Marine Pollution Bulletin 171 (2021) 112708

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

Taking a mass-balance approach to assess marine plastics in the South China Sea

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ARTICLE INFO

Keywords:
South China Sea
Plastic
Pollution
Mass balance equation
Box model
Policy

ABSTRACT

The South China Sea (SCS) is recognised as a global hotspot for plastic pollution. We review available field studies and identify a significant lack of data needed to construct a simple mass balance box model for plastic pollution in the SCS. Fundamental information on plastic mass input, transfer and sink terms are simply not available. Also unknown are the rates of accumulation in different environments, the dispersal pathways of plastic particles of different density, the residence times of plastic in the water column and the rate at which macroplastics are transformed into microplastics in different environments. Filling these information gaps is critical for states to determine adequate response measures, including developing and tracking impact of policies to deal with the problem of plastic pollution in the SCS.

1. Introduction

Plastic debris entering the ocean is a global, transboundary problem which poses a growing threat to the marine environment, ecosystem services, human health, safety and sustainable livelihoods, relevant to the United Nations Decade of Ocean Science for Sustainable Development (IOC-UNESCO, 2021). According to Statista, global production of plastic totaled around 368 million metric tons in 2019, more than 50% of which is produced in Asia (Statista, 2020). Although the exact amount that enters the ocean is uncertain, it is clear that Southeast Asia is particularly exposed and vulnerable to plastic pollution (GRID-Arendal and UNEP, 2016; Lasut et al., 2017). States of Southeast Asia are taking this issue seriously as is evidenced by actions of the Association of Southeast Asian Nations (ASEAN) and the Coordinating Body of the Seas of East Asia (COBSEA, 2019; ASEAN, 2019; UNEP, 2020).

In particular, the South China Sea (SCS) is expected to receive a significant fraction of land-based plastic pollution due to gaps in waste management systems as well as importing of plastic waste for disposal from other regions (Y. Wang et al., 2020c; C. Wang et al., 2020; Liang et al., 2021). Evidence is growing that plastic pollution, together with other cumulative human impacts, threatens the marine and coastal habitats and biota of the SCS. Although the total amount of plastic pollution that has entered the SCS since the 1950s is unknown, it is likely to be of the order of many millions of tonnes (Zhou et al., 2016). Lebreton et al. (2017) reported that six of the 20 rivers that carry the greatest loads of plastic pollution discharge into the SCS, with an estimated maximum total input of up to 300,000 t/year. According to estimates from Jambeck et al. (2015), countries bordering the SCS may contribute as much as 2.56–7.08 million tons of plastic pollution to the ocean every year. This broad range in estimates of plastic input from land to the ocean points to a high level of uncertainty and highlights the need for further research into plastic input from the land and other sources.

The aim of this paper is to review what is known about the fate of plastic once it has entered the SCS marine environment (Fig. 1). We focus on reported estimates of the mass of plastic of any size in the marine environment, whether in water, sediments or biota, in order to provide context for the development of policies and actions needed to deal with the problem.

2. State of research on the occurrence of marine plastics in the South China Sea

A recent review of marine plastics research from the 13 states of ASEAN+3 was completed by Lyons et al. (2020). Of the 371 papers examined, the authors identified several critical knowledge gaps,

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https://doi.org/10.1016/j.marpolbul.2021.112708
Received 22 February 2021; Received in revised form 30 June 2021; Accepted 5 July 2021
Available online 14 July 2021

namely increasing plastic survey efforts of the seabed, defining risks, and investigating transport, dispersal and modification pathways of plastics in the environment. Similar gaps were identified in Europe (Maes et al., 2018). Lyons et al. (2020) also noted that the literature for the SCS is vast and there has been a notable recent acceleration in the publication of scientific research on plastic pollution in Southeast Asia.

2.1. Plastic mass balance in the SCS

Any assessment of the mass of plastics residing in the SCS must account for both inputs (from land, rivers and other sources) plus possible sinks, where the plastic may end up stored for short or long time spans (i.e. in biota, ocean water column and seafloor environments). The scope of the problem is illustrated by listing the variables that must be addressed in a mass balance equation for plastic in the SCS (or for any ocean), as required for a simple box model, where input (source) terms are balanced by sinks (Fig. 2). The case studies cited in this review are listed in Table 1 along with the methods used to identify both macro-plastic (>5 mm in size) and micro-plastic particles (<5 mm in size). Hence our assessment includes plastic particles of any size.

Input terms include direct input from littering and dumping at the coast, together with indirect input of plastic from rivers and transported by wind (X. Wang et al., 2020) and by ocean currents carrying plastic into the SCS from outside areas. Also biota ingesting plastic on land may defecate or regurgitate plastic particles into the ocean (Stewart et al., 2020). Plastic debris is also derived from sea-based sources such as fisheries, aquaculture and shipping that may dominate in specific locations, including in parts of the SCS (Hong et al., 2014; Peng et al., 2019). For rivers we have Lebreton et al.'s (2017) estimate that six rivers discharge a maximum total input of 300,000 tonnes/year of plastic into

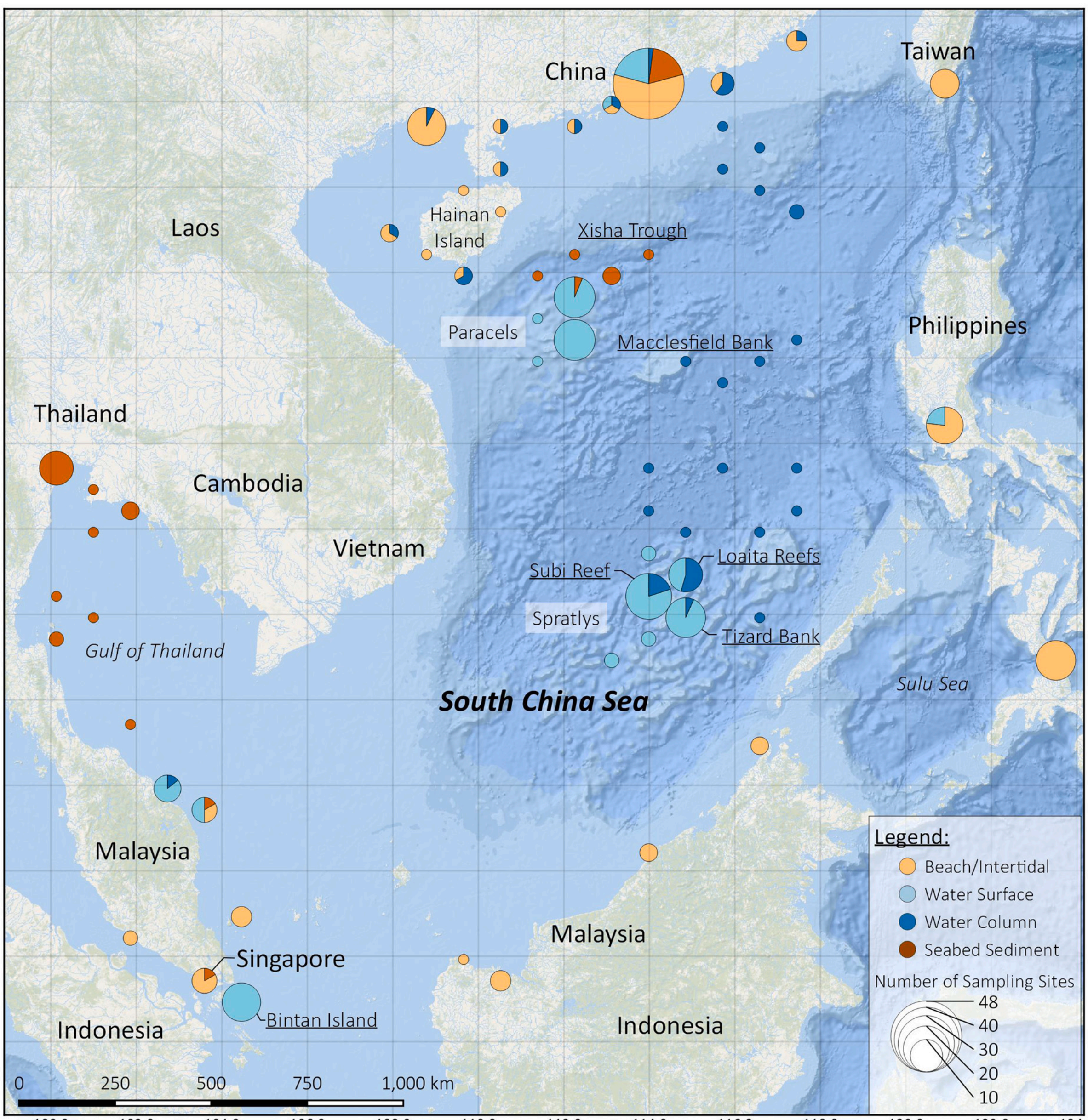

Fig. 1. Map of the South China Sea (SCS) and the marine plastic study sites included in this review. The continental shelf is shown in light blue; deep sea is darker blue. Country names are labelled with regular text; seas are labelled in italics; sampling sites of interest are labelled with underlined text. For the purpose of this article, the SCS refers to the entire basin surrounded by the land-masses of the southeast-Asian peninsula and those of the archipelago of the Philippines and Indonesia as well as Borneo, thereby including the Gulf of Thailand. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

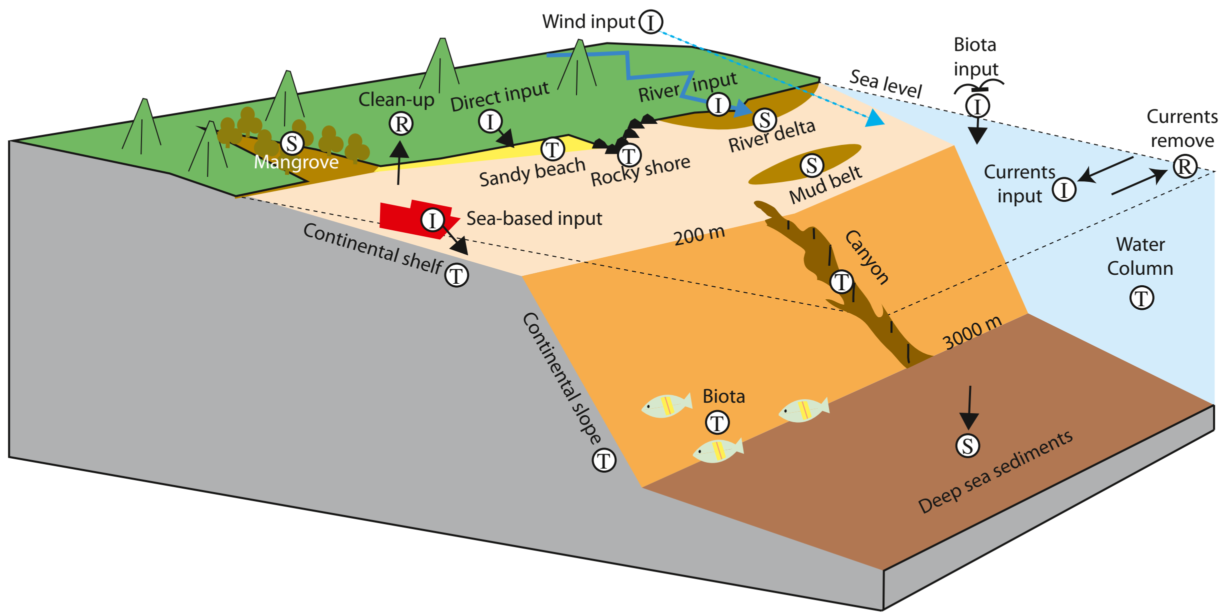

Fig. 2. Illustration of some important inputs (I), transitory environments (T) and sink environments (S) for plastic pollution in the ocean (see Eq. (1)).

the SCS. For combined rivers and land-based sources, Jambeck et al. (2015) estimated that, in 2010, SCS countries may have contributed as much as 2.56–7.08 million tonnes. Inputs of biota, wind, fishing and shipping are undetermined.

Quantification of the sink terms requires detailed field studies and understanding of other processes controlling mass balance. Plastic suspended in the water column, for example, is transitory since input terms are offset by output via settling of plastic particles to the seabed, plastic consumed by biota and particles washed ashore onto the coast. The water column also receives input of plastic particles that are resuspended from the seabed or exported from beaches, for example during storm events.

Plastic particles residing in different coastal environments may also be transitory in cases where, for example, the coast is eroding or in quasi-equilibrium with sediment (and plastic) import and export (i.e. along a rocky coast). Only net depositional coastal environments, such as river deltas, prograding strand plains, mangroves and seagrass beds where plastic particles are trapped by root systems and/or buried in stable sediment deposits, are true sediment sinks (Y. Huang et al., 2020; Martin et al., 2020). A similar situation occurs for shelf and deep-sea environments, only some of which are long-term, net sinks for plastic particles. Recent reports of plastic in submarine canyons, for example, have noted that most is passing through the canyon on its way to the deep sea basin (Zhong and Peng, 2021).

The plastic mass ingested by biota may mostly be transitory since plastic consumed and residing within living biota is offset via excretion and via death, where the plastic is either returned to the water column or deposited in seabed sediments. In other instances, plastic mass in biota could pass up the food chain (i.e. transfer of plastic from lower to higher trophic level organisms) where plastic becomes retained in larger, long-lived species (Auta et al., 2017).

Coral reefs may act as long-term sinks because plastic adheres to the coral surface and can become incorporated into the coral skeleton (Ding et al., 2019); over longer (decade to century) time spans the coral reef is eroded and it becomes incorporated into reef sediment deposits.

It is fundamental for building an accurate box model that the environment is spatially partitioned into transitory (T) and permanent sink (S) components each of which contain a resident, cumulative mass of plastic that is in a steady state (T) or increasing over time (S). The sum of these terms should equal the total mass of plastic input ("I" terms) minus the mass of plastic removed by currents exiting the SCS and clean-up operations (R). Assuming plastic is a conservative material, we can therefore write this equation:

$$\begin{aligned} & I_{river} + I_{wind} + I_{biota} + I_{land-based} + I_{sea-based} + I_{currents} \\ & \quad = T_{water-column} + T_{coast} + S_{coast} + T_{shelf} + S_{shelf} + T_{deep-sea} + S_{deep-sea} + T_{biota} \\ & \quad - R_{currents} - R_{clean-up} \end{aligned} \tag{1}$$

Field measurements of plastic occurrence in the SCS water column and in different sedimentary environments are listed in Table 1. In the following we will examine published studies of the water column, followed by the different sedimentary environments. The ingestion of plastic by marine biota is one important impact of plastic pollution as well as providing a temporary storage component (Eq. (1)), discussed further below. This will be followed by assessing the implications of the state of knowledge of plastic mass balance from a legal and policy perspective for interventions in the SCS.

2.2. *Quantifying occurrence of plastics in the SCS water column*

Research on quantifying microplastics floating and suspended in the water column have reported large quantities of plastics in the surface waters, ranging on the scale of thousands of particles/m^3 (Table 1). There are significant differences in the estimates of mass of plastic depending on the method used for sampling. Surface water samples using a neuston net systematically yield a result that is orders of magnitude less than estimates made based on filtered water samples (Fu et al., 2020). For instance, Cai et al. (2018) collected surface water samples (filtered at 44 μm) plus 333 μm bongo (neuston) net samples from depths of up to 200 m. They found a difference of five orders of magnitude between methods; the bongo net method measured 0.045 particles m^{-3} whereas the filtered water samples yielded a net concentration of 2569 particles m^{-3}.

Cai et al. (2018) estimated that the top 5 m of the SCS contained around 700 t of plastics; this is the current best available estimate of plastic mass present in the SCS surface waters. For comparison, Pabortsava and Lampitt (2020) collected water samples at 12 stations along a transect of the North and South Atlantic Oceans and found total mean concentrations of plastic comparable to those in the SCS (i.e. ~2500 particles m^{-3}); they estimated that the mass of plastic in the 32–651 μm size-class suspended in the top 200 m of the North and South

Table 1
List of selected studies reporting measurements of plastic pollution in sediments and water of different marine environments of the SCS. Studies include both macro- and microplastics.

Reference	Study location	Environment and sampling method	Reported mean plastic concentration
Water samples			
Fok et al., 2020	China - review of 96 studies (water, sediment and biota) incl. SCS	Review of 36 papers that reported MP in water, various methods etc., noting different results from different methods used.	0.13 to 19,860 particles m^{-3}
Fu et al., 2020	Review of MP pollution in China, including SCS marine waters	Review of literature plus six monitoring sections by State Oceanic Administration (PRC)	0.08 particles m^{-3}
Md Amin et al., 2020	Terengganu coast in Malaysia	5 stations, 5–24 m water depth, filtered at 45 μm	3300 particles m^{-3}
Lam et al., 2020	Pearl River Estuary	Floating plastic, 11 stations, towed manta net 333 μm mesh, macro-plastics (>5 mm) and microplastics (<5 mm), assessed separately	2.376 ± 0.700 microplastics m^{-3} 0.110 ± 0.039 macroplastics m^{-3}
Tan et al., 2020	Spratly (Nansha) Islands	24 × surface water sampled with 333 μm mesh neuston trawl	0.0556 ± 0.0355 particles m^{-3}
Nie et al., 2019	Gaven (Nanxun) Reef in Spratly Islands	15 surface water samples, filtered at 48 μm	1733 particles m^{-3}
Deocaris et al., 2019	Pasig River, Manila, Philippines	sieving 25.7 m^3 river water through a 0.35 mm mesh	1.32 particles m^{-3}
Ding et al., 2019	Paracel (Xisha) Islands, coral atoll	Transects of 3 atolls, seawater samples from outer reef slopes, reef flats, and lagoons	200 to 45,200 particles m^{-3}
Huang et al., 2019	Subi (Zhubi) Reef, SCS	Floating plastic, 30 stations, water samples filtered at 50 μm	1400–8100 particles m^{-3}
Lubis et al., 2019	Riau Islands, Indonesia	3 sites towed Neuston net, 160 μm mesh	5.33 particles m^{-3}
Wang et al., 2019	Loaita and Tizard Banks, SCS	12 sites towed Neuston net, 160 μm mesh	Loaita 0.57 ± 0.14 particles m^{-3} Tizard 0.33 ± 0.24 particles m^{-3}
Syakti et al., 2018	Bintan Island, Indonesia	11 sites towed Neuston net, 100 μm mesh	0.46 ± 0.25 particles m^{-3}
Cai et al., 2018	SCS transect	22 × water samples filtered at 44 μm	2569 ± 1770 particles m^{-3}
Cai et al., 2018	SCS transect	19 × 333 μm bongo net samples	0.045 ± 0.093 particles m^{-3}
Khalik et al., 2018	Malaysia coastal waters	5 × water samples filtered at 20 μm	130 to 690 particles m^{-3}
Zhou et al., 2016	Northern SCS coastal waters	12 sites surveyed 4 different years, trawl net method, floating (FMD) and submerged (SMD) marine debris (plastic fraction reported).	SMD = 39.4 g 100 m^{-2} FMD = 1.76 g 100 m^{-2}
Sediment samples			
Zhong and Peng, 2021	Paracel (Xishabei) submarine canyons	Video surveys from seven manned submersible dives, investigated litter piles in canyon scour pits.	Maximum size of ~241 m^3 litter pile
Fok et al., 2020	China - review of 96 studies (water, sediment and biota) incl. SCS	39 papers reported microplastic in sediment, various methods etc. noting different results from different methods used.	Surface sediment 102.9 to 802 particles kg^{-1} Bottom sediment 84 to 32,947 particles kg^{-1}
Fu et al., 2020	Review of MP pollution in China, including SCS beaches	Review of literature plus six monitoring sections by State Oceanic Administration (PRC) report on SCS beaches	245 particles m^{-2}
Bucol et al., 2020	Negros Oriental, Philippines	Lower intertidal sediments collected at 15 sites	82 particles kg^{-1}
Chen and Chen, 2020	Hengchun Peninsula, Taiwan	8 beach sites, high tide line	80–480 particles kg^{-1}
Y. Wang et al., 2020b	Gulf of Thailand	45 m water depth, 18 box core samples	150.4 ± 86.2 particles kg^{-1}
Li et al., 2020	Southern China	6 sites, mangroves, upper 5 cm of sediment taken at low tide	2249 ± 747 to 227 ± 173 particles kg^{-1}
Hamid et al., 2019	Pulau Tioman, Pahang, Malaysia	4 beaches × 5 transects sampled monthly	30 items m^{-2}
Li et al., 2019	Maowei Sea, China	10 sites, intertidal mangrove sediments	520 to 2310 particles kg^{-1}
Paler et al., 2019	Talim Bay, Lian, Batangas, Philippines	1 beach, 10 samples, filtered at 0.7 μm	260 particles kg^{-1}
Peng et al., 2019	Xisha Trough	Submarine canyons, 1729 and 3378 m water depth, 7 × submersible dives, survey using video camera	41 to 51,929 items km^{-2}
Tsang et al., 2017	Hong Kong harbor	9 transects, 3 repeats in 1 year, subtidal sediment samples by Eckman dredge	49–279 particles kg^{-1}
Matsuguma et al., 2017	Gulf of Thailand	4 sites sampled in 11–18 m water depth, sediments sampled by gravity corer	150–320 particles kg^{-1}
Mobilik et al., 2016	Sarawak and Sabah beaches	3 beach surveys in SCS	657 to 1208 items km^{-1}
Zhou et al., 2016	Northern SCS beaches	12 beaches in south zone, surveyed 4 different years (plastic fraction reported)	46.3 g 100 m^{-2}
Adnan et al., 2015	Likas Bay, Kota Kinabalu, Sabah, Borneo	1 beach, 6 transects, 10 m × 10 m	9467 g 100 m^{-2}
Noik and Tuah, 2015	Kuching, Sarawak, Malaysia	2 beaches, 3 sites at low tide, November 13 and August 14, top 2 cm sampled, sieved at 1 mm, total of 60 samples.	Reported as number of particles and total weight only.
Fauziah et al., 2015	Kuala Terengganu, Malaysia	Six beaches surveyed, a total of 2542 pieces of small plastic debris were collected.	265 g m^{-2}
Fok and Cheung, 2015	Hong Kong harbor	Strandline of 25 beaches	16 to 258,408 items m^{-2}
Zhao et al., 2015	Guangxi Province	3 tourist beaches, upper 5 cm of sand from four 50 × 50 cm2 quadrats	0.3 to 7.6 g m^{-2}
Mobilik et al., 2014	Pasir Pandak beach, Malaysia	4 beaches surveyed in Oct 2012	19.4 kg km^{-1}
Nor and Obbard, 2014	Singapore, Mangroves	Top 3–4 cm sampled by spoon, 1.6 μm filter	36.8 ± 23.6 particles kg^{-1}

Atlantic Oceans (an area of 81.2 million km^2) is 11.6–21.1 million tonnes, dominated by microplastics (mean size of 81 μm). They reported little difference between surface concentrations and those at intermediate depths of 50 to 170 m; hence it is not unreasonable to extrapolate the Cai et al. (2018) estimate of 700 tonnes in SCS upper 5 m of surface waters to 28,000 tonnes in the upper 200 m water depth.

To place these figures in a global context, Eriksen et al. (2014) estimated 233,400 tonnes of larger plastic items plus 35,540 tonnes of microplastics floating on the surface of the world's ocean; they reported that 70.4% of large items (by weight) found floating at sea were related to the fishing industry (mainly buoys and floats; 54%). This mass is compared to 49.3 to 89.6 million tonnes suspended in the upper 200 m of the ocean as extrapolated from data published by Pabortsava and Lampitt (2020). In other words, the amount suspended in the upper 200 m is ~200 times greater than the amount floating on the surface. Further research is required to determine the residence time of plastic particles in the ocean water column and if the mass of 28,000 tonnes suspended in the SCS water column is in steady state.

2.3. Quantifying occurrence of plastics in the SCS sediments

The International Coastal Clean-Up (ICC) reports that more than 550 tonnes of plastic waste have been collected along the coastline of the SCS coastal states in 2019. This waste is reported to be composed primarily of cigarette butts, plastic packaging from food items, plastic bottles and plastic bags (Ocean Conservancy, 2019a, 2019b) therefore pointing to littering behaviour and gaps in the management of public waste. Some estimates of marine plastic debris can be found for states that border the SCS but they follow different accounting methodologies and units and are often found in governmental reports and non-peer reviewed publications (Lyons et al., 2020). Peer reviewed publications that focus on or include surveys of marine plastic debris are devoted to specific and generally small geographic areas (Fig. 1; Table 1). The development of harmonised methodologies for marine plastic surveys is included among the work of COBSEA RAP MALI (COBSEA, 2019) and the ASEAN Framework of Action (ASEAN, 2019).

The technologies needed to accurately sample and quantitatively measure the number and mass of plastic particles have rapidly evolved in recent years. Progress has been made to address problems of contamination of samples with microplastics (especially fibres; Cowger et al., 2020), rapid screening (Maes et al., 2017) and correct identification of polymeric particles via application of micro-Fourier transform infrared (micro-FTIR) or micro-Raman spectroscopy (Löder and Gerdts, 2015). Challenges remain in the conversion of particle counts into estimates of mass needed to constrain models (Harris, 2020; Pabortsava and Lampitt, 2020); for the time being, nearly all results are reported (Table 1) as numbers of particles kg^{-1} (sediment) rather than mass. Mangroves and seagrass beds effectively trap plastic debris in their aerial root systems and sediments, respectively (Li et al., 2019; Y. Huang et al., 2020; Luo et al., 2021) but plastic mass accumulation rates have not been measured. Overall, there is no estimate available for the mass of plastic deposited in any of the main sedimentary sinks of the SCS (coastal, shelf or deep sea) and further research is needed to derive estimates for different regions and different environments. For context, Lebreton et al. (2019) estimated based on modelling that between 46.7 and 126.4 Mt of microplastic was stored along the world's shorelines in 2015 and Barrett et al. (2020) estimate, based on extrapolation of empirical data from 13 studies, that the total mass of microplastics that has accumulated in deep sea sediments globally is about 14.4 million tonnes.

Given the high estimates of the mass of land-based plastic input into the SCS mentioned above and the comparatively small mass of plastic particles estimated to reside in the SCS water column (28,000 tonnes), the question arises as to whether the estimated input is too large, if plastic debris are not dispersed further from the coast or whether they have a very short residence time in the water column and sink rapidly to the seabed. Further research is needed to answer these questions.

3. Quantifying hazards and risks of plastic pollution

3.1. Impacts on marine biota

The two main hazards and risks of plastic pollution for biota are entanglement of animals in plastic debris and the consequences of ingestion. In the Philippines, a social media-based study by Abreo et al. (2019) found that at least 17 marine species (48% cetaceans; 45% marine turtles; 7% fish) were affected by marine plastic litter through ingestion, entanglement, and/or asphyxiation (see also examples listed by Lyons et al., 2020). The impacts of plastic ingestion may include starvation of the affected organism as well as possible contamination by toxic chemicals transferred from the plastic particles, with potential risks for human health (Vethaak and Leslie, 2016).

Research in the SCS has documented the occurrence of microplastic particles in zooplankton (Md Amin et al., 2020). Since zooplankton is grazed upon by many filter-feeding organisms, the plastic debris bioaccumulates in the food web. Cases of plastic contamination in the SCS have been documented in shellfish (Li et al., 2018), fish (L. Zhu et al., 2019; Bucol et al., 2020; Koongolla et al., 2020), birds (C. Zhu et al., 2019) and sea turtles (Schuyler et al., 2016). As noted in Eq. (1), biota are a transitory storage component in the mass balance budget for plastic pollution. Research suggests that the total mass of plastic residing in biota may be small compared with the plastic mass in the water column and in sediments (Lusher et al., 2017). However there are no data available for estimating the total mass of plastic residing in SCS biota and further research is needed.

In terms of hazards and risks, the estimated values of microplastics suspended in the SCS water column (Table 1) appear mostly below the threshold value of Everaert et al. (2018) of 6650 particles m^{-3} with some exceptions for maximum values reported (Fok et al., 2020; L. Huang et al., 2020; Ding et al., 2019). In this regard the highest value reported by Ding et al. (2019) of 45,200 particles m^{-3} for transects of three atolls in Paracel Islands is much higher. The 'safe' concentration of sedimented microplastics (i.e. 540 particles kg^{-1} sediment; Everaert et al., 2018) is exceeded in mangroves (Li et al., 2019, 2020) which compares with predictions of recent exposure assessments (Harris et al., 2021) and also exceeded in case studies from China reviewed by Fok et al. (2020). Additional ecotoxicological research in which marine species from the SCS are chronically exposed to realistic environmental microplastic concentration series are urgently needed to confirm these concentrations are relevant for this region.

3.2. Modelling to quantify exposure, forecast, monitoring and planning

The physical processes that govern the dispersal of plastic pollution in the environment are complex. Computer modelling of plastic particle transport and dispersal in the ocean must take account of composition, shape and density of the plastic particles together with the prevailing wind, wave and current energy regime together with biological processes and chemical and physical changes such as weathering, fragmentation and biochemical processes (Critchell and Lambrechts, 2016; Hardesty et al., 2017; Koelmans et al., 2017; Atwood et al., 2019; van Wijnen et al., 2019). Transport of floating marine debris in the SCS was studied by Ko et al. (2018) who used backward-tracking simulation for litter collected from Pratas Islands, a small coral atoll located 170 NM southeast of Hong Kong in the northern SCS, to identify its source and likely transport pathways. The backward-tracking model simulation by Ko et al. (2018) predicted that the northeastern and eastern SCS (through the Luzon Strait between Taiwan and the Philippines) and the southwestern SCS are major external sources of macro litter to the Pratas Islands, where the extent of contribution depends on several parameters such as monsoonal winds, seasonal patterns of surface circulation, and current velocity. On modelling the transport of floating plastic debris in the SCS, Zhang et al. (2020) emphasised the importance of ocean current models that caused differences between simulations and observations found in their results.

Models are useful to predict the outcomes of management actions, for example achieving a reduction in the use of certain types of plastic may result in a lower exposure in specific environments predicted by the model. It is thus important that model resolution is adequate to meet the needs of users. In many cases high resolution (grid space of 100 m or less) is needed for the design of responses such as coastal and marine clean-up activities. Models support the identification of pollution hotspots and prioritisation of response actions at regional, national and local levels. Tracking of plastic pollution dispersal using computer models is a technology that has been shown to be useful to identify point sources and guide beach clean-up activities in Norway (https://www.grida.no/activities/424).

A key parameter for such computer modelling is taking into account the different densities of different plastic materials. Plastic with density greater than seawater (i.e. about 40% of plastic produced according to Andrady, 2015) will mainly sink to the seabed and become deposited in sediments close to the source (Harris, 2020; Harris et al., 2021). On the other hand, particles less dense than seawater will float on the water surface and may become locally incorporated into buoyant (fresh-water) river plumes, to be carried seaward and/or be advected along the coast by the prevailing wind and current regime. In this way plastic particles are sorted by their density along the coastline. Another parameter models must consider is fragmentation of large macroplastic into microplastics that are subsequently buried in accreting coastal deposits or become available for export back into the ocean (Harris et al., 2021).

3.3. Path forward for policy response

This scientific review highlights the gaps in the understanding of the inputs of plastic debris in the SCS as well as their fate in water, sediment and biota as described in Eq. (1). None of the terms of Eq. (1) is well quantified: the extent and sources of leakage of plastic litter into the marine environment, their behaviour, transport and fate into living or non-living parts of the marine environment are mostly unknown. Furthermore, except for physical impacts to marine life (e.g. entanglement with fishing gear and ingestion of plastic debris) the impacts of plastic on human health and the marine environment are unclear. This scientific uncertainty in the extent of plastic introduction in the marine environment and of its adverse effects, including on marine life, on human health and on other uses of the sea (pollution as defined in UNCLOS, Article 1(1)(4)) are a challenge to the determination of the most adequate policy response by coastal states. However, it is the responsibility of states to observe, measure, evaluate and analyse the risks or effects of pollution on the marine environment from activities under their jurisdiction and control (UNCLOS, Article 204) in order to protect and preserve the marine environment against pollution from marine plastic (UNCLOS, Articles 192 and 194).

This review suggests a four-step response approach: (1) fill the scientific gaps needed to assess sources, pathways and impacts from marine plastics in the ocean, including through the elucidation of the terms of mass-balance (Eq. (1)); (2) adopt a precautionary approach to guide immediate response options; (3) shape response options on science-based prioritisation and assessment of risks and, (4) establish an iterative approach to response options through their regular revision on the basis of new data from research.

Since its first enunciation in the 1992 Rio Declaration (Principle 15), the precautionary approach has been reiterated in a number of international legal instruments including by the ASEAN and COBSEA. According to this approach, where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation. The serious and possibly irreversible character of the adverse environmental harm created by the massive introduction of plastic particles in the marine environment is not debated and therefore reaches this threshold. State responses based on a prioritisation of risks are needed. The ASEAN Framework of Action and the COBSEA Regional Action Plan on Marine Litter provide a potential basis for such a prioritisation of risk but they do not articulate it in detail. The hotspot assessment approach taken by several ASEAN states with the support of the World Bank is an illustration of this (Shuker and Cadman, 2018).

4. Conclusions

Our review points to a significant lack of data from current field studies that are needed to construct a simple mass balance box model for plastic pollution in the SCS. Fundamental information on plastic mass input, transfer and sink terms in the SCS are simply unavailable for constructing a plastic mass balance. While the mass of microplastic residing in the upper 200 m of the SCS water column is currently estimated to be around 28,000 tonnes, the masses residing in sediments and biota are undetermined, as is the input of plastic into the SCS from the main sources. Further knowledge gaps necessary for understanding the plastic mass balance of the SCS include the rates of accumulation in different environments, dispersal pathways of plastic particles of different density, the residence times of plastic in transitory components (water column, non-depositional sedimentary environments and biota) and the physical and biological processes driving fragmentation of macroplastics into microplastics in different environments. On the policy front, states are strongly encouraged to adopt a precautionary approach to guide immediate response options, as well as incorporate a science-based prioritisation and assessment of environmental risks. Filling these information gaps is equally, if not more, critical for states to be in a position to shape their response measures and to develop more robust policies needed to deal with the problem of plastic pollution in the SCS.

CRediT authorship contribution statement

The authors each contributed as follows:
Peter T. Harris – article conception, drafting text, figure preparation
Jerker Tamelander – article conception, drafting text
Youna Lyons – article conception, drafting text
Mei Lin Neo – article conception, drafting text
Thomas Maes – article conception, drafting text.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The work described in this paper was produced with financial support from the Norwegian Agency for Development Cooperation (Norad), Ministry of Foreign Affairs. The authors thank Cheng Ling Lim for production of Fig. 1. MLN acknowledges the National Research Foundation, Prime Minister's Office, Singapore for supporting her research at the St John's Island National Marine Laboratory. YLL acknowledges funding from the Singapore Maritime Institute.

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