This paper is a non-peer reviewed preprint submitted to EarthArXiv. It is being submitted to Journal of Geoscience Education.

Title:

Microplastic transport and settling in the ocean: an interactive online teaching model to communicate scaling in environmental pollution

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Abstract

Microplastics pervade the sea surface, the water column, and the deep seafloor. They are vectors for other pollutants, such as heavy metals and persistent organic pollutants. A question remains as to how microplastics reach the seabed, over what time scales, and where they will end up. Many plastics initially float due to their low density, or to being incorporated into items with air cavities, but this buoyancy can reverse over time due to the growth of biofilms, or mineralisation of surfaces, and the breakdown of larger plastic objects. Understanding the spatial and temporal scales of ocean pollution is challenging, e.g., how can we understand the behaviour of a single microplastic bead in an ocean the size of the Pacific? Traditionally, particle settling is expressed using simple equations to express settling velocity in 1D. Here we provide two interactive online models for students to investigate the fate of microplastics floating in 1D, replicating a laboratory, and 2D replicating an ocean. Microplastic densities, sizes, biofilm growth, water salinity can be varied. In the 2D case an ocean surface current shows the distance which microplastics may float before sinking due to biofouling. Simple exercises can be developed for classroom teaching allowing students to test these parameters in a fun applet-based platform. Depending on the pedagogical objectives, students can use a range of provided parameters, or perform research to find their own. A series of exercises are provided, and an analysis of their use in the classroom is presented. This active learning model has clear pedagogical benefits over simple passive learning approaches, communicating environmental pollution and the scales of earth systems, for students from high school to university levels and in classroom, hybrid or remote teaching scenarios.

Introduction

The infamous 'ocean garbage' patches are now synonymous with ocean pollution and are perhaps the most easily recognisable evidence that humans are polluting the oceans and causing harm to the creatures that inhabit them (e.g. Van Sebille et al. 2012; Lebreton, 2022). It is relatively easy for students to develop a simplistic conceptual understanding of these masses of floating plastic waste, however, their smaller more insidious counterpart, microplastics, are less visible and therefore more difficult to understand conceptually. Microplastics are small plastic particles and fibres, which are found in the all environmental compartments investigated so far (e.g. Taylor et al., 2016).. Microplastics have been defined as ranging from <5 mm to 250 μm in diameter (Arthur et al., 2009; and many others), however, here we follow Browne et al. (2011) and Claessens et al. (2011), and other subsequent prominent investigations of microplastics (e.g. Van Cauwenberghe et al., 2013, 2015; Vianello et al., 2013; Dekiff et al., 2014) who suggested that <1 mm is more logical as this size class predominates in marine environments, and 'micro' generally refers to micrometer size range. Microfibres typically have lengths of 50 μm up to a few mm, and a diameter of <10 μm. Primary microplastic particles are either manufactured (e.g. microbeads in cosmetics, blasting media and other industrial applications; Zitko & Hanlon, 1991; USEPA, 1992; Fendall and Sewell, 2009; Mason et al., 2016), or secondary, when derived from the breakdown of larger plastic debris (e.g. Andrady, 2011; Cole et al. 2011; ter Halle et al., 2016). Microfibres are derived from synthetic and semi-synthetic (i.e., modified natural fibres) textiles and are commonly discharged from waste water treatment plants into rivers (e.g. Browne et al., 2011; Dubaish and Liebezeit, 2013).

Plastic waste in the marine environment has been extensively documented since the 1970s (e.g. Buchanan, 1971; Carpenter and Smith, 1972; Colton et al., 1974; Gregory, 1978); however it was later that the marine plastic problem attracted significant scientific and societal attention, when it became clear that plastic waste was having a negative effect on marine wildlife, particularly larger fauna such as dolphins and turtles (Barnes et al., 2009; Gall and Thompson, 2015). Microplastics were documented as early as 1972 on the surface of the Sargasso Sea (Carpenter et al., 1972), however, the potential consequences of microplastics for ocean life are only now beginning to be understood. Microplastics are readily available to many organisms throughout the marine food-web, either through consumption or being incorporated into tissue, and biomagnify up the food chain. Furthermore, as microplastics can be subject to adhesion and adsorption of a range of pollutants, and their potential to release toxic compounds as they break down, they present a considerable ecotoxicological threat (Teuten et al., 2009; Cole et al., 2011).

Given their typical low density, microplastics are extremely mobile in the environment, and have long residence times. Consequently, they are found globally, from the beaches of isolated oceanic islands (Costa and Barletta, 2015; Lusher, 2015), within Antarctic currents (Lusher, 2015), to the seafloor of the Arctic (Bergmann & Klages, 2012; Bergmann et al. 2017; Kanhai et al. 2019) and the sea ice above it (Bergmann et al. 2017). Our understanding of the locations of microplastic accumulation in the marine realm is limited, and in particular the seafloor distribution is poorly constrained (Thompson et al. 2004; Barnes et al., 2009; Ballent et al. 2013; Woodall et al. 2014; Martin et al., 2017; Kane & Clare, 2019; Kane et al. 2020). The seafloor is considered a sink for global plastics, which could account for much of the 'missing' microplastic in global budgets (Goldberg, 1997; Thompson et al., 2004; Ballent et al., 2013; Van Cauwenberghe et al., 2013; Pham et al. 2014; Woodall et al., 2014; Fischer et al. 2015; Courtene-Jones et al. 2017; Hardesty et al. 2017; Underwood et al. 2017).

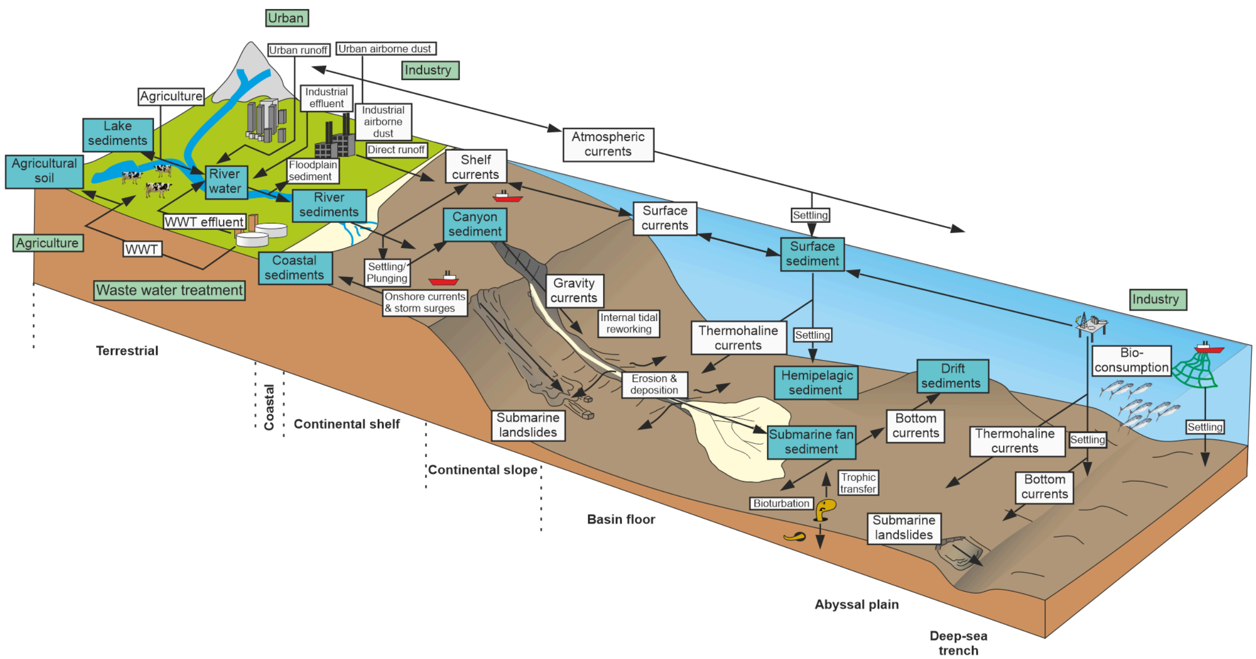

Fig. 1. Pathways for microplastics into and within the marine environment (modified from Kane & Clare, 2019).

Rivers are key conveyors of microplastics to the coast (e.g. Moore et al., 2011; Klein et al. 2015; Mani et al., 2015; Horton et al., 2017; Lebreton et al., 2017; Willis et al., 2017; Hurley et al., 2018; Pierdomenico et al., 2019); other contributors to the coastal zone include wastewater from treatment plants, shipyards, harbours and other industries (e.g. Stolte et al., 2015), and urban run-off (e.g. Patters and Bratton, 2016). When rivers reach the coast, the mineral sediment within them is either sequestered into shallow marine sediment deposits, where it is prone to reworking by coastal processes including longshore drift, or it is fed directly into a submarine canyon head (e.g. Zalasiewicz et al. 2016; Blum et al., 2018; Pierdomenico et al. 2019). Mineral sediment delivered by rivers is dominated by quartz (2650 kgm^{-3}), feldspar (2560 kgm^{-3}) and mica (2750 kgm^{-3}). Microplastics span a wider range of densities; from very low density, such as polystyrene (800 kgm^{-3}) to the densest which approach mineral densities, e.g., Polytetrafluoroethylene (2020 kgm^{-3}). Therefore, many microplastics have a tendency to float, at least initially, but this may change through time as particles: i) accumulate biofilms (biofouling; e.g. Lobelle & Cunliffe, 2011; Muthukumar et al., 2011; Long et al. 2015; Cole et al. 2016; Fazey & Ryan, 2016; Kaiser et al., 2017); ii) break down through UV light degradation (photodegradation; Shah et al., 2008); iii) act as focal points for precipitation of chemicals and minerals on particle surfaces (Mato et al., 2001; Corcoran et al. 2015); iv) undergo leaching of additives (Van Cauwenberghe et al. 2013, 2014); and v) form aggregates with other marine sediments (Galangi et al. 2015). Biofouling-induced densification has been suggested to explain the apparent lack of plastics on the sea surface: recorded levels of plastic at the surface are at least two orders of magnitude lower than anticipated (Cózar et al. 2014).

Pedagogical context

In earth and environmental science education, and careers, the ability to visualize and think spatially across a range of scales, and through time, is a necessity (Hegarty et al., 2010; Ormand et al., 2014) and educators are developing new ways to facilitate active student learning via digital means, to enable classroom- or hybrid-teaching based approaches to understanding complex spatial and spatio-temporal phenomena (e.g., Bond & Cawood, 2020; Casas & Estop, 2015; Chenet al., 2011; Fatemah et al., 2020; Ha & Fang, 2013; Ormand et al., 2014; Pugsley et al., 2023; Watson et al. 2023). Student understanding of basic concepts around water, and water systems, has been found to be lacking, particularly with respect to spatial and temporal scales of processes and their interactions (e.g. Arthurs & Elwonger, 2018; Arthurs, 2019; Baumfalk et al., 2019; Canpolat, 2006; Cardak, 2009; Dickerson & Callahan, 2006; Sadler et al., 2017; Sibley et al., 2007). This is true for oceans and oceanography (Yuretich et al. 2001; Arthurs et al. 2015; Firdaus et al. 2019; Hidayati et al. 2022), and especially marine pollution (Alves, et al. 2021; Cudaback, 2006; Cummins, and Snively, 2000; Gough, 2017; Marrero and Mensah, 2010). These issues are exemplified by considering the behaviour of a single tiny fragment of plastic in an ocean: a challenge many orders of magnitude more difficult to comprehend than the proverbial needle in a haystack (The Velvelettes, 1964).

To test the application of our model in a teaching scenario we have devised a simple exercise to guide students through the model, accompanied with a Microsoft Powerpoint presentation with some introductory material, with a questionnaire to complete before and after the exercise.

Therefore, the aim of this contribution is to provide a simple computational model for students to visualise the processes of microplastic settling in water and in the oceans. Specific objectives are to i) develop a settling model incorporating biofilm growth; ii) incorporate the effects of ocean surface currents on microplastic drift; iii) build a user-friendly web-based interface for students to examine the effects of biofilm growth and ocean transport of microplastics; iv) develop a set of exercises and a tutorial for students to use the model; iv) validate the utility of the model through analysing student response.

Plastic type	**Typical density kgm^{-3}**
Polytetrafluoroethylene	2200
Polyurethane	1200
Polyamide	1100
Polypropylene	880

Polyvinylchloride	1160
Polystyrene	800-965
HD pellets	1055

Table 1. Some common plastic types and their densities.

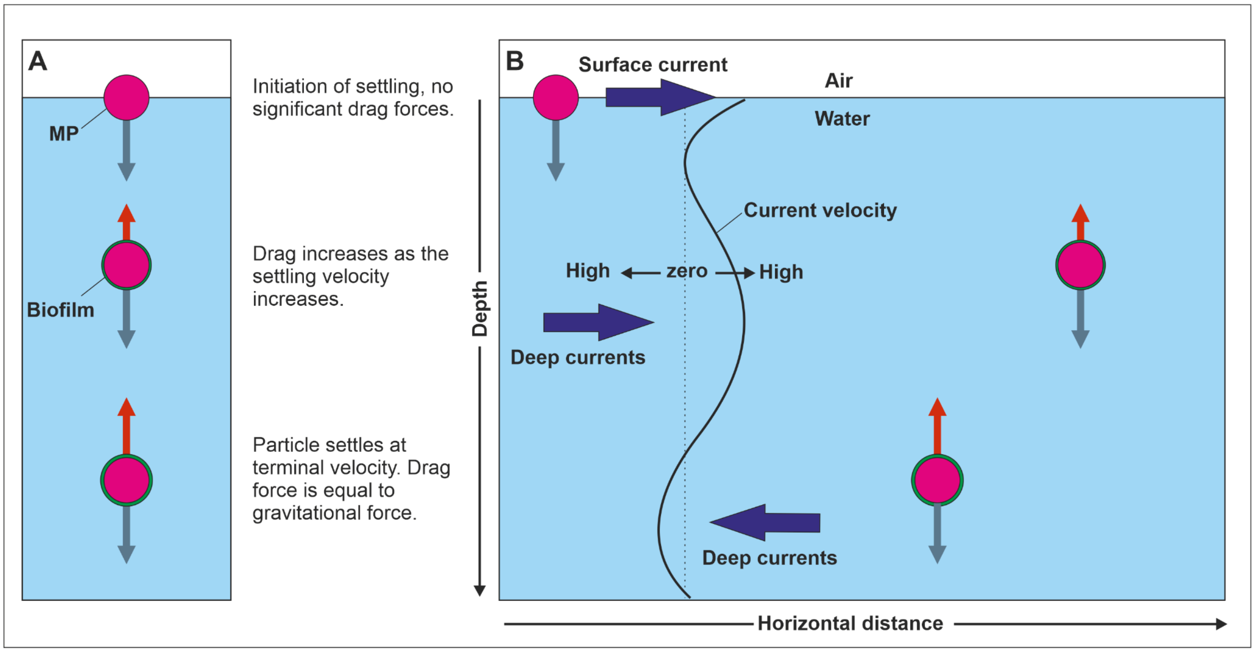

Figure 2. A) Settling in a vertical tube, e.g. a laboratory experiment or stationary water body. B) Settling in the ocean with active currents causing lateral advection of vertically settling particles. Terms related to equations to be added. MP = microplastic.

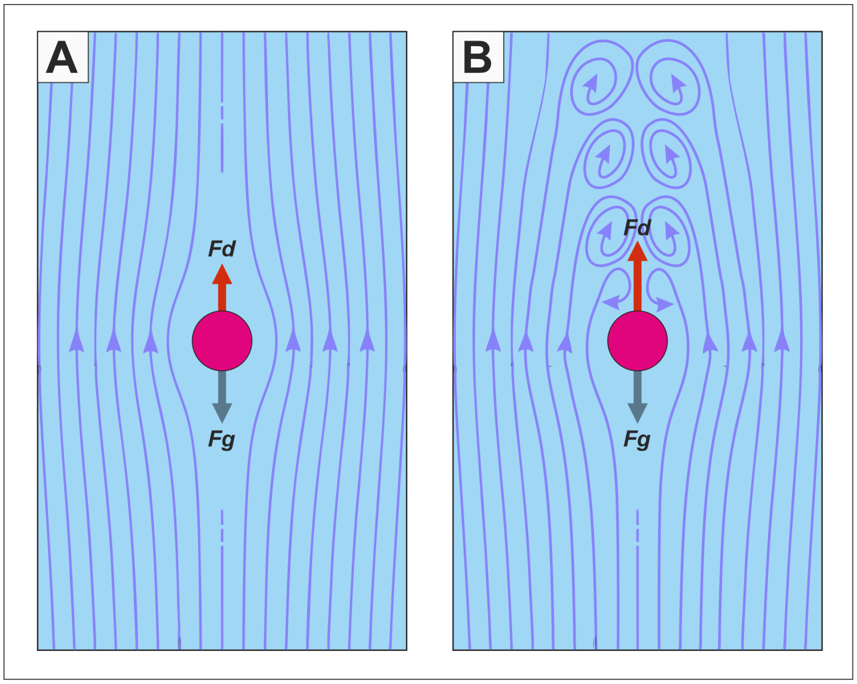

Figure 3. A. A settling sphere with simple fluid drag as a product of fluid viscosity, as modelled by Stokes Law. B. Form Drag caused by separation of boundary layers around the sphere.

Settling velocity models

Laboratory experiments to measure settling velocities for a range of plastic particles (Kowalski et al., 2016; Khatmullina & Isachenko 2017) have demonstrated the expected deviation from theoretical values (e.g. following Dietrich, 1982; Ferguson and Church, 2004). Both natural and plastic particles have a range of shapes and surface roughness so these theoretical values (for spheres) typically overestimate settling velocity for other shapes.

Particle shape

Microplastic shape affects settling velocities significantly, with spheres settling at the highest rate, generally followed by fragments then fibres, even when they have the same density (Khatmullina & Isachenko, 2017; Waldschläger & Schüttrumpf, 2019; Mendrik et al. 2023). Only a few settling experiments have included fibres, but it has been shown recently that shape and the consequent higher drag coefficients reduce settling velocities (Van Melkebeke et al. 2020; Mendrik et al. 2023). For simplicity and to match the pedagogical aims of this work we use spherical particles here, akin to microbeads.

Biofilms

A biofilm is a layer of bacteria or other microbes which can grow and adhere to the surface of microplastics and other materials. Biofilms can begin to grow on plastic surfaces within minutes to hours of entering an aquatic system (Zettler et al. 2013; Amaral-Zettler et al. 2020). The growth of biofilms can lead to changes in the buoyancy of microplastics, typically increasing their density leading to sinking, or to enhanced sinking rates of non-buoyant particles, and it has been demonstrated experimentally that biofilm growth can drastically change settling velocities of microplastics within hours (Mendrick et al. 2023). In addition it has been shown that the growth of biofilms is strongly dependent on microplastic polymer type, salinity, suspended sediment concentrations, and in turn these can increase the tendency for microplastics to bind together with clay to form heteroaggregates (Lagarde et al. 2016; Mendrik et al. 2023). Biofilms have been observed to grow at depths over 5000 m but growth rates across environments and water depths in the oceans are not well constrained (Murthy et al. 2023). For simplicity the model uses a variable linear biofilm growth rate, i.e., with the particle diameter increasing at a constant rate. However, in principle more complicated growth rates could straightforwardly be incorporated into the code by the user. Biofilm density is set at 1170 kgm^{-3}, based on the measurements of Zhang and Bishop (1994).

Ocean currents

Ocean surface currents have a wide range of velocities and can be driven by wind as well as temperature and salinity. Typical surface currents range from 0.01- 2.5 m/s, locally speeding up through narrow straits and due to convergence of flow cells in open oceans. These currents will drive the initial path of microplastics on the ocean surface. The Gulf Stream, for example, is affected by strongly westerly wind currents giving sea surface velocities of up to 2.5 m/s, which penetrates down to as much as 200 m water depth (Longhurst, 2010). In the model we set this to a value of 200 m, and for simplicity we used a sudden dropoff in current strength to 0 m/s at 200 m. Due to temperature- and salinity-driven (thermohaline) circulation, forming deeper currents in the oceans, microplastic fallout will not be in a simple vertical path. In the model we do not include these currents as to do so is very complicated and does not necessarily increase the pedagogical benefits as the model stands. In fact, there may be a range of different flow directions and current strengths at different depths in the water column (e.g. Bailey et al. 2024), meaning that a simple representation of deep-water currents is not feasible at present. Nevertheless we provide a summary here which can be used as part of the discussion with students on the applicability of the model results. Thermohaline stratification can create nepheloid layers that inhibit sediment fall-out and promote the lateral advection of fine sediments, while bottom-hugging contour currents can be agents of sediment reworking and deposition, and can develop large accumulations of fine-grained sediment, known as drift deposits (e.g. Stow and Lovell, 1979; Rebesco et al., 2014). Settling of microplastics to the seabed will only occur when the shear stress at the base of a flow is lower than the settling velocity, thus leading to inhibited settling and advection of microplastics. Given the typical velocities of near-bed thermohaline currents in many deep-sea locations worldwide (~0.1-0.6 m/s; McCave et al., 2017; Bailey et al. 2024), it is not surprising that thermohaline currents have been demonstrated to be an important control on microplastic transport and deposition in the deep-ocean (Kane et al. 2020). For example, microplastics and fibres in the Kuril–Kamchatka Trench have no immediately adjacent source area, and it has been suggested that northwards-flowing bottom currents in the trench could have brought material from Japan and from as far afield as Russia (Peng et al., 2018). Similarly, thermohaline currents have also been invoked for the transport of microplastic particles into the deep Fram Strait (Arctic Sea) owing to its distance from an obvious source (Bergmann et al. 2017). The result of these currents is that the particles falling through the water column may end up a very long distance from their starting point on the surface. The model is 2D so that particle travel distance is shown on the x-axis in a simple straight line, but it can be envisaged that 3D pathways in the ocean are more complicated, but nevertheless the distance travelled may be comparable.

Model design

Microplastic settling (and particle settling in general) is often considered in terms of pure vertical settling (1D), and experiments typically replicate that. Our two-part model is designed to allow students to compare vertical settling velocities in a stationary water column, i.e., replicating a laboratory setting, to settling in a 2-dimensional space impacted by a horizontal surface current, i.e., a simplistic representation of an ocean. The 1D model allows comparison to published work on microplastic settling, while the 2D model enables students to visualise the potential for long range transport of microplastics in the oceans as a consequence of surface and deeper currents. Students can select the polymer density, particle size and in the 2D model are able to vary ocean current strength and its depth range; in the 1D model they can select seawater or freshwater.

Parameter	**Description**
Particle shape	Spherical
Particle size	User defined (0.001-5 mm)
Salinity/water density	997 or 1020 kg/m^3 (typical of freshwater or seawater)
Biofilm density	Typical value 1170 kg/m^3
Biofilm growth rate	Linear growth rate 4×10^{-9} cm s^{-1}
Ocean surface current	A horizontal current directed away from the coastline at 1 ms^{-1} to a maximum penetration depth of 200 m.
Model Geometry	1D Model: Vertical settling tube, 1 metre water depth 2D Model: Shelf-slope-basin floor model

Mathematical Modelling

The model assumes that the particle is a smooth sphere of initial density ρ_0, initial radius r_0, and hence initial mass $m_0 = \rho_0 V_0$ where $V_0 = \frac{4}{3}\pi r_0^3$ is its initial volume. The particle's radius $r(t)$ then increases linearly in time as a spherical shell of biofilm grows on its surface:

$$r(t) = r_0 + kt\ .$$

The biofilm has a density $\rho_1 > \rho_0$, so the particle's total mass as a function of time t is

$$m(t) = \frac{4}{3}\pi r_0^3 \rho_0 + \left(\frac{4}{3}\pi r(t)^3 - \frac{4}{3}\pi r_0^3\right)\rho_1,$$

while its overall density $\rho(t)$ is its total mass divided by its total volume $V(t) = \frac{4}{3}\pi r(t)^3$:

$$\rho(t) = \frac{r_0^3(\rho_0 - \rho_1) + r(t)^3\rho_1}{r(t)^3}\ .$$

The particle's initial density is less than that of water ρ_W, but reaches ρ_W at a "critical time" t_c defined by $\rho(t_c) = \rho_W$. Solving for this critical time gives:

$$t_c = \frac{r_0}{k}\left(\left(\frac{\rho_1 - \rho_0}{\rho_1 - \rho_W}\right)^{\frac{1}{3}} - 1\right).$$

Until the critical time $t = t_c$ is reached, the particle will float on the surface of the water. Note that t_c is proportional to the particle's initial radius, and hence smaller particles will begin to settle at earlier times than larger particles.

From the critical time onwards the particle is subject to 4 forces:

i. Gravitational force: $\boldsymbol{F}_g = -m(t)g\hat{y}$,
ii. Buoyancy force: $\boldsymbol{F}_b = \rho_W V(t)g\hat{y}$,
iii. Stokes drag: $\boldsymbol{F}_s = 6\pi\mu r(t)(\boldsymbol{v}(t) - \boldsymbol{u}(\boldsymbol{x}(t)))$,
iv. Form drag: $\boldsymbol{F}_q = \frac{1}{2}c_D A(t)\rho_W|\boldsymbol{v}(t) - \boldsymbol{u}(\boldsymbol{x}(t))|(\boldsymbol{v}(t) - \boldsymbol{u}(\boldsymbol{x}(t)))$,

where g is the gravitational field strength, $\hat{y}$ is a unit vector pointing vertically upwards, μ is the dynamic viscosity of water, $\boldsymbol{v}(t) = \frac{d}{dt}\boldsymbol{x}(t)$ is the particle velocity, c_D is the form drag coefficient (equal to 0.47 for hard spheres), $A(t) = \pi r(t)^2$ is the particle's cross-sectional area and $\boldsymbol{u}(\boldsymbol{x}(t))$ is the flow velocity of the water at the particle's position $\boldsymbol{x}(t)$. The equation of motion for the particle at time $t \geq t_c$ is then

$$\frac{d}{dt}(m(t)\boldsymbol{v}(t)) \ = \ \boldsymbol{F}_g + \boldsymbol{F}_b + \boldsymbol{F}_s + \boldsymbol{F}_q \, ,$$

i.e.,

$$\frac{d}{dt}\big(m(t)\boldsymbol{v}(t)\big) = -\big(6\pi\mu r(t) + \tfrac{1}{2}c_D\rho_W\pi r(t)^2|\boldsymbol{v}(t) - \boldsymbol{u}(\boldsymbol{x}(t))|\big)\big(\boldsymbol{V}(t) - \boldsymbol{U}(\boldsymbol{x}(t))\big) + (\rho_W - \rho(t))V(t)g\hat{y}.$$

This non-linear coupled system of ordinary differential equations has no analytic solution and can only be solved numerically. However, the time and length scales involved in the relevant physical context present a challenge; a particle may take many hours or days to fully settle, and may travel thousands of kilometres in the process, which would require a numerical solution with an impractically large number of small time steps. The pedagogical applet must be able to generate trajectories quickly from any values of the constants ρ_0 and r_0 selected by the students, so it is useful to make some approximations that take advantage of the vast range of scales in the problem.

To make the range of scales more apparent, we introduce the following dimensionless variables and constants:

i. $s(t) \ = \ r(t)/r_0 \, ,$
ii. $\boldsymbol{V} \ = \ \boldsymbol{v} \, / \, v_q \, ,$
iii. $\boldsymbol{U} \ = \ \boldsymbol{u} \, / \, v_q \, ,$
iv. $\gamma \ = v_q/(2v_s),$
v. $s_c = s(t_c) = (\varepsilon_W/\varepsilon)^{1/3},$
vi. $\delta \ = kv_q/(\varepsilon_W g r_0),$

where v_q is the settling velocity of a particle of radius r_0 and density ρ_1 subject only to quadratic form drag (with no Stokes drag),

$$v_q \ = \ \sqrt{\frac{8\varepsilon_1\rho_1 r_0}{3\rho_W c_D}} \, ,$$

while v_s is that of the same particle subject only to Stokes drag (with no quadratic form drag),

$$v_s \ = \ \frac{2\varepsilon_1\rho_1 r_0^{\,2}}{9\mu} \, ,$$

with $\varepsilon_W = (\rho_1 - \rho_W)/\rho_1$ the excess density of the biofilm relative to the water, and $\varepsilon = (\rho_1 - \rho_0)/\rho_1$ that of the biofilm relative to the plastic. In terms of these new variables, the equation of motion becomes:

$$\delta \frac{d}{ds}\left((s^3 - \varepsilon)\boldsymbol{V}\right) = -\left(\frac{1}{v_s}s + \frac{1}{v_q^2}s^2\,|\boldsymbol{V} - \boldsymbol{U}|\right)(\boldsymbol{V} - \boldsymbol{U}) - (s^3 - s_c^3)\,\hat{y}\,,$$

with the linear scale factor $s(t)$ now used as a dimensionless measure of time. The biofilm growth rate k has dimensions of speed, but this speed is very small compared to gr_0, which means that the dimensionless constant factor δ multiplying the left-hand side (LHS) is also very small: $\delta << 1$. This suggests a very simple approximation scheme in which the LHS is set to zero. Physically, this represents a particle always effectively at terminal velocity relative to the water, but with a terminal velocity whose magnitude slowly *increases* in time with the linear scale factor $s(t)$. This reduces the differential equation to an algebraic (quadratic) equation, which may straightforwardly be solved for any values of the initial constants. The error introduced is of order $\delta << 1$, so this will give a reasonable approximation to the particle's motion.

In the 1D case of a particle settling in a glass tube, the water is assumed to be at rest, so its velocity field $\boldsymbol{u}(\boldsymbol{x}) = 0$ for all values of $\boldsymbol{x}$, which greatly simplifies the problem. The particle is at its terminal velocity when the total force is equal to zero:

$$0 = -\left(\frac{1}{v_s}s + \frac{1}{v_q^2}s^2\,|\boldsymbol{V}|\right)\boldsymbol{V} - (s^3 - s_c^3)\,\hat{y}$$

Taking $\boldsymbol{V}$ to be in the -ŷ direction and solving this quadratic equation leads to the following expression for the dimensionless terminal velocity:

$$V_T(s(t)) \;=\; \frac{1}{s(t)}\left(\gamma - \sqrt{\gamma^2 + s(t)^3 - s_c^3}\right).$$

The same expression may also be found by treating the coefficients of the 1D differential equation as constants and then solving using the usual method for 2nd order equations with constant coefficients. Note that at the critical time, when the density reaches that of water, one can see that $V_T(s(t_c)) = V_T(s_c) = 0$, so the initial velocity is zero, but increases in magnitude (in the -ŷ direction) as time progresses. The dimensionful velocity $v_T(s(t))$ is then

$$v_T(s(t)) \;=\; \frac{v_q}{s(t)}\left(\gamma - \sqrt{\gamma^2 + s(t)^3 - s_c^3}\right),$$

which can be integrated to give the vertical position $y(t)$ as a function of time:

$$y(t) \;=\; \int_{t_c}^{t} v_T(s(t))dt \;=\; \frac{r_0 v_q}{k}\int_{s_c}^{s} V_T(s)\,ds\,.$$

This integral can be evaluated directly, resulting in:

$$y(t) = \frac{2r_0 v_q}{3k}\left(\gamma - \sqrt{\gamma^2 + s(t)^3 - s_c^3} + \frac{3}{2} ln\left(\frac{s(t)}{s_c}\right) + \sqrt{s_c^3 - \gamma^2}\left(tan^{-1}\left(\frac{\sqrt{\gamma^2 + s(t)^3 - s_c^3}}{\sqrt{s_c^3 - \gamma^2}}\right) - tan^{-1}\left(\frac{\gamma}{\sqrt{s_c^3 - \gamma^2}}\right)\right)\right),$$

assuming that $y(0) = 0$ and provided that $s_c^3 > \gamma^2$. On the other hand, if $s_c^3 < \gamma^2$ then the integral instead gives:

$$y(t) = \frac{2r_0 v_q}{3k}\left(\gamma - \sqrt{\gamma^2 + s(t)^3 - s_c^3} + \frac{3}{2} ln\left(\frac{s(t)}{s_c}\right) + \sqrt{\gamma^2 - s_c^3}\left(coth^{-1}\left(\frac{\sqrt{\gamma^2 + s(t)^3 - s_c^3}}{\sqrt{\gamma^2 - s_c^3}}\right) - coth^{-1}\left(\frac{\gamma}{\sqrt{\gamma^2 - s_c^3}}\right)\right)\right).$$

However, it turns out that $s_c^3 > \gamma^2$ for all values of the parameters r_0 and ρ_1 of interest for the applet, so in fact only the first expression is required. However, the second expression may be required if one would like to incorporate larger spheres.

In the 2D case we employ the same approximation, making the assumption that the particle is always at terminal velocity relative to the frame of the flowing water. This terminal velocity then evolves very slowly in time just as in the 1D case. Assuming the flow to be purely horizontal, this leads to the same vertical velocity as above, while the horizontal component is simply equal to $\boldsymbol{u}(\boldsymbol{x}(t))$, where we take $\boldsymbol{u}(\boldsymbol{x}) = 1\text{ms}^{-1}$ for all $\boldsymbol{x}$ down to 200m depth and $\boldsymbol{u}(\boldsymbol{x}) = 0$ for depths deeper than this.

The Applet

The model is developed in GeoGebra, which is an interactive geometry, algebra, statistics and calculus application, intended for learning and teaching mathematics and science from primary school to university level. The model is freely accessible through GeoGebra and is available on multiple platforms, with apps for desktops, tablets, smartphones and on the web. The 1D model can be found here: https://www.geogebra.org/m/refpu3kc and 2D model here: https://www.geogebra.org/m/xgkuaugk. In addition, for teaching purposes, we used a QR code for students to access directly from the classroom presentation, or from their lecture notes.

Like all Geogebra applets, these applets may be edited and resaved by other educators wishing to use an adapted version for their own teaching.

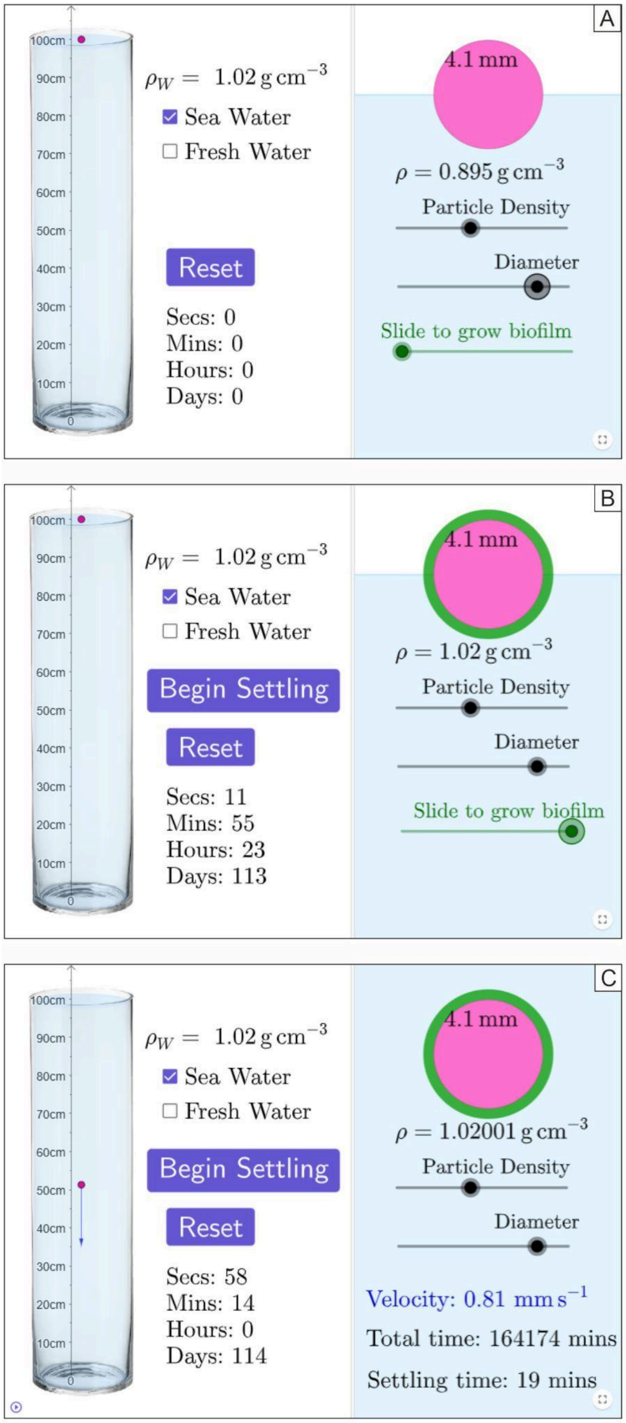

Figure 4. 1D microplastic settling applet interface. A) Starting screen showing variables: sea water / fresh water, particle density, diameter of particle, and a slider to show the effects of biofilm growth. B) Once the particle has reached the density of the water it is in, the 'Begin Settling' button will appear. C) Once the particle begins to settle a display of settling velocity, total time, and setting time will appear; this display stops when the particle comes to rest.

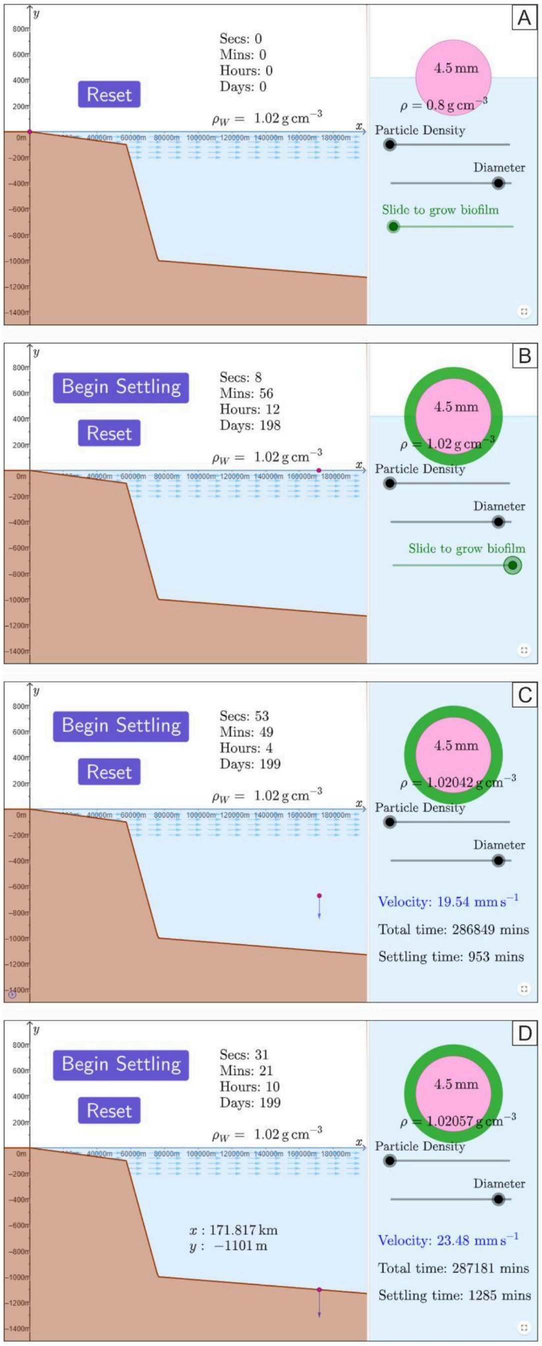

Figure 5. 2D microplastic settling applet interface. A) Starting screen showing the continental shelf-slope-basin floor geometry, and fixed horizontal currents penetrating to 200 m water depth; variables: particle density, diameter of particle, and a slider to show the effects of biofilm growth. B) As the biofilm slider is moved the particle will move on the surface until it reaches the density of seawater, then the 'Begin Settling' button will appear. C) Once the particle begins to settle a display of settling velocity, total time, and setting time will appear; D) a display of the x-y distance travelled appears when the particle comes to rest.

Model validation

The model was tested with a class of 63 students enrolled on the Masters in Pollution and Environmental Control, at the University of Manchester. The class was given a 50 minute lecture on microplastics in the environment (Supplementary Materials 1), followed by a two-hour practical class where the applet was utilised with a series of exercises where the students used the model to collect a series of data and plot them onto graphs (Supplementary Materials 2). A series of 'blank' graphs were provided to speed up the process but could equally be part of the exercise (Supplementary Materials 3). A number of different exercises could also easily be formulated using the model, so these are seen as a starting point. The feedback was very favourable, with students showing marked improvement in their understanding of the distribution of plastics in the oceans. Statement 1: "*Most microplastics in the ocean are currently floating on the sea surface*" was given with a yes/no/unsure option. Initially most students (48.4%) thought that most plastics floated on the ocean surface, 38.7% thought they would be on the seafloor, and 12.9% were unsure; post-exercise this changed to the majority (87.8%) thinking they would be on the seafloor, 9.8% on the surface and some still unsure, and 2.4% unsure. Statement 2 reversed this with "*Most microplastics in the ocean are currently on the seafloor*", with yes/no/unsure options. Initially most students (48.4%) thought that most were on the seabed, 29% thought they would be on the surface, and 22.6% were unsure; post-exercise this changed to the majority (80.5%) thinking they would be on the seafloor, 9.8% on the surface and some still unsure, and 8.7% unsure. These statements are ostensibly the same, and highlight the degree of uncertainty the students had, but with a convincing improvement in their understanding, and more importantly one of the key mechanisms for the process of microplastic sinking (biofilm growth). The next question: "*Dense biological films can grow on microplastics and make them sink. If two microplastic particles have the same density, and biofilms grow on their surface, which will start to sink first?*" prompted students to start thinking about the physical process of biofilm growth. Intuitively most students considered the larger particles to start sinking faster than smaller ones. The model demonstrates that for a smaller particle size, the biofilm growth volume soon becomes proportionally larger than the particle volume, as smaller particles have a larger surface area than larger particles, which is perhaps counterintuitive. 52.4% of students thought the larger particles would sink first, whereas 47.6% thought he smaller particles; post-exercise this had reversed to 32.5% thinking smaller particles would sink first, and 67.5% thinking the smaller particles would sink first. A final question was asked in the post-exercise survey: "Did this exercise help you to understand microplastic distribution in the oceans?" with a choice of 5 answers (1. Extremely helpful, 2. very helpful, 3. Helpful, 4. not helpful, 5. Not at all). Answers were overwhelmingly positive with 70.7% saying 'extremely helpful', 24.4% 'very helpful', and 4.9% 'helpful'. We also asked for short written feedback to the question "Any feedback", to which we received 11 answers, which while not particularly helpful, were affirming: "no", "very useful", "Thanks for the interesting activity!", "Very impressive", "excellent teacher ! ", "Perfect!", "Thank you professor", "Makes sense and easy to use", “Visualising is easier with the app but a bit small on phone, but ok.”, “Thanks Drs” and “Thanks you Dr Ian and Dr Mia”.

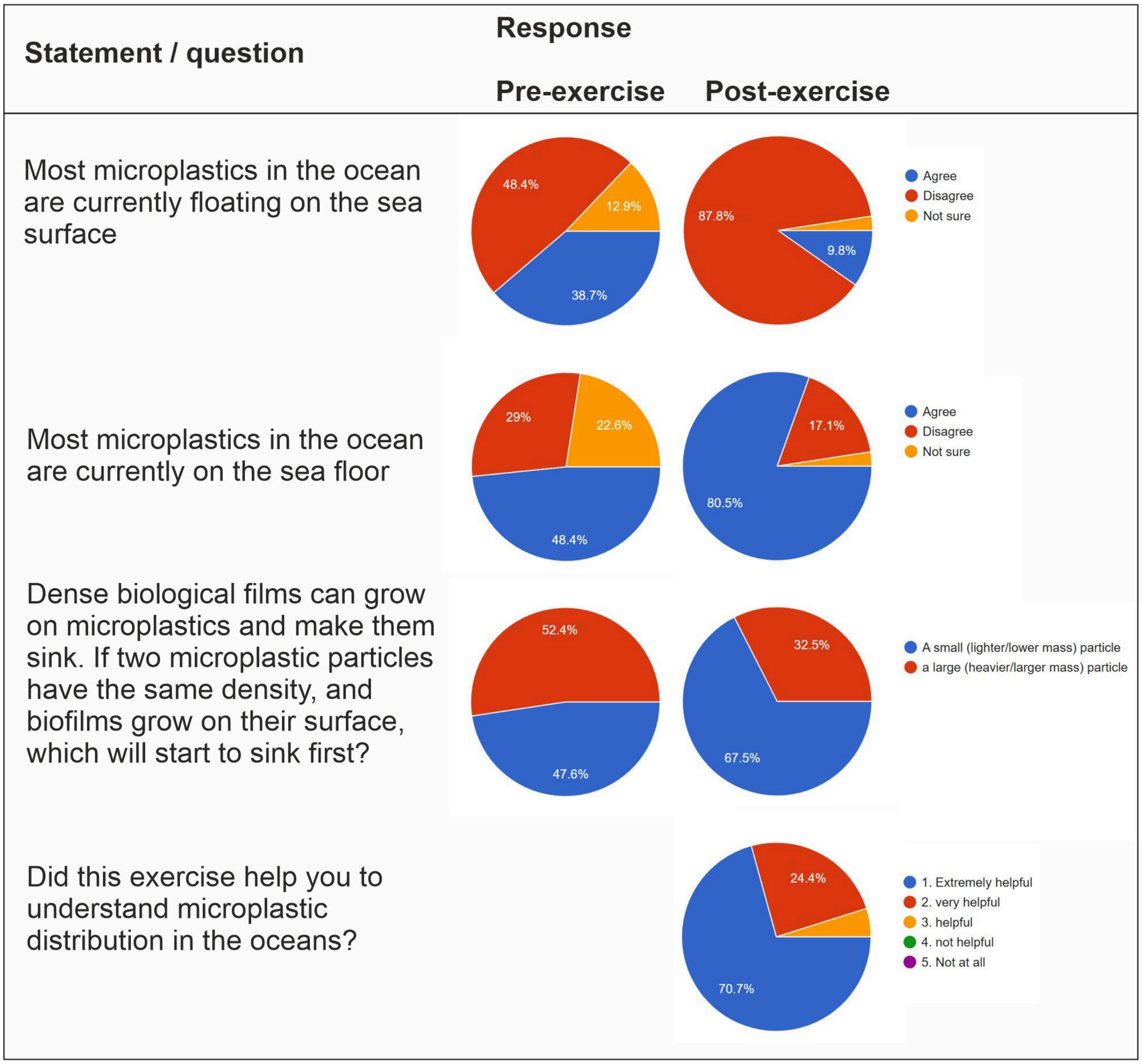

Figure 6. Student feedback based on an online questionnaire set before and after the exercise. n=63.

Limitations

The model is simplistic, as indeed any model of nature necessarily is. Other factors which affect microplastic particle sinking are not taken into account, e.g. mineral sorption, leaching, and more complicated particle shapes. In addition the effect of deep sea currents is not incorporated into the present model. We decided against this as the resultant particle resting point would not reflect the distance from the starting point in a simplistic way, and their complicated 3D pattern in nature is not easily implemented into such a model. Nevertheless, these models show in a simplistic way the effect of microplastics subject to biofilm growth, and how initially buoyant particles will sink, at different times, based on their starting density and size; in addition the challenge of understanding scaling from sub millimetre particles to oceans is tackled.

Conclusions

This study describes the development of two interactive online models for students to investigate the fate of microplastics floating in 1D, replicating a laboratory, and 2D replicating an ocean. Microplastic densities, sizes, biofilm growth, water salinity can be varied. In the 2D case an ocean surface current shows the distance which microplastics may float before sinking due to biofouling. We developed simple exercises for classroom teaching allowing students to test various parameters in a fun applet-based platform. An analysis of their use in the classroom was overwhelmingly positive. Teaching materials are provided as appendices but we encourage the use of the applet in any way deemed appropriate, for example testing the model results against results given in previous published studies, or against theoretical models. This active learning model has clear pedagogical benefits over simple passive learning approaches, communicating environmental pollution and the scales of earth systems, for students from high school to university levels and in classroom, hybrid or remote teaching scenarios.

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