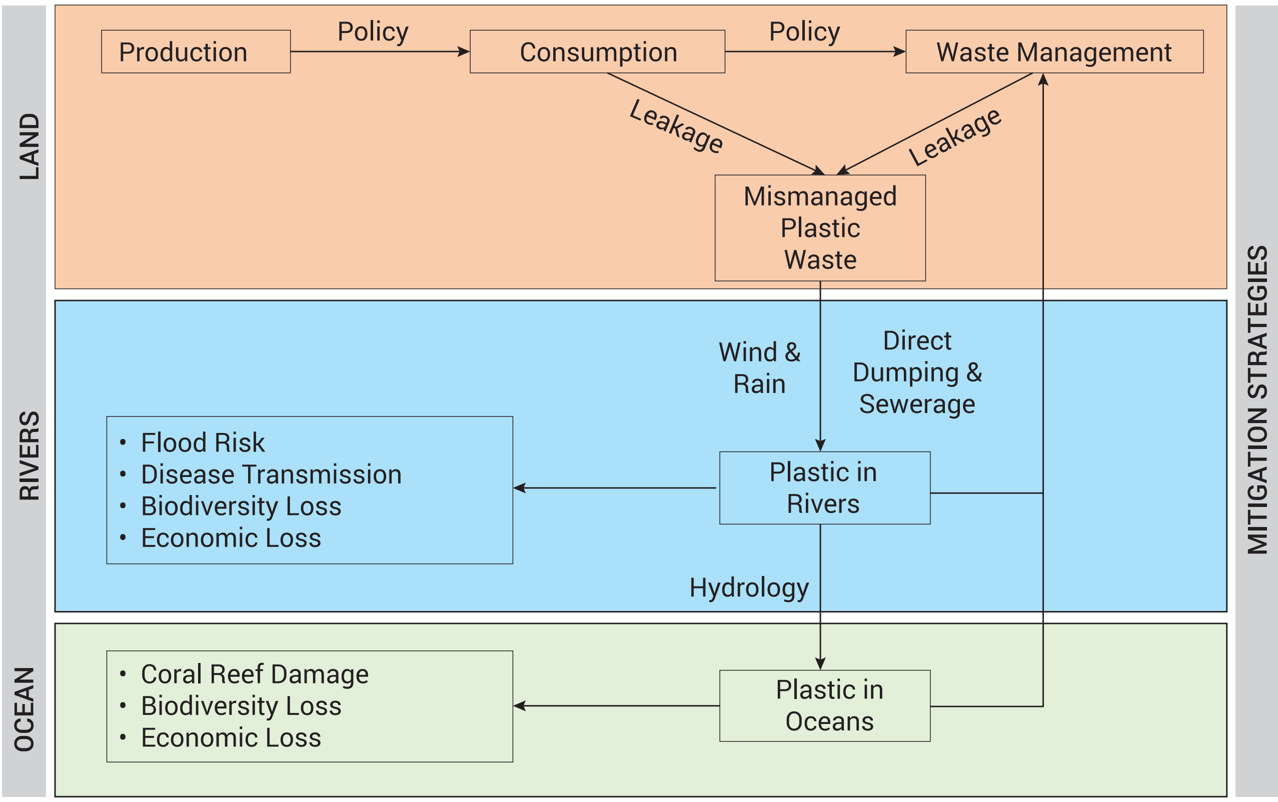
Chapter 12: Recommendations for preventive and corrective action and intervention

To move from data collection towards action, it is necessary to formulate, implement and evaluate policies for intervention and prevention. "Intervention policy" as used in this report refers to strategies used to reduce existing plastic concentrations in fresh water; "prevention policy" as used here refers to methods used to prevent the input of plastics to the environment. The relevance of intervention and prevention policies depends on local conditions such as existing plastic pollution, current waste management systems or the interest of local stakeholders.

The design and implementation of intervention and prevention policies are challenging because consideration must be given to the conflicts between different stakeholder groups, the many interconnected and dynamic social and environmental factors and the uncertainty about the effects of action (Kirschke and others, 2017). To address such challenges, it is recommended that (1) human and financial resources for the planning and administering of measures be increased; (2) nexus thinking – for both the water and the waste sectors as well as the respective stakeholders – be integrated; and (3) diverse governance instruments, such as regulations, persuasion and economic incentives, be used.

A Conceptual flow of plastic from production to consumption, waste management and leakage into the natural environment (land, rivers and ocean) with possible points of action for policies is provided in figure seven.

Figure 7. Conceptual flow of plastic from production to consumption



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