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Plastic as a Sediment – A Universal and Objective practical solution to growing ambiguity in plastic litter classification schemes

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Abstract

There is a universal and growing challenge of ambiguity in plastic classification schemes, which affects the predictability of plastic accumulation in all environments world-wide. Plastic pollution is an ever-growing global issue, and understanding plastic items and their sedimentological relationship is a solution to this increasing concern. Definitions of micro-meso- and macro- plastic is inconsistent between studies, as are categories of plastic, and the properties recorded. This is understandable because every project has a different objective, but the consequence is that different studies are not laterally relatable. It is widely agreed that as a community, we need a system that has room for specialism of study but has an objective basis that can allow for inter-project and inter-disciplinary collaborations. By considering plastic as a sediment, we can outline an objective and quantifiable classification scheme that builds on the principles of sedimentology for use in plastic studies, such that we can better understand why plastics accumulate where they do. This is importantly not just another classification scheme, but a philosophically grounded solution to a long-standing challenge that is set to be of increasing significance. Additionally, whilst these advances may be of immediate usefulness to the scientist interested in plastic transport and accumulation, the environmental scientist or biologist will find that these philosophies and classification scheme will aid to quantitatively support and compliment aligning data. Through this, our new plastic and sediment environment can be further understood both spatially and temporally, and connected to other studies. We outline the key philosophies of sedimentology and use these to: i) unify and define plastic size classification from nano-scale to mega- and introduce giga- scale; ii) we outline a shape classification that can tackle simple through to complex shapes; iii) we discuss and demonstrate the importance of total density over polymer density; and iv) we discuss the importance of material properties. In using this classification scheme, we can relate any plastic item to any other item, and to itself over time. This manuscript contains a summary and worksheet that can be used in the field or in a laboratory to utilise this scheme and present objectively comparable results. We are confident that the philosophies presented here will be of use to the plastic research community, such that we can integrate plastic studies with longstanding and deeply understood sedimentological knowledge, thereby enhancing our understanding of plastic routing and accumulation in the environment.

Introduction

Plastics, or synthetic polymers, are extremely versatile materials that are commonly synthesized from fossil hydrocarbons (Thompson *et al.*, 2009), and designed to meet various product requirements for many purposes worldwide (Nkwachukwu *et al.*, 2013). The last decades have seen the rising popularity of plastic lead to an exponential increase in global production of approximately 9,200 million tons of plastics between 1950 to 2017, an estimated 5,300 million tons of which has been discarded and may enter the environment if mismanaged (Geyer *et al.*, 2017; Borrelle *et al.*, 2020; Geyer, 2020; UNEP, 2021)(Geyer *et al.*, 2017; Geyer, 2020; UNEP, 2021). Unfortunately, on a global perspective, mismanagement of plastic is common and plastic litter has been found in almost every terrestrial and marine environment on Earth (e.g. Andrady, 2011; Zylstra, 2013; Eriksen *et al.*, 2014; Pham *et al.*, 2014; Wagner *et al.*, 2014; Woodall *et al.*, 2014; Peeken *et al.*, 2018; Allen *et al.*, 2019; Bergmann *et al.*, 2019; Meijer *et al.*, 2021). This is concerning because there is growing evidence for ecological harm from plastics, (e.g. Wright *et al.*, 2013; Cole *et al.*, 2015; Gall & Thompson, 2015; Kühn *et al.*, 2015; Lusher *et al.*, 2015; Bakir *et al.*, 2016; Wang *et al.*, 2016; Galloway *et al.*, 2017) and many plastics are designed to be long-lasting, so items in the environment may persist for up to thousands of years (Gregory & Andrady, 2003; Chamas *et al.*, 2020; Turner *et al.*, 2021). Consequently, plastics and its residuals have become a ubiquitous component of natural environments and will likely turn into an integral element of the depositional record of the Anthropocene, hence posing substantial ecotoxicological, structural, and environmental risks to be faced by future generations (Waters *et al.*, 2016; Zalasiewicz *et al.*, 2016; Rillig *et al.*, 2021).

Inconsistent approaches and definitions

To better asses global ecotoxicological risks, a number of studies have focused on identifying main pollution sources and estimated global plastic waste budgets as well as potential sinks for plastics in natural environments (Pruter, 1987; Browne *et al.*, 2011; Eriksen *et al.*, 2014; Woodall *et al.*, 2014; Jambeck *et al.*, 2015; van Sebille *et al.*, 2015; Geyer *et al.*, 2017; Koelmans *et al.*, 2017; Lebreton *et al.*, 2017, 2019; Lau *et al.*, 2020). However, the terminology, classification, and techniques used to describe plastic litter in studies of plastic pollution lacks consistency (Hidalgo-Ruz et al., 2012; Filella, 2015; Van Cauwenberghe *et al.*, 2015; Hartmann *et al.*, 2019). This is a widely recognized challenge and there have been many calls for harmonization from macro litter classification studies (Vriend *et al.*, 2020) through to soil studies (Weber *et al.*, 2022). In particular, size classes have been extensively critiqued and Hartmann et al. (2019) shows that there are more than 15 different size schemes used across various studies. Such discrepancies have come about because different studies have had varying requirements and may have been discipline- or case-specific, from marine life toxicology (e.g. Arthur *et al.*, 2009; Bermúdez and Swarenski 2021) to aerial microfibre dispersal (e.g. Dris *et al.*, 2016; Allen *et al.*, 2019), so the focus, definitions, and techniques have varied accordingly. These inconsistencies lead to challenges with evaluating correlations and relatability of one study to another, thereby limiting many studies to discipline-restricted, regional, or case specific methodologies or classifications (e.g., OSPAR, 2010; Van Emmerik *et al.*, 2020). Even within internally consistent studies, the findings differ depending on if the item classification is executed via item category, item material, or item function (Vriend *et al.*, 2020). A unified approach would contribute to a universal perception of global plastic pollution and its consequences (Hartmann *et al.*, 2019; Kooi & Koelmans, 2019; Hapich *et al.*, 2022), with advantages on a multi-disciplinary and multi-regional scale (van Calcar & van Emmerik, 2019). These advances are critical for better predicting the environmental behavior of plastic and the global distribution of plastic litter (e.g. Enders et al., 2019; Filella, 2015).

Plastic and sediment

A plastic item is commonly classified by its size and polymer type, but if the item is larger or indeed more distinguishable, it is typically classified based on its recognized prior function, such as “nurdle”, “bottle”, or “balloon”. Yet, using an item’s name as its primary descriptor has limited use when seeking to understand its hydromechanics, as a “bottle” may be any number of differing sizes and properties (Vriend *et al.*, 2020), particularly when related to international studies where manufacturing may be different. Additionally, a Polyethylene terephthalate (PET) bottle with its lid on full of air will float, but with its lid off, it may collect water or sediment and sink, yet these “status” descriptors are missing in most studies. Lastly, it is very common for plastic studies to have at least one miscellaneous “bucket” category such as “unidentifiable”, “film”, or “fragment”, which is ambiguous as these broad categories can contain significant variability. Also, plastic disintegration is happening by degradation and fragmentation all the time both through natural processes and mechanical disintegration through waste management (Ragaert *et al.*, 2017). Therefore, the proportion of global plastic that is classified as “unidentifiable” is ever increasing and already too common for further insight in most cases. A central component of the challenge is how to describe plastic, either as an individual item, or as a component of a natural system. Sedimentology already bridges the gap of how to understand and connect particles and landscapes, therefore, in this paper, we recommend accepting and reframing plastic items as sediment particles as it opens a wealth of possibilities provided by the well-structured and rigorously tested framework in the discipline of sedimentology. Importantly, this will not be just another classification scheme, but a philosophically grounded solution to a long-standing challenge that is widely understood to be of increasing significance. This approach will begin a paradigm shift in thinking to connect human-made materials and impacts back into natural systems.

The core strength of sedimentology lies in its understanding of the physical parameters that are drivers of the cause-and-effect chain of processes through an environment, which is underpinned by fundamental physics (e.g., Reading, 1996 and references therein), and more recently, modelling techniques (Ara Rahman & Chakrabarty, 2020). Sedimentology is formed on a quantitative and consistent framework that includes well established schemes for the classification of sediments, such as descriptions of size and shape of individual sediment grains, and the statistical properties of grain-size distributions (Wentworth, 1922; Passega, 1957; Boggs, 2009). Such complexities may be organized at different scales, from grains to the context and evolution of a sedimentary system (e.g., aeolian, riverine, or marine environments). Sedimentology considers both the transport and deposition of sediment, as well as the deposit itself, meaning that the origin and future of a sediment can be assessed at any point on its route, enabling long-term processes and trends of a grain or landscape to be interpreted. Therefore by studying the composition and architecture of the resulting sedimentary deposits on Earth and beyond, we can understand and predict the cause and effect processes, and driving mechanisms of past and prospective future sedimentary landscapes (Collinson *et al.*, 2006 and references therein).

In soil description for field surveys, plastics are considered as “synthetic solids” and described by their abundance, colour, size, composition, hardness, and weathering (FAO, 2006), but this is insufficient as plastic is more complex than natural sediment (Weber *et al.*, 2022). Natural sediment is composed of comparatively simpler and more consistent particles (i.e., mainly natural minerals), whereas the far greater range of complexity seen in plastic particles presents challenges to the adaptations needed to overcome in applying sedimentological principles to plastics. The fundamental framework for particle motion is universally applicable and may be related across engineered and natural materials (Enders *et al.*, 2019), therefore by centring the classification on properties that are known to impact particle motion in natural systems, we can build a sedimentologically based understanding of plastic as sediment. We openly note that there are limitations in the predictability of plastic behaviour using these principles (Chubarenko *et al.*, 2018; Khatmullina & Chubarenko, 2019; Waldschläger & Schüttrumpf, 2019a), however, it is a good first step to use and adapt sediment transport models to predict the relative deposition of sediment and plastic particles because there is extensive existing knowledge in sedimentology that can be connected (e.g., Enders *et al.*, 2019). Additionally, microplastics of different sizes and densities are found in different sedimentary environments, indicating that their transport and accumulation relate to the sedimentary environments (Hidalgo-Ruz *et al.*, 2012).

In this paper, we use the framework and philosophies of sedimentology to create inter-disciplinary and international harmony in the community's approach for understanding plastic particles, through creating a future-proofed, quantitative, and unambiguous classification methodology. To achieve this, we focus on the size, shape, density, and material properties of plastic to account for variability and complexity of plastic morphology and behavior. Such insights will lead to a clearer understanding of the short and long-term consequences of plastic in the environment, i.e., how it will accumulate, fragment, and transform as it routes through different environments from its source to its terminal resting place. This classification will provide a foundational descriptive tool for scientists of all disciplines and provide better interconnectedness of individual studies by fulfilling the requirements to: i) prioritize description over interpretation, as even if we know that an item is a bottle, it can be of any shape and size and in any state of fragmentation; ii) consider the state of the plastic particle as naturally found in relation to its surrounding environment; and iii) streamline the significance of observations when determining the particle transport-mechanics that the particle may display. All such descriptors will remove relativity in predictive models, so that environmental monitoring studies can be more targeted and, allow researchers to undertake representative sampling and provide consistency across disciplines and latitudes (Kane & Fildani, 2021; Waldschläger *et al.*, 2022).

Background

Sedimentology, sediments, and sediment transport

In its classic sense, sedimentology is the study of sediment movement and accumulation in the environment. Knowledge of sedimentary processes has been refined with continued success in their essential roles in hydrocarbon exploration, as well as in risk assessments of natural hazards and in estimating global carbon dioxide (CO_2) budgets (Pettingill, 2004; Jakob, 2005; Galy *et al.*, 2007; Hage *et al.*, 2020). Most processes considered in sedimentological transport and deposition are driven by Newton's laws of motion and may be explained with available fluid dynamics models. These models can predict which grains will be mobilised at a certain flow velocity by a fluid, such as air or water in a given environment (e.g. Hjulström, 1936; Shields, 1936; Bagnold, 1979), e.g., through knowing the velocity of a flow, and the particle's characteristics, these models can inform if sediment in a river would be transported on the riverbed or as suspended load in the water column (Hjulström, 1936; Shields, 1936).

Based on these principles, sedimentologists can largely predict the type of transport for sediments under specific flow conditions, where specific types of sediment are likely to be deposited, the shape of the space that the deposit will take up, and how that may change over time (Allen, 1965; van Rijn, 1993; Reading, 1996). The scale of application of these principles is such that sedimentologists consider the source to sink system, whereby the sediment is eroded from the landscape and transported to an ultimate sink, or terminal resting place, such as the deep ocean. Additionally, the modelled principles also work in reverse whereby the internal structure of sediment deposits, or the depositional architecture in a sedimentary environment, provide insights into flow characteristics and sedimentation processes that formed the deposits (Allen, 1971, 1985; Collinson *et al.*, 2006). Critically, sedimentology has a strong temporal context, therefore its principles can aid understanding far into both the past and into the future, e.g., the premise that a grain will break down into smaller grains, and the rate will depend on many factors including mineral hardness and environment. Therefore, sedimentological principles and techniques apply to both recent deposits in terrestrial and aquatic environments, as well as to ancient, often million years old deposits in the sedimentary rock record (Reading, 1996; Mutti *et al.*, 2009).

Sediment classification schemes

Sediment classification schemes have been developed to highlight the important aspects of a particle in the environment that will influence, and in total determine, its hydrological behaviour over time and space. The term “natural sediment” encompasses an enormous variety of minerals and other solid materials forming the texture and fabric (i.e., grain type and arrangement) of the sediment or sedimentary rock. Here, we focus on schemes that have been developed to describe and classify siliciclastic sediments that are mainly composed of minerals and rock fragments and classified by the grain size, grain shape, and fabric (e.g., Boggs, 2009), as they are the most directly relatable to plastic particles, hence contain the most adaptable components. Natural siliciclastic sediments are commonly made of minerals, such as quartz or feldspar, and fragments of eroded rock known as lithic clasts. The combined composition of individual particles describes the properties and texture of a sediment and allow for interpretation of the history of particle transport, whilst predicting its movement into the future.

Density

The most common natural particles to be considered in sediment transport processes are quartz, clay (such as Montmorillonite and Kaolinite), and biologically created particles such as calcite. The density of quartz is 2.65 g/cm^3, Montmorillonite 1.7-2.0 g/cm^3, and Kaolinite 2.16-2.68 g/cm^3. Biologically created particles are commonly organic matter (0.9-1.3 g/cm^3) and calcite (2.71 g/cm^3) (Duda & Rejl, 1990), which are also abundant in some systems where wood, algal debris, corals, and bivalves may be abundant. Quartz is one of the most abundant minerals on the Earth's surface, so sedimentology is most well understood with one dominant density and minimum variety therein, within which most grain-to-grain interactions are mutually impactful on the grains themselves.

Grain size

A definable, quantified grainsize, i.e., the minimum or maximum diagonal axis diameter or the intermediate value of a grain (Krumbein, 1941) is described by the average grainsize of the sediment. The Udden-Wentworth scale is a widely used grain-size scale that encompasses the entire range of sizes seen in the natural world (Udden, 1914; Wentworth, 1922) (Fig. 1), and is the dominant approach for describing lithified sediment. In this scale, sizes are categorised into the Wentworth size classes that are delimited by integers of Phi (Φ), a logarithmic grain-size scale to base 2. Thus, the size boundary of each Wentworth size class is twice as large as the preceding class.

Millimeters (mm)		Micrometers (μm)	Phi (ϕ)	Wentworth size classes		Rock type
	4096		-12.0	Boulder	Gravel	Conglomerate/ Breccia
	256		-8.0	Cobble		
	64		-6.0	Pebble		
	4		-2.0	Granule		
	2.00		-1.0	Very coarse sand	Sand	Sandstone
	1.00		0.0	Coarse sand		
1/2	0.50	500	1.0	Medium sand		
1/4	0.25	250	2.0	Fine sand		
1/8	0.125	125	3.0	Very fine sand		
1/16	0.0625	63	4.0	Coarse silt	Silt	Siltstone
1/32	0.031	31	5.0	Medium silt		
1/64	0.0156	15.6	6.0	Fine silt		
1/128	0.0078	7.8	7.0	Very fine silt		
1/256	0.0039	3.9	8.0	Clay	Mud	Claystone
	0.00006	0.06	14.0			

Figure 1 – The Udden-Wentworth scale for the size classification of natural sediments (modified from (Wentworth, 1922).

Unconsolidated sediments or sedimentary rocks are generally composed of grains or clasts of various sizes, such that the grain size of a sediment texture is best represented by a distribution of grain sizes rather than by a single value. These distributions are commonly visualised in histograms by either plotting the individual volume percent of each grain-size class or the cumulative volume percent of the grain sizes (Fig. 2).

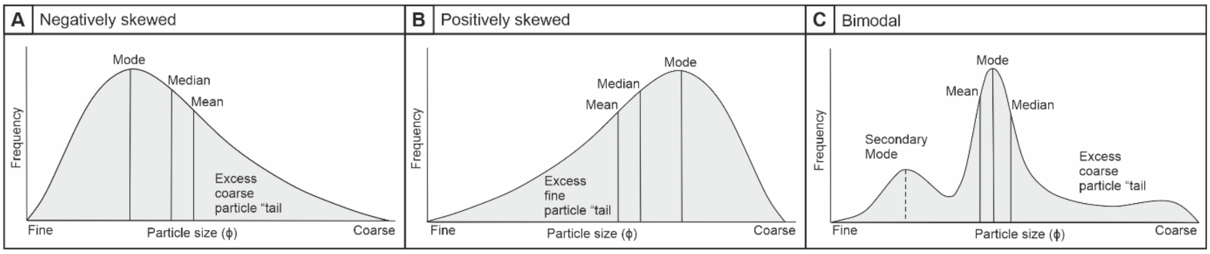

Figure 2 – Visualised histogram grainsize distribution curves showing A) Negative skew; B) Positive skew; and C) bimodal distributions.

Based on the visualised histogram distribution, various grain-size parameters can be calculated that are useful to further characterise the texture of the sediment (see review by Boggs, 2009):

1) the **mode** represents the most frequently occurring grain-size class, and the median represent the 50th percentile of the cumulative distribution curve (e.g., d50) and is widely used in sedimentology to communicate the overall sediment grain size (Fig. 2).
2) the **sorting** of the sediment is defined as the Phi standard deviation of the mean grain-size value and describes the magnitude of the spread of grains sizes within the grain-size distribution. The sorting parameter is categorised into 6 classes ranging from very well sorted to very poorly sorted (Inman, 1952; Folk, 1968; Jerram, 2001) (Fig. 3).
3) the **skewness** describes the degree of symmetry of the distribution curve on the histogram, whereby a positively skewed grain-size distribution is dominantly fine grained and a negatively skewed distribution is dominantly coarse grained (Inman, 1952; Folk & Ward, 1957; Folk, 1968) – (Fig. 2).

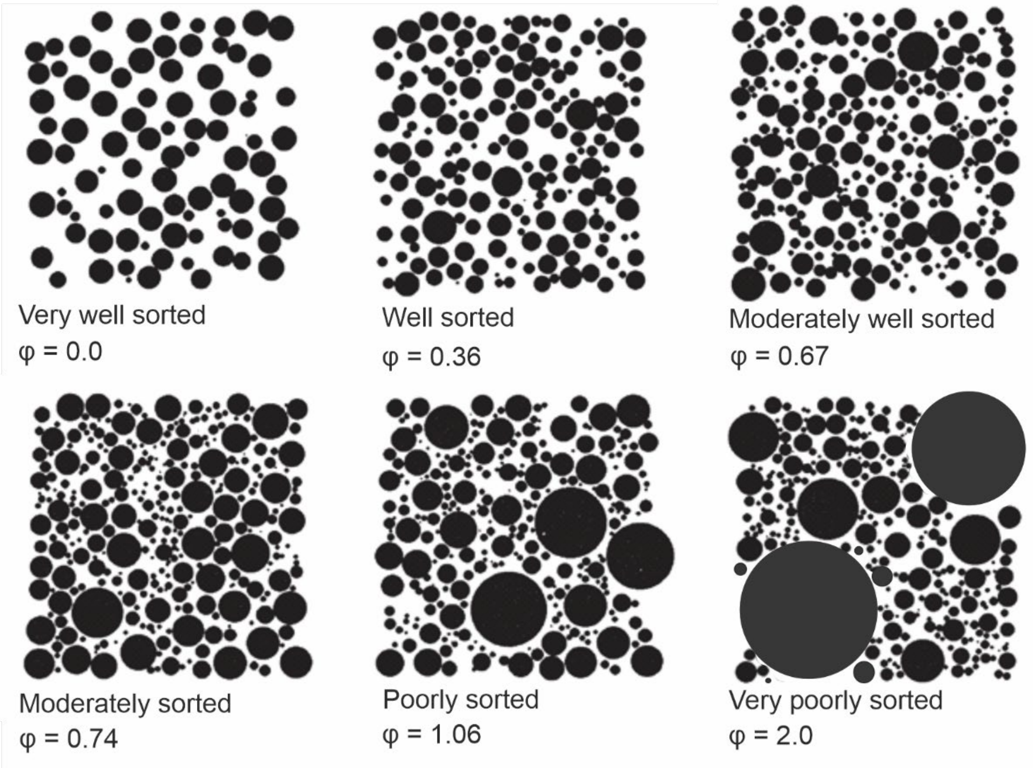

Figure 3 – Visualisation of sediment textures with different grain-size sorting parameters. Modified from (Jerram, 2001)

Grain shape

The shape is defined by three key properties: surface texture, form, and roundness (Barrett, 1980 and references therein) – (Fig. 4).

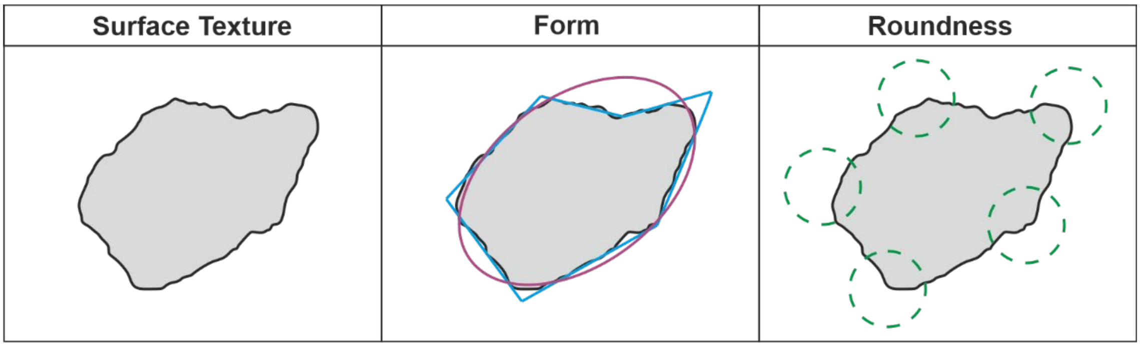

Figure 4 – Grain shape definition based on form, roundness, and surface texture. Modified from (Barrett, 1980)

1) The **surface texture** describes the microrelief on the surface of the grain such as scratches and cavities (Krinsley & Doornkamp, 1973; Mahaney, 2002), which are in the micrometre scale so commonly examined by microscopy techniques. More than 40 specific types of surface textures have been described such as V-shaped etch pits, grooves or scratches, conchoidal fractures and abrasion features (Mahaney,

2002; Boggs, 2009). Most of these features are created by grain-to-grain interaction or collisions during transport or by abrasion through wind and water (Jackson & West-Thomas, 1994; Mahaney, 2002 and references therein).

2) The **form** of a grain is most widely described using the simple and illustrative scheme proposed by Zingg (1935). It uses the elongation (ratio of the intermediate (i) to long grain axis (l)) and the flatness (ratio of the short (S) to intermediate grain axis) as plotted in Fig. 5, hence each shape is classified as either a disc, sphere, blade, or rod.

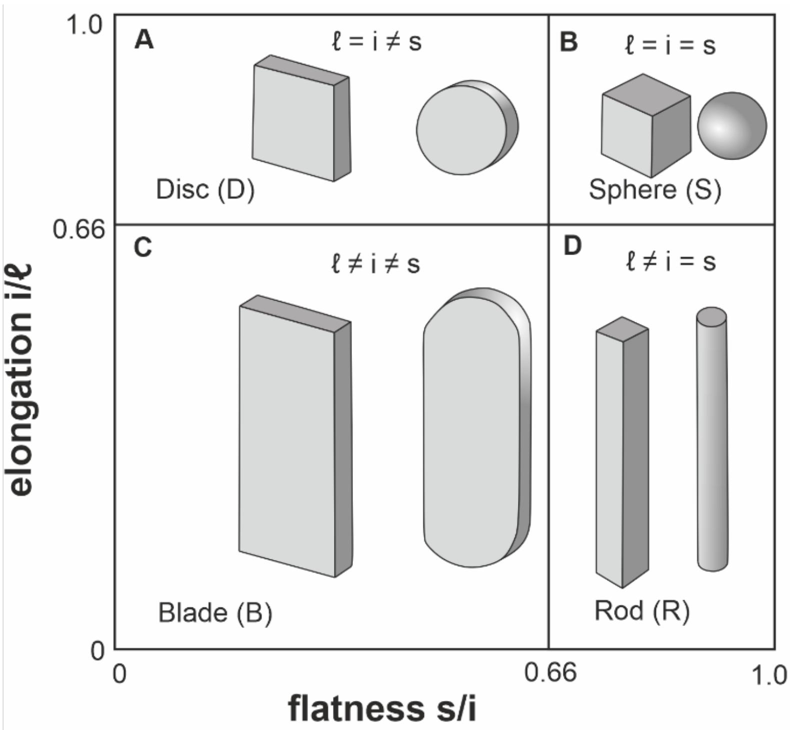

Figure 5 – A grain shape classification after (Zingg, 1935). Four different grain forms are identified based of the relation of the grain axes.

3) Grain **roundness** describes the sharpness of the edges and corners of a grain and is independent of the grain form or surface texture. One of the most widely used roundness scale schemes today was introduced by Powers in 1953, and is a further development of previous roundness classification schemes (e.g., Wadell, 1935; Russell & Taylor, 1937; Pettijohn, 1949). In Powers' scheme, six different grain roundness classes are defined ranging from very angular to well rounded (Fig. 6).

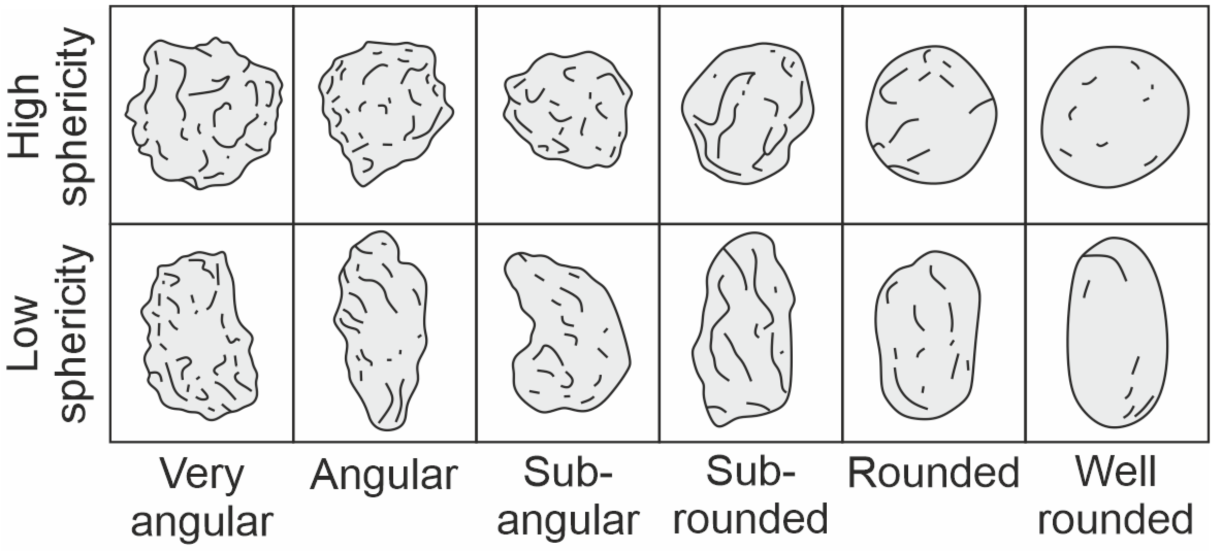

Figure 6 - Roundness classification scheme after Powers (1953). Roundness is independent of grain form and divided into six classes raging from very angular to well rounded.

Basic principles of sediment transport

Flowing air, ice, and water exert forces over sediment particles and may be strong enough to transport them. Although the specific aspects of transport may be different in each environment, their motions are based on the same physical principles. In this section, we describe them in the context of fluvial environments.

Sediment transport may occur via two main modes: bedload (moving along the bed or substrate by saltating, sliding, or rolling), or suspended load (moving away from the bed and not interacting with it e.g., in the water column of a river). The properties of the particles and the strength of the forces acting upon them, dictate the transport mode.

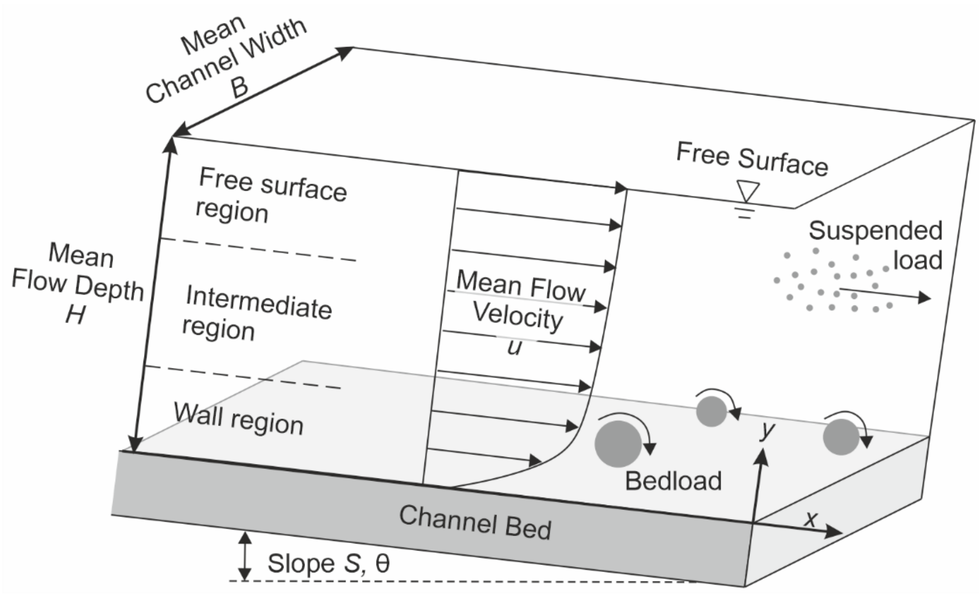

Figure 7 – A figure to show basic processes that act in a flowing system such as a river (modified from Earl *et al.*, (2014)).

Consider a river reach, with mean flow depth H, mean channel width B, mean bed slope S, and mean flow velocity U. These variables are used to calculate the reach-averaged near-bed shear stress τ_b, i.e., the tangential force per unit bed area acting on the particles:

$$\tau_b = \rho_f gHS \qquad (Eq. 1)$$

Where ρ_f = fluid density and g = gravitational acceleration. The bed shear stress may be used to calculate the shear velocity u_*:

$$u_* = \sqrt{\tau_b/\rho_f} \qquad (Eq. 2)$$

These variables describe the flow intensity and its ability to transport sediment particles (Shields, 1936; van Rijn, 1993). Shields (1936) conducted a set of experiments to quantify the conditions for incipient motion for natural sediment particles, and famously established a dimensionless parameter known as the Shields number, which is given as:

$$\tau_c^* = \frac{\tau_{bc}}{\rho gRD} \qquad (Eq. 3)$$

where R = submerged specific gravity of the sediment particle (Eq. 4), D = characteristic particle size (typically expressed as a grain diameter, and the subscript 'c' denotes critical and refers to the shear stress value above which a particle would start moving (incipient motion). It has long been recognized that particle shape also affects its mobility and recent work has provided new insights into its implications (e.g., Cassel *et al.*, 2021; Deal *et al.*, 2023). To account for grain shape effects in bed load sediment mobility, Deal *et al.*, (2023) introduced a shape-corrected Shields number $(C^*/\mu^*)\tau_c^*$ where C^* is an effective drag coefficient, and μ^* is an average bulk friction coefficient. This modified Shields number also applies when treating plastic as a sediment. The submerged specific gravity of a particle (Eq. 4) is a key variable controlling its mobility and buoyancy.

$$R = \frac{\rho_s - \rho_f}{\rho_f} \qquad (Eq. 4)$$

Where ρ_s = sediment density. Particles with R < 0 float on the surface of the fluid, whereas particles with R > 0 sink. The rate at which they sink depends on their settling velocity and the ambient fluid conditions. The size, density, and shape of a particle all affect how fast it settles in quiescent clear water, i.e., its settling velocity v_s (e.g., Ferguson & Church, 2004). In flowing water, the ratio between the settling velocity and the shear velocity dictates if a particle is transported by the flow near the bed or in suspension; this may be quantified using the Rouse number (Rouse, 1937) expressed as:

$$P = \frac{v_s}{\kappa u_*} \qquad (Eq. 5)$$

Where κ = von Karman constant ($\kappa = 0.41$). If P > 2.5 the particles travel as bedload and for smaller values, the particles travel in suspension.

Plastic litter and transport of plastic

Research on plastic pollution stemming from several disciplines, does not offer a universal and connected approach to describe plastic litter (Hartmann *et al.*, 2019). However, there are fundamental underlying themes within the varying approaches that relate to the physicality of the particle, which are density, size, and shape. Since these are also used in sedimentology, they will aid our deeper understanding of plastic as a sediment particle, and form the focus of the following section. We recognize that there is significant additional research on plastic properties, but our goal is to find a set of simple connected themes that can form a common framework for further detail to be added where relevant to the study at hand. In addition, we provide recommendations on the language and word choice where required, for example, terms such as "ensemble", "garbage patch", or "community" have been used to describe where multiple plastic items accumulate (Khatmullina & Chubarenko, 2019), but here we use "accumulation" as it is objective, more broadly applicable and is widely used in sedimentology.

Plastic litter classification schemes

Much of the challenge in determining a consistent language and classification of plastic materials stems from the diversity, and complexity of their morphology and properties (GESAMP, 2015; SAPEA, 2019). Per definition, plastics are materials containing as an essential ingredient a high polymer, which is a macromolecule, composed of many repeating subunits (i.e., monomers). The most commonly used synthetic polymers – also known as the "Big Six" of plastics –, are polyester (PET), high- and low-density polyethylene (HDPE, LDPE), polyvinylchloride (PVC), polypropylene (PP), and polystyrene (PS) (PlasticsEurope, 2020). Apart from these commodity polymers, however, the categorisation of materials to the term plastics is in dispute and also varies across different scientific disciplines (Hartmann *et al.*, 2019). Rubber for example, is not considered as plastic according to some chemistry polymer definitions (International Organization for Standardization, 2013); nonetheless, environmental scientists argue to categorise tyre particles as plastics, because modern tyres are mainly made of synthetic rubbers that are comparable to plastics (Kole *et al.*, 2017; Halle *et al.*, 2020; Knight *et al.*, 2020). Such discrepancies in the definition of materials as plastics have also been raised by Hartmann et al. (2019), who consequently proposed three defining criteria, namely: (I) chemical composition, (II) solid state, and (III) solubility (see their Table

1). For this paper the plastic material definition by Hartmann et al. (2020) is adopted, and plastic is defined according to those three criteria.

Once an item has been identified as plastic and allocated to a specific group of polymers, it is typically further assessed by its size (e.g. micro or microplastic), shape (e.g. fragment or fibre), and if possible, origin (e.g. primary or secondary) (e.g., Wagner *et al.*, 2014; Hartmann *et al.*, 2019). However, in contrast to the above-mentioned standardised classifications schemes that have been developed to describe natural sediments, the scientific disciplines describing and categorizing plastic litter mainly lack such standardised definitions (e.g. Provencher *et al.*, 2020). Consequently, size and shape classes as well as nomenclature used in publications on plastic pollution are either not defined at all, or contrasting schemes are used throughout different studies, making a comparison of results challenging (Filella, 2015; Burns & Boxall, 2018; Hartmann *et al.*, 2019; Provencher *et al.*, 2020).

Polymer density

The most common plastic particles range in density from 0.92 g/cm^3 to 1.5 g/cm^3 (Table 1 – modified from (Harris, 2020), and there are more plastics that exhibit an even greater range of density besides these. The dominant types of plastic particle (Table 1) are used in a vast and increasing number of products, from plastic bags to clothing and carpets. As such, these are the most available plastic types, such that much plastic modelling and experimentation has so far developed around the properties of these particles (Chubarenko *et al.*, 2018; Waldschläger & Schüttrumpf, 2019b; Russell *et al.*, 2023).

Density g/cm^3	Chemical name	Common example
0.92	Polypropylene (PP)	Bottle caps, rope
0.95	Polyethylene (PE)	Plastic bags
1.01-1.09	Polystyrene (FPS)	Floats, containers
1.15	Polyamide (Nylon)	Fishing nets, clothing
1.24	Cellulose acetate	Cigarette filters
1.3	Polyvinyl chloride (PVC	Plastic film
1.35	Polyesther	Clothing
1.39	Polyethylene terephthalate (PET)	Plastic bottles, carpet, clothing
1.5	Rayon	Clothing

Table 1 – Density, chemical names, and examples of common plastic types (modified from Harris (2020).

Plastic litter particle size

The first size classification scheme was introduced by Gregory & Andrady, (2003) who introduced the terms macro-, meso-, and microlitter to describe and classify anthropic marine debris. The size boundaries of these classes were based on mesh sizes of commonly used sieves and encompassed plastic items in the size range of 63µm (0.63 mm) to 15cm (150 mm); although the proposed size scale did not include items between (0.500 mm) to 5 mm (Gregory & Andrady, 2003). Later studies adapted the terminology to macro-, meso-, and microplastics and extended it at the lower and upper ends by nano- and megaplastics respectively. This terminology represents the generally established nomenclature for plastic size classes (e.g., Thompson *et al.*, 2004; Browne *et al.*, 2007; Moore, 2008; Arthur *et al.*, 2009; GESAMP, 2015; Hartmann *et al.*, 2019). However, despite the general consensus on the nomenclature, there still exists no standardised or generally accepted definition on the size boundaries of the different size classes (Filella, 2015; Burns & Boxall, 2018; Chubarenko *et al.*, 2018; Hartmann *et al.*, 2019) (Figure 9). The reasons for the use and establishment of multiple size schemes in plastic research are not clear, but likely a combination of size boundaries tailored to specific research topics – such as ability of specific organisms to ingest it (Bermúdez & Swarzenski, 2021), or detection limitations due to mesh sizes (Arthur *et al.*, 2009; Chubarenko *et al.*, 2018), random adaptation of size boundaries proposed or used in previous studies, or application of more advanced technology to detect plastics (Materić *et al.*, 2022). Consequently, more than 15 different size classification schemes have been proposed and established over the past two decades, and size definitions remain ambiguous and conflicting (e.g., Hartmann *et al.*, 2019; Provencher *et al.*, 2020). Smaller plastic scales have been more heavily disputed as there is a larger body of work in micro- and nano plastics due to the immediate ecotoxicological concerns. For instance, the upper size boundary of nanoplastics varies between 100 nm to 335 µm, the upper boundary of microplastics between 0.5 to 5 mm (with 5mm being the most frequent used definition), the upper boundary of mesoplastics (if this class is selected and defined in the scheme) between 10 to 25 mm, and the upper boundary of macroplastics (if boundary defined) between 15 to 100 cm (Fig. 9). Where studies define mega plastic, the lower boundary may be as small as 50 cm (The Ocean Cleanup, 2022), and if an upper boundary is defined, it may be 200 cm (Bermúdez & Swarzenski, 2021). Consequently, the comparison of size distribution of environmental plastic litter across different studies might be challenging – if not impossible, if no specific size boundaries are provided.

Plastic litter particle shape classification

Plastic products have been designed for multiple applications and exhibit a large variety of complex shapes (Nkwachukwu et al., 2013); and accordingly the shape variety of plastic litter items reveal a similar complexity. Plastic items in the environment will break down into smaller pieces due to abrasion and fragmentation, or change their shape and surface structure due to biological, photic or chemical degradation (Corcoran et al., 2009; Andrady, 2015; Chubarenko et al., 2018), so there is an infinite spectrum of shape possibilities. Presumably because of this complexity, a universal shape description scheme to grasp the full spectrum of shape varieties of plastic litter has not been developed yet, and – similar to the size classification – no standardized and commonly accepted shape classification scheme exists. Shapes of plastic items may be generalised into their dominant dimensions, i.e., quasi – one-, two-, and three-dimensional shapes, which describe fibres, flakes, and spheres in context (Chubarenko *et al.*, 2016). Shapes are substantial because each dominant dimension shape type settles differently in different flow regimes (Francalanci *et al.*, 2021).

Many of the plastic items encountered in the environment – in particular macroplastics – may be identified as distinct goods, and therefore their shape is typically described as such (i.e. plastic bottle), rather than on the basis of their geometrical shape (e.g. OSPAR Commission 2010; van Emmerick et al., 2020; Hapich et al., 2022). If plastic items cannot be identified, or if they are too small, they are typically described using a nomenclature that has been established over the past decades, consisting of fragments, granules, pellets or nurdles, spheres or spherules, beads, foams, filaments, fibres, films, and flakes (Hidalgo-Ruz et al., 2012; European Commission, 2013; Zhang et al., 2017; Chubarenko et al., 2018; Hartmann et al., 2019; Rochman et al., 2019) (Fig. 8). In addition, some of the shapes may have more specific descriptors. For example, fragments may be round, subround, angular, subangular, twisted, or curled; and pellets may be cylindrical, disks, flat, ovoid, or spheroids (Hidalgo-Ruz et al., 2012; Rochman et al., 2019). Further, the general appearance of plastic items may be specified by adjectives such as: irregular, elongated, degraded, rough, and with broken edges (Hidalgo-Ruz et al., 2012). However, as noted by (Hartmann et al., 2019), some of these shape descriptors are used interchangeably (e.g. pellets, nurdles, speres, beads), or their definition is ambiguous and subjective.

Figure 8 – Examples of different microplastic shapes. After (Chubarenko *et al.*, 2018).

Motion and transport of plastic items

Plastic behaviour has been extensively theorised and reviewed (Chubarenko & Stepanova, 2017; Chubarenko *et al.*, 2018; Enders *et al.*, 2019; Hoellein *et al.*, 2019; Khatmullina & Chubarenko, 2019; Lechthaler *et al.*, 2020; Waldschläger *et al.*, 2022), and the transport dynamics of plastics have been studied for many years (Ballent *et al.*, 2012, 2013;

Chubarenko *et al.*, 2016; Horton & Dixon, 2018). Bedload transport relations have even been developed and tested with plastic materials in addition to sediment (e.g., Fernandez Luque, R., & van Beek, 1976) but have not been evaluated when both materials are mixed. Despite plastics being increasingly recognised to behave differently to natural sediments (Khatmullina & Chubarenko, 2019), the underpinning physics are the same (Enders *et al.*, 2019), and valuable predictive capacities exist (Hidalgo-Ruz *et al.*, 2012; Kane & Fildani, 2021; Waldschläger *et al.*, 2022). Therefore understanding the relationship of plastic to sediment is a critical interim step on the way to fully understanding the independent dynamics of plastic, such that many studies seek to find advantageous correlations that can open connectiveness in understanding.

Probably the most fundamental parameter to determine the transport behaviour of plastic is the settling velocity which can be determined experimentally (Kowalski *et al.*, 2016; Khatmullina & Isachenko, 2017; Waldschläger & Schüttrumpf, 2019b; Waldschläger *et al.*, 2020; Van Melkebeke *et al.*, 2020; De Leo *et al.*, 2021; Zhang & Choi, 2021; Francalanci *et al.*, 2021; Khatmullina & Chubarenko, 2021; Choi *et al.*, 2022; Kuizenga *et al.*, 2022; Mendrik *et al.*, 2023). Additionally, many laboratory experiments in flume tanks have been undertaken under different flow conditions (Waldschläger & Schüttrumpf, 2019a; Alsina *et al.*, 2020; Pohl *et al.*, 2020; Bell *et al.*, 2021; Russell *et al.*, 2023). Such experiments find that whilst classic settling equations are able to accurately predict the settling velocity of simple microplastic shapes like spheres and cylinders, they do not provide an accurate prediction for more complex shapes such as fibres or films (Khatmullina & Isachenko, 2017; Waldschläger & Schüttrumpf, 2019b; Mendrik *et al.*, 2023). Additionally, research has shown that the settling velocity of microplastics can be significantly influences by factors such as secondary motions (Khatmullina & Chubarenko, 2019; Zhang & Choi, 2021) and biofouling (Van Melkebeke *et al.*, 2020; Waldschläger *et al.*, 2020; Mendrik *et al.*, 2023). Laboratory experiments in flume tanks show that when plastic is on its own, i.e., plastic particles are only interacting with other plastic particles of similar properties, it behaves just like sediment and can contribute to understanding sediment bedload equations (Fernandez Luque, R., & van Beek, 1976). However, when plastic and sediment are mixed, transport relations become different as plastic and sediment have different densities and their interactions are affected by the relative buoyancy of both particle types, leading to differences in particle mobility. Such differences range from plastic exhibiting a wider range of movement than natural sediment (e.g., Alsina *et al.*, 2020), to the scale of accumulations varying on a bedform scale (e.g., Russell *et al.*, 2023).

Studies are increasingly finding that the importance of different plastic characteristics on its behaviour, differs depending on the study, which can be distilled to the plastic particle density, size, shape, and particle properties. For example: i) shape seems to affect the settling of a particle more than small variations in size (Khatmullina & Isachenko, 2017; Mendrik *et al.*, 2023); ii) if a plastic particle floats, its size and density does not meaningfully influence the rate at which wave action will aid it drifting to shore (Alsina *et al.*, 2020); iii) fibres may be entrained and deposited at markedly different thresholds than natural sediment (Waldschläger & Schüttrumpf, 2019a), and likely to be deposited by being pushed into the deposit by settling sediment grains (Pohl *et al.*, 2020), which is novel to sedimentology; and iv) elongate shapes have a different impact than spheres on erosion from bedforms (Russell *et al.*, 2023).

To create a connected understanding of these findings, which can be input into models, the plastic needs to be categorized consistently because if items are characterised by material or how it was functional, it changes the results (e.g., Vriend *et al.*, 2020). Notably, there is a lack of understanding of complex shapes, such as fibres and films, which limits the input of such studies into modelling. As such, the parameters that are used in modelling (van Sebille *et al.*, 2015, 2020; Díez-Minguito *et al.*, 2020), are too simple, thereby the findings have a confined application. The philosophies and practicalities of sedimentology provide the basis to make these improvements.

Plastic as a Sediment

In accepting plastic as a sediment, we can meaningfully integrate the philosophies of sedimentology into how we observe and understand plastic, i.e., how to objectively understand a plastic particle in the environment, and guidance and limitations on interpretation. Existing schemes for assessing the physical parameters of plastic, are not appropriate to simply merge and adapt because many have discipline- or region-specific parameters or purposes (Van Emmerik *et al.*, 2020; Bermúdez & Swarzenski, 2021). Here, we build a novel underpinning framework using the principles and philosophies of sedimentology, so that we have a united understanding and don't reinvent already existing principles. For example, quasi – one-, two-, and three-dimensional shapes (Chubarenko *et al.*, 2016), may be directly related to the sedimentological principle of rod, disc, and sphere (Fig. 5), which are quantifiably described and have long been in existence (Zingg, 1935). Research has been done in these areas for a long time (Komar & Reimers, 1978) and more recently adapted to plastic (Francalanci *et al.*, 2021). Multiple terminologies for the same principle are not required if we include plastic particles as novel sediment particles.

Before offering a methodological solution to treat plastic as a sediment, we highlight three challenges associated with building a connective understanding of the objective principles of plastic particles and their form that may be linearly and consistently reported using the principles of sedimentology:

- Density is far more variable in common plastics than common natural sediments, which means that the behaviour of plastic does not generally scale with particle size as we know from sedimentology.
- Grain size is described on a continuous scale for sediment, but for plastics there are many different schemes, which are discontinuous. We need to incorporate common names from nano- to mega- into a continuous size scale that has divisions that combine physical and functional attributes of plastic particle sizes.
- Sediment grain shape is simple and scale independent, whilst plastic has far more variable morphology, therefore we need an approach that is both flexible and simple.

Present classifications within sedimentology will be insufficient to overcome these challenges, but the core underpinning philosophies from sedimentology can be applied to develop a solution that can align with, and grow with, the developing complexities of plastic sediment. The philosophies of sedimentology, explained below, will be extended to present our four-part universal plastic description methodology.

Objective observation before interpretation

A structured observation is consistent, whereas interpretations may vary between scientists or over time as more techniques are discovered and used. Therefore, it is critical to clearly differentiate between observation and interpretation to enable full, non-assumptive, objective recording of data. From the objective framework, interpretations can be made and discussed, and variables can be isolated and independently inspected to identify trends. Additionally, such interpretations are flexible to change as the observations are stable, and the descriptive framework can be added to, so that detail may be captured in studies with a more specific objective. The challenge amplifies as we move to larger particle sizes such as macroplastics, as many items are readily recognisable to us from our households, thus we name them familiarly. However, the physical attributes of that particle are only somewhat accounted for because of the dominant interpretation-first approach, from which it is challenging to then apply a particle transport-mechanics understanding.

At present, in plastic studies, if an object is readily identifiable (e.g., bottle), this interpretive name is given, whereas if the object is *not* known (e.g., fragment), it is binned as "unidentifiable" or described, typically by scale and polymer type. Therefore, if an item is misidentified, there is no route to return to the observations of every item equally and reconsider an alternative interpretation from base principles. In the River-OSPAR protocol (OSPAR, 2010; van Emmerik & Schwarz, 2020), there are 111 specific item categories, but these categories have been largely developed on studies of European rivers as they are the most frequently studied (Owens & Kamil, 2020). Additionally, in its approach, the scheme seeks to label items such as "bottle", though is not able to account for different scales (beyond small or large) or the composition or state of degradation of the bottles. Different scientists may categorise a container as a bottle, and it will behave differently in the landscape if crushed or inflated. As such, the term "bottle", and other such terms are a subjective interpretation based on past function of the plastic particle, not an objective description of its present geometrical morphology. Another example is how shape descriptors such as pellets, nurdles, spheres and beads are often interchanged, so the terminologies are subjective interpretations and not descriptions (Hartmann et al., 2019). It's important to not wrongfully interpret the terms pellets, nurdles, or beads as they may refer to raw pre-production plastics, and therefore represent primary microplastics, which is an important distinction when seeking to understand plastic in an environmental context. Whilst, this description might be accurate in many instances, microplastic derived from broken down larger plastic items, known as secondary microplastics may exhibit similar shapes and could thus be mistaken for primary microplastics (e.g., Hartmann et al., 2019; Provencher et al., 2020). The term “fragment” infers that it is a secondary microplastic and typically refers to angular particles of rigid polymers, however, if a fragment of unidentifiable film is found, it is still a fragment, yet commonly classified as film. Therefore, we see that using subjective and interpretive terminologies is confusing and hampers the objective collection of plastic data and the interpretive process.

An objective classification scheme cannot directly address the breakdown and change in size and shape of a plastic particle as it represents a snapshot of the particle in both space and time. It is therefore not appropriate to directly interpret if a plastic is primary or secondary prior to describing its features and geometries. This is the case for sediments, which only records the present state of the material, e.g., sand or pebbles. To aid with harmonizing the approach towards plastic particles, we extend the geometry-focussed approach of sedimentology such that both plastic and sediment must all be described in comparable terms first and interpretations may occur later.

Deeply Rooted Allowance for Temporality

A classification scheme can provide the tools to objectively represent a snapshot of a plastic particle, and therefore cannot directly infer changes to a particle. However, if a series of snapshots are collected, a broader understanding can be developed so that particle and landscape change and the related processes may be indirectly inferred over time. Where we have understandings of processes of plastic in the environment, the majority is from laboratory experiments where observation may be consistent and under controlled conditions, so the temporal context does not need to be inferred. In nature, that temporal context may be indirectly inferred with a series of objective snapshots, which can allow for the indirect understanding of changes over space and time.

In sedimentology, a quartz (SiO_2) grain will become increasingly rounded and smooth the longer it is in the environment, as it becomes intermittently fractured and subsequently smoothed out. The number of objective “snapshots” taken throughout this process define the resolution at which these geometrical transitions may be determined. With plastic, it is key to remember that it is part of this same temporally complex system as sediment, and plastic particles become altered, break down, and perhaps deform, over time. Therefore, a plastic particle will become smaller as it is physically or chemically changed by the environment. In the context of the snapshot, the present state of the item gives the most reliable data on the processes of plastic in the environment, i.e., if it is found deposited, you may only read the deposited state of the item, and any reading on its transport is inferred.

The state of the item and the temporal limits of observation are important to recognise. In sedimentology, we take great lengths with each observation to maintain the spatial and temporal context of a sample, i.e., we record material in situ and preserve its state during analysis where possible. If material must be brought out of situ, then it is preserved in its found state and samples may be taken for processing. Additionally, the precise location for each sample is recorded, and if important to the study, the orientation is recorded also. If the material or environment is sensitive to change, the time and date, perhaps as well as the status of the tide or water level is marked and recorded. In short, out of situ material should be collected with enough information to be able to exactly replace it in its full environmental context.

In some plastic studies, it is necessary to collect the material and then assess it later, which means manually and superficially cleaning sediment and organic debris from studied items to approximate their sampled condition (e.g., de Lange *et al.*, 2023), however, in most studies, the process of item collection and processing is not shared. If materials are removed, untangled, reshaped, organised, emptied of water and sediment, or cleaned then the data that is then collected is disconnected from the environmental processes, i.e., you may discern <u>what</u> was transported, but you lose the data to work towards understanding <u>how</u> that transport and deposition occurred.

Indeed, the context of the plastic particle is important to understand it as a sediment. Consider an empty plastic bottle: as well as knowing the polymer density, it is critical to know if the lid of the bottle is on or off to better assess how it has been transported. If the lid is on and the bottle contains air, then it creates a seal, and the object will be persistently buoyant for some time. If the lid is off, then it may be buoyant for significantly less time as the bottle cavity could fill with water, sediment, or even other plastics. Each of these scenarios will result in a different transport mechanism for the bottle, therefore such observations are a significant element when considering plastic particles in context with the environment. Items that can contain water such as bottles with no lid or cups have been found to be associated with the water level. This is thought to be because of their increasing mass due to taking on water, i.e., fixation, which is an environmentally controlled secondary deposition by the river, though care with assigning causal relationships ought to be taken (Roebroek *et al.*, 2021).

Differently, consider a rope that is found as a tightly wound coil. Initial observations conclude that the rope has been transported in this form, therefore it should be measured and assessed in this form also. To unwind the rope and measure that would be an irrelevant statistic in determining its transport process to this position. For as far as it is possible, every item should be examined as it exists in the environment before it is recovered, i.e., in-situ. For materials that necessarily need to be taken out of situ for study, the in-situ context is the grain size of the sediment surrounding it and the location from where the sample was taken from, as well as the size and shape distribution of the plastic particles. The plastic grains will need to be separated from the natural sediment for the analysis, which is no issue as the solution here is in finding reasonable contextualised solution that is based on the scale and capacity of the study. If the collection and processing is explained and performed consistently, it will fit the framework that follows.

Significance of a Framework for Plastic Particle Attributes

A typical description of sediment would not extend beyond the techniques outlined earlier in this paper unless a specialist question was raised. If a study on the surface scratches of sediment grains was required, then the additional observations would be included in the textural observations of the grains, thereby fitting into the existing framework, and enriching the story thusly. It is through the framework and unified understanding of the significance of basic sediment attributes that allows for studies to be related between field sites and enriched where appropriate. Therefore, despite the complexity and diversity of sedimentological data, the findings all follow the same philosophy enabling both simplicity and complexity to co-exist such that the inter-relation of multiple studies can be readily achieved.

In plastic studies, the diversity of characteristics that could be assessed per plastic particle is vastly greater than those of sediment. We presently have no consistent approach and a multitude of unknown unknowns, such that it is critical for the consistent classification to be a flexible framework that can develop for specialist studies. We need a clear and simple structured framework that can be flexibly added to, and even once the significant attributes are known it may still be the most appropriate method, as this approach is one that remains robust and central to sedimentology.

The following classification scheme unites common approaches for observing sediment and plastic with a focus on the characteristics that seem to drive plastic behaviour in the environment, i.e., size, shape, total density, and mechanical properties. Below is the proposed framework that is simultaneously familiar and novel, with the goal to further our knowledge of plastic in the environment.

A Universal Classification Scheme for Plastic

Here we present a unification of the fundamental physical principles of plastic assessment, which is based on the sedimentological approach and includes novel approaches where existing methods are insufficient. This is not just another classification; it is a universally applicable and flexible methodology allowing cross-discipline studies and connecting the physical characteristics of plastic to their processes and accumulation tendencies, thereby enabling deeper understanding from studies, even those of a fixed temporality. Importantly, the core principles are shared with sedimentology, which will allow for the development of comparison between sediment and plastic particles, so that we can establish an understanding of context between sediment and plastic and aid in prediction of behaviour and distribution of particles in the environment. The methodology itself allows for flexibility and development of its components, such that it may provide a consistent framework for a range of studies.

Key recommendations for the methodology are that it ought to be carried out in-situ, i.e., at the site where the plastic particles are found. Additionally, none of the sub-categories below are intended for isolated use; all elements ought to be considered to allow for full description of plastic items of various scales. This includes cases where a trait may not be considered significant in an environment, because the data needs to be comparable to other environments where that trait is significant. To ensure this, a summary sheet of the methodology and a log sheet for recording observations may both be found in the supplementary material (Supp. 1 and 2). Until now, many of the definitions for plastic derive from practical uses, therefore our refinement has continued along this route such that we have a new combined philosophy to consider plastic as a sediment.

Unifying Size Classification for Plastic

Despite the robust size classification scheme for sediment (Fig. 1), it would not be appropriate to directly relate it to plastic because: i) that would be too discordant with prior studies to be of practical use; and ii) it would not divide plastic into categories that are themselves useful for further understanding. Additionally, the properties of artificial materials as compared to natural materials are so variable in size that it makes little practical sense to enforce the classification.

It is recognised that, like all natural materials, plastic size is a continuum (Kooi & Koelmans, 2019), however, plastic is most typically defined into size divisions of nano, micro, meso, macro, and mega, of which there is no settled definitions (e.g., Hartmann *et al.*, 2019). Whilst the scale of sizes is of course a continuum, there needs to be a stepped understanding that is of meaningful use as this is the language used by researchers in the field, as is the case in sedimentology (Fig. 1). The focus of size definitions and justifications therein is often limited in studies; therefore, the boundaries are poorly defined, which is why they are not so fixed between studies. Subject-specific size classifications may be helpful towards a particular study or aim (e.g., Bermúdez & Swarzenski, 2021), but it is not the purpose of a classification scheme to elucidate everything, it is an objective classification that aids understanding the objective character of a particle. Whilst this approach is imperfect, it clears the objective, which is to provide distinction in uniting a fundamental underpinning language and understanding for a wider purpose than one discipline.

In sedimentology, the size classification for all sizes was developed at the same time such that all sizes were categorised from the beginning and used consistently. In plastic research, this has not been the case, which means that different reasoning is given to different size brackets because of focus of the study in which it was decided. If the boundaries for plastic sizes were justified as their names are structured, the prefix “micro” in microplastic would be defined as being between 1 micron – 1000 microns (i.e. 1 millimetre). Yet understandably, to be compliant to the purpose of the study, the boundary definitions have been defined functionally, e.g., the upper boundary for the size of microplastic is 5 mm (Andrady, 2015), which is an upper particle size that is commonly ingested by many marine animals and has the potential to cause harm to them and the rest of the food chain (Arthur *et al.*, 2009).

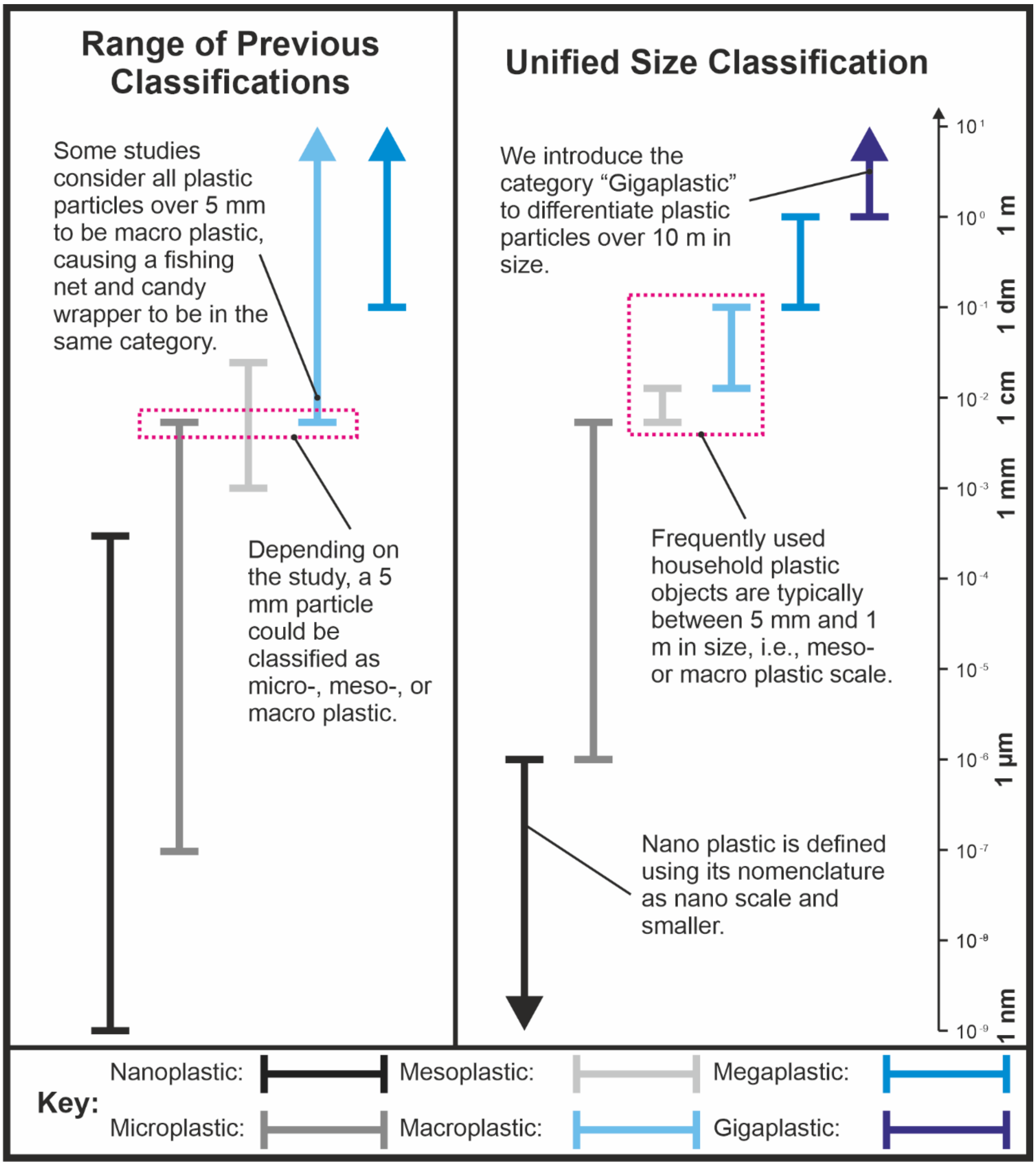

Figure 9 – The combined range of upper and lower boundaries gathered from previous classification schemes, demonstrating a wide range. In the present range of classifications, the same particle could be justified as micro-, meso-, or macroplastic, therefore, the unified and justified revision on the right offers the opportunity to return quantified meaning to these terms. Boundaries from: (Arthur *et al.*, 2009; Barnes *et al.*, 2009; Stamm, 2011; Desforges *et al.*, 2014; Andrady, 2015; GESAMP, 2015; Koelmans *et al.*, 2017; Hartmann *et al.*, 2019).

As studies are increasingly seeking to understand plastic routing, such that the passage of plastic into the natural world can be mitigated, the importance of this unified classification scheme cannot be overstated. This guidance is for the full range of plastic sizes with the boundaries defined by distribution and routing rather than function, offering consistency and a rationale behind the boundaries, which is a universally applicable framework (Fig. 9). Each size boundary is delineated such that it offers insight into where it may accumulate. Even if a study does not directly seek to understand plastic accumulation, for studies to be laterally relatable between disciplines, they need to be routed from a common methodology. In this instance, they are routed between the physics of sedimentology and where humans intervene the natural processes, the functionality of the plastic particle in a societal context.

Nanoplastic (≤1 nm - 1 μm)

There is no minimum size for nanoplastic because they can be smaller than 1nm and therefore ought not to be excluded by setting a minimum size. The definition for nanoplastic is determined practically by the nomenclature, therefore from 1nm to 1000nm (1μm), which aligns with Browne *et al.*, (2007), Andrady, (2015), GESAMP, (2015).

Microplastic (1 μm – 5 mm)

Microplastics are the most intensely studied of all the size classifications. The upper boundary for microplastic has been widely accepted as 5 mm since the NOAA (Arthur *et al.*, 2009) meeting, therefore, it is impractical to move. Therefore, the size boundary from microplastics is from 1 μm to 5 mm.

Mesoplastic (5 mm – 5 cm)

The size increment from 5 mm to 5 cm represents a distinctive size category that represents a functionally distinctive category of pocket-sized, thereby widely portable, plastic items. Many items commonly found in an urban environment such as cigarette butts, sweet wrappers, hair elastics, and much more, are casually readily transported where people travel, therefore we anticipate higher incidence of items this size on streets, in drains, and in street-side refuse bins. It is of particular importance also because items this size would easily fit through the gaps on most drain covers, therefore mesoplastics and smaller represent the most likely size bracket to route to waterbodies via drains. Again, whilst not all studies need to operate in this spatial and temporal framework, by utilising this classification, a deeper understanding of the study findings will be possible.

Macroplastic (5 cm – 1 m)

Macroplastic is commonly the uppermost size consideration attributed to plastic items, but it seems grossly insufficient to consider everything from a pop bottle to a caravan exterior in the same category because they will behave remarkably differently in the environment and accumulate under different physical principles. We most frequently interact with plastic items smaller than 1 m in size, which is reflected by the typical depth of a household refuse bin.

Notably, the presence of and size of a household waste bin reflects the experience of residents of countries with a higher GDP, however the plastic items are typically generated with such consumers in mind, so the size category and functionality of plastic items this size is similar between locations. The upper limit for macroplastics has been placed at 1 m, which aligns with GESAMP (2015), and Andrady (2015), because this is the maximum item size that can comfortably fit into a household waste bin, and much day-to-day waste does not exceed this size. Therefore, in considering human-driven environmental accumulations of macroplastic, it may be of high frequency in landfill sites household waste, dominantly sized macroplastic and smaller, is disposed of.

Megaplastic (1 m – 10 m)

Megaplastic recognises the boundary at which plastic waste is more likely to be taken to a specialist refuse site, rather than disposed of through household waste collection. As such, they may be referred to a landfill site, recycling facility, or to specialists for dismantling composite components. The upper limitation here is 10 m, as this is the boundary at which plastic items are larger than what would be commonly used in the household sector, and are more likely found in the commercial sector. Due to the differences in management of this scale of waste, the way that plastic of this scale accumulates will differ from the other size categories.

Gigaplastic (≥ 10 m)

The term gigaplastic is newly introduced in this study to describe plastic items that are 10 m or over in size. They are differentiated from megaplastic because the larger size indicates a large-scale and specialised process, which are managed and manufactured in set facilities, and possibly decommissioned in a similar space also. As such, there is a gathering of plastic components that may have been part of an aeroplane or train carriage for example, that may independently, or as part of a composite that is, in total, be within this size range. Plastic materials over 10m in size are most used by industries, such as housing, fishing, or commercial transport, so some polymer types and chemical pollutants may be more prevalent.

Novel shape classification scheme for plastic litter

There is a wide variety of complex classifications and descriptors, which may be appropriate for specific studies, but for this basic framework we have refined it to a simple overarching shape describing dimensions, and holes, i.e., the minimum framework requirement for interstudy relatability. It is important to study the shape of a particle because it affects its motion properties and behaviour (Stückrath *et al.*, 2006).

Dimensions

Sediment particles are described by their dimensions as a disc, sphere, blade, or rod (Figure n), which may be directly applied to plastics. It is a scale independent approach because both a fibre and a drainpipe would be considered a rod, and a disc is anything from a paint flake to a vinyl record. This framework aligns with approaches in plastic studies that outline quasi-one, -two, and -three dimensional particles (Chubarenko *et al.*, 2016; Francalanci *et al.*, 2021). For more complex shapes, we can approximate with surprising consistency. If there is uncertainty due to shape complexity, such as protruding elements, or cavities, then this decision ought to be executed via considering the total average shape it will take up in space, e.g., a plastic coat hanger is a disc. Additionally, the length:width:depth ratio (Fig. 5) can be quantified in the field and the category of rod, disc, sphere, or blade calculated later.

Holes

The other component of shape that we assess to classify the character of a plastic particle is the existence and nature of holes. In mathematics, the study of topological homeomorphism can be used to objectively define the number of holes in a three-dimensional shape. Topology is the mathematical study of the properties of geometric objects that are preserved under deformation; a homeomorphism is the mapping and preservation of topological space under topological deformation, i.e., a continuous function between topological spaces with a continuous inverse function. In this classification, we take inspiration from this mathematical concept and use it to describe holes as topological features in plastic particles (Fig. 10).

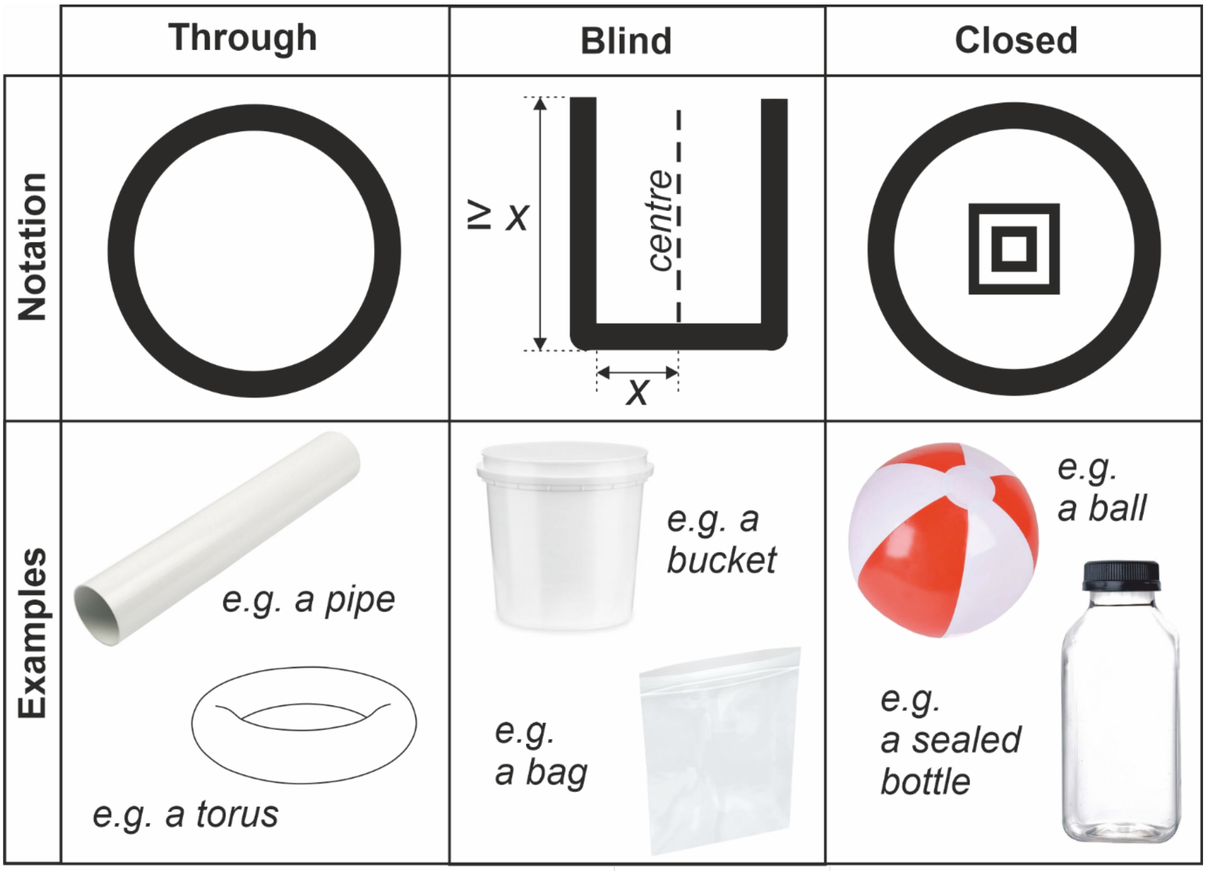

Figure 10 – Demonstrates simple hole examples, and examples. Note that in blind hole, x represents half of the internal width of the container. If the blind hole was not round, x would be half of the internal width of the container at the narrowest point.

Through holes go through an entire object, such as a hole through a pipe or a doughnut and may be objectively defined using homeomorphism. Blind holes are cavities where the hole is a depression in the object, such as the hole that defines a bucket. In this framework, we quantifiably define a blind hole as a hollow whose minimum depth is greater than half of the width of the hole, as measured at the narrowest point on the inside of the hole. If the blind hole has an opening that has an average diameter that is less than the average width of the hole, it is always named a blind hole regardless of the internal depth of the hollow. In this study, we also consider closed holes, i.e., there is no route for material to readily move into or out of the hole.

As well as aiding with the description of an object, each type of hole will contribute to the understanding of how an item will be transported, and perhaps how it will interact with the environment on its journey, i.e., how it may generate microplastics due to abrasion and fragmentation, and how and where it will accumulate.

- **Through holes** are important to consider because, depending on their dimensions, they can create settings of differing depositional and biological environmental conditions inside.
- **Blind holes** are important because they can create protected microenvironments for sedimentation, and internal surfaces are less likely to become abraded.
- **Closed holes** are important because they are a concealed environment and if they trap air, water, or sediment, they may affect the net density and thus buoyancy of the plastic item and are therefore critical to understanding the mechanics of plastic in the environment.

If we consider a sphere of plasticene, anything that it can be moulded into without breaking it into multiple pieces, breaking the surface to form a through hole, or joining it up in places to form a through hole, is considered homeomorphic with that sphere. As such, the shapes of a soccer ball, a bucket, an open crisp packet, or a dinner plate are homeomorphic to a sphere, as they can be moulded from one shape to another without breaking the surface. Within these examples, a dinner plate has no holes, a soccer ball has a closed hole, and the bucket and open crisp packet each have a blind hole, though none have through holes because if they did, they would not be homeomorphic with the sphere.

A through hole, disrupts the topological space of a sphere, thereby defining a new principal shape as exhibited in Figure 11 by a doughnut. The doughnut on the right of Figure 11 is homeomorphic with a pipe, a funnel, or a straw, as each has one through hole so can be moulded from one to another without disrupting the topological functions. However, a mug is also homeomorphic with a doughnut, as it has one through hole, though also demonstrates a blind hole. The blind hole, where you would put your coffee, can be removed through topologically deforming the object and so does not disrupt the continuity of the topological function. Therefore, if the mug had no handle, it would be homeomorphic with a sphere. Figure 11 shows how a mug is famously homeomorphic with a doughnut.

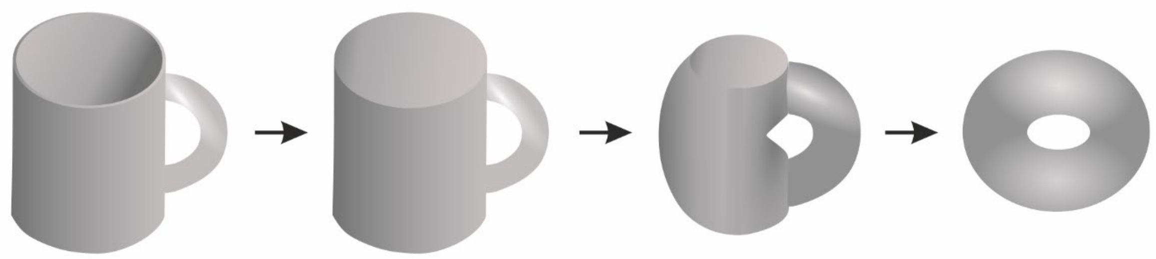

Figure 11 – A famous topological shape is how the mug can morph into a doughnut, i.e., a torus. The blind hole in the mug may be filled in and as the mug becomes its most simple topological form, the torus results.

It is through describing the number of each type of hole that we can record key characteristics of a plastic particle. The methodology of recording holes is scale-independent and can apply to any level of complexity through the notation: TnBnCn (Fig. 12).

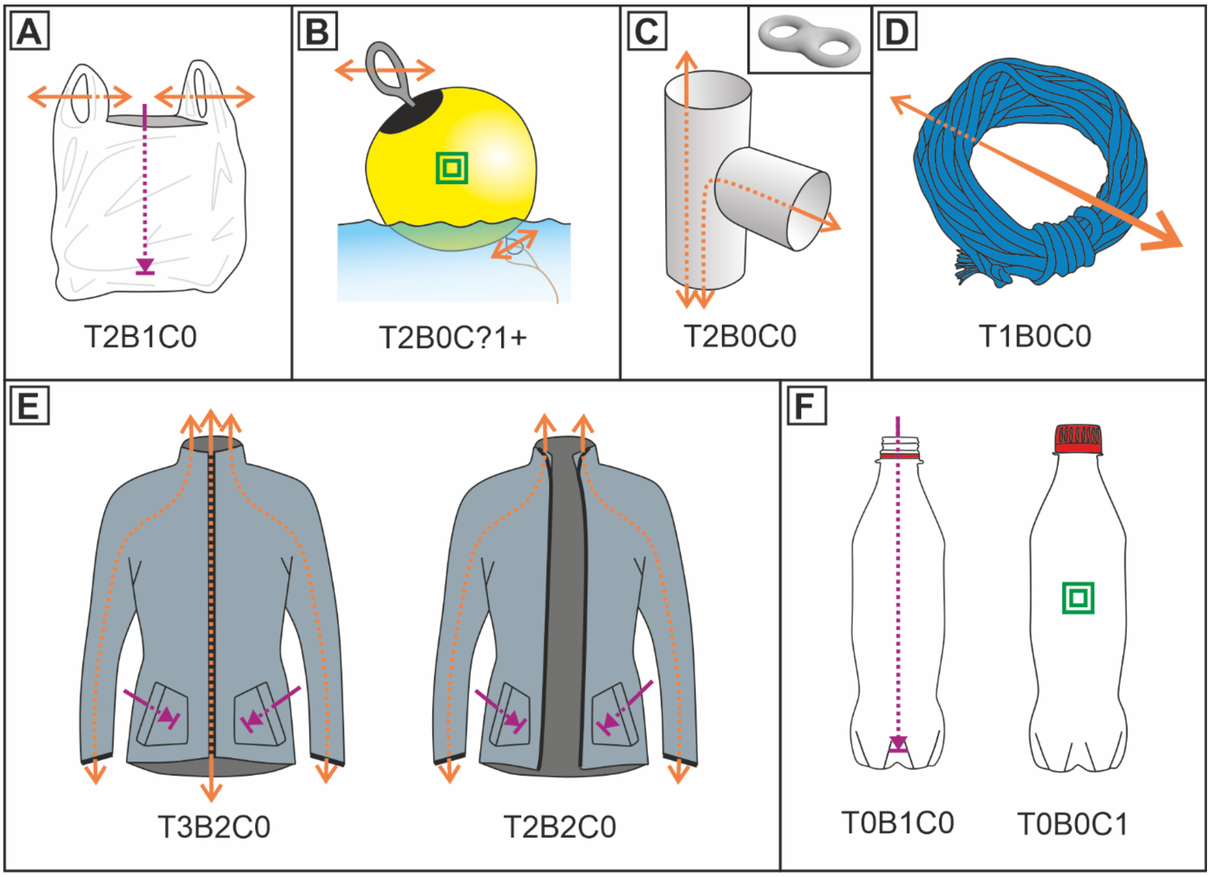

Figure 12 – Examples of the application of the hole descriptor methodology. Purple arrows represent blind holes, orange arrows are through holes, and green symbols are closed holes. A) A plastic bag where the handles are through holes and the bag itself is a blind hole; B) an ocean buoy where there is opaque plastic and at least one closed hole assumed, and two through holes; C) a pipe junction with two through holes, as its homeomorphic alternative is a double torus as shown in the insert; D) a coil of rope with one through hole; E) a jacket with two pockets both zipped up and unzipped, where the zipped jacket has an additional through hole than the unzipped jacked; F) a bottle with no lid on exhibiting a blind hole, and a bottle with a lid on exhibiting a closed hole.

There are three additions to the notations that aid clarity of observation:

1. Where the shape becomes more complex, it is key to decide how much detail to record whereby the behaviour of an item will not be better constrained by increasing

the accuracy of the description. As a baseline for this this framework we suggest 10 of each type of hole, and this will change with different studies. To notate this, if the plastic particle demonstrates more than 10 examples of a hole type in an item, notate as 10+, e.g., polystyrene foam packaging would be notated T0B0C10+. For very complex objects, such as a 3D printed model where there are numerous through holes, blind holes, and closed holes, it would be notated as T10+B10+C10+. For the purposes of understanding its environmental behaviour, from this we can determine that it is a complex and porous object, which is significant.

2. If the item is made of a polymer that is opaque, but at least one closed hole is suspected, a question mark (i.e., "?") is used to precede the minimum hole value and show that it is an interpretation. For example, the ocean buoy in Figure xB is made of an opaque yellow polymer and therefore it is not possible to constrain if a closed hole is present, and how many may be present, yet it is suspected, so it is notated T1B0C?1+.
3. Additionally, we must consider textures that are themselves composed of through holes, such as a net, fabric, or rope, as they have the capacity to hold water and other material and change its function as a result of its porous properties, as well as shed microfibres. Whilst a simple net may be notated as T10+B0C0, challenges arise when considering a fishing net where the mesh is shaped into a blind hole, as the net itself is composed of through holes, thereby invalidating the existence of a blind hole. The efficacy of a scale dependency for hole categorization is limited when applied to the range of mesh sizes, so instead we use a notation for texture: i) where the material is composed of more hole than solid is notated as "net", so a mesh is notated as TnetB0C0; or ii) where the material is composed of more solid than hole is porous and notated as "por" for porous, so a towel is notated as TporB0C0.

Whilst it is important to record all the holes in an object, some will be more important than others in defining the shape and function of the object in the environment, e.g., a pipe with a small hole drilled into it would notate as T2B0C0, but the small hole may not be of importance to the sedimentary dynamics. As such, a secondary and *interpretive* note is made with the goal to minimise deep consideration of incidental holes that do not aid to understand the overall shape of the object. This additional note is an entirely subjective and interpretive operation but sets an important philosophy to prioritise descriptions.

Additional parameters for observation

There are two additional parameters that ought to be observed and they are considered separately here as they are comparatively more subjective considerations than the size and shape of the item. The parameters that we consider in this section are the net density and polymer type, and the chemical, electrical, and mechanical properties of a plastic particle. Each of these has important impacts on how plastic will behave in the environment, therefore it is included as a critical component for observation so that plastic particles can be fully considered in context with sedimentary particles in the environment.

Net Density and Polymer Type

In sedimentology, the density of a sediment grain normally directly relates to its mineralogy or composition, for example, the density of quartz is 2.65 g/cm^3, which is the typical density of quartz-rich sand. The density of plastic ranges from < 0.05 to 2.3 g/cm^3 (e.g., Chubarenko *et al.*, 2016), which is significantly different to the average for natural materials. However, there are natural materials such as amber, which have a similar density to plastic and have been studied to compare the environmental behaviour (Chubarenko & Stepanova, 2017). Additionally, pumice is a naturally occurring volcanic rock (2.65 g/cm^3 - 3.3 g/cm^3), which, illogically from density alone, can float on water. Pumice can float because it is porous, i.e., full of air bubbles, so can form rafts on rivers, lakes, and oceans. As time passes, the porosity in the pumice becomes water-logged, so the pumice will settle to the bottom of the water body. The properties of pumice in the environment are determined by its net density rather than the molecular density of the rock itself.

The absolute density (Ad) (also often referred to as relative density) is an important parameter because it controls the buoyancy of the plastic particle. In water, positively buoyant items (Ad < water density) will float on the water surface while negatively buoyant (Ad > water density) items will settle though the water column, eventually reaching the sediment bed or seafloor. Neutrally buoyant items (Ad -1 ~ water density) have an absolute density equivalent to that of water and will suspend within the water column. When considering the transportation of the particle, the buoyancy determines the shear stress required to initiate and sustain motion, as well as the settling velocity (Ferguson & Church, 2004), which in turn impacts its Rouse number (Eq. 5). As such, it is critical to consider absolute density of a particle such that we can understand its motion in transport and identify areas of accumulation. Additionally, the Ad value ought to be considered in relation to the size of the particle, such that the submerged specific gravity (R) may be calculated (Eq. 4), and multiplied with the diameter (D) to find the RD value of the particle (Russell *et al.*, 2023). The RD value is important because two items may be of the same density, but different sizes, therefore may behave differently in the environment.

The material properties of a particle in the environment may change over time due to effects of weathering, chemical leaching (Persson *et al.*, 2022), and growth of biofilms (Galloway *et al.*, 2017; Burns & Boxall, 2018; Mendrik *et al.*, 2023), which will change the Ad of the particle over time. Additionally, plastic may be combined with natural components such as water, sediment, and air, which may alter its mobility in the natural environment, also through affecting the particle's Ad value. Figure 13A shows how a bottle with a lid on, exhibiting a closed hole, will have different buoyancies in fresh water depending on the composition of the materials in the closed hole. In Figure 13B, we see the closed hole is now a blind hole as the lid is off for each bottle depicted. As a bottle with no lid on moves through the environment, it may temporally change its Ad value, whereas if the lid is secured, the Ad value is more fixed. If a bottle is full of air and discarded with the lid on, it will likely remain buoyant for a longer time than a bottle with no lid, which may become partially or entirely filled with water or sediment.

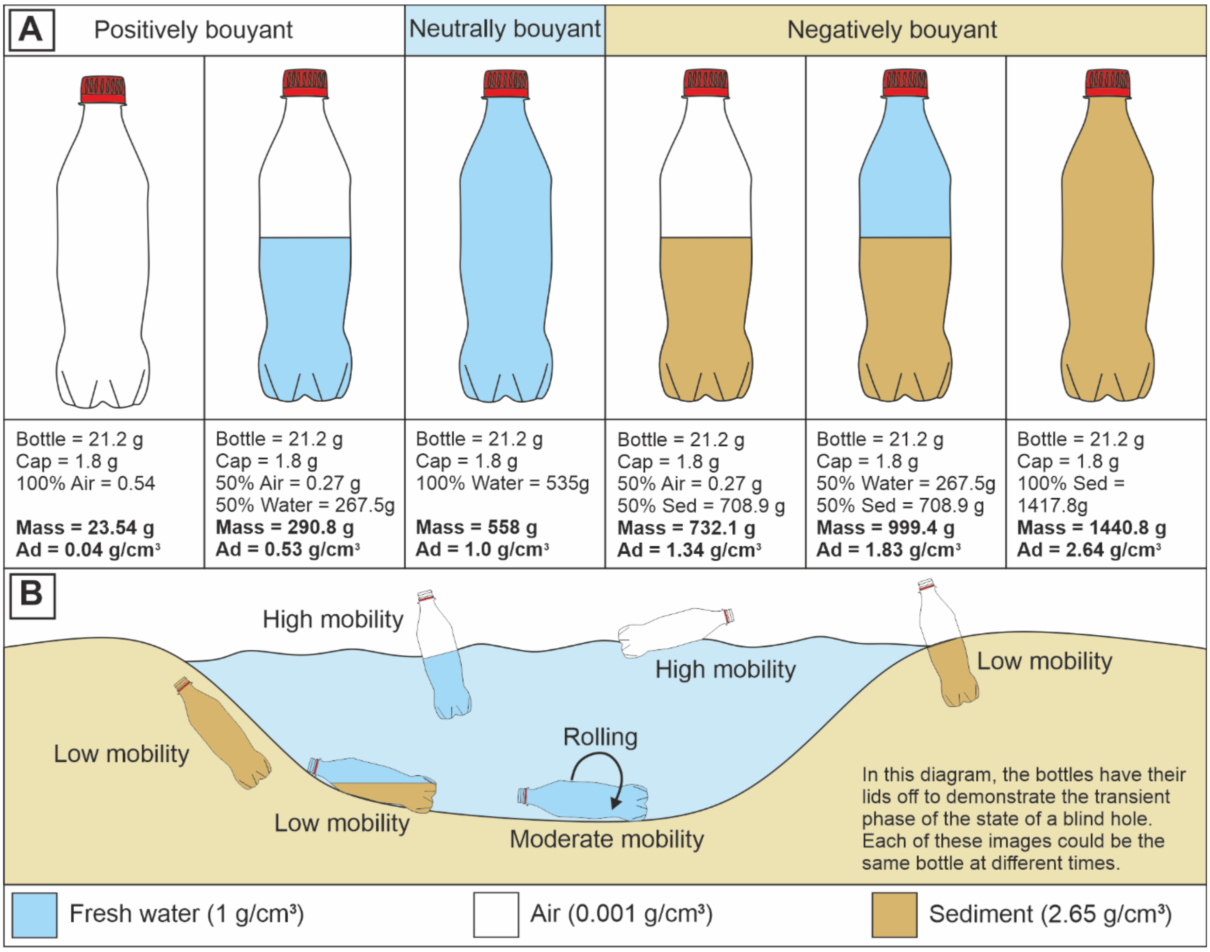

Figure 13 – A) A demonstration of the importance of using Absolute Density (Ad) over plastic density. The bottles represented in the figure are 500 cm^3, made of polyethylene terephthalate (1.38 g/cm^3), and the bottle lids of polypropylene (0.92 g/cm^3). The bottle can hold up to 535 cm^3 (internal volume – used to calculate bottle content) and displaces 545 cm^3 of water (external volume – used to calculate Ad). B) The impact and importance of different Ad values in the environment.

Many commonly produced plastics (50-60% of all produced) are less dense than water, so float on water (Lebreton *et al.*, 2019), and some plastic types are the most resiliently buoyant particles in the natural environment and may be hydrophobic. The transience of the floating phase of plastic materials prior to their eventual burial is longer than for most natural particles, therefore we need to discuss the terminology for how we characterise them. Floating plastic particles sit at the air – water barrier, so are mobilised and transported by different processes (Roebroek *et al.*, 2021), such as wind, as they interact with different components of the system, e.g., floating plastic is more likely to be caught in tree branches, or collected on environmental clean-up operations, than material that travels in the water column or interacts with the riverbed (Vriend *et al.*, 2020).

If we seek an existing widely used terminology that is applicable for floating material that may be vegetation, engineered, or natural sediment, we find that the closest term is “wash load”. Wash load represents the finest, therefore most mobile, fraction of the suspended load, so it is in near permanent suspension during its transport. Wash load is considered a function of the upstream catchment i.e., not related to the transport capacity of the flow, but on the rate at which sediment becomes available, so it is not easy to quantify with standard sediment transport models and must be quantified through site-specific measurements (van Rijn, 1993). As such, we find that there is no broad and widely-used term for floating sediment that can account for all of vegetation, engineered materials such as plastic, and natural sediment.

It is clear however that the term ought to begin with “floating” rather than “positively buoyant” or a variation of this, as “floating” is common between disciplines and studies. For example, for sedimentology studies, “floating pumice raft” (e.g., Manville *et al.*, 2002), for plastic studies, “floating plastic” (e.g., van Sebille *et al.*, 2015), and for vegetation studies “floating vegetation” (e.g., Schreyers *et al.*, 2021), and additional variations therein such as “floating debris” (e.g., Lebreton *et al.*, 2019).

If we turn to plastic studies for a solution, the term “floating plastic” could never logically extend to sediment or vegetation, and “floating item” (e.g., Bravo *et al.*, 2011), limits the observer to what would be subjectively perceived as an item. A grain of sand would rarely be considered an item, so the above existing terminologies persist the separation between natural sediment and manmade materials that we are seeking to unite.

The term “floating particles” is an option, but infers the particles themselves rather than inferring the motion of transport in its moved “load”. To emphasise this point, one would describe “bedload” in motion, and “bedload particle” properties. Therefore, if the first part of the descriptive framework tool must be "floating", the second must be "load", such that we may unambiguously discuss all material that floats on a waterbody as an element of the sedimentary system; here we coin the term "**floating load**". We consider this to be a minor, yet important adjustment of the existing frameworks that will have important repercussions in unifying our understanding of what forces act upon the transport of plastic as a sediment (Fig. 14).

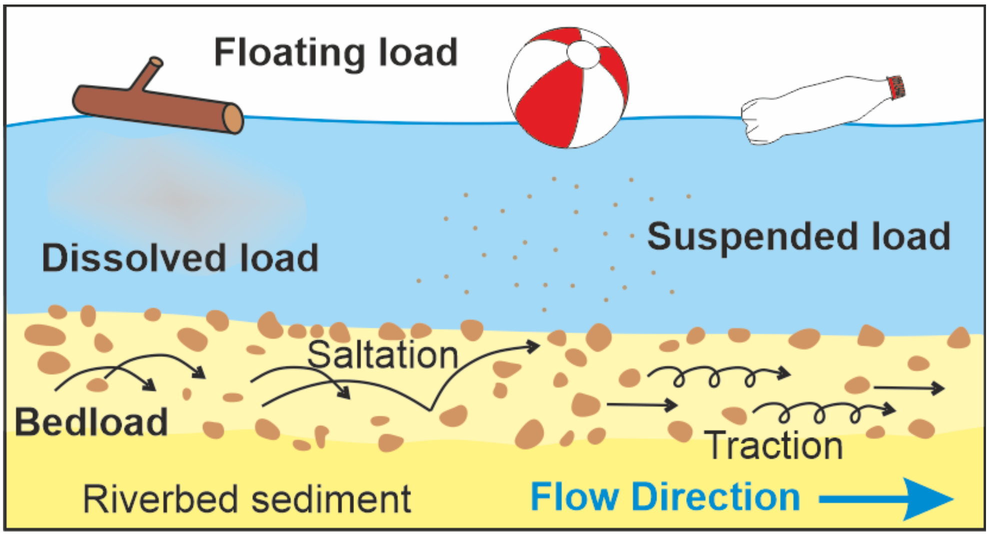

Figure 14 – A figure to show the variation of transport of natural sediment in open channel flow (e.g. rivers)

Chemical, electrical, and mechanical properties

Plastics have a greater range of variability in chemical, electrical, and mechanical properties than natural sediment, which are constantly changing in the environment (Galloway *et al.*, 2017) and affect its durability (Thompson, 2006). As well as mechanical fragmentation, plastic particles can photo- or thermo-oxidise, undergo hydrolysis, and biodegrade (Gewert *et al.*, 2015; Dimassi *et al.*, 2022). For example, molecular changes to the polymer type and leaching additives, may lead to increased brittleness, thereby exacerbating its ability to fragment into microplastics (Song *et al.*, 2017), such as a flexible polymer may become more brittle through exposure to humidity or UV light (Lopez *et al.*, 2006). Rates of change and fragmentation of plastic depends on the polymer and its morphology and degradation grade, but this remains poorly investigated outside laboratory conditions (Gewert *et al.*, 2015). Therefore, whilst the polymer type is helpful to know, it does not reliably solve the objective description of the properties of a plastic particle in its temporarily present condition. Therefore, whilst plastics are a new category of sediment, the mechanisms by which sedimentology works are clearly insufficient to manage description and understanding of plastic behaviours, as we have outlined through this manuscript. However, by describing key properties, we can add to our descriptions and knowledge of the distribution of, and relative importance of, plastics with certain properties across the environment.

To record plastic properties, and therein the transformation of durability of plastic polymers, we here propose to assess individual characteristics of plastic particles. Such insights will enable better modelling of particles and help us to understand how plastic behaves as a sediment particle. This section is a preliminary review of the range of behaviours that we need more specific studies on, and explanations of how those properties may impact the potential behaviour and disintegration of plastic in the environment.

Property	**Description**	**Importance**
Colour	Predominant colour of the plastic item or particle	Variation in temperature due to differences in light absorption may vary degradation and fragmentation rates. Certain colour might attract specific organisms that mistake plastic items for food potentially influencing the transportation and deposition history of the plastic particle (Ryan, 2016).
Opacity	No light can penetrate the item through the polymer itself. Holes and porosity are not included here.	Although UV protection may be on some transparent items (Sackey *et al.*, 2015), opacity versus translucency can signal UV transparency and therefore potential influence of UV light on its degradation, so may impact the items structural longevity. Additionally, it affects the ecology that may develop inside or underneath it. Colour also ought to be recorded (Martí *et al.*, 2020)
Transparency	Some to almost all light can penetrate the item, such that it does not significantly obscure the view behind the item. Translucency is included in this category.	
Brittleness	The material will break or shatter without significant deformation when under stress	Brittle plastics are stiffer and have lower impact strength, except for reinforced plastics (Rosato & Rosato, 2003). A brittle plastic in the environment may more readily disintegrate to microplastics than one that it more flexible and can deform
Plasticity	The material can undergo irreversible or permanent deformations without breaking	

	or shattering	plasticly (Tang *et al.*, 2019).
Softness	It can be readily marked by another object	Hardness can be quantified using methods such as the Brinell hardness testing or Mohs hardness scale, and is a characteristic of durability that is related to brittle and plastic properties (Gerberich *et al.*, 2015). A harder plastic may be more abrasion resistant than a soft one, and therefore be more resistant to fragmenting into microplastics
Hardness	The material is more able to withstand surface indentation and scratching	
Flexibility	A material that can be bent or stretched repeatedly without breaking in response to an applied force	Materials with these properties can become more brittle and less flexible or elastic under high humidity and UV light exposure (Lopez *et al.*, 2006; Dimassi *et al.*, 2022), so may readily degrade to microplastics, but it is a more temporally complex response, therefore important to record.
Elasticity	Where a material can return to its original size and shape after being deformed by an applied force	
Static electricity	Electric charges within or on the surface of a material may affect its tendency to attach to other materials.	Attachment to other particles, such as plastic, minerals, and water, affect its ability to float or sink. Where plastics are charged, they may flocculate with themselves or clay minerals (Besseling *et al.*, 2017; Andersen *et al.*, 2021). Where a plastic is hydrophobic, it strongly affects its ability to biodegrade (Dimassi *et al.*, 2022) and may enhance surface tension to form air pockets that aid buoyancy.
Hydrophobicity	Where the properties of the molecule seemingly repel water, it is described as hydrophobic. In some studies, this is referred to as the plastic particles “Wettability” (Waldman & Rillig, 2020).	

Table 2 – A summary of key properties to assess of plastic particles in the landscape that may provide information on its ability and present tendency to produce microplastics.

Implications for sediment and plastic transport modelling

This new methodology has implications for sediment and transport modelling in that through using the framework consistently, we will be able to understand plastic behavior more accurately in the environment and identify knowledge gaps. Sediment grain size and plastic concentration can be correlative (Enders *et al.*, 2019), so forms an important starting point for how we shape our understanding of plastic routing in the environment. For example, consider a sediment particle with density ρ_s and volume V_s and a PVC particle with density ρ_{PVC} and volume V_{PVC}. The weights of these particles are $W_s = \rho_s g V_s$ and $W_{PVC} = \rho_{PVC} g V_{PVC}$. Assuming that the sediment and PVC particles have the same volume ($V_s = V_{PVC}$), the sediment particle has a density of 2.65 g/cm³ (quartz) and the PVC particle a density of 1.2 g/cm³, the ratio of their weights becomes $W_{PVC}/W_s = 1.2/2.65 = 0.45$. The PVC particle is 0.45 times the weight of the sediment particle or inversely $1/0.45 = 2.2$ times more mobile. When the particles are under water, the relevant weights for the calculation are the submerged weights, i.e. $W = (\rho_s - \rho)gV = \rho gRV$. In this case, $R_s = 1.65$ and $R_{PVC} = 0.2$. The ratio of the submerged weights becomes $R_{PVC}/R_s = 0.2/1.65 = 0.12$. Under water, the PVC particle is 0.12 times the weight of the sediment particle or inversely $1/0.12 = 8.25$ times more mobile.

However, we must remain mindful of the limitations that arise due to the diversity of plastic particle characteristics in size, shape, net density, and material properties. We can use these existing equations as a starting point and see what the resulting numbers would be but cannot assume that it is right without testing as in many cases, we may require entirely new understandings. For example, using the Corey shape factor coefficient, 1D, 2D, and 3D shapes have been found to settle differently across different flow regimes (Francalanci *et al.*, 2021), and bedload sediment transport is affected by particle shape (e.g., Deal *et al.*, 2023), providing important insight into a particle characteristic that sedimentology had not sufficiently considered. Material such as paint flakes seem to align with existing models (Enders *et al.*, 2019), but other materials, even in simple shapes, may not (Chubarenko & Stepanova, 2017; Khatmullina & Chubarenko, 2019; Waldschläger & Schüttrumpf, 2019b; Mendrik *et al.*, 2023), and films and fibres introduce additional uncertainty due to their properties, particularly particles that change their shape when settling (Zhang & Choi, 2021; Choi *et al.*, 2022). A bottle with no lid, or an item of clothing, both have a high level of unpredictability, so determining its precise environmental routing may never be possible, but probabilities can be determined. Present knowledge and practices in sedimentology offer a starting understanding that can offer insight into knowledge gaps. Incorporating such probabalistic dependencies into models will be an important next step (Khatmullina & Chubarenko, 2019). Other approaches to manage such uncertainties are entropy theory

(Khorram & Ergil, 2018), ensemble, or accumulation, forecasting (Shamshirband *et al.*, 2019), and machine learning algorithms (Goldstein & Coco, 2014). Additionally, progress is needed in understanding heterogeneous mixtures in the environment, from differences in size to differences in particle properties, and how this will in turn impact hiding effects and broader-scale dynamics of sedimentary environments (Pohl *et al.*, 2020; Russell *et al.*, 2023).

Whilst the physics are consistent in a fluid, how particles behave with characteristics such as elasticity, are not understood, and presently not consistently documented in the field. However, we now have a new methodology for approaching the description and recording of plastic particles, which can be applied in both the field and laboratories. Therefore, the inputs for models and machine learning techniques can be improved as we seek to understand the passage and accumulation of our new sediment in the environment.

Practical Application of the Methodology

To ensure that the methodology outlined is easy to use consistently, a summary sheet and log sheet for recording the data have been provided as supplementary material (Supp. 1 and 2). The bar along the top of the sheet aids to record the precise location, therefore the environment, and in-situ information of the study site. The first column allows for numeration of the plastic particles which is useful for later reference. The second narrow column may be used to indicate which items may be related or composite, which is explained and demonstrated in Supplementary Material 2. The long axes in each direction is the recorded, which in turn define the dominant shape as sphere, disc, rod, or blade (S, D, R, or B respectively). The total number of through holes, blind holes, and closed holes are recorded under All T,B, and C, and the holes that define the shape as most important are then recorded under Dominant T, B, and C. If the material is known, it may be recorded under "Material", followed by recording of Mass, Volume, and Absolute Density. Equations for determining each are in Supplementary Material 2. Finally, colour, texture, and properties are recorded, and the defining properties ought to be recorded first with the secondary properties following. In other information, if the item can be named then it is listed here along with any other key characteristics that are not otherwise recorded.

Locality________________ Grid Reference______________ Date__________ Sheet____of____

No.	Axes			Shape	All			Dominant			Material	Mass	Volume	Abs. Density	Colour	Texture	Properties	Other information
	Long ℓ	Interm. i	Short s	(S/D/R/B)	T	B	C	T	B	C		M	V	Ad				

Figure 15 – The recommended methodology for recording the data of plastic particle attributes.

Conclusions

Our understanding of plastic behaviour in the environment is presently limited by the variety of classification schemes, and what each scheme records therein. Sedimentology teaches us the power of having one universally recognised classification; findings and discoveries can be built into one unified understanding that advances our knowledge of the physical attributes and behaviours of sediment in the environment. Plastic studies have a variety of aims and objectives, such that the schemes used are often sufficient for the realm of the study. However, studies are increasingly seeking to draw broader conclusions for their findings that require integration with an environmental understanding, which sedimentology provides. Even where studies seek to take a snapshot of plastic composition in an area, these tools will help towards integrating that study into a broader understanding of environmental plastic. The scheme proposed in this manuscript treats plastic as a sediment and may be used in any environment, and even extended to describe a range of materials and composites beyond plastic. As such, we unify our definitions of plastic with sedimentology providing the connecting philosophies: i) to objectively observe the plastic particle before interpretation; ii) to allow for temporal context; and iii) to understanding the significance of the recorded attributes. We propose methodologies for quantifying the size, and shape of a plastic particle, and discuss net density and material properties.

- For size, we reflect on the meaning behind each division and find that size can be meaningfully connected to function and site of accumulation.
- For shape, we quantify the dimensions to classify an overall shape and then discover the number of and nature of the holes in the item.
- For density, we discuss the importance in assessing the absolute density of the item rather than the density of the polymer, as it is more helpful for understanding the broader context and mobility of the plastic particle.
- For material properties, each element we seek to note has implications for its behaviour in the environment that we are just beginning to understand.

The methodology is accessible, and the logging sheet and summary sheet are in the supplementary materials (Supps 1, 2). The methodology outlined in this paper fills this critically required need to redefine the way that we view plastic in the environment, so this novel framework will allow for this and for our understanding as plastic as a sediment to develop. Additionally, it is important to note that application of this methodology is not just restricted to plastics, but the approach may be applied to any natural or anthropogenically produced particle, as plastic is not the only anthropogenic component of concern in the landscape (Kiessling *et al.*, 2019).

Limitations and Future Work

The central limitation to this methodology is arguably in its complexity and we urge readers to study the summary sheet (Supp. 2) for clarity. As we are still in the phase of the third philosophy of sedimentology, to understanding the significance of the recorded attributes, we are not yet able to reasonably simplify the methodology. To simplify before we understand the parameters and their implications therein, is to limit observation. Future work ought to seek to populate our understanding of variability in plastic in the environment and therefore establish how much precision we need in these studies. Additionally, where complexity of a plastic particle is high, its shape and form may not be sufficiently considered, however extensive thought was provided to this dilemma and further complexity to the method was not workable. We encourage this manuscript to be viewed as an interim point for the understanding of plastic as a sediment and there are many outstanding questions, all of which will aid in understanding the complexities of plastic in the environment.

Competing Interests

The authors have no competing interests to declare.

Supplementary Material

Locality____________________ Grid Reference__________________ Date___________ Sheet____of____

No.	Axes			Shape	All			Dominant			Material	Mass	Volume	Abs. Density	Colour	Texture	Properties	Other information
	Long ℓ	Interm. i	Short s	(S/D/R/B)	T	B	C	T	B	C		M	V	Ad				

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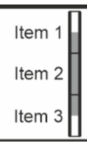
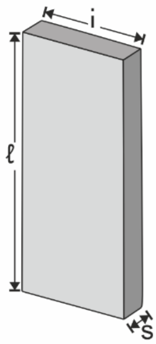
Summary sheet for classifying plastic as a sediment

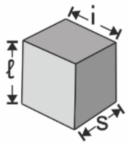


Multiple joined particles are a "compound" item. Describe each item separately and indicate that they are related through using the narrow column on the log sheet. In a set of 3 (or more) items, the first and second boxes will be filled in the lower and upper halves respectively and the middle box(es) entirely filled.

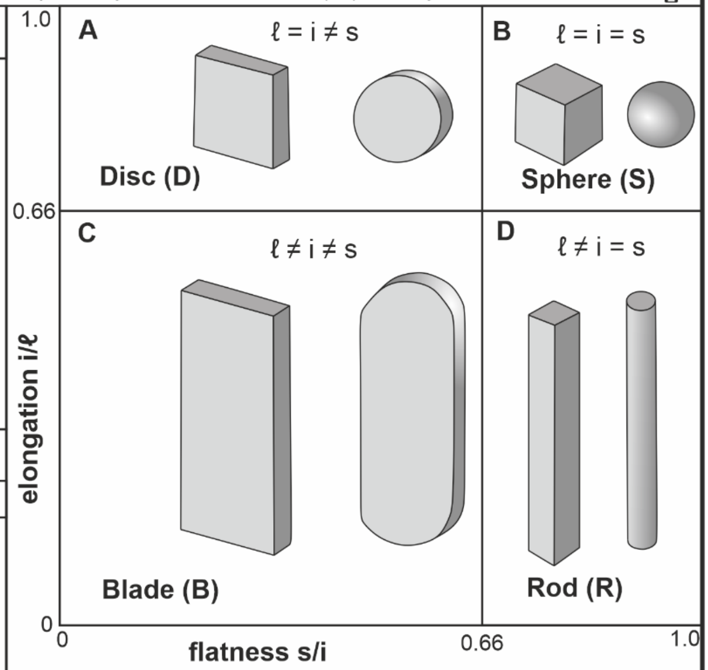
Dimensions



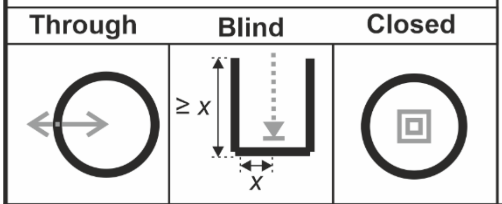
Nanoplastic (≤1 nm - 1 μm)
Microplastic (1 μm – 5 mm)
Mesoplastic (5 mm – 5 cm)
Macroplastic (5 cm – 1 m)
Megaplastic (1 m – 10 m)
Gigaplastic (≥ 10 m)



The longest measurement in each direction is recorded.



Types of Hole



Hole Notations

- Number of holes : Through; Blind; Closed = TnBnCn
- If a number exceeds 10 as 10+, e.g., T10+B0C0
- If the item is opaque but at least one closed hole is suspected notate with "?" e.g., T0B0C?1+
- If the material is more hole than solid, notate as "net" e.g., TnetB0C0
- If the material is not solid, but more solid than hole, notate as "por" for porous e.g., TporB0C0

Dominant holes are the ones that define the structure of the item. It is interpretive so may be a factor of function.

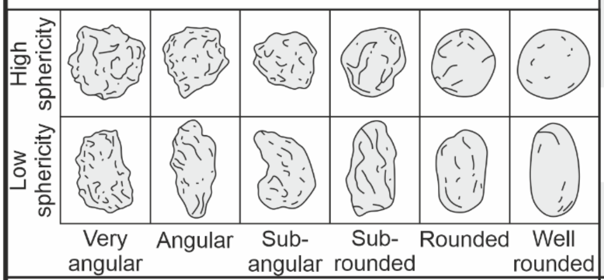
Colour

The dominant colour of the item should be recorded and if there is no colour, record as "colourless".

Material Properties

O - Opacity No light can penetrate the particle itself.	**T - Transparency** Some to almost all light can penetrate the particle.
B - Brittleness Breaks under stress without significant deformation.	**P - Plasticity** Can be permanently deformed without breaking.
S - Softness Can be readily marked by another object.	**H - Hardness** More able to withstand surface indentations.
F - Flexibility May be repeatedly stretched without breaking.	**E - Elasticity** Returns to original size and shape post deformation.
St - Static Electricity May have a tendency to attach to other materials.	**Hy - Hydrophobicity** Where the item properties seemingly repel water.

Surface texture



Convert absolute density, mass, and volume

$$\textbf{Absolute Density} = \frac{\text{mass}}{\text{volume}}$$

$$\textbf{Mass} = \text{absolute density} \times \text{volume}$$

1204

$$\textbf{Volume} = \frac{\text{mass}}{\text{absolute density}}$$

Other Information

- If the shape is further definable (e.g., curled / twisted) or object is recognised, include details or item name here.
- Include information on the status of the item in relation to physical environment, i.e., content of sand, water, or air.
- Any biological activity can be noted here, e.g., algal films or other growths / interactions with fauna.
- If alterations to the item exist, interpretations on the natural or mechanical derivations can be noted.

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