

REVIEW

Particle sources and transport in stratified Nordic coastal seas in the Anthropocene

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Particles of all origins (biogenic, lithogenic, as well as anthropogenic) are fundamental components of the coastal ocean and are re-distributed by a wide variety of transport processes at both horizontal and vertical scales. Suspended particles can act as vehicles, as well as carbon and nutrient sources, for microorganisms and zooplankton before eventually settling onto the seafloor where they also provide food to benthic organisms. Different particle aggregation processes, driven by turbulence and particle stickiness, composition, abundance and size, impact the transport and sinking behavior of particles from the surface to the seafloor. In deep coastal waters, the deposition, resuspension, and accumulation of particles are driven by particle stickiness, composition and aggregate structure. In contrast, wave-driven and bottom current-driven processes in the nepheloid benthic boundary layer of shallow waters are of greater importance to the settling behavior of particles, while the retention capacity of benthic vegetation (e.g., seagrasses) further influences particle behavior. In this review, we consider the various processes by which particles are transported, as well as their sources and characteristics, in stratified coastal waters with a focus on Nordic seas. The role of particles in diminishing the quality of coastal waters is increasing in the Anthropocene, as particle loading by rivers and surface run-off includes not only natural particles, but also urban and agricultural particles with sorbed pollutants and contaminants of organic, inorganic and microplastic composition. Human activities such as trawling and dredging increase turbidity and further impact the transport of particles by resuspending particles and influencing their vertical and horizontal distribution patterns. An interdisciplinary approach combining physical, chemical and biological processes will allow us to better understand particle transport and its impact on coastal waters and estuaries at an ecosystem level. There is a need for development of novel analytical and characterization techniques, as well as new in situ sensors to improve our capacity to follow particle dynamics from nanometer to millimeter size scales.

Keywords: particles; transport; coastal seas; aggregation; settling behavior; turbidity; trawling; seagrasses; aquaculture; microplastics; anthropocene

Introduction

Particles are a fundamental component of the ocean, as they facilitate the transport of matter and provide surfaces for chemical reactions, while also acting as vehicles for the transport of nutrients, contaminants, and plastics from land to sea and impacting the distribution of sediments (Nowack and Bucheli, 2007; Wright et al., 2013; Corsi

et al., 2014; Jeandel et al., 2015). They transfer metabolized energy from the upper productive layers to below the photic zone, act as a source of organic matter to the mesopelagic and benthic communities, and regulate turbidity and thus photosynthetically available water depths (Volkman and Tanoue, 2002; Turner, 2015).

Traditionally, particulate matter was defined as material unable to pass through a 0.45 μm filter to distinguish dissolved solutes from settling matter (Goldberg et al., 1952). Later a 0.2 μm filter was employed increasingly because such 'sterile filtration' better selected for all living particles (Verdugo, 2012; Jeandel et al., 2015). The particulate fraction may include mineral particles from rivers or resuspended sediment (e.g., sand, silt, clay, or metal oxides) and particles of organic origin such as viruses, bacteria, phytoplankton, fecal pellets, detritus and biopolymer aggregates (e.g., transparent exopolymeric particles

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(TEP), marine snow aggregates; **Figure 1**). However, it is now known that the fraction passing through a $0.45\ \mu\text{m}$ filter also contains particulates in the form of colloids, macromolecules, biopolymers and nanoparticles (Filella, 2007). In addition, in the Anthropocene natural particles are being contested in abundance by synthetic nanoparticles (Corsi et al., 2014), contaminants and microplastics (Wright et al., 2013; Wagner et al., 2014). Thus, marine particles occur in many different shapes, sizes and compositions, and can be both living and dead organic as well as lithogenic pieces of matter (Newton and Liss, 1990) (**Figure 1**).

Particle transport occurs on a multitude of scales, from Brownian motion on the nanoscale and millisecond movements on a microscale to vertical settling in meters per day, and from horizontal current transport occurring dynamically in coastal seas to the slow movement in gyres within ocean basins at a scale of kilometers per hour (Nittrouer and Wright, 1994; Burd and Jackson, 2009). The coastal zone in particular is an extremely dynamic environment for particles and a zone where anthropogenic activities are concentrated (Halpern et al., 2008). Increased sediment input to the coastal seas has a range of sources from both the land and from offshore activities (**Figure 2**), which include dredging (Newell et al., 1998; Essink, 1999) and drilling operations (Breuer et al., 2004), as well as fishing activities such as bottom trawling (e.g., Ferré et al., 2008).

Greater particle abundance is also expected due to our changing climate: increased precipitation leads to rapidly increasing abundances of iron oxides and colloidal organic matter in rivers in the northern Hemisphere (e.g., Kritzberg and Ekström, 2012), precipitation and turbidity are correlated in catchments (Göransson et al., 2013), and stronger winds increase wave-driven turbidity in shallow coastal waters which can affect the submerged coastal vegetation such as seagrass (Harley et al., 2006; van der Heide et al., 2007). Climatically forced particle loads to the coast as well as anthropogenic activities lead to a multitude of impacts, such as decreased light availability to macro- and microalgae (Essink, 1999; De Boer, 2007), particle-bound contaminants, and local increased deposition and smothering of benthic organisms including shellfish, sponges, and corals (e.g., Essink, 1999; Gilmour, 1999; Kutti et al., 2015). Increased nutrient run-off frequently exacerbates these effects, leading to a range of problems such as intensification of (potentially harmful) algal blooms (Hallegraeff, 2010) and an expansion of coastal hypoxia (Zhang et al., 2010). Growing global aquaculture activities are also placing heavy demands on coastal ecosystems (Holmer et al., 2005), while coastal waters are also subjected to major inputs of waste material such as plastics, chemical compounds and other pollutants (Browne et al., 2011; Wright et al., 2013; Corsi et al., 2014) (**Figure 2**). A combination of both human impacts and hydrodynamic

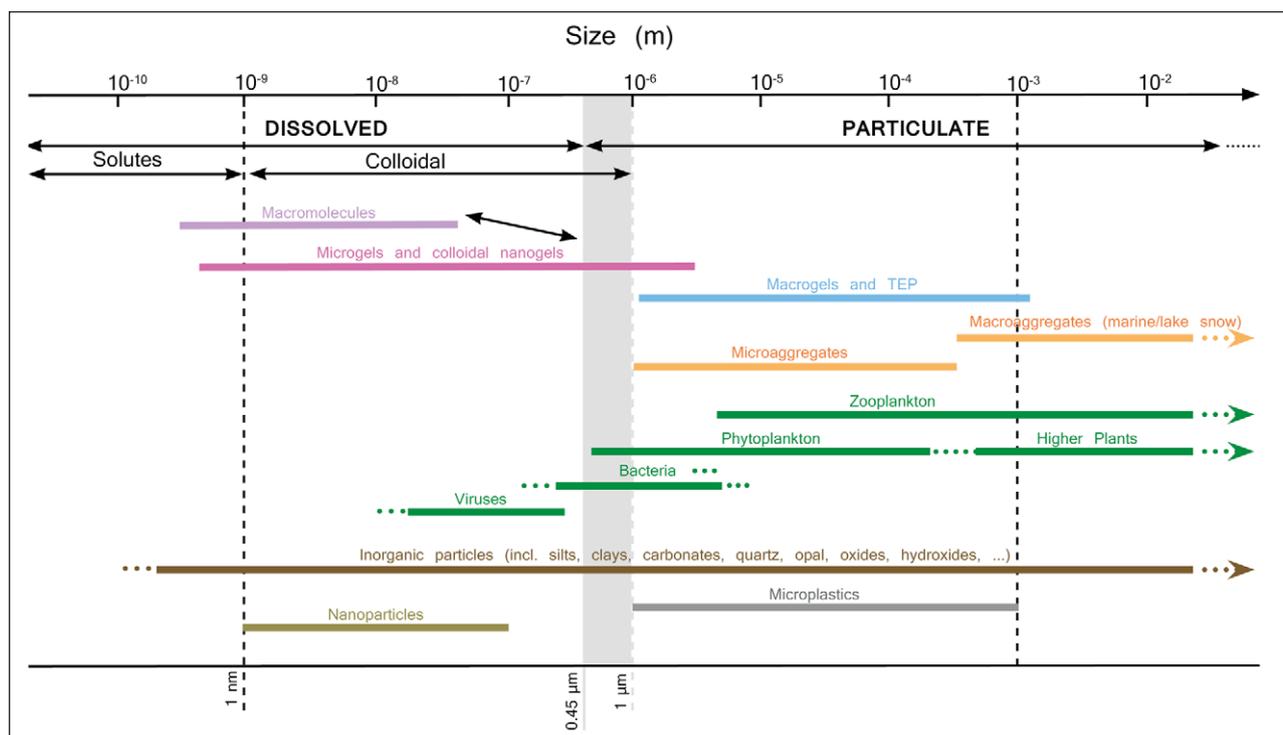


Figure 1: Approximate size ranges of particulates in coastal waters. Particles in coastal seas encompass a wide range of particle types, both organic and inorganic, which are not necessarily restricted to any defined filter cut-off points (e.g., $0.45\ \mu\text{m}$) as indicated by the grey transition zone. Organic particles include organisms such as viruses, bacteria, phytoplankton and zooplankton, which can also aggregate to form larger particles such as macroaggregates. These organisms are also producers of macromolecules such as proteins and carbohydrates, which can anneal to larger microgels and subsequently macrogels, including, for example, transparent exopolymeric particles (TEP). Today, microplastics and nanoparticles are additional particulate components found in coastal waters. DOI: <https://doi.org/10.1525/elementa.149.f1>

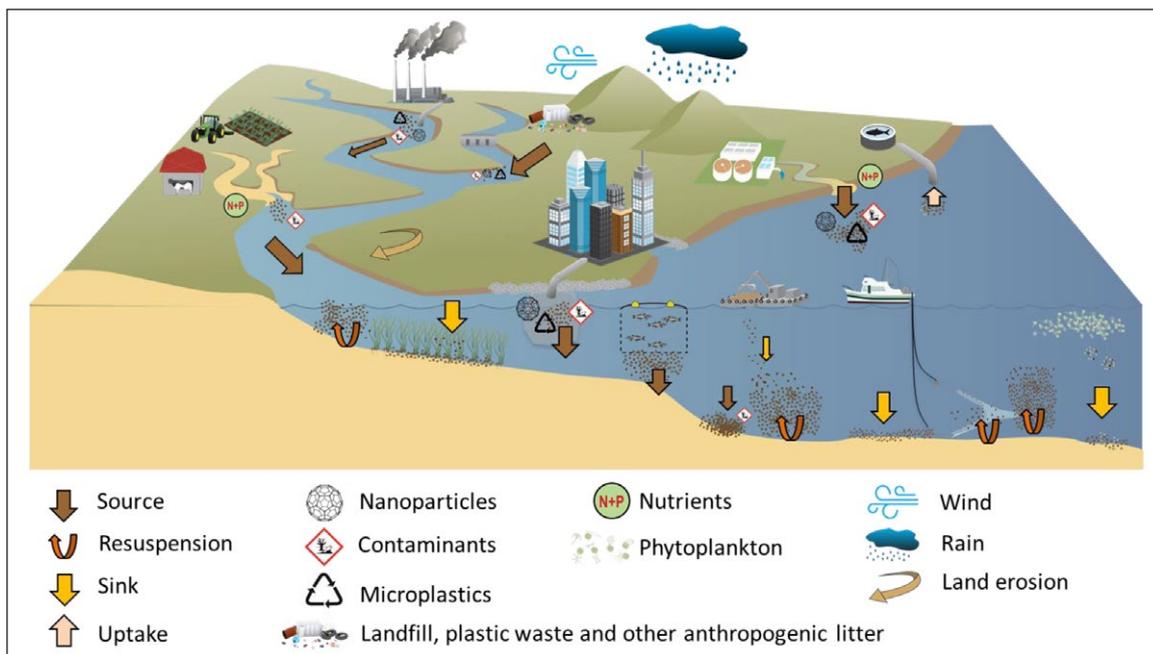


Figure 2: Particle sources and sinks in anthropogenic coastal areas. Sources of particles in coastal areas from urban regions, aquaculture, sewage treatment plants, farming and industry introduce a range of particles into the waters, including nanoparticles, contaminants and microplastics. Natural particle inputs to coastal waters include lithogenic particles via land weathering (wind, rain) and erosive processes as well as organic particles such as phytoplankton. Particles sink and accumulate, particularly in seagrass beds, sheltered areas and deep basins. Aggregation processes increase particle size and thus sinking rates; however, particles are also resuspended by hydrodynamics, river run-off and activities such as dredging and trawling. DOI: <https://doi.org/10.1525/elementa.149.f2>

processes thus influence the distribution of particles, both on temporal as well as spatial scales in coastal zones.

Improved understanding of how particles are distributed in the coastal zone is prerequisite for successful coastal management. Thus we describe relevant natural particle transport mechanisms such as sinking and resuspension (**Figure 2**) before addressing how anthropogenic activities in the coastal zone are affecting the sourcing of particles but also interactions with their environment. We review these key particle sources, pathways and transport processes with a focus on stratified water columns occurring in estuaries with little tidal impact, including the Baltic Sea from its entrance from the North Sea in Skagerrak on the west coast of Sweden to the Bothnian Bay on the northeastern Swedish coast. The Baltic Sea is characterized by both vertical and lateral salinity gradients from Skagerrak to the Bothnian Bay. It is stratified by a shallow thermocline from spring to autumn, and permanently stratified by a halocline which occurs deeper through its basins. Examples of research focus and knowledge gaps are highlighted throughout emphasizing the need for more interdisciplinary approaches combining fields such as physical oceanography, marine chemistry, sedimentology, biology and marine technology.

Natural mechanisms of particle transport

Suspended and sinking particles represent a continuum, from nanoscale colloids with supramolecular properties, through micron-sized clays and bacteria, to mm-sized TEP and aggregates of particles (**Figure 1**). They transport carbon and energy in marine ecosystems but also scavenge

and transport other abiotic particles, including microplastics, oil spill components, and other pollutants (Olsen et al., 1982; Shahidul Isam and Tanaka, 2004). The transport, transformation and fate of particulate material in coastal waters, involving natural hydrodynamic processes at both vertical and horizontal scales as well as processes of aggregation and disaggregation, are thus extremely complex.

Horizontal vs. vertical transport

In most parts of the ocean, the mean flow is mainly horizontal with only local and intermittent vertical upwelling or downwelling. Horizontal eddies can be large and energetic, leading to effective horizontal dispersion, typically with more energy at larger length scales (Thorpe, 2005). Vertical eddies are smaller and less energetic, but nevertheless constitute the main vertical transport mechanism for soluble substances outside of areas of upwelling or downwelling (Talley et al., 2011). Particles can be positive, negative or neutral in buoyancy; for particles of similar density, the larger ones will sink faster (Lynch et al., 2015). Small particles ($<5 \mu\text{m}$), however, are virtually non-sinking ($<1 \text{ m d}^{-1}$), even if their densities are more than double that of the surrounding water. Aggregation processes can increase the sinking velocities of organic particles, so that larger aggregates composed of many particles ($>0.5 \text{ mm}$ in size) can have sinking rates of several tens to hundreds of meters per day (Asper, 1987; Alldredge et al., 1990; Berelson, 2001), providing a substantial vertical flux of particles to the seafloor (Burd and Jackson, 2009; Turner, 2015; **Figure 2**) as part of the ‘biological carbon pump’ (Volk and Hoffert, 1985). Large and heavy particles will

sink quickly and only be transported a small distance by horizontal mean flow. Particles with slow sinking velocities will move considerably in the direction of the mean flow while sinking.

Deposition and erosion processes

The sinking of particles leads to an accumulation close to the seafloor, forming a benthic nepheloid layer, often coinciding with the bottom boundary layer (BBL). The currents in the BBL are exposed to friction against the seafloor, which causes a velocity shear, which in turn induces turbulence. The turbulence can keep particles in the BBL in suspension for a long time (months), transporting them long distances, depending on the velocity in the BBL (Thorpe, 2005). Particles in the BBL will eventually be deposited on the seafloor, contributing to a new top layer of sediment. If the currents in the BBL are strong, the frictional forces can cause erosion of sediments, leading to resuspension of particles and reversion of the deposition. The combined effect of deposition and erosion determines the accumulation rate at any given location. On erosion bottoms the accumulation rate is negative; on transport bottoms the deposition and erosion are in balance, yielding zero accumulation rates. Particularly in coastal zones, wave-induced energy and strong bottom currents are the natural processes that easily resuspend sediments and keep them in suspension (Simpson and Sharples, 2012; **Figure 2**). As a generality, larger particles require stronger flows to be eroded. For smaller particles, the cohesive forces are more effective; they therefore also require stronger currents to be eroded. According to the classical Hjulström curve (Sundborg, 1956), particles around 0.2 mm are the ones that are most easily eroded, requiring flow velocities of approximately 20 cm s⁻¹. However, Hjulström conducted his investigation in the Swedish river Klarälven, where particles are mostly of mineral origin. More recent research has shown that the onset of cohesive forces and the critical erosion velocities vary not only with particle size, but also depend on organic content and composition (Thomsen, 2003). On the one hand, particles with an organic content are typically less dense than mineral particles, hence requiring lower flow velocities to erode; on the other hand, the presence of microbial exudates can also increase adhesive forces and stabilize sediments (Dade et al., 1990; Thomsen and Gust, 2000; Son and Hsu, 2011).

Along the waters adjacent to the Swedish coastline, sedimentation processes are mostly controlled by currents and motion in the benthic boundary layer via surface wave action (Corell and Döös, 2013), with the seasonal thermocline being significant for the water column stratification typically found in Baltic Sea waters (Leppäranta and Myrberg, 2009). Sinking and suspension processes at both the small and large scale therefore need to be well understood, which requires the application of a combination of various techniques and disciplines. Corell and Döös (2013), for example, used a 3D ocean circulation model combined with an off-line particle-tracking model to evaluate the potential movement of sediment at two

geomorphologically different areas off the Swedish east coast, as part of an assessment of where to locate a future underground nuclear repository. As with most models, assumptions have to be made and certain factors are not fully parameterized, which means this model has its shortcomings. They include the lack of a turbulence model to account for particle dynamics in areas of low mixing and the lack of a functional model regarding wind-induced short surface waves (Corell and Döös, 2013). In another study, Kurhrt et al. (2004) simulated the transport of sedimentary material in the western Baltic. They coupled a 3D ocean circulation model to both a wave model and a BBL model, but did not use particle-tracking. Both Corell and Döös (2013) and Kurhrt et al. (2004) represent valid modelling approaches, but neither included aggregation and disaggregation of particles. Jackson and Burd (2015) have thoroughly reviewed these processes and the different approaches to modelling them. Scientists need to think broadly and in multi-disciplinary terms, including aspects such as biological activity.

Many studies have revealed the complexity of erosion and deposition processes, including the importance of sediment and seafloor characteristics and of biological activity (see, e.g., Lynch et al. (2015), for a thorough description of both theoretical and modelling approaches). Graf and Rosenberg (1997) show in their review that benthic organisms significantly alter both deposition and erosion, often increasing the physically induced deposition and erosion by a factor of two or more. Organisms exert this effect directly by interacting with the particles in the sediment and in the BBL, or indirectly by altering the sediments and seafloor and the dynamics of the current flow.

Aggregation as an important transport mechanism

Aggregation increases the sinking velocities of their composite organic particles and is therefore an efficient mechanism rapidly removing photosynthetically fixed CO₂ from the surface of the ocean (Turner, 2015; **Figure 2**). Aggregation itself is controlled primarily by three factors: (1) the characteristics of the composite particles, such as their origin (e.g., diatoms, coccolithophores, fecal material, lithogenic input, etc.), concentration, density, size distribution and shape; (2) the physical mechanisms that lead to the collision of suspended particles, including Brownian motion and diffusion, differential settling, and turbulent shear; and (3) the stickiness of the particles, which can influence the probability of particles staying together after they have collided (Alldredge and Silver, 1988; Jackson, 1990; Kiorboe et al., 1994; Beauvais et al., 2006; Burd and Jackson, 2009). Regarding the physical mechanisms, Brownian motion generally relates to nanoparticles and macromolecules which move with rapidly changing direction on the nanometer scale, causing collisions between particles in the nanometer to submicron size domains and perikinetic aggregation (Elimelech et al., 1995). For slowly diffusing micrometer-sized particles such as clay particles, which are frequently dominant in estuarine ecosystems, orthokinetic movements (smaller

and larger sizes moving with different speeds under turbulent shear) are more important for their collisions and aggregation (McCave, 1984), while for even larger particles and aggregates, such as millimeter-sized marine snow, differential settling becomes the dominant collision and aggregation process (Burd and Jackson, 2009). Aggregation due to the differential settling velocities of particles is particularly important for particles of dissimilar size in environments with low turbulence, while in the upper ocean and coastal environments, small-scale turbulence brings particles together to collide and form aggregates (McCave, 1984; Jackson, 1990; Kjørboe, 1997).

In turbulent environments the formation and presence of gel-forming extracellular polymeric substances (EPS) and resulting larger (particulate) structures such as TEP play a critical role for aggregation processes, as it is the stickiness of TEP that 'glues' together other particles (Passow, 2002; Bar-Zeev et al., 2015) and affects the overall morphology of resulting aggregates (Stoll and Buffle, 1998). An increase in stickiness can lead to higher coagulation efficiency and subsequently enhanced particle flocculation (Beauvais et al., 2006). Turbulence may increase the coagulation processes of TEP, but stronger turbulence may also increase disaggregation (Riebesell, 1992; Ruiz and Izquierdo, 1997) and maintain the TEP pool suspended in surface waters (Beauvais et al., 2006). TEP can even be positively buoyant and thus reduce sinking velocities of aggregates and vertical C fluxes (Azetsu-Scott and Passow, 2004; Mari et al., 2017). The effect of turbulent flows on TEP production itself is not fully understood, although it does appear to increase with the intensity of turbulence (Beauvais et al., 2006; Pedrotti et al., 2010).

In relation to anthropogenic impacts, questions arise on how the presence of biopolymers such as TEP affects, for example, the water quality of intake waters of aquaculture activities. How do such biopolymers affect the aggregation processes of microplastics, and how are nanoparticles attaching to these polymers? An interdisciplinary approach addressing the relevant physics, chemistry and biology of such systems is needed; it could be used, for example, to better understand the impact of aggregate properties and TEP produced by diatoms and other microalgae on the exchange of gases, nutrients, and solutes between sinking aggregates and the ambient water. Combining techniques such as laboratory analyses for TEP production (Engel, 2009), microsensor profiling (measuring chemical species such as O_2 and NH_4^+ ; e.g., Ploug and Bergkvist, 2015), and particle image velocimetry (Ploug and Jørgensen, 1999; Kjørboe et al., 2001) can provide a holistic understanding of the occurring processes (Ploug and Jørgensen, 1999; Ploug, 2001; Ploug and Passow, 2007), preferably in a setting very similar to the natural environment. Hence, aggregates are studied in vertical flow chambers, in which aggregates are stabilized in the water by an upward flow velocity that balances their natural sinking velocity, thus allowing aggregates to be examined under hydrodynamic conditions similar to those of sinking aggregates (Ploug and Jørgensen, 1999).

Anthropogenic particle sources and interactions in the coastal ocean

Both natural and synthetic particles co-occur in the marine environment. Their physicochemical behavior and interactions with each other, in relation to the physical and chemical dynamics of coastal seawater, and their impacts on marine ecosystem components can, however, differ, and particularly in terms of their inherent toxicity and their propensity to act as carriers for other associated pollutants.

Natural particles as vehicles for contaminant solutes

Heavy metals and many organic pollutants frequently have their first point of entry to the ocean via coastal ecosystems (**Figure 2**). They may enter as solutes but associate to a large extent with natural particles, through sorption or incorporation. Particle association influences both their bioavailability and transport behavior in estuarine and coastal waters (Gustafsson and Gschwend, 1997; Lead et al., 1999). Colloids, the smallest non-settling particles, are primarily responsible for most of the contaminant sorption, which is attributed to their ubiquitous abundance and large specific surface area with many efficient binding sites. To a large extent colloids bind most metals in freshwaters (Lyvén et al., 2003); as an example, iron oxide colloids act as so-called 'nanovectors' for transport of lead from soils through rivers to the sea (Hassellöv and von der Kammer, 2008). The role of particles for sorbing organic pollutants is less well studied, but endocrine disruptors, pharmaceuticals and polycyclic aromatic hydrocarbons (PAHs) have been found to partition effectively with colloids (Gustafsson et al., 2001; Liu et al., 2005; Maskaoui et al., 2007). In estuaries most colloids are aggregating colloids, with the contaminants largely following the fate of the aggregates, including the persistence of stabilized, organic-rich aggregates in coastal waters (e.g., Stolpe and Hassellöv, 2010).

Synthetic nanoparticles

In the last decade the extensive research and development efforts within nanoscience and nanotechnology have led to numerous products containing nanomaterials in all application areas, from cosmetics to coatings and antimicrobial textiles (Corsi et al., 2014). There is an increasing concern about the risks associated with nanoparticles to ecosystems due to the special reactivity of many nanomaterials (Handy et al., 2008). Initially, the marine environment did not receive as much research attention as freshwater environments, but scientists are now investigating the emission patterns, behavior and transport, and ecotoxicity of nanoparticles to key components of marine ecosystems (Corsi et al., 2014; Callegaro et al., 2015). Especially important are the physicochemical dynamics that occur in the strong salinity gradients of estuaries and the role of natural organic matter interactions in colloidal behavior and aggregation processes. To advance the study of these processes, the development of highly sensitive

and selective analytical and characterization techniques, adapted specifically for nanoparticles in seawater, is needed.

Microplastic pollution

Microplastics released into the marine environment are also intricately linked to the natural marine particle matrix and have the potential to affect, as well as be affected by, the dynamic processes that control vertical particle transportation (**Figure 2**). Microplastics released into the coastal zone are a heterogeneous group of particles, including preproduction pellets (Lechner et al., 2014), fibers from textiles (Browne et al., 2011), microbeads from cosmetic products (Napper et al., 2015) and fragmented plastic debris to name only a few sources. In order to understand their interactions in the environment, one must distinguish between different types of plastics (Browne et al., 2011). They can be divided into two broad main categories: floating and sinking particles. Microplastics from material with a higher density than water, such as polyvinyl chloride (PVC), polyethylene terephthalate (PET) and most polyamides, are expected to sink more readily compared to, for example, polyethylene and polypropylene, which have a typical density of $0.9\text{--}1\text{ g cm}^{-3}$ (Wright et al., 2013). Moreover, transport will also be affected by the size and the shape of the particles (Ballent et al., 2012). Smaller particles, for example, have a lower rise velocity and are more affected by vertical transport (Reisser et al., 2015). A release of less buoyant microplastics can therefore lead to higher concentrations close to the emission source, thus causing a more localized pollution problem, whereas buoyant plastics can be transported further away from the source.

Plastic degradation can lead to a change in crystallinity which is linked to the material density (Lu et al., 1995; Singh and Sharma, 2008). Additionally, biofouling (Fazey and Ryan, 2016) and biotransformation (Watts et al., 2015) can change the properties of the material. Subsequently, material that enters the ocean as buoyant can become less buoyant over time. Holmström (1975) found polyethylene on the ocean floor already in the 1970s. Fazey and Ryan (2016) evaluated the effect of biofouling on buoyant microplastic and found that particles showed a 50% probability of sinking after an exposure of between 17 and 66 days only. The rates of degradation and biofilm formation are likely to be further affected by seasonal variations of UV radiation, temperature and biological activity (Fazey and Ryan, 2016; Weinstein et al., 2016). Further studies where low-density types of particles are being found in sediment samples also confirm the effect of biofouling on sedimentation processes (Thompson et al., 2004; Morét-Ferguson et al., 2010; Browne et al., 2011; Chubarenko et al., 2016). In samples from different environments off the west coast of Sweden (**Figure 3**), microplastic composition in terms of polymer type, level of degradation and biofouling was studied using techniques such as Fourier transform infrared spectroscopy (FTIR; **Figure 3**), image analysis, scanning electron microscopy and Raman spectroscopy (Hidalgo-Ruz et al., 2012; Fries et al., 2013; Rocha-Santos and Duarte, 2015; Karlsson et al., 2016)

in the laboratory and indicated that the particles had undergone degradation. Microplastic particles are thereby known to be affected by degradation, biofouling and biotransformation, and also to interact with the natural particle matrix of marine snow (Van Cauwenberghe et al., 2013; Wright et al., 2013). Once incorporated, microplastic particles have the potential to change the normal sinking rate of the aggregates themselves (Long et al., 2015) and may thus influence the role of aggregates within the biological carbon pump, particularly in the coastal zone.

All of these factors can, individually and in combination with each other, affect the buoyancy and sinking/settling properties of the particles, which in turn will affect their vertical and horizontal transportation, likely explaining some of the discrepancies observed between modelled amounts of plastic material entering the environment and what is found in field samples. In the future, predictive transport and fate models need to consider the effects of degradation, polymer type and particle size. In order to better understand how these factors affect transportation, particles found in field samples need to be analyzed for material composition using chemical analysis and imaging techniques such as FTIR or Raman. Because the material changes with degradation and biofouling, studies of these processes are vital both to predict fate of the material and to accurately interpret the findings in field samples.

Aquaculture activities

Particle inputs to the coastal zone due to human activities are not restricted to synthetic micro- and nanoparticles, but also occur as a consequence of other activities such as aquaculture. Aquaculture activities take a variety of forms: net cages in the ocean, flow-through systems such as open raceways, intertidal or pond aquaculture, and land-based tank systems (**Figure 2**). In all of these instances, the discharge of particulate matter is of concern, but is particularly important in open-net fish cages, where outflows of waste are difficult to control (Brager et al., 2015). Uneaten food and fecal matter may settle below and around farm sites leading to deposition of organic matter that can be up to 20 times higher than background values (Tlustý et al., 2000). Water transport processes are important as particle dispersion patterns are influenced by particle size and flocculation, tidal flow, topography and residual circulation, turbulence, as well as wind and wave energy (Lander et al., 2013; Law et al., 2016). Because smaller particles remain longer in the water column, they have a greater tendency for horizontal movement: airborne dust from feed pellet distributors for instance can be carried even greater distances by wind, or transported in surface films (Hargrave, 2003). Dissolved waste products have been recorded up to 1 km away, while particulate sedimentation from aquaculture sites can affect the benthic environment to a radius of 100 m around farm sites (Sarà et al., 2004). The composition of particulate waste depends on the farming methods, species, feed quality, management practices and stocking density, but the settlement of particulates is consistent, resulting in increased turbidity (Bongiorni et al., 2003) and an increase of organic solids that eventually

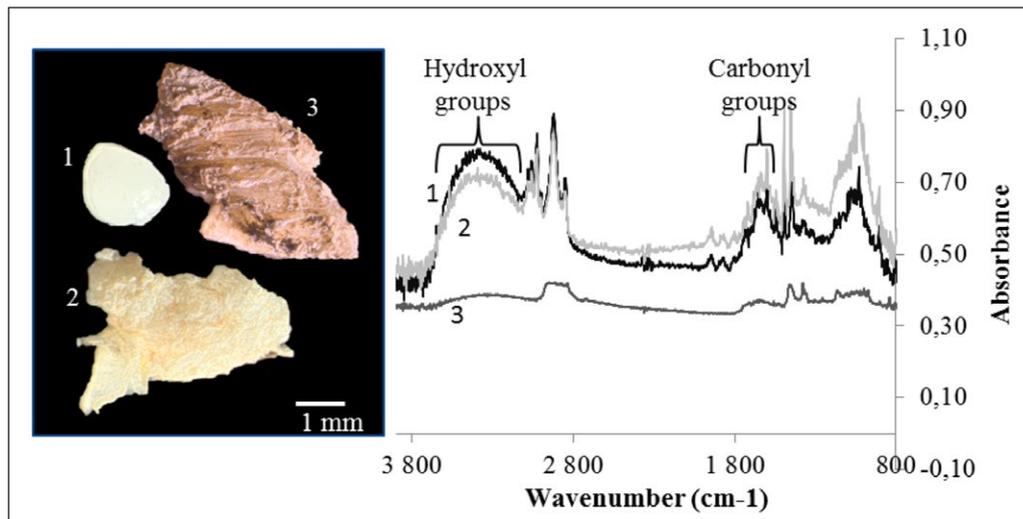


Figure 3: Microplastic particles investigated by Fourier transform infrared spectroscopy. Left: Examples of three different particles found in the coastal surface waters west of Sweden, in November 2015. The particles, as seen in the photograph, differ in size and structure. Right: Using Fourier transform infrared spectroscopy (FTIR), particles 1 and 2 were recognized as polystyrene and particle 3, as polypropylene. The photograph also indicates that the particles have undergone degradation, which is further supported by the formation of hydroxyl groups (around 3000 cm^{-1}) and a formation of carbonyl groups (1714 cm^{-1}) in the FTIR spectra. The formation of these groups has previously been associated with degradation for both polypropylene and polystyrene (Wang et al., 1996; Qin et al., 2005). (Left photo: Sameh Az Aldeen; right data: Karlsson, T, Hassellöv, M, unpublished). DOI: <https://doi.org/10.1525/elementa.149.f3>

settle on the sediment under and near farms (Tomassetti et al., 2016). Changes in sediment biogeochemistry due to anoxic conditions, including the production of hydrogen sulfide, ammonium, and methane, in turn affect the marine environment by altering the habitat and community composition of all levels of flora and fauna (bacteria, seagrasses, meiofauna and macrofauna; see, for example, Holmer et al., 2005; Hargrave, 2010; Martinez-Garcia et al., 2015).

Aquaculture practices, however, are not only a source of particulates but are themselves also affected by other particles already present in the environment (**Figure 2**). Human activities such as urbanization, construction, agriculture, and mining cause short-term or long-term increases in particulates at aquaculture sites that have been shown to negatively impact spawning, growth and reproduction (Bash et al., 2001). What effect the intake of microplastics and other pollutants have is not well documented, but hatcheries are particularly vulnerable to small fluctuations in water quality at their intakes (Attramadal et al., 2016). The existence of TEP, an important particle type in aggregate formation, is often overlooked in relation to aquaculture activities, especially in hatcheries (Joyce and Utting, 2015).

Bottom trawling and dredging

Although resuspension of sediments occurs in shallow (<5 m depth) and deeper coastal waters as a consequence of natural transport processes and events (**Figure 2**), sediments are also resuspended by human activities such as bottom trawling (Ferré et al., 2008), dredging (Newell et al., 1998; Essink, 1999) and drilling (Khondaker, 2000). Bottom trawling affects the seafloor (Puig et al., 2012; Martín et al., 2014b), but also the water column above

it (O'Neill and Summerbell, 2011; Bradshaw et al., 2012) by suspending sediments from the seafloor (**Figure 2**). This action may result in the relocation of sediment to deeper areas (Martín et al., 2014a) and even in sediment gravity flows (Palanques et al., 2006). Resuspension of sediments may reduce the organic content of the surface layer (Pusceddu et al., 2014) and mobilize nutrients (Dounas et al., 2007) and contaminants (Bradshaw et al., 2012). Elevated turbidity may reduce light, thus affecting primary producers (e.g., seagrasses) in shallow waters (Moore et al., 1997; Essink, 1999; De Boer, 2007). Elevated turbidity can also affect egg and larvae of fish and invertebrates, through adherence-associated loss in buoyancy of the egg, the disturbance of larval settlement behavior, and increased mortality (Gilmour, 1999; Westerberg et al., 1996), and affect aquaculture activities. Changes in the quality and size of suspended particles may affect feeding and oxygen consumption by suspension feeders such as sponges (Tjensvoll et al., 2013; Kutti et al., 2015), while fish may be affected by fine particles that clog their gills (Humborstad et al., 2006).

The mechanical force of a trawl lifts resuspended particles into a plume that rises above the seabed. The same force creates strong vertical mixing. In stratified waters this forcing will lead to local vertical homogenization. The plume thus not only has high particle concentrations and turbidity, but also has a density that deviates from its surrounding. Pressure gradients will force the plume to intrude the surrounding water at its neutral density level (Thorpe, 2005). In stratified waters this process thus enhances dispersion of trawl plumes and associated particles.

The Kosterhavet National Park on the west coast of Sweden is well suited for investigating the sediment

resuspension effect from trawling (**Figure 4**), but this effort requires an interdisciplinary approach with physical oceanographers, marine biologists and fishery experts. It also requires the application of multiple methods, including fishing vessel monitoring and use of state-of-the-art instrumentation, such as the Laser in-situ Scattering and Transmissometry (LISST) particle analyzer (Agrawal and Pottsmith, 2000). In the National Park, trawling activity is restricted to the weekdays Monday–Thursday, with closures in place from Friday to Sunday. Multiple investigations of the turbidity on Sunday (last day of closure) and the following Monday (first day of trawling) have allowed for quantification of the effect, as exemplified in **Figure 4B**. In Kosterhavet, the trawling activity has an impact on the turbidity at depths where trawling occurs. The average effect on the turbidity is moderate, 0.05 NTU compared to background levels after one day of trawling. However, the variation increases by as much as 75%, with many more instances of high turbidity, and the background level is also likely affected by the trawling (Wikström et al., 2016; Linders et al., 2017).

Dredging has similar effects on particles and their transport as trawling. Resuspension occurs during both the removal and eventual disposal of the dredged material (Netzband and Adnitt, 2009). Turbidity is increased, and enhanced deposition at dump sites impacts the benthic fauna and flora (Newell et al., 1998; Essink, 1999). Dredging often takes place in heavily industrialized areas, such as harbors, which may lead to the mobilization of contaminated sediments (Fichet et al., 1998; Essink, 1999; Sturve et al.,

2005). One of the most important drivers for dredging is the increasing seaborne trade as shipping channels and ports are maintained and expanded (IADC, 2015). Several Nordic governments have expressed an ambition to expand the seaborne transport capacity: for example, Norway's 'National Transport Plan 2018–2029' (www.regjeringen.no/no/dokumenter/meld.-st.-33-20162017, in Norwegian), and the Swedish Maritime Administration's 2016 report on the potential for short sea shipping (http://www.sjofartsverket.se/pages/106206/Slutrapport_rev_2017-01-17.pdf, in Swedish). Further drivers for dredging also include the increasing pressures on coasts and their waters due to population growth, energy demands and development of water-related tourism, as well as the need for coastal protection (IADC, 2015).

Benthic organisms as particle sinks: seagrass meadows

Benthic organisms present in coastal and deeper waters actively contribute to the resuspension and trapping of particles (Graf and Rosenberg, 1997). Bioturbators, such as the lugworm *Arenicola marina*, can destabilize the sediment by reworking and loosening the top grains of the sedimentary matrix. In contrast, bacterial biofilms and sedentary organisms, such as tube-builders (e.g., *Polydora cornuta* and *Lanice conchilega*) and seagrass meadows, can stabilize the sediment by binding sediment particles (Fonseca, 1989; Delgado et al., 1991; Volkenborn et al., 2008). Benthic organisms can thus modify the bottom topography, which can alter interactions with near bottom velocities. For example, coastal submerged vegetation

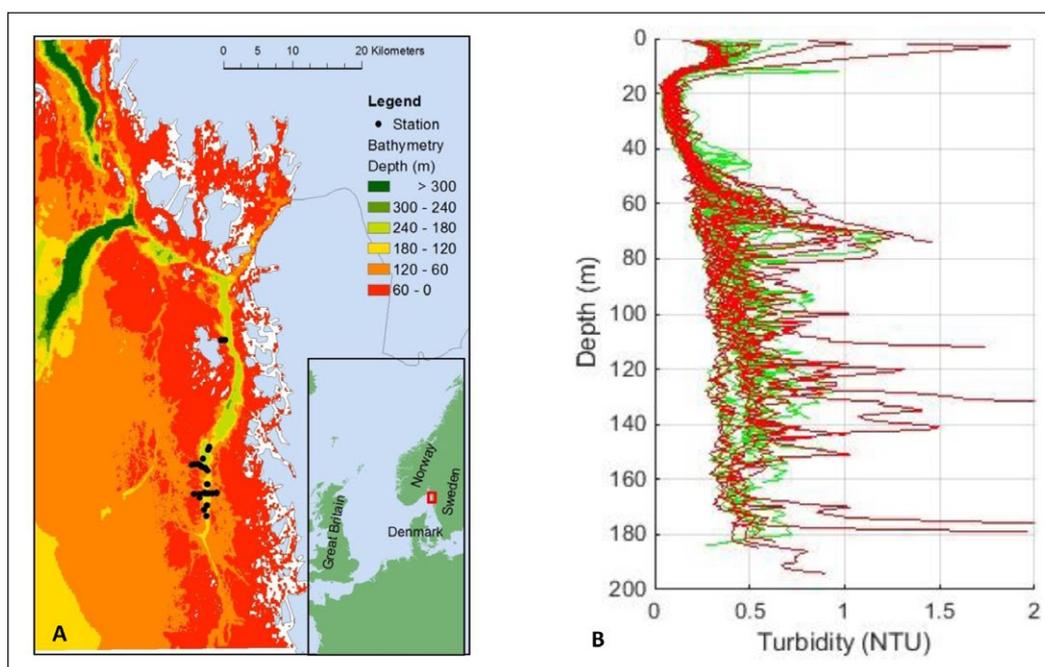


Figure 4: Map of Kosterhavet National Park and turbidity profiles from an offshore trench. (A) Kosterhavet National Park is located on the west coast of Sweden (see inset). Colors from red to green distinguish the bathymetry of the area in the northeastern Skagerrak, with black dots marking the locations of measurement stations sampled on 4–5 October 2014 in a trench off the coast. **(B)** Vertical profiles of turbidity (where NTU indicates nephelometric turbidity units) on Sunday, 4 October (green, no trawling), and Monday, 5 October (red, trawling), in the trench. Note the regulated upper depth limit for trawling at 60 m. DOI: <https://doi.org/10.1525/elementa.149.f4>

such as seagrass can increase the bottom roughness and the height of the benthic boundary layer (Infantes et al., 2012). In shallow areas (<5 m depth), the hydrodynamics of waves and currents are among the main factors increasing water turbidity by resuspending sediment. This sediment in suspension alters the water quality and reduces the light penetration depth, until particles settle to the seabed or are redistributed (De Boer, 2007). Water transparency is crucial, however, for submerged coastal vegetation because they need high levels of light for growth and development (Duarte, 1991). Sediment stabilization by vegetation maintains good water quality, representing a positive feedback that keeps light available for the plants (van der Heide et al., 2007; Maxwell et al., 2016) (**Figure 5A**).

Seagrasses are common in Nordic coastal waters and, as ecosystem engineers, modify both the biotic and the abiotic environment of their ecosystem. They can reduce flow velocities and attenuate waves (Bouma et al., 2005; Infantes et al., 2012), and thus decrease turbidity through the reduction of fine suspended sediment particles in the water column which accumulate instead within the seagrass meadow (Ward et al., 1984). Seagrasses are able to affect particle flux directly through loss of momentum and increased path length from particle collisions with leaves (Hendriks et al., 2008). A large-scale recovery of the seagrass *Zostera marina* in the US after restoration showed a dramatic decrease in the water turbidity once the seagrass was established, indicating the positive feedback of aquatic vegetation (Orth et al., 2012). Other benthic organisms such as filter feeders (e.g., the mussel *Mytilus edulis*) increase biodeposition by trapping nutrients and particles from the water column (Kautsky and Evans, 1987). The use of mussel farms to improve water quality has been suggested in Sweden by Lindahl et al. (2005), because they were estimated to reduce 20% of the total dissolved and particulate nitrogen in the water.

However, in areas where vegetation has been affected negatively by anthropogenic causes (e.g., eutrophication, dredging, fishing activities, coastal development), flow velocities are higher than in existing vegetated beds, resulting in sediment resuspension events that prevent plant development. For example, in the area of Marstrand on the Swedish west coast, 90% of the eelgrass *Zostera marina* has been lost since the 1980s (Baden et al., 2003). Studies suggest that the primary mechanism behind the decline is an increased abundance of ephemeral algal mats, caused by eutrophication in combination with overfishing, that cover the eelgrass beds during the summer, and which have caused a trophic cascade that promotes growth of the algae (Moksnes et al., 2008; Baden et al., 2010; Baden et al., 2012). Despite decreasing nutrient loads to the coastal waters, there has not been a natural recovery of eelgrass (Nygqvist et al., 2009; SwAM, 2012). In these sites, turbidity is high due to the resuspension of fine clay particles (**Figure 5B**), and thus light penetration is low. In locations where the environment has shifted from a vegetated state to a state of bare sediment (e.g., Marstrand, Sweden), seagrass restoration could be challenging as particle resuspension and turbidity are preventing plant establishment (Infantes et al., 2016b; Moksnes et al., 2016). Other factors might also prevent restoration, including the presence of predators and bioturbators, the sediment composition, hydrodynamics or light (Infantes et al., 2011; Eriander et al., 2016; Infantes et al., 2016a), such that additional management plans might be needed.

Seagrass ecosystems provide important services in coastal seas by supporting high biodiversity (Duffy et al., 2015), reducing coastal erosion by attenuating waves (Infantes et al., 2012; Luhar et al., 2017), trapping particles and reducing resuspension (Hendriks et al., 2008), trapping CO₂ and functioning as carbon sinks (Röhr et al., 2016). Management actions are needed to break feedbacks that are preventing seagrass development and to

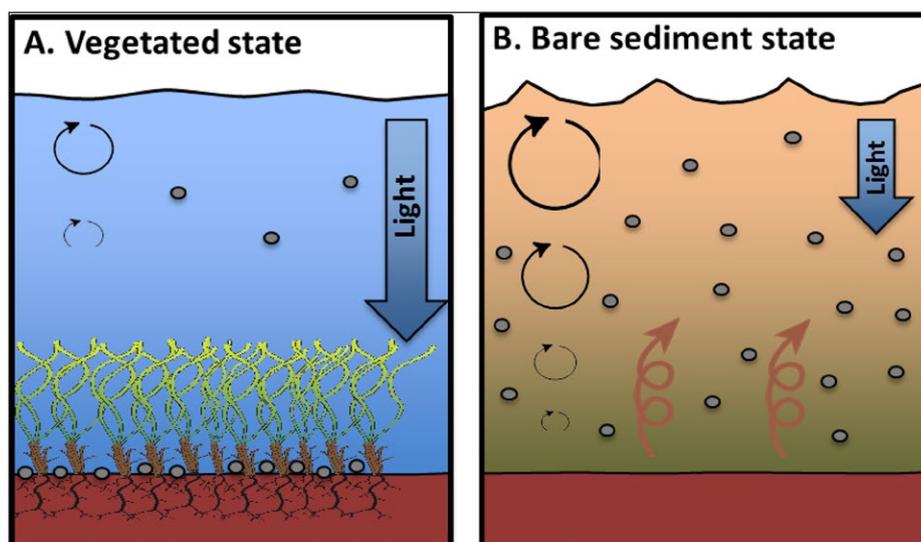


Figure 5: The effects of presence or absence of vegetation on particles in the water column. The presence of vegetation (**A**) reduces hydrodynamics and sediment resuspension, resulting in an increased depth of light penetration in the water column. In contrast, the absence of vegetation (**B**) leads to sediment resuspension, which increases turbidity and reduces light penetration. DOI: <https://doi.org/10.1525/elementa.149.f5>

promote plant growth with regard to seagrass restoration. For example, temporary floating wave barriers to attenuate waves and reduce sediment resuspension could be implemented until vegetation is established. Adding coarse sand over fine muddy sediments (sand-capping) before restoration could also be used as a measure to reduce resuspension and improve water clarity for plant growth. Yet, before these actions are implemented, it is necessary to understand the local coastal hydrodynamics to ensure their efficiency and prevent further environmental degradation.

Summary and future perspectives

The coastal zone is a highly dynamic environment and frequently the first point of entry for many natural as well as anthropogenic particles such as microplastics, heavy metals and waste from aquaculture activities. We have highlighted the particular importance of particles in stratified coastal waters and estuaries, their roles in natural processes, their formation and transport, and their interactions with anthropogenic activities. We have further stressed their complexity and emphasized the need for interdisciplinary approaches involving marine biologists, chemists, geologists and physical oceanographers to achieve a mechanistic understanding of particle processes in the coastal waters of the Anthropocene. Raising our understanding of particles and our ability to manage coastal waters will require investigations in controlled laboratory and mesocosm settings, actual in situ observations of the coastal ocean, and incorporation of relevant processes into numerical models.

We have identified two areas of research that are fundamental to our understanding of particle transport and that demand more research attention: the role of turbulence, and the size spectra and abundance of particles. Turbulence is important for small-scale and large-scale production, transport and transformation of organic particles in marine environments. Yet, our quantitative and mechanistic understanding of the influence of turbulence on these processes remains poor. In future studies, we propose new combinations of in situ approaches to quantify turbulence in relation to particle size spectra and abundance, with ex situ laboratory studies to improve our mechanistic understanding of particle dynamics. In situ monitoring may involve a wider range of optical and multi-frequency acoustic sensors. Novel laboratory approaches may involve holographic microscopy and confocal microscopy for analysis of 3D particle composition of, for example, TEP, in addition to chemical analysis of composite particles and their diversity.

Particle parameters often display higher natural variability than other hydrographic parameters. Given this variability and the interest in expanding trawling and dredging activities, frequent monitoring of particle parameters is warranted. Particle size is one of the most defining parameters, but particle size distribution remains largely unmapped in most of the Nordic coastal ocean and lacking in current monitoring efforts. Today off-the-shelf optical sensors for in situ measurements of particle size distribution exist, including sensors using near forward scattering

(Agrawal and Pottsmith, 2000), macroscopic imaging (e.g., Picheral et al., 2010), and holographic imaging (Davies et al., 2015). Some of these sensors could easily be included into existing monitoring programs.

Advancing understanding of both topics would thus benefit from improved water column monitoring. Currently, vertical profile monitoring is carried out once per month or less in most of the Nordic waters (<http://marine.copernicus.eu/>) and largely conducted from research vessels. Expecting this costly form of monitoring activity to expand is unrealistic. We suggest the expansion of automated or semi-automated monitoring, well exemplified with the FerryBox on commercial ships along diverse routes (www.ferrybox.org) and with monitoring buoys and moorings within the joint European JERICO project (www.jerico-ri.eu/). The JERICO project (Puillat et al., 2016) aims to integrate the existing automated systems for operational monitoring of the coastal and shelf seas and to stimulate the development of new systems. However, too little is done currently and what is implemented scarcely covers the coastal zone. A fundamental problem is that we need to monitor the whole water column, from the sea surface to the seafloor. This requirement could be achieved from a mooring with multiple sensor packages arranged on a vertical line or possibly by one sensor package moving along a vertical line. The Wirewalker is a successful example of the approach with a moving package, with package movement powered by the ocean waves, creating vertical heaving of the wire suspended beneath a surface buoy (Pinkel et al., 2011; Lucas et al., 2017). Another more flexible option is to use unmanned gliders. This technology has come of age, with proven reliability, decreasing costs, and the capability of hosting many types of sensors (Rudnick, 2016), recently including sensors for particle size distribution (e.g., www.sequoiasci.com).

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Competing interests

The authors have no competing interests to declare.

Author contributions

- Contributed to conception and design: TL, EZ, EI, MH
- Contributed to writing of manuscript: EZ, TL, EI, AJ, TK, MH, HP, MS
- Compiled and integrated the manuscript: EZ
- Contributed revisions to the manuscript: EZ, TL, HP, EI, TK, MH, AJ, MS
- Approved the submitted version for publication: TL, EZ, AJ, EI, HP, MH, TK, MS

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