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The unaccountability case of plastic pellet pollution

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ABSTRACT

Plastic preproduction pellets are found in environmental samples all over the world and their presence is often linked to spills during production and transportation. To better understand how these pellets end up in the environment we assessed the release of plastic pellets from a polyethylene production site in a case study area on the Swedish west coast. The case study encompasses; field measurements to evaluate the level of pollution and pathways, models and drifters to investigate the potential spread and a revision of the legal framework and the company permits. This case study show that millions of pellets are released from the production site annually but also that there are national and international legal frameworks that if implemented could help prevent these spills. Bearing in mind the negative effects observed by plastic pollution there is an urgent need to increase the responsibility and accountability of these spills.

1. Introduction

Plastic material is an integral part of our daily lives and the annual production is today > 300 million tons (PlasticsEurope, 2014). Most thermoplastic articles and materials originate from virgin plastic pellets, also called preproduction pellets, beads, or nurdles. These are produced in polymeric production industries, or to some extent in recycling facilities. The pellets typically have a diameter of 2–5 mm and are regular in shape. Smaller powders, often referred to as fluff, are also produced and have more irregular shapes and sizes. The produced pellets are subsequently transported from the production site, with train, truck and/or ship to the facility where the final product is being molded or extruded from the virgin material. This material can however be lost in all steps during the production chain, from preproduction, to the final item production.

The first scientific reports to document the occurrence of plastic pellets in the environment were published during the 1970's (Carpenter and Smith, 1972; Carpenter et al., 1972). Since then plastic pellets have been found in surface water samples and on beaches all over the world (Colton et al., 1974; Gregory, 1977; Morris and Hamilton, 1974; Fernandino et al., 2015; Eriksen et al., 2013). Plastic pellets are also found on beaches that are not directly in contact with petrochemical or polymer industries. Although they can be in minority in comparison to other plastic litter (do Sul et al., 2009; Fok and Cheung, 2015) they are commonly found, showing the possibility for large scale transport.

Several species of fish and birds have shown to ingest plastic pellets (Carpenter et al., 1972; Kartar et al., 1973; Baltz and Morejohn, 1977) and although the potential risks of microplastic ingestion to marine organisms are hard to quantify, the list of species known to ingest plastic in the marine environment is currently in the hundreds (Kühn et al., 2015), and includes species from all trophic levels (Eriksson and Burton, 2003). The effects of ingestion of macroplastic debris are well documented (Browne et al., 2015; Kershaw et al., 2015). Few studies conclusively address the effects of pellets ingestion and the types and amounts of microplastics used in laboratory studies are rarely consistent with those found in the field (Phuong et al., 2016). But studies on the effects of microplastics show that they have the potential to be passed up through the food chain (Setälä et al., 2016), and the plastic particles can have physiological effects, including changes in reproduction (Sussarellu et al., 2016), metabolism (Cole et al., 2015; Lu et al., 2016) and behavior (Mattsson et al., 2014). Other studies that have focused on the propensity for plastics to act as vectors of environmental toxins find that levels of common POPs can be up to 10^7 times higher in plastic pellets than in sea water (Koelmans et al., 2016; Holmes et al., 2012). A number of studies indicate that microplastics can act as vectors for pollutants from the environment into organisms

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(Rochman et al., 2013; UNEP, 2014), but the importance of this factor compared to uptake via normal feed contamination or exposure to other naturally occurring particles in the environment is still uncertain (Koelmans et al., 2016). Additionally some of the additives used in plastic products have been shown to migrate from microplastics to biota (Rochman et al., 2013).

Plastic pollution can also lead to significant economic losses, for example through losses in revenue from tourism and the cost of beach cleaning (UNEP, 2014; Mouat et al., 2010; Leggett et al., 2014). Although these costs are based on the total amounts of plastic on beaches, pellets are commonly found during beach cleaning campaigns and thereby a contributing factor to the costs.

The occurrence of plastic pellets in the environment was linked to industrial outlets already in the 70s where researchers first started calling for precautionary measures within the industry (Hays and Cormons, 1974). Even so, a study in the river Rhine from 2015 showed that 60% of the identified plastic particles were spherules, with a possible linkage to different industries along the river (Mani et al., 2015). Similarly pellets were measured at a mean density of 693 items per 1000 m^3 in the river Danube with the highest value of 138,219 per 1000 m^3 during a heavy rainfall (Lechner et al., 2014). These were, according to a press release by a close plastic production company, at least in part due to losses at a production site (Borealis, 2014). In Austria plastic is classified as a filterable substance, and the limit for discharge is 30 mg/L. This limit, extrapolated to a year's worth of discharge amounts to 94.5 tons/year, is a threshold that researchers have questioned due to the high volumes it allows for (Lechner and Ramler, 2015). Although the actual levels that leach into the environment from the production plants are unknown a recent study in the UK indicates a national yearly loss of 5–53 billion pellets (Cole and Sherrington, 2016). The results from that study is however based on estimates on the percentage loss provided from the industry and although there are examples of studies, as mentioned above, where high concentrations of pellets have been found close to production plants there is very limited data on the actual runoff.

In order to better understand how and why plastic pellets end up in the environment a case study approach was used where we investigated the major plastic industry complex in Sweden. Although the specific volumes of pellet spills may differ from site to site there is ample evidence of their occurrence, both through present and historical studies from independent researchers and the companies themselves. As the world-wide market is dominated by a few big companies, with concentrated production facilities, although a worldwide distribution and manufacturing network, there is also reason to believe that the routines would be similar on other sites. Within the case study we therefore investigate the industries associated permits and regulations, reviewed potential environmental and economic impacts and investigated the total runoff as well as the present pellet pollution situation in the nearby area. These aspects were investigated in a multidisciplinary approach, including environmental surveillance, measurement of pellet fluxes, hydrographical mapping and modelling as well as legal studies and environmental impact assessments.

2. Case study description

In the chemical industry cluster in Stenungsund, there is a polyethylene production facility in the center, with supporting industries such as an ethylene producing cracker, and also several smaller companies involved in the handling and transport of the produced pellets. Polyethylene has been produced in Stenungsund since 1963, and the production volume has gradually increased. It is the only polyethylene production site in Sweden and the annual polyethylene production capacity in Stenungsund amounts to 0.75 Mtons (Mark- och miljödomstolen Vänersborg, 2015), which corresponds to approximately 5% of the European polyethylene demand (PlasticsEurope, 2014).

The expansion of and changes in the production has required a long row of updated and revised permits throughout the years. The current permit was approved in 2007, but the decision on some conditions was postponed because of lack of information. Since then the release of particles was not mentioned in the decisions until 2013 (Mark- och miljödomstolen Vänersborg, 2013), twenty years after the first problem formulations and legal recommendations to avoid pellet spills were provided by the US EPA (US EPA, 1992). The permit background report showed high amounts of plastic particles in the effluent and the company was assigned to investigate it further. The background material also show that the company has reported that several of the additives that are used in the plastic are classified as toxic for water living organisms (Mark- och miljödomstolen Vänersborg, 2015).

In 2014 the company issued a press release stating that “our aim is to not lose a single pellet” explaining its zero pellet loss objective (Borealis, 2014). In the company's yearly environmental report, a description of their sewage and storm water treatment was presented. The storm water drains has during recent years been led from the production site through a polyethylene separator, known as a skimmer-pit, to remove particles that float or sediment. The water is then led to Stenunge Å, a small creek running by the production site, which empties into the industrial harbor. The industrial sewage system collects water from process areas; this water is led through a density separator to separate light density liquids and polyethylene. After treatment the water is led to Askeröfjorden (Borealis, 2016) (see Supplementary material 2A for a more detailed record of the company permits).

The produced polyethylene pellets are loaded for shipping and moved from the production site by road transport but can then be further transported by boat, ferries or railroad (Mark- och miljödomstolen Vänersborg, 2015; Borealis, 2016). Records from inspections, and observations in this study, show that plastic spills have been reported in proximity to transport and storage areas as well as on sites where other companies handle waste or cleaning from the production company (Supplementary material 2B).

2.1. Description of the area

The study site is located within the Orust-Tjörn fjord system on the Swedish west coast. In close proximity, there are several important Natura 2000 areas and the shores are mainly steep and rocky interrupted by bays with beaches of protected to moderately exposed character. Along some shorelines shallow salt marsh grass meadows grazed by bird life and cattle and sheep also occur. The surface water within the fjord system has been estimated to have a residence time in the order of 40 days (Hansson et al., 2013). Organic material is transported by rivers and streams into the fjord system and although a portion of it is transported out of the area, low rates of water exchange leads to accumulations in the sub-basins (Hansson et al., 2013). The fjords inside the islands of Orust and Tjörn are not directly influenced by any larger rivers, so rather than a typical estuarine circulation the circulation in the fjords is to a large degree influenced by the stratification outside the fjords as well as local wind forcing. The main water exchanges are through the southern entrance and are caused by upwelling and downwelling of the coastal stratification (Björk et al., 2000) which is strongly related to regional wind patterns (Hansson et al., 2013). The steric pressure gradient resulting from the fresher surface waters at the southern entrance give rise to a general counterclockwise circulation (Björk et al., 2000).

Although tidal currents are relatively strong in some of the more narrow straits, the general area has weak tides (< 0.2 m amplitude). The area is however strongly influenced by the Baltic Current, which carries low-saline water from the Baltic Sea northward along the Swedish coast as well as North Sea water that joins the Baltic Current via the Jutland Current. Below and outside the Baltic Current, there also is a general cyclonic circulation of the more saline Skagerrak waters. This circulation that carries surface waters from a large part of northern

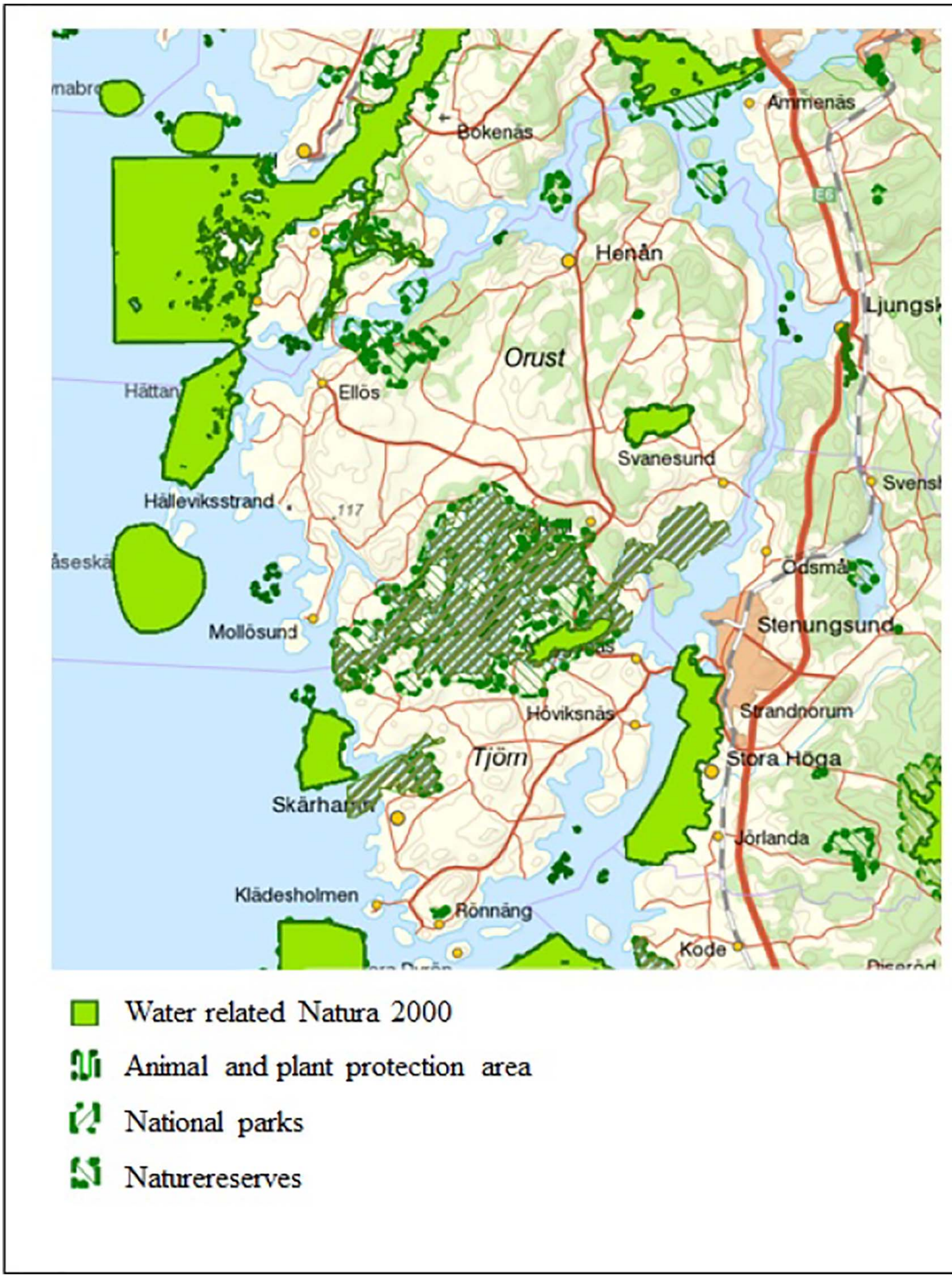

Fig. 1. Protected areas within the case study area (map adapted from Vissnet).

Europe, combined with dominating south-westerly winds that blow the surface waters onshore, has proven to cause a concentration of marine litter along the northern beaches of west Sweden including the west facing beaches of Orust and Tjörn (Strand et al., 2015).

2.2. Potential ecologic and economic consequences of pellet spills in the case study area

The durability of the pellets and their potential for long range transport result in potentially far-reaching consequences of industrial spills of plastic. Their propensity for long-range transport is however in part dependent on the characteristics of the surrounding area. Consequently in this case, a majority of the material is expected to accumulate close to the runoff areas and thereby be of local and regional concern. The Skagerrak Kattegat area is of importance from an ecosystem service perspective (Swedish E.P.A., 2009) and marine litter in Swedish waters have shown to negatively affect ecosystem services (Havs- och vattenmyndigheten, 2017).

Several protected areas are located in close proximity to the case study area (Fig. 1). In fact, 20% of the marine area in Skagerrak and Kattegat is protected (Havs- och vattenmyndigheten, 2017), but as many coastal areas; the region is also subjected to multiple stressors

(Jutterström et al., 2014). The marine environment close to the case study area is high in biodiversity (Havs- och vattenmyndigheten, 2017) and several of the important species in the area are filter feeders such as brittle stars, sponges and blue mussels (Havs- och vattenmyndigheten, 2017) which may be vulnerable to microplastic plastic spills. Specifically filter feeders have been shown to ingest high concentrations of microplastics when compared to animals employing other feeding strategies (Setälä et al., 2016). For provisioning services in Swedish waters, marine litter is expected to have a moderate negative effect on food, and for regulating services, a moderate negative effect on the regulation of toxic substances (Havs- och vattenmyndigheten, 2015). This may be of additional importance in this case as concern has been raised about the release of plastic additives and bi-products that are toxic for water living organisms from the production facility (Mark- och miljödomstolen Vänersborg, 2013).

Furthermore, the region of Bohuslän is identified as an area of national interest for outdoor life. One example is the extensive recreational fishing of brown trout in Stenunge å, where recent analyses of their stomach content have shown that 68% of the fish has ingested microplastics (Karlsson et al., 2017). The importance of recreation and tourism in the area is further mirrored in the fivefold increase in population that occurs during the summer, also reflected in the additional summertime increase in leisure boating; 27% of the guest nights for recreational boats are in the northern part of Bohuslän (Havs- och vattenmyndigheten, 2017). Although any detailed calculations on the cost that the plastic spills from industry have on recreational values are beyond the scope of this study, marine litter has repeatedly been shown to have a negative economic effect on tourism and recreation (Mouat et al., 2010; Leggett et al., 2014; Hays and Cormons, 1974; Jang et al., 2014; Botero et al., 2017). In fact, it has been estimated that marine litter in Swedish seas has a strong negative effect on ecosystem services within cultural values related to recreation and aesthetics (Havs- och vattenmyndigheten, 2015).

3. Materials and methods

To assess the current situation of plastic spills in the case study area a combination of measurements and photo documentation in the field in combination with theoretical calculations and models was performed (Supplementary material 3A). The results were then related to the legal documents, permits and policies.

3.1. Pellet discharge to surrounding waterways

Field measurements were made to assess the hourly runoff of particles from the production plant site into Stenunge Å. Sampling was performed on the 20th February 2016. A net was places so that the surface water of the river outside the production site was collected using a 300 μm mesh (See Fig. 2). The full sample was size fractionated into > 2 mm, 2–1 mm and 1–0.3 mm. The plastics in the > 2 mm fraction were manually separated from the organic material, counted, sorted according to color and weighed (Mettler Toledo). A subset of 20 pellets were then measured with Fourier transform infrared spectroscopy (FTIR, Nicolet iN10, reflection mode 64 scans) for identification purposes. Additionally the surface degradation for 10 particles was compared through FTIR-ATR (256 scans). From the smaller fractions triplicate subsamples of a few grams were taken and the number of particles/g was counted in a stereomicroscope. 25 particles from the smaller fractions were analyzed with FTIR in reflection mode (64 scans).

3.2. Dispersion of pellets

3.2.1. Theoretical dispersion in the area

In order to estimate the spread of the pellets released from the production plant, GPS-drifters were deployed. One drifter with the dimension of 11 × 21 × 7 cm and a density about 500 kg/m^3 and two drifters with the dimensions of 11 × 8 × 5 cm and density of density about 800 kg/m^3 were deployed in the end of March-beginning of April, and followed until they stranded. Wind data was retrieved from the meteorological station Måseskär. Theoretical estimates of the dispersion from the source were established based on the observed typical drifting times and distances together with earlier published estimates of surface water residence times and mean flows through the system (for a detailed description of the calculations see supplementary material for the result Section 4.2.1).

3.2.2. Field measurements on nearby beaches

In order to assess the pellet pollution level in the archipelago where the plastic industry is situated, the number of pellets on the beaches was surveyed. There are standardized methods to survey beaches for macroscopic marine litter (OSPAR Commission, 2010; Cheshire and Adler, 2009). In these guidelines, a 100 m stretch of beach from the water to the end of the beach should be completely surveyed for an extensive range of standardized items. Pellets are categorized in the databases of UNEP and OSPAR, but not required to be counted, only documented as a yes/no. Beach dynamic processes have been shown to affect the distribution of the pellets (Moreira et al., 2016) and to count pellets on 100 m beach is extremely time consuming for a normal sand beach, but for the rocky archipelago of the Swedish coastline with small irregular bays, this practice is not even applicable. Our method of choice was to manually search and count the number of pellets found per unit hour of searching. The same person was carrying out the search surveys to maximize comparability. Although we acknowledge the method not to be linearly quantitative, and to some extent is influenced by the characteristics of the specific beaches, it more than fulfills the objective of the study; to assess the relative abundance density of pellets on beaches in the case study area.

3.3. Legal aspects

Relevant laws and regulations were reviewed through looking through the company permits, scientific literature on the topic and through searching for relevant cases brought up in the European commission. The legal framework was then examined through an established methodology (Gipperth, 1999; Westerlund, 2003), analyzing the relationship between environmental objectives, legal requirements and enforcement. Legal requirements were determined by the analysis of traditional legal sources such as legislation and case law. The analysis of the permits and decisions made by courts and authorities provides an understanding of how the implementation of general rules of conduct is applied and enforced.

4. Results and discussion

4.1. Pellet runoff to surrounding waterways

During a time span of 1 h (date 2016-02-20), 4086 pellets were caught by a net that spanned the whole transect of the creek, collecting the surface water. Analysis confirmed that both new and older degraded plastics were present in the collected sample (Supplementary material 4A).

Using the water flux on the sampling day (0.293 m^3/s, obtained via the Swedish Meteorological and Hydrological Institute, vattenwebb.smhi.se), we calculated that that the concentration of pellets in the creek was about 3870 pellets/1000 m^3. This can be compared with the average density of 727 pellets and spherules/1000 m^3 measured in the Danube.

During the sampling occasion in Stenungssund, the rainfall at the nearby Kamperöd measurement station (SMHI) was 13.5 mm during the 24 h period of the sampling day, which corresponds to a 94% fractile for that station; i.e. on average it rains more than this on 22 days

Fig. 2. Sampling setup for measuring the total pellet runoff during 1 h. On the upstream side of the small bride (A) wooden pieces were placed so to lead the surface water into one of the tunnels and on the downstream part (B) a net was attached which led all the material floating on the surface to a collection sock at the end.

of a year, which means that this was a large but not extreme rain fall. No overflows of the storm water holdings in the production area were reported (Borealis, 2017) hence the measured release is expected to be normal for the time and weather conditions. In order to estimate the average flux, four separate calculations based on different assumptions were made (Supplementary material 4B for calculations):

1) Flux threshold, where the pellets were assumed to remain in the banks until the water rises. This assumption would give 23,500 pellets/day
2) Constant concentration of pellets related to the mean flux; gives 70,000 pellets/day
3) Rain assumption, pellet spills between rainfalls; 8200 pellets/day.
4) Constant concentration of pellets in the creek, i.e. the measurement is representative of a continuous release; 98,000 pellets/day

Although daily variations may be large, these different assumptions would correspond to an annual release between a minimum of 3 million and a worst case scenario of 36 million pellets. The total weight of the pellets in the sample was 99.28 g resulting in an average weight of 0.02 g/pellet. From the above calculated values, we can thereby deduce that the annual weight of the spilled pellets would be between 73 and 730 kg. However, when smaller fractions down to 300 μm (Fig. 1B) were included in the measurements of hourly runoff, the total particle count was over 500,000 particles. This indicates an approximate hundredfold increase in particle release compared to the release of pellets alone. The majority of the particles (78%) were translucent to white fluff, although fragments (> 21%) and pieces of foil (1%) were also present. The weight of these smaller particles was low, with an average mass of 0.0007 g, but if this weight was extrapolated to the above calculated values for the average flux of pellets, and multiplied with a hundred to match the relative particle counts, the approximate annual release would be between 200 and 2600 kg. The total weight of the particles in the smaller fractions is thereby approximately three times the weight of the pellets, which highlights the importance of including spill of material in the smaller fractions. When included, the total release of plastic particles above 300 μm from the production site would be between 300 and 3000 kg annually.

Notably, these numbers do not account for overflows, which were reported to occur twice in 2016, and which in the Danube has been associated with the release of large volumes of pellets (Lechner et al., 2014). During site inspections of US plastics production plants in the nineties it was noted then that existing barriers was not effective during intense rainfalls (US EPA, 1992). Our measurements neither account for the spills observed on sites other than the production area, such as cleaning facilities, ports or transport and storage areas (Supplementary material 4C). Additionally, only 5% of the European polyethylene production occurs at this site and similar conditions are to be expected on other production locations.

Most of the both particle abundance and volume were below 1 mm with increasing counts for smaller sizes (Fig. 3). It is therefore likely that a smaller mesh size would show an even higher level of particle runoff from the production site. A quantitative sampling for smaller sizes would however require a different sampling protocol as smaller particles might be more evenly distributed through the water column, whereas pellets are expected to float at the surface. Due to these differences in distribution patterns, dependent of particle size the particles below 1 mm may also be underestimated. Furthermore, the spread of the fluff and the fragments may be harder to assess in samples taken further away due to their irregular shapes (Fig. 1).

Previous studies that have assessed pellet spills have primarily been based on estimates provided from the industry (Cole and Sherrington, 2016) and rarely account for smaller fractions. These results are therefore unique as they provide onsite measurements of pellet runoff. They also highlight the importance of including the smaller fractions in

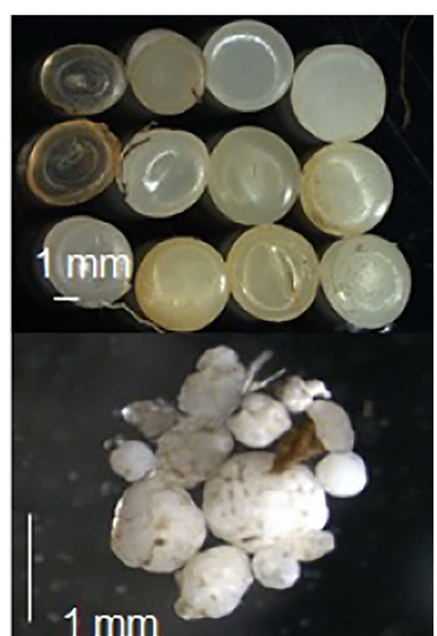

Fig. 3. Typical particles found in the runoff from the production plant. The upper image shows translucent pellets and the lower image shows fluff and fragment found in the lower size-fractions.

future studies.

4.2. Dispersion of pellets

4.2.1. Theoretical calculation of the dispersion from a local source

In a scenario where the pellets that are released from the production site are not assumed to beach in the area a steady state would be reached after 50 days, in accordance with the water exchange within the fjord. If the more conservative estimate of number of released pellets (3 million pellets per year ≈ 0.1 pellets/s) is used, the concentration in the fjord would in that case be $1 \cdot 10^{-2}$ pellets/m^2 and the total number in the system would be 0.5 million pellets (Supplementary material 4D).

However, the drifter studies indicate that the typical floating distances are of order 0–5 km with most typical distances of order 1–2 km. After that, the drifters land on the surrounding beaches (Supplementary material 4D). It remains unclear when and how the drifters get back into the fjord from the beach, which would require further studies.

For a more realistic estimate of pellet dispersion and the concentration of pellets within the fjord system the beaching needs to be included in the calculations (Supplementary material 4D), and with this approach we find that pellets remain in the fjord area. The model is built on general assumptions on drift and is thus applicable on other location. The parameters have however to some extent been fitted to local conditions (fjord with complex topography with rocky shores and small bays). The drift of surface particles tends to follow the wind, but here the general wind direction is not aligned with the fjord (while in practice it often follows the fjord direction more closely than wind outside the fjord). Taken together with the drifter study we find it reasonable that particles travel a few km's before reaching a beach (this was partly based on a crude estimate on the probability of wind directions for the area). Using the conservatively estimated release of 0.1 pellets/s would after 10 years result in 31 million particles on the surrounding beaches. The concentration would be highest at the release site with 1500 pellets/m (750 pellet/m beach) and decrease linearly to 0 pellets/m about 40 km from the release site. With a continued release of pellets the concentration would increase further and the pellets would also spread further with time, although the calculations imply that these increases would not be linear (Supplementary material 4D). None of these estimates include sinking which would require further studies. These measurements and calculations highlight the importance of including beaching and re-mobilization when studying plastic distributions, especially when the sources are not situated directly at open coasts.

4.2.2. Observed pellet pollution on nearby beaches

The relative amount of pellet pollution was higher in close proximity to the production site (Fig. 4), although a higher concentration was also found south of the harbor where a lot of the material is known to be handled for transport. The highest amount was found at the mouth of Stenunge å, where counting was limited to 2 min (instead of an hour) during which 7030 pellets were found. The corresponding values for 1 h of beach count was 211,000. High concentrations were found in several of the surrounding protected areas. The abundance on surveyed beaches decrease with increasing distance from the industrial area, but it is notable that relatively high pellet abundance can be found in all regions to the north in the fjord system, some 35 km away. The color signature of the pellets that is found in the Stenunge Å creek (white, black, blue and yellow) is also found in resembling proportions in the archipelago. When sampling beaches on the west coast of the island Orust or away along the coast, other color signatures are found possibly as a result of long range transport (Supplementary material 4E).

4.3. Legal framework and policies

There are no existing international frameworks or European (EU) laws which specifically address plastic pollution due to industrial spills. It is also rare that pellet spills are directly regulated on national levels. There are however exceptions and it should be noted that the US EPA provided regulation recommendations to specifically prevent plastic spills already in the nineties (US EPA, 1992) and today there is a Clean Water Act in the USA, where the California Water Code (chapter 5.2) states that the state board and the regional boards “shall implement a program to control discharges of preproduction plastic” (CaliforniaLaw, 2007). However, most countries today have some type of legislation aiming at generally protecting the environment from pollution. At international and EU level there are also several legislations more or less applicable dependent on where in the lifecycle of the material and where the plastic spill occurs (for EU in part reviewed in European Commission (2013) and Steensgaard et al. (2017)).

During production, transport and usage, some of the more relevant regulations are the Packaging Directive (Directive 2008/98/EC, 2008), REACH (Regulation (EC) No 1907/2006) and the Industrial Emissions Directive (Directive 2008/98/EC, 2008). If shipped at sea, the release of the pellets would be prohibited due to Annex V of the MARPOL Protocol of 1978 (IMO, 1973), a treaty that was set up to prevent pollution and dumping of garbage from ships. If the pellets (loss) are considered as waste materials, it's appropriate to consider the Basel convention (UNEP, 1989) and in relation to EU the European Framework directive on waste is also important as it identifies an extended producer responsibility (article 8) as a key principle for waste management.

In 2014, Franz Obermayr submitted a question to the European commission regarding the pollution of European rivers and lakes with plastic pellets (European Parliament, 2014). The question was divided in 6 parts, mostly concerning how the commission was planning to address the raw material that had earlier that year been shown to end up in the Danube. The commission answered that the member states are responsible to comply with suitable environmental regulations and also mentioned the waste framework directive and the industrial emissions directive (Directive 2010/75/EU, 2010). Moreover marine litter is identified as one of the key factors affecting the status of the environment and member states are demanded to take sufficient measures to decrease the quantities of marine litter to levels not causing harm to the coastal and marine environment, according to the European Union Marine Strategy Framework Directive (MFSD) (European Union, 2008).

In excess of international conventions UNEP and NOAA in 2011 initiated the Honolulu strategy, a framework to reduce the impacts of marine debris. One of the proposed actions on this strategy, directed towards land based sources, is the development and implementation of regulatory tools to avoid release of pellets, when voluntary commitments are not sufficient (NOAA/UNEP, 2011). The Honolulu strategy further guides the work of the voluntary global partnership on marine litter (GPML) and is recognized within the Manilla declaration (UNEP, 2012).

In Sweden the Swedish Environmental Code regulates all handling of plastic pellets during the entire lifecycle, from pellet to product to waste. A set of rules of conduct (Chapter 2 in the Environmental Code) require all operators independent of the actors size and type, to take precautionary measures, by e.g. getting sufficient knowledge about the risk for human health and the environment, locating their activity in a place causing the least environmental impact, adhering to the substitution principle through, when applicable, replacing chemical products and chemicals with alternatives that have fewer negative environmental impacts, and using best available technology. These rules apply to all activities as long as it is not proven unreasonable when comparing benefits with costs. In relation to protected areas, like Natura 2000 areas or nature reserves, the level of demanded precautions is set higher.

When submitting an application for a permit (which is mandatory

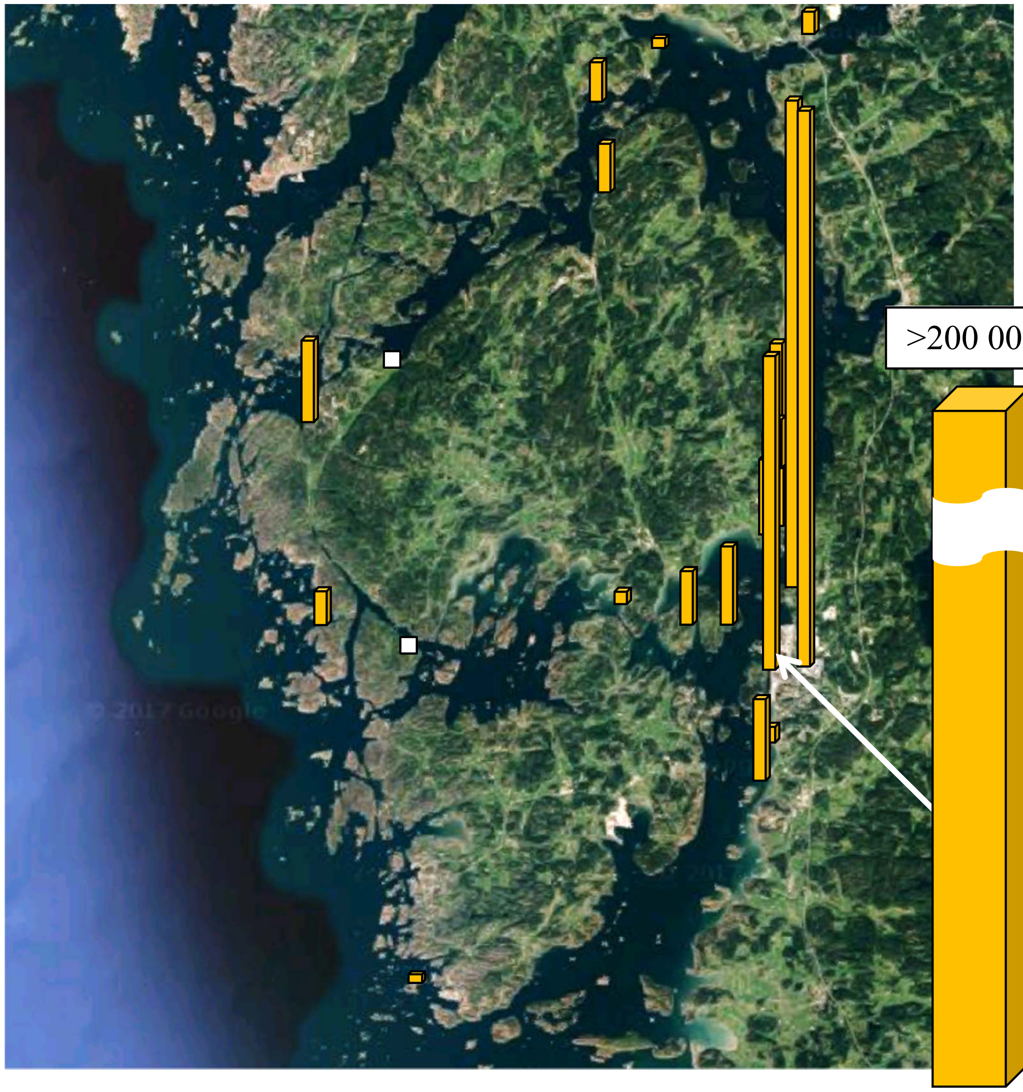

Fig. 4. Results from measurements of pellets on beaches in the area. The heights of the yellow bars are relative to the number of pellets found per hour and person. White squares show examined sites where no pellets were found (Map adapted from Google maps). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

for starting or changing larger industries and activities presumed to have an environmental impact), the operator needs to prove that the activity can fulfill the general rules of conduct. Conditions for a permit are set in order to assure this fulfillment and are controlled by both the activity itself and a supervising authority. In case a producer of pellets chooses to expand their production a new permit is necessary (See supplementary material section 2A for a chronological detail of the company permits). In order to enforce the general rules of conduct in relation to smaller activities the supervising authority may issue an injunction demanding the activity to fulfill more specific requirements.

It can therefore be stated that there are several frameworks, on international, European and national levels in place that should hold the different actors involved responsible for preventive measures, and accountable for extensive spills of plastic into the environment. The suitable policies and legislations have, however, not been sufficiently implemented and enforced. In the case study the company permits only recently started to mention and regulate pellets. The lack of specific conditions relating to plastic spills has allowed a continuous release of plastic materials. This could in part be explained as a consequence of treating plastic materials as though they were ordinary benign products, similar to natural bulk commodities, and persisting in doing so even in the face of an increasing body of scientific data that show several potential harmful consequences of plastic litter for environmental and economic values.

5. Conclusions

In this work we make a first estimation of the total release of preproduction pellets from a production site to the surrounding environment and find it to be between 3 and 36 million pellets annually. We also show that if smaller fractions of plastic particles, down to 300 μm were included, these numbers were multiplied with a factor of hundred and the mass by a factor of three. Extensive occurrence of pellets on regional beaches are wide spread although declining further away from the industrial complex area but still extend several tenths of km in the complex archipelago. Furthermore, we show documentation of spills around areas of subcontracted companies involved in transport, storage, cleaning and waste management. The release is expected to be a consequence of inadequate precautions during production, loading, transport and handling of the material. Although the quantity of the spills may vary at different locations this case study is likely to be representative of the processes that have led to the documentation of pellet pollution on beaches and in water samples globally. Due to recent changes in the production company permit, they have recently installed

10 μm filters in the drains on the premises to avoid further pollution. Although the effect of the installed filters remains to be investigated, this shows that there are now technical solutions readily available to prevent pollution which could prove to be efficient on other production sites. However, it is important to include handling practices and preventative measures at sites where downstream actors handle the materials as well.

The cumulative historical pollution, here indicated by the presence of aged particles, remains clearly mirrored in the surrounding areas where they may have negative effects on ecosystem services and biota. While the full impact of this type of pollution is currently under investigation by the scientific community, and effects are not yet fully elucidated, we cannot ignore the hazardous nature of pellets and their potential to cause harm to the environment.

There is a regulatory framework in place, on international, European and national levels, that if implemented could to a high degree prevent these spill or leakage events. However, as seen in the study by Lechner and Ramler in Austria (Lechner and Ramler, 2015), as well as in the current case study, these regulations, laws, and policies have not been adequately enforced on industrial spills of microplastics. These results therefore highlight the importance of addressing plastic spills from industry through existing regulations and regular inspections. It also indicates a systematic error associated with plastic pollution where, even though the pollutants can visually be seen, we as a society still fail to react.

Polyethylene and other types of plastic materials are produced in many other places, and there are several different companies involved in the production and transportation of plastics. The authors therefore recommend that spills of plastic during transport, loading, storage and production in industrial settings be specifically included in control programs and permit conditions. It is vital that this applies to all companies involved in the handling of the material to increase the responsibility for prevention and the accountability following unintentional plastic spills.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2018.01.041.

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