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Future microplastics in the Black Sea: River exports and reduction options for zero pollution

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ABSTRACT

The Black Sea receives increasing amounts of microplastics from rivers. In this study, we explore options to reduce future river export of microplastics to the Black Sea. We develop five scenarios with different reduction options and implement them to a Model to Assess River Inputs of pollutaNts to seA (MARINA-Global) for 107 sub-basins. Today, European rivers draining into the Black Sea export over half of the total microplastics. In 2050, Asian rivers draining into the sea will be responsible for 34–46% of microplastic pollution. Implemented advanced treatment will reduce point-source pollution. Reduced consumption or more collection of plastics will reduce 40% of microplastics in the sea by 2050. In the optimistic future, sea pollution is 84% lower than today when the abovementioned reduction options are combined. Reduction options affect the share of pollution sources. Our insights could support environmental policies for a zero pollution future of the Black Sea.

1. Introduction

Plastic pollution is an issue in many seas worldwide (Lebreton et al., 2017; Meijer et al., 2019b; Ryberg et al., 2019). The Black Sea is an example and suffers from land-based pollution including cities and sewage systems (Berov and Klayn, 2020; D'Hont et al., 2021; González-Fernández et al., 2021; Lechner et al., 2014; Pojar et al., 2021). The Black Sea is unique for three reasons. First, the sea is semi-enclosed (Aleksandrov et al., 2017; Slobodnik et al., 2017). Thus plastics tend to accumulate over time (BSC, 2019). Second, the drainage area of the sea is approximately 2.5 million km^2 and is divided into 107 sub-basins (Fig. 1). These sub-basins drain through more than 20 countries located in the European and Asian continents (Slobodnik et al., 2017). Third, the sea receives plastics from the three large transboundary rivers: Danube, Don and Dnieper (Fig. S1) (D'Hont et al., 2021; Pojar et al., 2021). The Danube River is one of the longest rivers in Europe and drains through more than ten countries (Pojar et al., 2021). However, rivers export increasing amounts of plastics in different sizes (Kooi and Koelmans, 2019): macro- (>5 mm, (González-Fernández et al., 2021)) and microplastics (<5 mm, (D'Hont et al., 2021); van Emmerik and Schwarz (2020)).

A spatially explicit assessment of microplastic export by rivers does not exist for 107 sub-basins draining into the Black Sea. Existing studies focused either on specific locations (Aytan et al., 2019b; Berov and Klayn, 2020; Cincinelli et al., 2021; Eryaşar et al., 2021; Lechner et al., 2014; Terzi et al., 2022) or plastic-type (Aytan et al., 2016; González-Fernández et al., 2021; Şener et al., 2019). Studies covering the entire drainage area of the Black Sea are lacking for river export of microplastics by source and sub-basin. Many existing studies focused on field experiments that are local and time-specific (Aytan et al., 2020; Cincinelli et al., 2021; Collignon et al., 2012; Eryaşar et al., 2021; Levent et al., 2018; Oztekin and Bat, 2017). Some studies focused on river export of microplastics, but either globally (van Wijnen et al., 2019) or continentally (Siegfried et al., 2017). They did not focus on the Black Sea. Other studies focused on the state of the Black Sea, but often for specific basins or other pollution types such as eutrophication, chemical pollution and biodiversity losses (BSC, 2019; Gonzalez-Fernandez, 2020; Lazăr et al., 2018; Levent et al., 2018; Slobodnik et al., 2017; Strokal and Kroeze, 2013).

Sources of microplastic pollution are hardly researched for 107 sub-

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basins of the Black Sea region in a spatially explicit way. Rivers export microplastics to the Black Sea. During this export, microplastics can be retained in sediments (Baysal et al., 2020; Pojar et al., 2021). Generally, microplastics in rivers originate from diffuse and point sources (An et al., 2020). Diffuse sources are, for instance, the degradation of macroplastics into microplastics in rivers (van Wijnen et al., 2019). Macroplastics in the environment result from mismanaged solid waste (Lebreton and Andrady, 2019) and/or agricultural films (Qi et al., 2020). Macroplastics in the Black Sea are reported to result from plastic bottles, packaging materials, polystyrene pieces *etc.* (González-Fernández et al., 2021). Point sources of microplastics in water are often from sewage systems that discharge microplastics to rivers (Siegfried et al., 2017). Sewage systems discharge microplastics from personal care products (PCP), household dust, fibres and car tyre wears (Siegfried et al., 2017; van Wijnen et al., 2019). Some studies report on the importance of ships and flooding as the sources of plastics in the coasts of the Black Sea (Gündoğdu et al., 2018; Korshenko et al., 2020; Oztekin and Bat, 2017; Roebroek et al., 2021). Field studies exist on analysing source types and the abundance of microplastics, but limited in time and space (Aytan et al., 2019a; Aytan et al., 2020; Berov and Klayn, 2020; Cincinelli et al., 2021; Pojar et al., 2021; Şener et al., 2019; Terzi et al., 2022). Those field studies indicate the importance of fibres in microplastic pollution of the Black Sea coastal waters. However, riverine export of microplastics from point and diffuse sources at the sub-basin scale is limited for the entire drainage area of the Black Sea. This analysis is needed to formulate effective solutions for pollution reduction in the future.

Future trends in river export of microplastics to the Black Sea are also limited. In addition, options to reduce future pollution under global change are hardly explored for the Black sea. Many studies analysed future trends (Blaas and Kroeze, 2016; Lau et al., 2020; Li et al., 2019; Vermeulen et al., 2015) and explored the effects of reduction options (Buckley and Carney, 2013; Li et al., 2019; Strokal et al., 2014). However, those studies often focused on other types of pollution such as nutrients (Strokal et al., 2014; van Puijenbroek et al., 2019), pathogens (Vermeulen et al., 2015), and pharmaceuticals (Acuña et al., 2020). Lebreton and Andrady (2019) developed scenarios for municipal waste products including plastics. But those scenarios are not specific to microplastics. van Wijnen et al. (2019) focused on scenarios for microplastics, but not specifically for the Black Sea. Strokal et al. (2014) developed scenarios for the Black Sea, but not for microplastics. Strokal et al. (2021a) developed five scenarios for emissions of multiple pollutants to 10,226 rivers from point sources. These scenarios are based on the recent Shared Socioeconomic Pathways (SSPs) (Dellink et al., 2017; Kc and Lutz, 2017). They include microplastics and cover 107 sub-basins of the Black Sea, but do not include diffuse sources and climate change impacts. Furthermore, recent European policies such as the “Zero Pollution Targets” are not considered in the scenarios of Strokal et al. (2021a), and their effects are not well studied for cleaning the Black Sea from microplastics (Aydın, 2021; Strokal, 2021). This makes challenging to explore reduction options to support Sustainable Development Goals (SDGs).

Large-scale models exist to quantify water pollution. However, they often focus either on the world for plastic pollution (Lebreton et al., 2017; Meijer et al., 2019b; Schmidt et al., 2017) or on other pollutants (Beusen et al., 2015; Font et al., 2019; UNEP, 2016). A few models quantify river export of microplastics including the Black Sea region (Siegfried et al., 2017; van Wijnen et al., 2019). They do not focus on sub-basins. The Soil & Water Assessment Tool (SWAT) is widely applied for the Black Sea region, but mainly for nutrients (Cools et al., 2011; Malagó et al., 2017; Osypov et al., 2016). Recently, the Global Model to Assess River Inputs of pollutAnts to seAs (MARINA-Global) has been developed for 10,226 sub-basins (Strokal et al., 2021a). MARINA-Global includes 107 sub-basins of the Black Sea and microplastics. This model allows for a spatially explicit analysis of the drainage area of the Black Sea. The model also enables calculations of the source attribution and exploring future trends. The MARINA-Global model simulates inputs of microplastics to rivers in mass. However, there are two disadvantages of the model for the Black Sea. First, the model does not consider diffuse sources and retentions of microplastics in rivers. Second, the model does not have scenarios with reduction options for the Black Sea.

In this study, we explore options to reduce future river export of microplastics to the Black Sea. Our study focuses on large-scale modelling that includes 107 sub-basins draining into the Black Sea. We calculate river export of microplastics by source and sub-basin up to 2050. We develop five scenarios with different reduction options and implement them into the updated version of the MARINA-Global model. The Black Sea can serve as an example for other seas requiring effective strategies to reduce future microplastic pollution. Our results could support the formulation of effective policies for large transboundary rivers.

2. Materials and methods

2.1. Modelling microplastics

The original MARINA-Global model (Strokal et al., 2021a) quantifies annual inputs of microplastics, a pathogen, nutrients and triclosan to rivers from sewage systems in 10,226 sub-basins. For microplastics, these inputs in rivers are calculated in mass. For example, the main purpose of the model is to simulate loads of microplastics in units such as kg/year. In this study, the model is applied for 107 sub-basins draining into the Black Sea (Fig. 1). The focus is on the annual river export of microplastics by source and sub-basin for the period of 2010–2050. Point and diffuse sources are considered in this study. Point sources are sewage systems discharging microplastics to rivers from PCP, car tyres, household dust and fibres. Diffuse sources are microplastics in rivers from the degradation of macroplastics and untreated waste on land. River export of microplastics is calculated from 107 sub-basins using consistent datasets in time and space.

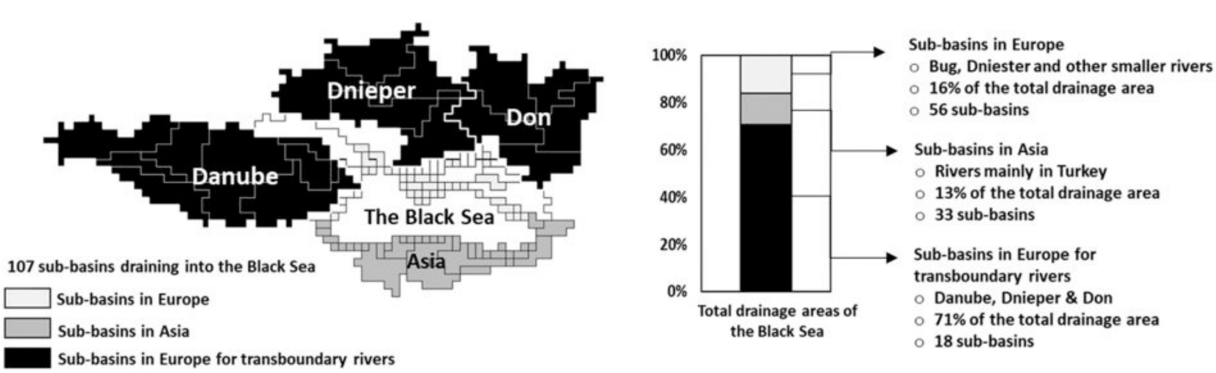

Fig. 1. The study area including 107 sub-basins draining to the Black Sea (details are in Fig. S1).

Table 1
Overview of model inputs that vary among sub-basins, pollution sources, years and alternative scenarios. The drainage basin of the Black Sea consists of 107 sub-basins. Years include 2010 and 2050 for a baseline scenario (S_{BL}). Alternative scenarios assume improvements in the wastewater treatment (S_{WWTP}), reductions in the consumption of plastics (S_{CONS}), better waste collection (S_{COLL}) and all together (S_{OPT}). Section 2.2 provides the scenario descriptions. Abbreviations of the model inputs and their units are in the main text of Section 2.1. Table S1 provides model inputs and Table 2 describes scenarios.

Model inputs	Vary among				Reference or equation
	Sub-basins[1]	Sources[2]	Years	Alternative scenarios	
$WS_{MI.i.j}$				S_{CONS}, S_{OPT}	A, C, D
Pop_j[3], $Popcon_j$[3]					C, D, Table S2
$hw_{frem.j}$[3]				S_{WWTP}, S_{OPT}	
$WS_{f.j}$, $WS_{s.j}$		[4]		S_{CONS}, S_{COLL}, S_{OPT}	Eqs. (5)–(6)
$t_{res.f.j}$[5]					A, B, Eqs. (13)–(14)
WS_j		[4]		S_{CONS}, S_{COLL}, S_{OPT}	Eq. (7)
$PW_{env.j}$		[4]		S_{CONS}, S_{COLL}, S_{OPT}	Eq. (8)
F_{macro}, $t_{res.s}$, C_{env}, C_f, C_s					A, Table S1
$PW_{badly.j}$		[4]		S_{CONS}, S_{COLL}, S_{OPT}	Eq. (9)
$PW_{uncoll.j}$		[4]			Eq. (10)
$PW_{coll.j}$		[4]			Eq. (11)
$frPW_{badly.j}$[6]		[4]		S_{COLL}, S_{OPT}	A
$PW_{prod.j}$		[4]		S_{CONS}, S_{OPT}	Eq. (12)
$Coll_{rate.j}$[6]				S_{COLL}, S_{OPT}	A
$W_{mun.j}$		[4]		S_{CONS}, S_{OPT}	
$P_{content.j}$[6]					
$Area_{land.j}$ & $Area_{aver}$					C
$L_{MI.j}$					A, D
$FQ_{rem.j}$[7]					A, D, G, Eq. (16)
$Q_{nat.j}$[8]					E
$Q_{act.j}$[9]					F, E

References:
A: van Wijnen et al. (2019); B: van Wijnen et al. (2017); C: Strokal et al. (2021a); D: Siegfried et al. (2017); E: Hydrological VIC model: Liang et al. (1994), van Vliet et al. (2016), van Vliet et al. (2017); F: Mayorga et al. (2010), Fekete et al. (2010); G: Strokal et al. (2016), Wang et al. (2020).

Remarks
[1]Only for laundry fibres, personal care products and car tyre wears. *Per capita* consumptions depend on OECD and ECA sub-basins (see Fig. S1).
[2]Laundry fibres, personal care products, household dust, car tyre wears, macroplastics degradation.
[3]Strokal et al. (2021a) prepared the 0.5° grid population that we aggregated to sub-basins (the sum of gridded values). Strokal et al. (2021a) also prepared the 0.5° grid population with sewage connections at 0.5° that we aggregated to sub-basins. We summed the gridded values (connected people/year) over the corresponding sub-basins and then divided this by the total population (people/year) to get the fraction of the population with sewage connections per sub-basin (0–1). We followed Strokal et al. (2021a) for removal fractions ($hw_{frem.j}$) that are assigned for microplastics based on the phosphorus removal (Siegfried et al., 2017) (Table S2). Strokal et al. (2021a) calculated the phosphorus removal for the 0.5° grid using primary, secondary and tertiary treatments. We aggregated this to sub-basins using the gridded population.
[4]Only for macroplastics as a diffuse source.
[5]Wee adjusted the approach of van Wijnen et al. (2019) to sub-basins. $t_{res.f.j}$ is calculated using either Eq. (13) or Eq. (14) depending on sub-basin.
[6]These fractions vary among OECD and ECA sub-basins (see Fig. S1 for their locations).
[7]The approach of Strokal et al. (2016), Wang et al. (2020) is adjusted to microplastics using van Wijnen et al. (2019) and Siegfried et al. (2017).
[8]We derived water discharges for the 0.5° grid that is located at the outlet of the sub-basin from the VIC hydrological model for 2010 and 2050 Representative concentrative Pathway 2.6. For 2010, we averaged over the 30 years of the period 1980–2010 and the five Global Climate Models (GCMs). For 2050, we averaged over the 30 years of the period 2020–2050 and the five GCMS. Then, we calculated the sub-basin-specific water discharges by subtracting the upstream discharges if needed.
[9]Actual water discharges for 2010 are calculated using the ratio of Q_{nat} and Q_{act} from Mayorga et al. (2010) and natural water discharges from the VIC hydrological model (see above). For 2050, actual water discharges are calculated using population growth.

For this, the original MARINA-Global model (Strokal et al., 2021a) for the Black Sea is improved in four aspects (Text S1, Figs. S1–S5, Tables S1–S2). *First,* the modelling approach for microplastics is updated by including missing sources. The original MARINA-Global model included only point sources of microplastics in rivers, these being sewage systems (Strokal et al., 2021a). Diffuse sources are added to the model by adjusting a modelling approach of van Wijnen et al. (2019) to 107 sub-basins. Microplastics in rivers from diffuse sources result from untreated waste on land (for laundry fibres and PCP) and macroplastics degradation. *Second*, for the point sources, the consumption rates of microplastics are updated for car tyre wears, laundry fibres and PCP using the data from van Wijnen et al. (2019) (Table S1). *Third*, hydrology and retentions of microplastics in rivers are added to the model by adjusting the modelling approach of van Wijnen et al. (2019) to 107 sub-basins (see Figs. S2–S5). This allows us to account for climate change impacts. *Fourth*, new scenarios that are developed based on more recent Socio-economic Pathways (SSPs) for urbanization and plastic waste management and Representative Concentrative Pathways (RCPs) for hydrology (see details below). The original MARINA-Global model was also based on SSPs, but not specific for the Black Sea. One of the SSP scenarios is modified as the baseline for the Black Sea (see Section 2.2). The original MARINA-Global did not consider the retentions and hydrology of riverine microplastics. We now do in the improved version of the model for the Black Sea (Figs. S2–S5). Below, we describe the model for the Black Sea.

- Calculating river export of microplastics

The MARINA-Global model for the Black Sea calculates river export of microplastics by source from sub-basins (kg of microplastics exported by rivers to the Black Sea per year) as follows:

$$Ld_{MI.i.j} = \left(RSpnt_{MI.i.j} + RSdif_{MI.i.j}\right) \times FE_{riv.o.MI.j} \times FE_{riv.m.MI.j} \quad (1)$$

where,

$Ld_{MI.i.j}$ is the river export of microplastics (MI) from source i and sub-basin j into the sea (kg/year);

$RSpnt_{MI.i.j}$ is the input of microplastics to rivers from point source i in sub-basin j (kg/year);

$RSdif_{MI.i.j}$ is the input of microplastics to rivers from diffuse source i in sub-basin j (kg/year);

$FE_{riv.o.MI.j}$ is the fraction of microplastics in rivers that are exported to the outlet of sub-basin j (0–1);

$FE_{riv.m.MI.j}$ is the fraction of microplastics that are exported from the outlet of sub-basin j to the river mouth (coastal waters, 0–1).

o Calculating inputs of microplastics to rivers from point sources ($RSpnt_{MI.i.j}$)

The input of microplastics to rivers from point sources of laundry fibres, PCP, household dust and car tyre wears ($RSpnt_{MI.i.j}$, kg/year) is calculated according to the MARINA-Global model of Strokal et al. (2021a), but with updated information *per capita* consumption rates from van Wijnen et al. (2019). This is done as follows:

$$RSpnt_{MI.i.j} = \left(WS_{MI.i.j} \times Pop_j\right) \times Popcon_j \times \left(1 - hw_{frem.j}\right) \quad (2)$$

where,

$WS_{MI.i.j}$ is the *per capita* consumption of microplastics for source i in sub-basin j (kg/cap/year, Table 1);

Pop_j is the population in sub-basin j (people/year);

$Popcon_j$ is the fraction of population with sewage connections in sub-basin j (0–1, Table 1);

$hw_{frem.j}$ is the removal fraction of microplastics during treatment in sub-basin j (0–1, Tables 1 and S2).

o Calculating inputs of microplastics to rivers from diffuse sources ($RSdif_{MI.i.j}$)

These inputs are calculated according to the modelling approach of van Wijnen et al. (2019) that is integrated into the MARINA-Global model for 107 sub-basins of the Black Sea. The input of microplastics to rivers from diffuse sources of laundry fibres and PCP ($RSdif_{MI.i.j}$, kg/year) is calculated as follows:

$$RSdif_{MI.i.j} = \left(WS_{MI.i.j} \times Pop_j\right) \times \left(1 - Popcon_j\right) \quad (3)$$

The input of microplastics to rivers from diffuse sources of macroplastics degradation ($RSdif_{MI.i.j}$, kg/year) is calculated as follows (the summary of this approach is in Fig. S2):

$$RSdif_{MI.i.j} = F_{macro} \times \left(WS_{f.j} \times t_{res.f.j} + WS_{s.j} \times t_{res.s}\right) \quad (4)$$

$$WS_{f.j} = WS_j \times C_f \quad (5)$$

$$WS_{s.j} = WS_j \times C_s \quad (6)$$

$$WS_j = PW_{env.j} \times C_{env} \quad (7)$$

$$PW_{env.j} = PW_{badly.j} + PW_{uncoll.j} \quad (8)$$

$$PW_{badly.j} = PW_{coll.j} \times frPW_{badly.j} \quad (9)$$

$$PW_{uncoll.j} = PW_{prod.j} \times \left(1 - Coll_{rate.j}\right) \quad (10)$$

$$PW_{coll.j} = PW_{prod.j} \times Coll_{rate.j} \quad (11)$$

$$PW_{prod.j} = W_{mun.j} \times P_{content.j} \quad (12)$$

$$t_{res.f.j} = \left(\frac{Area_{land.j}}{Area_{aver}} \times 60\right) \Big/ 365 \quad or \quad (13)$$

$$t_{res.f.j} = \left(0.4 + 0.6 \times \frac{5000}{Area_{land.j}}\right) \times \left(\left(\frac{Area_{land.j}}{Area_{aver}} \times 60\right) \Big/ 365\right) \quad (14)$$

where,

F_{macro} is the relative release rate of microplastics from macroplastics (/year, Tables 1 and S1);

$WS_{f.j}$ is the input of macroplastics into the fast fraction in sub-basin j (kg/year);

$t_{res.f.j}$ is the average residence time for macroplastics in the fast fraction in sub-basin j (years, Table 1). It is calculated using either Eq. (13) or Eq. (14) depending on the sub-basin. If a sub-basin is both draining into the sea directly and the land area of this sub-basin exceeds 5000 km^2, then Eq. (14) is applied otherwise Eq. (13) is applied. This approach is from van Wijnen et al. (2019) but adjusted to the sub-basin modelling approach of the MARINA-Global model.

$WS_{s.j}$ is the input of macroplastics into the slow fraction in sub-basin j (kg/year);

$t_{res.s}$ is the average residence time for macroplastics in the slow fraction (years, van Wijnen et al. (2019), Tables 1 and S1);

WS_j is the input of macroplastics to rivers in sub-basin j (kg/year, Table 1);

C_f is the coefficient for the fast fraction (0–1). It is 0.95 from van Wijnen et al. (2019) (Tables 1 and S1);

C_s is the coefficient for the slow fraction (0–1). It is 0.05 from van Wijnen et al. (2019) (Tables 1 and S1);

$PW_{env.j}$ is the plastic waste entering the environment in sub-basin j (kg/cap/year, Table 1);

C_{env} is the coefficient for entering macroplastics from the environment to rivers (unitless). It is set at 0.5 from van Wijnen et al. (2019) (Tables 1 and S1);

$PW_{badly.j}$ is the plastic waste that is inadequately collected in sub-basin j (kg/cap/year);

$PW_{uncoll.j}$ is the plastic waste that is not collected in sub-basin j (kg/cap/year);

$PW_{coll.j}$ is the plastic waste that is collected in sub-basin j (kg/cap/year);

$frPW_{badly.j}$ is the fraction of plastic waste that is collected, but inadequately managed in sub-basin j (0–1, Tables 1 and S1);

$PW_{prod.j}$ is the plastic waste production in sub-basin j (kg/cap/year, Table 1);

$Coll_{rate.j}$ is the collection rate of plastic waste in sub-basin j (0–1, Tables 1 and S1);

$W_{mun.j}$ is municipal waste production in sub-basin j (kg/cap/year, Tables 1 and S1);

$P_{content.j}$ is the plastic content in municipal waste in sub-basin j (0–1, Tables 1 and S1);

$Area_{land.j}$ is the area land in sub-basin j (km^2, Table 1);

$Area_{aver}$ is the average area land of the largest 50 river basins in the world (km^2, Tables 1 and S1).

o Calculating river export fractions ($FE_{riv.o.MI.j}$ and $FE_{riv.m.MI.j}$)

In the MARINA-Global model, the export fractions of microplastics reaching the sea are calculated according to the two approaches: the sub-basin scale modelling approach of the MARINA model for sub-basins (Strokal et al., 2016; Wang et al., 2020) and the modelling approach of Siegfried et al. (2017) and van Wijnen et al. (2019) for microplastics. These two approaches are now fully integrated into the MARINA-Global model for 107 sub-basins of the Black Sea.

The export fraction of microplastics reaching the outlet of the sub-basin ($FE_{riv.o.MI.j}$, 0–1) is calculated as follows:

$$FE_{riv.o.MI.j} = \left(1 - L_{MI.j}\right) \times \left(1 - FQ_{rem.j}\right) \quad (15)$$

$$FQ_{rem.j} = \left(Q_{nat.j} - Q_{act.j}\right) / Q_{nat.j} = 1 - Q_{act.j} / Q_{nat.j} \quad (16)$$

where,

$L_{MI.j}$ is the fraction of microplastic retention in rivers as a result of sedimentation and degradation in sub-basin j (0–1, Table 1);

$FQ_{rem.j}$ is the fraction of microplastic that is removed from rivers as a result of consumptive water use in sub-basin j (0–1, Table 1);

Table 2
Descriptions of the scenario for the Black Sea. Alternative scenarios assume improvements in the wastewater treatment (S_{WWTP}), reductions in the consumptions of plastics (S_{CONS}), better waste collection (S_{COLL}) and all together (S_{OPT}) relative to the baseline scenario (S_{BL}). All assumptions are for 107 sub-basins (Fig. 1). Section 2.2 provides the scenario descriptions. Abbreviations of the model inputs and their units are in the main text of Section 2.1. Table S1 provides model inputs and Fig. S6 provides a schematic overview of the scenarios. Decreases in the table are from 2010 to 2050. SSP2 is a Shared Socioeconomic Pathway 2.

Model inputs	Scenarios for 2050				
	S_{BL}	S_{WWTP}	S_{CONS}	S_{COLL}	S_{OPT}
Socio-economic development and urbanization					
Gross Domestic Product	SSP2[A]	S_{BL}	S_{BL}	S_{BL}	S_{BL}
Human Development Index	SSP2[A]	S_{BL}	S_{BL}	S_{BL}	S_{BL}
Population (Pop_j)	SSP2[A]	S_{BL}	S_{BL}	S_{BL}	S_{BL}
Population with sewage connections ($Popcon_j$)	At least 75%	S_{BL}	S_{BL}	S_{BL}	S_{BL}
Microplastic management					
Wastewater treatment ($hw_{frem.j}$)	SSP2[A]	At least 95%[D]	S_{BL}	S_{BL}	At least 95%[D]
Production or consumption *per capita*:					
∘ Plastic waste ($W_{mun.j}$)	Estimated[B]	S_{BL}	50% decrease[E]	S_{BL}	50% decrease[E]
∘ Microplastics in personal care products ($WS_{MI.i.j}$)	2010[C]	S_{BL}	50% decrease[E, F]	S_{BL}	50% decrease[E, F]
∘ Microplastics in laundry fibres ($WS_{MI.i.j}$)	2010[C]	S_{BL}	50% decrease[E,G]	S_{BL}	50% decrease[E,G]
∘ Microplastics in household dust ($WS_{MI.i.j}$)	2010[C]	S_{BL}	50% decrease[E,H]	S_{BL}	50% decrease[E,H]
∘ Microplastics from car tyre wears ($WS_{MI.i.j}$)	2010[C]	S_{BL}	S_{BL}	S_{BL}	S_{BL}
Plastic waste collection ($Coll_{rate.j}$)	2010[C]	S_{BL}	S_{BL}	At least 90%[E,I]	At least 90%[E,I]
Plastic waste collected, but managed badly ($frPW_{badly.j}$)	2010[C]	S_{BL}	S_{BL}	0%[E,I]	0%[E,I]
Characteristics					
Relation to pollution sources	–	Point	Point, diffuse	Diffuse	Point, diffuse
Relation to Sustainable Development Goals (SDG)	–	SDG 6 & 11	SDG 6 & 12	SDG 6 & 9	SDGs 6, 9, 11, 12

Justification
A: Strokal et al. (2021a).
B: Lebreton and Andrady (2019). We took the value of 2010 and applied the change from Lebreton and Andrady (2019). The change corresponds to mismanaged plastic waste projected for 2020 and 2060 based on the business as usual trends. See the main text of Section 2.2 for details.
C: Values are in Table S1.
D: Based on advanced technologies for microplastics (Liu et al., 2021; Talvitie et al., 2017) to support Sustainable Development Goals 6 (sanitation) and 11 (cities).
E: Based on the "Zero Pollution Target" from the Green Deal: a 50% reduction in waste production for plastics by 2030 (European Commission, 2021).
F: We assume less consumption as a result of using plastic-free cosmetics (Kettenmann, 2016; Terry, 2012) (*e.g.*, https://www.beatthemicrobead.org/).
G: We assume less consumption as a result of using plastic-free detergents (*e.g.*, https://www.becausehealth.org/non-toxic-laundry-detergent-2540974607.html).
H: We assume less consumption as a result of using eco-friendly flooring materials (Jalaluddin, 2017; Nasr et al., 2020).
I: Based on plastic strategies to increase waste recycling and collection (EEA, 2020) and plastic reduction targets for European countries (EEA, 2019).

$Q_{nat.j}$ is the natural water discharge at the outlet of the sub-basin j before consumptive water use (km^3/year, Table 1);

$Q_{act.j}$ is the actual water discharge at the outlet of the sub-basin j after consumptive water use (km^3/year, Table 1).

Most sub-basins of the Black Sea drain directly into the sea. This implies that the outlet is the river mouth for them. Thus, the model only calculates $FE_{riv.o.MI.j}$ (Eq. (15)). This is not the case for the three large rivers: Danube, Dnieper and Don (Figs. S3–S5). For these rivers, $FE_{riv.m.MI.j}$ (see Eq. (1) and Text S1) is calculated in addition to $FE_{riv.o.MI.j}$ (see Eq. (15)). This is because the drainage area of the three large rivers is further divided into up-, middle-and downstream sub-basins. Interactions between the sub-basins take place. Microplastics that leave the outlet of an upstream sub-basin, can still be deposited in the soil or extracted from the water in a more downstream located sub-basin before they reach the Black Sea. $FE_{riv.m.MI.j}$ accounts for this and reflects retentions during transport from upstream to downstream (coastal sea). A detailed description is provided in Text S1 and Figs. S3–S5.

2.2. Scenario description

We develop five scenarios: S_{BL}, S_{WWTP}, S_{CONS}, S_{COLL} and S_{OPT} (Fig. S6). S_{BL} is the baseline scenario. The other scenarios are relative to this baseline scenario (Table 2, Fig. S6). S_{BL} assumes the socio-economic developments and urbanization according to the Shared Socioeconomic Pathway 2 (middle of the road) (Strokal et al., 2021a). The economic growth and urbanization rates are high. The Gross Domestic Product (GDP) in the drainage basin of the Black Sea will increase by 142% between 2010 and 2050. In 2050, 180 million people are projected to live in the drainage basin of the Black Sea. This is slightly lower than in 2010 (190 million people). Around two-thirds of the population in 2050 will be living in urban areas (Strokal et al., 2021a). The share of population living in the three largest basins (Danube, Dnieper and Don) is 60% in the total population of the drainage area (Table S6, Fig. 1 for the locations of the basins). However, the share of the Asian population in the drainage area of the Black Sea is projected to increase to over 30% in 2050 according to the S_{BL} scenario (Table S6). For the European basins, the share of population is projected to decrease in the future (Table S6). This implies that the European basins may be less populated in 2050 than in 2010. This is opposite for the Asian basins where more population is expected in 2050 compared to 2010. We assumed at least 75% of the total population with sewage connections. Wastewater treatment will not improve largely and thus removal rates will remain as in 2010 (ranging from 0.5 to 0.95 among 107 sub-basins, (Strokal et al., 2021a)). Future waste production follows the business-as-usual trends from Lebreton and Andrady (2019). As a result, *per capita* production of plastic waste is assumed to increase by 15% during 2010–2050 for all sub-basins except for Asian sub-basins (located in Turkey and Georgia) and the upstream sub-basin of Danube (see Figs. S1–S5 for locations). For the Asian sub-basins, this increase is 106%. For the upstream Danube, it is 16%. *Per capita* consumption of microplastics in laundry fibres, PCP, household dust and from car tyre wears will remain as in 2010. Waste management including collection rates will also be as in 2010 following the current developments.

S_{WWTP}, S_{CONS}, S_{COLL} and S_{OPT} follow the socio-economic and urbanization as in S_{BL}, but have the implementation of different reduction options (Table 2, Fig. S6). In these scenarios, achieving Sustainable

Development Goal 6 (SDG, clean water) is important. In the scenario S_{WWTP}, people will focus on reducing pollution by making cities more sustainable, thus also contributing to SDG 11 (sustainable cities). Efforts will be made to improve wastewater treatment by implementing advanced technologies (Liu et al., 2021; Talvitie et al., 2017). We assume the in 2050 wastewater treatment will remove at least 95% of the microplastic in human waste in all sub-basins of the Black Sea (Table 2). Examples of advanced technologies are in Liu et al. (2021). Advanced technologies are end-of-pipe reduction options and will affect microplastics reduction from points sources (sewage systems) in rivers.

In the scenario S_{CONS}, people will focus on reducing pollution (SDG 6) through sustainable consumption and production of plastics (Table 2, Fig. S6). This will also support SDG 12 (responsible consumption and production). People will do their best to achieve the "Zero Pollutant Targets". These targets have been recently introduced in Europe and aim to contribute to zero pollution in the future (European Commission, 2021). One of the targets aims at a 50% decrease in plastic waste production (European Commission, 2021). We assume that people will use plastic-free products to reduce plastic waste in the entire basin of the Black Sea (Jalaluddin, 2017; Kettenmann, 2016; Nasr et al., 2020). Therefore, we assume a 50% decrease in *per capita* production or consumption of (micro)plastics for all sub-basins during 2010–2050 (Table 2). This option aims to reduce microplastic at the source before reaching rivers. It will affect microplastic reduction from point and diffuse sources.

In the scenario S_{COLL}, people will focus on reducing sea pollution by improving and increasing the collection of plastic waste (Table 2, Fig. S6). Efforts will be done on recycling plastics and avoiding badly managed collected waste according to the European ambitions (EEA, 2019). Collection systems will be innovated, thus contributing to SDG 9 (innovation and infrastructure). As a result, the collection rate will be at least 90% in all sub-basins. All waste will be managed safely (zero mismanaged waste, Table 2). These are end-of-pipe reduction options, affecting microplastic reduction from diffuse sources.

The scenario S_{OPT} assumes an optimistic future (Table 2, Fig. S6). People will invest in reduction options towards zero pollution. This will support achieving SDG 6 (clean water) by improving wastewater treatment (S_{WWT}, SDG11), reducing production and consumption of (micro) plastics (S_{CONS}, SDG12), innovating collection systems and increasing their rates for plastics to avoid mismanaged waste (S_{COLL}, SDG9). In this future, "Zero Pollution Targets" of the European Union are important (EEA, 2019, 2020). This optimistic future combines reduction options at the source (S_{CONS}) and end-of-pipe in all sub-basins (S_{WWTP}, S_{COLL}, Table 2). Thus, microplastic will be reduced from both diffuse and point sources.

2.3. Model performance

We evaluate model performance following the "building trust" approach of Strokal et al. (2021a). This includes three options. First, we reflect on the performance of the modelling approaches for the Black Sea. Second, we compare the modelled results with available observations and other modelling studies. Third, we perform a sensitivity analysis in which we test the sensitivity of model outputs to changes in uncertain model parameters. We select 11 model parameters for which data are limited. These are (1) F_{macro}, (2) $t_{res.s}$, (3) C_{env}, (4) C_f and C_s, (5) $W_{mun.j}$, (6) $P_{content.j}$, (7) $frPW_{badly.j}$, (8) $WS_{MI.i.j}$ for laundry fibres, (9) $WS_{MI.i.j}$ for PCP, (10) $WS_{MI.i.j}$ for car tyre wears and (11) $WS_{MI.i.j}$ for household dust (see the original values in Table S1). Model parameters from 1 to 7 are used to calculate the river export of microplastics from diffuse sources. The other model parameters are used to calculate the river export of microplastics from point sources. We change model parameters by +10% except for C_f and C_s. These two model parameters are interrelated: changing C_s will lead to changes in C_f (see Eqs. (5) and (6) in Section 2). Thus, we first increase C_s by 10%. Then, we calculated C_f as 1 minus the fraction of C_s. We run the model with changed model parameters for the year 2010. Results of the model evaluation are presented in Section 3.1.

3. Results

3.1. Model evaluation

Our model integrates the existing modelling approaches of van Wijnen et al. (2019), Siegfried et al. (2017) for microplastics, and Strokal et al. (2021b) and Wang et al. (2020) for sub-basins. These approaches have been evaluated for a set of individual rivers. van Wijnen et al. (2019), Siegfried et al. (2017) developed the approach for the world and European rivers including the Danube River draining into the Black Sea. Evaluation results of the previous studies (Siegfried et al., 2017; van Wijnen et al., 2019) build trust in using the existing modelling approaches for quantifying microplastic water pollution by source. Furthermore, the original MARINA-Global model has also been evaluated (Strokal et al., 2021a; Strokal et al., 2019) and internationally accepted for water quality analysis (UNEP, 2021).

Observations for model validation are available for the Danube River (Hohenblum, 2015; Lechner et al., 2014; van der Wal et al., 2015) but are limited for the other rivers of the Black Sea region. Observations also differ among field studies that are site- and time-specific (Table S4). Field studies often provide results in units (***e.g.***, items/m^3, Table S4) that are not easily comparable with our units (***e.g.***, kg/year). Our model calculates 0.71 kton/year of microplastics entering the Black Sea from the Danube River (Table S4). Lechner et al. (2014) estimated 1.5 kton/year based on measurements. This is lower than our estimate because of the difference in time and place. For example, our river export is annual and calculated for the river mouth. Lechner et al. (2014) sampled waters at specific locations and times that do not often match with our spatial and temporal level of detail. Another reason is that we account for microplastic sources from municipal waste, cars, personal care products, household dust and laundry. The study of Lechner et al. (2014) focused mainly on microplastics in fish larvae. Hohenblum (2015) estimated microplastics (<5 mm particles) in two locations of the Danube River. Their observations are generally lower than in Lechner et al. (2014).

Our modelled pollution hotspots (***e.g.***, urbanized sub-basins) are generally in line with the estimates of González-Fernández et al. (2021) for macroplastics along the Black Sea coasts (Table S4). Field studies for microplastics indicate pollution hotspots around the Danube delta (Pojar et al., 2021), cities such as Istanbul (Şener et al., 2019) and along the southern coast of the Black Sea (Aytan et al., 2020; Aytan et al., 2016; Eryaşar et al., 2021; Oztekin and Bat, 2017; Terzi et al., 2022) (Table S4). This is consistent with our findings indicating higher microplastic export from sub-basins having large cities. Our study shows increasing levels of pollution from the southern rivers (see Section 3.2).

Existing models also differ in their estimates and often focus on macroplastics (Jambeck et al., 2015; Lebreton et al., 2017; Meijer et al., 2019b; Schmidt et al., 2017; Siegfried et al., 2017). Lebreton et al. (2017) modelled from around 2.3 to 9.3 kton/year of plastics in Europe. Our results are within this range. The model of Siegfried et al. (2017) quantified 4.1 kton/year of microplastics entering the Black Sea (Table S5). Our results are lower because of differences in time and we account for retentions of microplastics at the sub-basin scale. This means that our retentions are generally higher than in the existing basin-scale models, leading to more microplastics in the rivers and thus lower microplastics in the sea. Our model results for the Danube, Dnieper, Don and southern rivers are somewhat in line with the European model of Siegfried et al. (2017) (Table S5). For the Dnieper River, our model calculates 0.33 kton of microplastics entering the sea with the range of 0.04–0.12 kton/year among the sub-basins (Table S5). Siegfried et al. (2017) estimated the range of 0.10–0.25 kton/year. A similar conclusion is for the Don River (Table S5). For the southern rivers, our model calculates 0.84 kton/year entering the Black Sea, which is higher than in Siegfried et al. (2017). The models of Meijer et al. (2019b), Jambeck

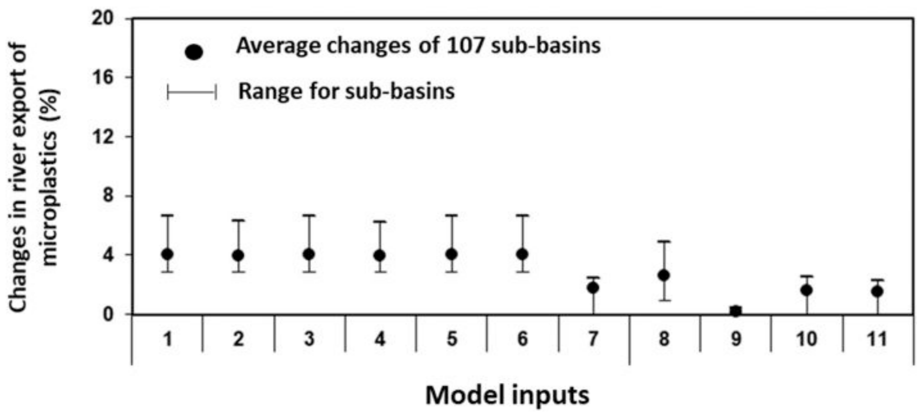

Fig. 2. Results of the sensitivity analysis for the Black Sea. Eleven model parameters were changed relative the original model run for 2010: (1) F_{macro}, (2) $t_{res.s}$, (3) C_{env}, (4) C_f and C_s, (5) $W_{mun.j}$, (6) $P_{content.j}$, (7) $frPW_{badly.j}$, (8) $WS_{MI.i.j}$ for laundry fibres, (9) $WS_{MI.i.j}$ for PCP, (10) $WS_{MI.i.j}$ for car tyre wears and (11) $WS_{MI.i.j}$ for household dust. Changes in river export of microplastics are calculated relative to the original model run for the year 2010. Model inputs 1–7 influence calculations of diffuse-source pollution. Model inputs 8–11 influence calculations of point-source pollution. Source: see Section 2 for the description of the abbreviations and the sensitivity analysis.

et al. (2015) and Schmidt et al. (2017) focus on the global analysis and macroplastics, which is different from our study. Some studies report on the importance of laundry fibres in plastic pollution in the Black Sea areas (Aytan et al., 2016; Pojar et al., 2021; Topçu et al., 2013). This is consistent with our study (see Sections 3.2–3.6). Topçu et al. (2013) report on the importance of macroplastics in plastic pollution. Our model estimates less than half of microplastics in the Black Sea is from macroplastics in 2010 (Fig. 2).

Our model outputs are fairly sensitive to changes in the uncertain model parameters (Fig. 1). For the Black Sea region, model outputs changed between 0 and 4% as a result of increasing the eleven model parameters by 10%. The range for the sub-basins is from 0% to 7% depending on the model input (Fig. 2). The lowest sensitivity is for the microplastic consumption in PCP (No. 9 in Fig. 2). This is because PCP is not an important source of microplastic pollution in the sea. This is also found in field studies (see Table S4 for the references).

Based on the abovementioned evaluation, we consider our model appropriate to analyse river export of microplastics by source and sub-basin to the Black Sea.

3.2. Sea pollution with microplastics in 2010

Rivers export 2.6 kton of microplastics to the Black Sea in 2010 (Fig. 3). Around half of this amount is from diffuse sources and the other half is from point sources. Diffuse sources include microplastics in rivers from laundry fibres, personal care products (PCP) and macroplastics degradation. The latter takes the dominant share in the diffuse-source pollution of the sea. Point sources include microplastics in rivers from

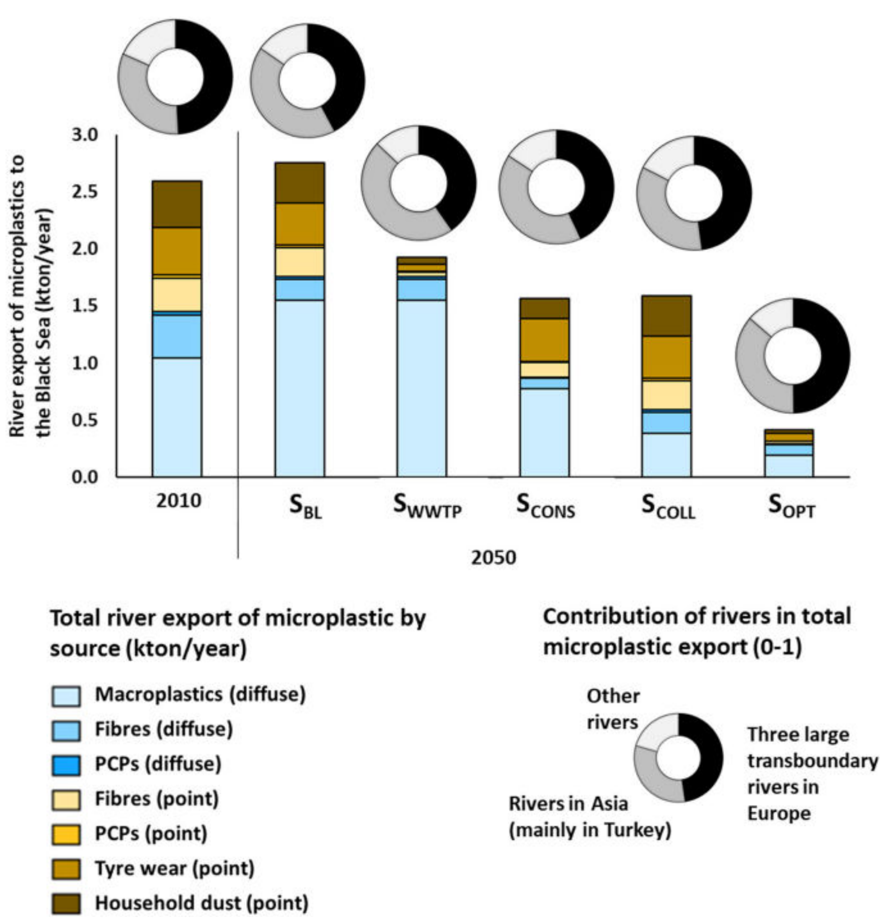

Fig. 3. River export of microplastics to the Black Sea from all sub-basins and sources (kton/year) and the contribution of the rivers in this export (0–1) in the years 2010 and 2050 according to the five scenarios. S_{BL} is the baseline scenario assuming low population growth, high urbanization and medium economic developments with reactive environmental management. S_{WWTP}, S_{CONS}, S_{COLL} and S_{OPT} are alternative scenarios of the baseline scenario and assume improvements in the wastewater treatment (S_{WWTP}), reductions in the consumptions of plastics (S_{CONS}), better waste collection (S_{COLL}) and all together (S_{OPT}). Locations of the rivers are in Fig. 1. PCP is short for personal care products. Source: the MARINA-Global model for the Black Sea (see Section 2 for the model and scenario descriptions).

laundry fibres, PCP, car tyre wears and household dust from sewage systems. Car tyre wears and household dust takes the dominant share in the point-source pollution of the sea (Fig. 3).

European rivers draining into the Black Sea are responsible for over half of the microplastics in the sea (Fig. 1). They include the three transboundary rivers draining through 71% of the Black Sea basin: the Danube, Dnieper and Don (Figs. 1 and S1). The entire drainage basin of the Black Sea is divided into 107 sub-basins and their river exports to the sea differ largely (Figs. 1 and 4). The highest microplastic export per km^2 is generally calculated for sub-basins close to cities such as Odessa (Fig. S1). The drainage area of the Danube, Dnieper and Don is classified into up-, middle- and downstream sub-basins (Figs. 4–6). Up-and middlestream sub-basins contribute largely to the sea pollution from the Danube and Don. The Sea pollution from the Dnieper results largely from human activities in the up-and downstream sub-basins (Fig. 6). Human activities include mismanaged plastic waste and sewage effluents that are driven by urbanization activities (*e.g.*, more cities with more sewage connections). In almost all sub-basins, point and diffuse sources are important contributors to microplastics in their rivers (Fig. 4). Several exceptions exist. Diffuse sources dominate in the river

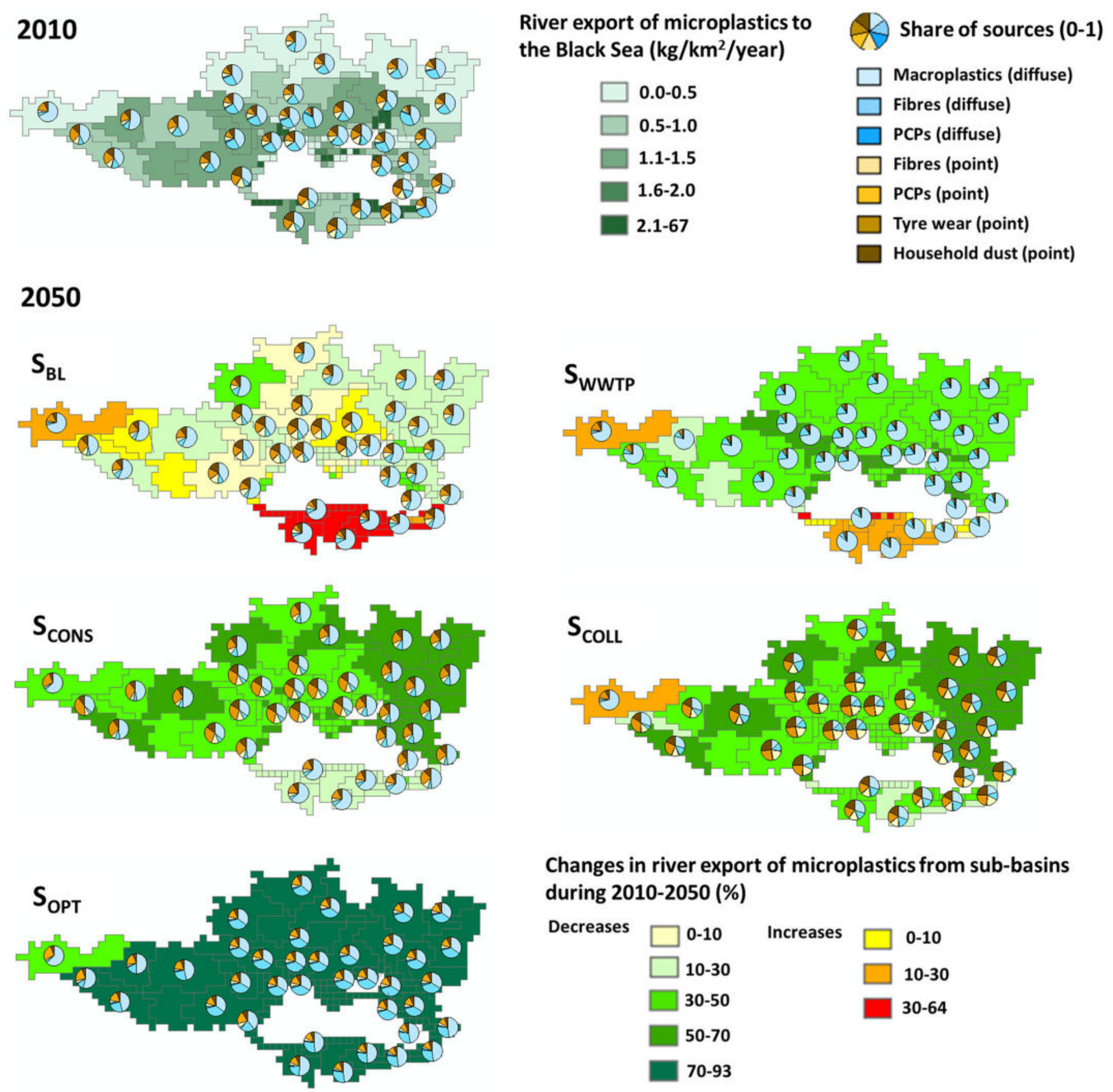

Fig. 4. River export of microplastics to the Black Sea by sub-basin in 2010 (kg/km^2/year), the share of sources in river export of microplastics in 2010 and 2050 (0–1), and the changes in river export of microplastics during the period of 2010–2050 (%) according to the five scenarios. The share of sources are shown for sub-basins with the drainage area higher than 5000 km^2. S_{BL} is the baseline scenario assuming low population growth, high urbanization and medium economic developments with reactive environmental management. S_{WWTP}, S_{CONS}, S_{COLL} and S_{OPT} are alternative scenarios of the baseline scenario and assume improvements in the wastewater treatment (S_{WWTP}), reductions in the consumptions of plastics (S_{CONS}), better waste collection (S_{COLL}) and all together (S_{OPT}). PCP is short for personal care products. Source: the MARINA-Global model for the Black Sea (see Section 2 for the model and scenario descriptions).

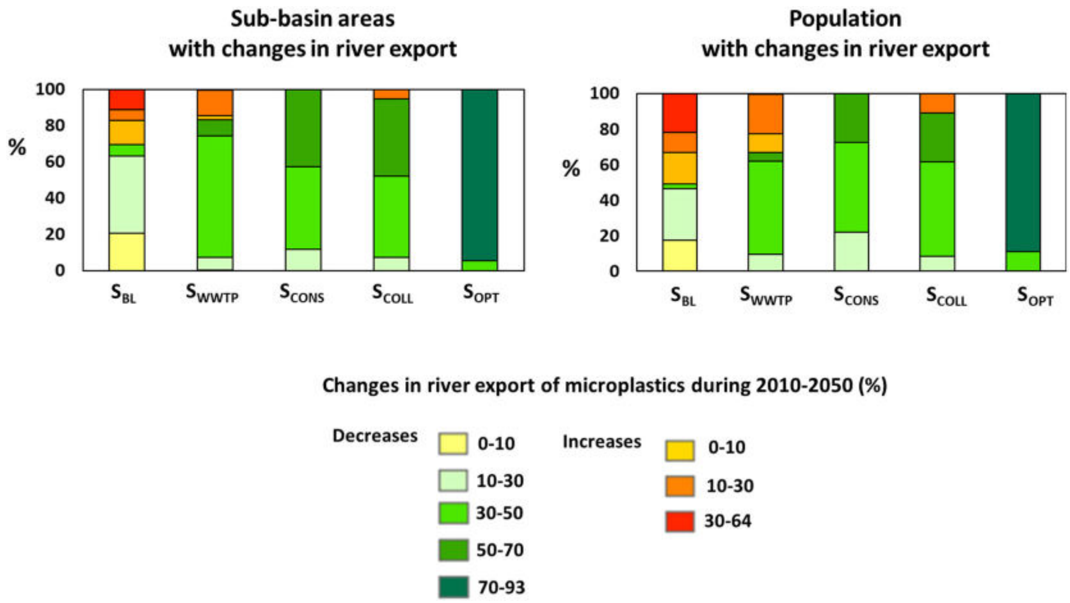

Fig. 5. Percentage of the sub-basin area and population with changes in river export of microplastics to the Black Sea during 2010–2050 according to the five scenarios (%). The changes in river export of microplastics are shown in Fig. 4. S_{BL} is the baseline scenario assuming low population growth, high urbanization and medium economic developments with reactive environmental management. S_{WWTP}, S_{CONS}, S_{COLL} and S_{OPT} are alternative scenarios of the baseline scenario and assume improvements in the wastewater treatment (S_{WWTP}), reductions in the consumptions of plastics (S_{CONS}), better waste collection (S_{COLL}) and all together (S_{OPT}). Source: the MARINA-Global model for the Black Sea (see Section 2 for the model and scenario descriptions).

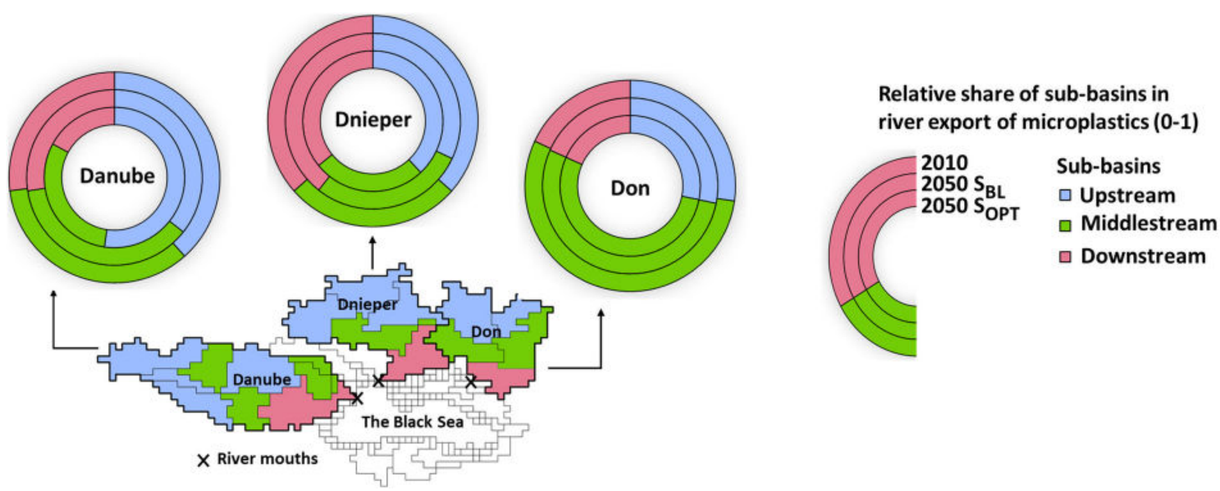

Fig. 6. The relative share of up-, middle- and downstream sub-basins to river export of microplastics from Danube, Dnieper and Don in 2010 and 2050 according to the two scenarios (0–1). S_{BL} is the baseline scenario assuming low population growth, high urbanization and medium economic developments with reactive environmental management. S_{OPT} is an alternative scenario of the baseline scenario and assumes improvements in wastewater treatment, reductions in the consumption of plastics, and better waste collection. The share of the sub-basins for the other scenarios is shown in Table S3. Source: the MARINA-Global model for the Black Sea (see Section 2 for the model and scenario descriptions).

pollution of the upstream Danube sub-basin and point sources dominate in the river pollution of some Asian sub-basins (located in Turkey and Georgia).

3.3. Increasing microplastic pollution in the future

We calculate increasing trends in river export of microplastics in the baseline scenario for 2050 (S_{BL}, Fig. 3). In total, rivers are projected to export 2.8 kton of microplastics to the Black Sea in 2050. This is only a 6% increase compared to the level of 2010. However, there are large spatial variabilities among rivers and their sub-basins (Figs. 1, 4 and 6). Asian rivers located mainly in Turkey are expected to be responsible for 43% of the total microplastic export to the sea in 2050 (Figs. 3 and S1). This is mainly a result of increased urbanization, sewage connections and mismanaged waste. These Asian rivers only flow through 13% of the Black Sea basin (Figs. 5 and S1). River export of microplastics from the Asian sub-basins (*e.g.*, Turkey) is projected to increase by 30%–64% during 2010–2050 depending on sub-basins (Figs. 4 and S1). These increases for the Asian sub-basins are the highest compared to the other sub-basins. For the upstream Danube sub-basin, increases range from 10% to 30% during 2010–2050 (Fig. 4). Slight increases in river export of microplastics (<10%) are calculated for a few European sub-basins (see Figs. 1 and S1 for locations). For the remaining sub-basins, river export of microplastics is projected to decline by 2050. We calculate that around half of the population will live in sub-basins for which increases in river export of microplastics are calculated for 2050 (Fig. 5).

Diffuse and point sources will be important in sea pollution. Around 60% of the total microplastic export will result from diffuse sources such as macroplastics degradation (Fig. 3). The remainder will be from point sources where laundry fibres and dust will dominate. In all sub-basins, at least half of microplastics in rivers is projected from diffuse sources and the rest from point sources (Fig. 4).

Higher microplastic pollution levels in the sea are the net effect of human activities on the land. The population is projected to decline in many sub-basins, but more people are projected to live in cities in 2050. As a result, at least 75% of people will be connected to sewage systems, but the removal efficiencies during treatment will be as in 2010. This will lead to more microplastics in rivers from sewage systems (point sources). In addition, collection rates and *per capita* consumption of (micro)plastics will not improve compared to the level of 2010. This explains more microplastics in rivers from both diffuse and point sources. Other reasons for sea pollution are associated with climate, microplastic retentions in rivers and travelling distances towards the sea. Climate change will influence the water availability in rivers. Microplastics can be retained in rivers as a result of fragmentation and sedimentation or removed *via* water consumption. Microplastics from upstream usually travels longer distances towards the river mouth compared to the downstream sub-basins.

3.4. Advanced technologies for pollution reduction

We calculate decreasing trends in river export of microplastics in a scenario with the assumed implementation of advanced technologies for 2050 (S_{WWTP}, Fig. 3). Rivers are projected to export 1.9 kton of microplastics to the Black Sea in 2050. This is 26% lower than in 2010 (Fig. 3). This reduction is only for point-source pollution (sewage systems).

In this future, the implementation of advanced technologies is assumed and could remove almost 95% of microplastics in the wastewater during treatment. As a result, fewer microplastics enter rivers from sewage systems. This illustrates that advanced treatment is effective to reduce future point-source pollution in the sea, but not diffuse-source pollution. However, increases in diffuse-source pollution are calculated for the Asian sub-basins and the upstream Danube (Figs. 4–5). This indicates that implementing advanced technologies will not be enough to reduce future sea pollution from those sub-basins. Many Asian rivers flowing into the Black Sea will export at least 10% more microplastics in 2050 than in 2010 (Figs. 4 and S1). Thus, the contribution of the Asian rivers in the total microplastic export to the sea is projected to increase up to 47% compared to the S_{BL} scenario (Fig. 3). Furthermore, the upstream sub-basin of the Danube will also export more microplastics to the sea in 2050 than in 2010 (Fig. 4). Increases in future microplastic exports are calculated for 17% of the drainage basin that will accommodate around 33% of the population in 2050 (Fig. 5). For the rest drainage area, we calculate decreases in microplastic exports to the sea (Figs. 4–5).

Diffuse sources will dominate in the sea pollution. In all sub-basins, at least two-thirds of microplastic exports to the sea are projected from diffuse sources mainly from macroplastics degradation (Fig. 4). For the total pollution level, diffuse sources are responsible for almost 90% of the microplastics in the sea (Fig. 3). This is a result of point-source reductions.

3.5. Lower plastic consumption for pollution reduction

We calculate a decrease of 40% in total river export of microplastics to the Black Sea between 2010 and 2050 in a scenario with less plastic consumption (S_{CONS}, Fig. 3). This reduction is for point- and diffuse-source pollution. A larger reduction effect is calculated for diffuse sources than for point sources (Fig. 3).

In this future, the "Zero Pollution Targets" are met for reducing plastic waste production, and additional policies are assumed to replace plastic products with plastic-free cosmetics, plastic-free detergents, and eco-friendly flooring materials (see Table 2 for examples). This will reduce *per capita* (micro)plastic consumption (Table 2). As a result, we calculate reductions in river export of microplastics between 2010 and 2050 for all sub-basins (Fig. 4). This indicates that decreased (micro) plastic consumption will be effective enough to reduce future sea pollution from all sub-basins to below the level of 2010. For the European rivers, reductions are above 30% for this period. For the Asian rivers, it is below 30% (Fig. 4). The contribution of the Asian rivers in total river export of microplastics to the Black Sea is projected at 41% in 2050 (Fig. 3). Over two-thirds of the population will live in sub-basins for which we calculate reductions of at least 30% in microplastic pollution (Fig. 5).

Point and diffuse sources will be important in this future. For some sub-basins, point sources will dominate in the sea pollution (*e.g.*, the northern part of the Black Sea). For other sub-basins, diffuse sources will dominate (*e.g.*, the upstream Danube, many sub-basins in Turkey and of the Don River, see Fig. 1 for locations). For the total river export from all 107 sub-basins, the share of point and diffuse sources is almost equal (Fig. 3).

3.6. Higher plastic collection for pollution reduction

We calculate a decrease of around 40% in total river export of microplastics to the Black Sea between 2010 and 2050 in a scenario with more plastic collection (S_{COLL}, Fig. 3). This reduction is only for diffuse-source pollution.

In the future, the collection rate of plastics will be at least 90% as inspired by the European environmental policies. As a result, the badly managed plastic waste is assumed to be zero. This will lead to fewer macroplastics in the environment and thus in rivers. Consequently, fewer microplastics from macroplastics degradation will be exported by rivers to the sea (Fig. 3). For over two-thirds of the sub-basin areas, we calculate reductions of at least 30% in river export of microplastics to the sea during 2010–2050 (Figs. 4–5). These areas will accommodate around two-thirds of the population in the drainage basin (Fig. 4). However, the contribution of the Asian rivers to sea pollution will be 35%, which is lower than in the S_{BL}, S_{WWT}, and S_{CONS} scenarios (Fig. 3). In contrast, the contribution of the upstream Danube sub-basin to sea pollution will be higher than in the S_{WWT}, and S_{CONS} scenarios (Fig. 4).

Point sources will dominate in sea pollution. Almost two-thirds of the total microplastic exports to the sea are projected from point sources (Fig. 3). This includes laundry fibres, PCP and car tyre wears from sewage systems. At the sub-basin scale, the points sources will contribute the dominant amounts of microplastics in rivers and thus in the sea. This holds for many sub-basins except for the upstream Danube (Figs. 3 and 4). For this sub-basin, the diffuse source (macroplastics degradation) will remain dominant.

Reduction effects between the S_{COLL} and S_{CONS} scenarios are similar. In this S_{COLL} scenario, all rivers are projected to export 1.7 kton of microplastics in 2050 (Fig. 3). This is almost the same amount as projected by the S_{CONS} scenario. The difference between the two scenarios is in the share of diffuse and point sources. Point sources dominate in S_{COLL} whereas both point and diffuse sources are important in S_{CONS} (Figs. 3–4). This difference is a result of the effects of reduction options. S_{COLL} focuses on more plastic collection affecting diffuse sources: more macroplastics collected, thus fewer microplastics in the sea. As a result, the share of diffuse sources is lower and the share of point sources is higher. In contrast, S_{CONS} focuses on *per capita* reduction in plastic consumption. This affects both point (fewer microplastics from laundry fibres, dust and PCP) and diffuse (fewer microplastics from macroplastics) sources.

3.7. The optimistic future for zero pollution

We calculate a decrease of 84% in total river export of microplastics to the Black Sea between 2010 and 2050 in this optimistic scenario

(S_{OPT}, Fig. 3). This reduction is for both point- and diffuse-source pollution.

In this future, we combine reductions options assumed in the scenarios of S_{WWT}, S_{CONS} and S_{COLL}. We assume that all those reduction options are implemented in all sub-basins by 2050. As a result, rivers are projected to export 0.4 kton of microplastics in 2050, which is much lower than in 2010 (Fig. 3). Reductions among sub-basin range from 70% to 93% for river export of microplastics during 2010–2050 except for the upstream Danube (Fig. 4). For the upstream Danube sub-basin, this reduction is >30%. Therefore, the share of this sub-basin to microplastic export by the Danube is calculated at 50% (Fig. 6). Most of the population will live in the sub-basins for which we calculate at least a 70% reduction in their river exports to the sea during 2010–2050 (Fig. 5).

Diffuse sources will be important contributors to sea pollution. Around two-thirds of microplastics in the sea will be from diffuse sources (Figs. 3 and 4). This also holds for almost all sub-basins (Fig. 4). In some sub-basins, half of the diffuse-source pollution will be from macroplastics degradation and a half from laundry fibres originated from untreated human waste (*e.g.*, the centre and east part). The upstream Danube will dominate by macroplastics degradation. This also holds for diffuse-source pollution in the Asian rivers (Fig. 4).

In this scenario, we show that implemented advanced technologies, reduced consumption and increased collection rates of plastics are effective in the reduction of future pollution. This holds for many sub-basins draining into the Black Sea. For the upstream Danube sub-basin, reduced consumption of plastics is more effective in pollution reduction (the S_{CONS} scenario) than the other options. This is because the treatment and collection rates are, today, already high in this sub-basin. Opportunities for future pollution reductions are in reducing the consumption rates of plastics. For the Asian rivers, both reduced consumption of and increased collection rates of plastics are effective to reduce future pollution to below the level of 2010 (the S_{CONS} and S_{COLL} scenario). Combing these reduction options with advanced wastewater treatment could technically lead to pollution reductions of >70% during 2010–2050. This illustrates including advanced technologies in future pollution control for the Black Sea region.

4. Discussion

4.1. Uncertainties and limitations

Our model integrates knowledge from different disciplines including hydrology, biogeochemistry, waste treatment and socio-economic aspects (see Section 2.1). The model aims at quantifying river export of microplastics by source and sub-basins. The model provides outputs in mass (*e.g.*, kg/year). The model allows for future analyses and exploring the effectiveness of management options to reduce river export of microplastics to the Black Sea. The model is applied to 107 sub-basins. All these aspects make the improved MARINA-Global model advantageous for the Black Sea compared to other existing models (Lebreton and Andrady, 2019; Lebreton et al., 2017; Meijer et al., 2019a).

As with any integrated model, our model has uncertainties in model inputs, approaches and scenario assumptions. Some model inputs were aggregated from existing datasets to sub-basins using population densities (Table 1). Other model inputs were directly taken from existing studies and were not sub-basin specific (Table S1). This may under-or overestimate the importance of microplastic retentions in the river systems and introduce uncertainties. However, our sensitivity analysis shows that our conclusions are not largely affected by uncertain model inputs (Fig. 1, Section 3.1).

Our modelling approach has limitations. For example, the approach does not account for some microplastic sources such as air-borne microplastics (Revell et al., 2021), ships (Kaptan et al., 2020), flows from the Mediterranean sea, nurdles from industries (Jiang et al., 2021), and agricultural films (Piehl et al., 2018). As a result, our microplastic pollution levels might be underestimated. The model calculates river exports of microplastics in mass (*e.g.*, kg/year). The model does not distinguish microplastic particles, different sizes and polymer types. These are the limitations of the model. On the other hand, our aim is to explore options to reduce future microplastic pollution in the sea from sewage systems (from cities) and mismanaged solid waste. We consider important sources of microplastics in sewage namely PCP, car tyre wears, fibres and household dust. Thus, our main conclusions are not affected by uncertainties associated with missing sources. Another limitation of our modelling approach is in the seasonal effects. Extreme events can increase the plastic mobilisation (Roebroek et al., 2021). Floods can bring microplastics from land to the Black Sea (Gündoğdu et al., 2018). Our study focuses on annual trends over the period of 2010–2050. Future studies could build on this and include the seasonal effects. Our modelling approach is based on existing approaches that were previously evaluated (Section 3.1). Our approach is for sub-basins, which is one of the strengths of our model, and fits the aim of our research.

We realize that our assumptions for the scenarios are uncertain. Nevertheless, we believe that the scenarios provide useful information for water pollution management. We aimed at exploring options to reduce future pollution. The scenario analysis approach, we used, is widely accepted for regional water pollution analyses (Lau et al., 2020; Lebreton and Andrady, 2019; Strokal et al., 2014; Wang et al., 2020; Yasin et al., 2010). Our scenarios should not be interpreted as reality. The scenarios show the technical feasibility of certain options to reduce pollution under global changes. Our scenarios are largely supported by existing policy ambitions (Table 2).

4.2. Comparison with other regions

The Black Sea is deep and semi-enclosed, accumulating pollutants over time (Slobodnik et al., 2017). Thus, pollutants stay insight of the sea for a longer period. This is different for the seas that are open and have regular circulations implying that pollutants move over time. Compared to the European seas (Schmidt et al., 2017), the rivers of the Black Sea region contribute around 20% to the European sea pollution (Table S5). This percentage is higher (around 45%) for the share of the Black Sea rivers in the Mediterranean sea pollution (Table S5). However, some rivers of the European sea region export fewer microplastics compared to the southern rivers of the Black Sea. For example, the Rhine and Po rivers in eastern Europe are calculated to export between 0.02 and 0.40 kton of microplastics to the coastal waters (Siegfried et al., 2017; van der Wal et al., 2015) (Table S5). Our southern rivers are calculated to export much more microplastics (0.84 kton) to the Black Sea in the year 2010 (Table S5).

Compared to other regions, rivers of the Black Sea region are not yet in the top of 20 most polluted rivers in the world (Jambeck et al., 2015; Lebreton et al., 2017; Meijer et al., 2021; Ryberg et al., 2019). Global estimates for microplastic pollution differ among studies (Boucher et al., 2017; Lebreton et al., 2017; Lechner et al., 2014; Ryberg et al., 2019; Sherrington et al., 2016) (Table S5). They suggest Asian rivers as the main contributors to global plastic pollution (Table S5). For example, the Asian Yangtze and Ganges rivers are estimated to export 330 kton and 120 kton of plastics to the seas, respectively (Lebreton et al., 2017). The Indonesian rivers are estimated to export from 13 kton to 39 kton of plastics to the sea (Lebreton et al., 2017). This is much higher than the total river export to the Black Sea in 2010 (2.6 kton, Fig. 3, Table S5). An important reason is that we focus on microplastic. Lebreton et al. (2017) focus on plastics including macroplastics. Therefore, our results are lower compared to the results of Lebreton et al. (2017). Other reasons are associated with the difference in population densities, waste management and environmental policies.

The Black Sea drain through two continents: Europe (*e.g.*, Danube River) and Asia (Figs. 1 and 3). This makes the drainage area of the Black Sea unique but challenges pollution reduction. This is because reduction options to clean the Black Sea will require efforts from both continents. Generally, pollution from the European rivers is expected to decrease in the coming years (Figs. 3–4) as a result of European policies (European Commission, 2021). It is the opposite of the Asian rivers (Figs. 3–4). These trends coincide with trends for nutrient pollution in the Black Sea (Grizzetti et al., 2021; Kovacs and Zavadsky, 2021; Strokal et al., 2014). Increasing trends in pollution are also modelled for the Asian rivers under global change with limited environmental policies (Lebreton and Andrady, 2019; Wang et al., 2020).

Large-scale studies are generally limited to the sources of microplastics in rivers worldwide (see also Section 1). van Wijnen et al. (2019) showed the importance of macroplastics (diffuse sources) for many rivers in the world. Siegfried et al. (2017) concluded the importance of car tyres in sea pollution with microplastics (point sources) for the European rivers. All this is in line with our findings for the Black Sea (Section 3). Other studies emphasized the importance of laundry fibres (Pojar et al., 2021). We distinguish between diffuse and point sources for laundry fibres. Both are important for the Black Sea (Fig. 2). In the future, the share of sources may change depending on reduction options (Figs. 3–5).

4.3. Implications for policy

Our results could support the formulation of effective policies for large transboundary rivers (Strokal, 2021). We focused on the rivers draining into the Black Sea (Fig. 1). Among the rivers, Danube (Hohenblum, 2015), Dnieper (Strokal, 2021; Strokal and Kovpak, 2021) and Don (Strokal and Kroeze, 2013) are transboundary draining through more than 20 countries. We show where (sub-basins) and what options are effective to reduce microplastic pollution in the Black Sea. For example, reducing the consumption of plastics in the upstream Danube sub-basin is effective to reduce microplastics pollution (S_{CONS} scenario, Fig. 3). For the other sub-basins of Danube, improving wastewater treatment (S_{WWTP}) and increasing the collection rates (S_{COLL}) are effective in pollution reduction. Our scenario analysis can serve as an example for other transboundary rivers in the world.

Cleaning the Black Sea requires coordination efforts from the European and Asian (*e.g.*, Turkey) countries. Our scenarios are inspired by the European Union policies (Section 2.2). We assume the implementation of such policies in non-European Union countries by 2050 (*e.g.*, The Russian Federation, Ukrainian and Turkey). We believe that it is possible considering the timeframe and economic developments. In fact, some non-European Union countries such as Ukraine show a strong wish to integrate the European Union policies in their national environmental legislations (Strokal, 2021). In addition, the countries may also have their own policies to reduce microplastic pollution. Examples are Turkey's policies about plastic waste import, zero waste, and landfilling (Gündoğdu and Walker, 2021; Senturk and Dumludag, 2021). These policies are aligned with the ambitions of the "Zero Pollution Target" European policy that is assumed in our scenarios. Thus, we believe that our assumed reduction options in the scenarios have the potential to be implemented in both European and Asian countries of the Black Sea region.

Our scenarios are largely based on existing European ambitions to support SDG. We incorporated the "Zero Pollution Target" for waste reduction (European Commission, 2021). This target aims to reduce 50% of plastic waste production by 2030. This target was incorporated into the S_{CONS} and S_{COLL} scenarios for 2050 (Table 2). We combined this target with other recycling and collection ambitions (EEA, 2019) (S_{COLL}) or with the use of plastic-free products (S_{CONS}, see Table 2). Our results show that it is possible to reduce around 40% of microplastics in the sea by 2050 in the S_{CONS} and S_{COLL} scenarios. The European target is to reduce microplastics in the environment by 30% by 2030 (European Commission, 2021). We show that it is technically possible for the Black Sea by 2050 when implementing reduction options for plastic consumption (at the source) or better collection (end-of-pipe). Combing these reduction options with better wastewater treatment will reduce microplastics by over 80% from most Asian and European rivers draining into the Black Sea (Fig. 3). This shows opportunities to reach zero pollution in the future.

Our scenario results can support SDGs 6 (clean water), 9 (sustainable innovation and infrastructure), 11 (sustainable cities) and 12 (responsible consumption and production). Achieving SDG targets is on the agendas of many countries (McGowan et al., 2019; Sachs et al., 2019; Strokal, 2021). Our model results can help to fill in the data gap for SDG indicators. For example, for SDG 6, indicators are pollution levels in microplastic export by rivers and their trends. These are model outputs (Section 2, Figs. 2–4). For the other SDGs, indicators could be based on model inputs (Table 2). For example, for SDG 9, indicators could be plastic waste collection rates that are modified for the S_{COLL} scenario in our study. For SDG 11, wastewater treatment efficiencies could form an indicator to reflect on sustainable cities (*e.g.*, S_{WWTP} scenario). For SDG 12, production or consumption rates of (micro)plastics *per capita* could be indicators (*e.g.*, S_{CONS} scenario, Table 2). Our scenarios contribute to the achievement of SDG 6 while also co-benefit other SDGs such as SDG 9 (S_{COLL}), 11 (S_{WWTP}), and 12 (S_{CONS}). This study can be an example for other pollution types such as eutrophication (van Puijenbroek et al., 2019; Wang et al., 2020), pharmaceuticals (Acuña et al., 2020), and pathogens (Vermeulen et al., 2019).

5. Conclusions

We explored options to reduce future river export of microplastics to the Black Sea. To this end, we developed five scenarios with different reduction options for the year 2050. B_{BL} is the baseline scenario assuming low population growth, moderate economic development and high urbanization rates (modified Shared Socioeconomic Pathway 2). The plastic waste management and treatment efficiencies follow the current trends. S_{WWTP}, S_{CONS}, S_{COLL} and S_{OPT} are alternative scenarios of the baseline scenario and assume improvements in the wastewater treatment (S_{WWTP}), reductions in the consumptions of plastics (S_{CONS}), better waste collection (S_{COLL}) and all together (S_{OPT}). We implemented those scenarios to a Model to Assess River Inputs of pollutaNts to seA (MARINA-Global) for 107 sub-basins draining into the Black Sea. We improved this model by adding microplastic retentions in rivers, hydrology (based on Representative Concentrative Pathway 2.6) and missing pollution sources. We ran the model for 2010 and 2050 for the five scenarios.

Model results show that European rivers are, today, responsible for over half of the annual microplastic export by rivers to the Black Sea. Both diffuse (*e.g.* macroplastics) and point (sewage systems) sources are important contributors to sea pollution. In 2050, Asian rivers are projected to be responsible for 34–46% of microplastics in the Black Sea depending on the scenario. In the baseline scenario (S_{BL}), river export of microplastics is projected to increase especially for the Asian rivers and the upstream Danube sub-basin. In the scenario with implemented advanced technologies (S_{WWTP}), river export of microplastics is projected to decrease during 2010–2050 from point sources, but not for all rivers. In the scenarios with reducing *per capita* microplastic consumption (S_{CONS}) or increased plastic collections (S_{COLL}), rivers will export 40% fewer microplastics to the sea in 2050 than in 2010. In the optimistic future (S_{OPT}), it is possible to reduce pollution by 84% when the abovementioned reduction options are combined. Reduction options affect the dominance of point (S_{COLL}), diffuse (S_{WWT} and S_{OPT}) or both (S_{BL} and S_{CONS}) sources in the future pollution. Our insights could support environmental policies to ensure a zero pollution future for the Black Sea.

CRediT authorship contribution statement

Vita Strokal: Methodology, Validation, Writing - Review & Editing, Project administration. Eke J. Kuiper: Conceptualization, Data collection & analysis, Methodology, Software, Writing - Original Draft. Mirjam P. Bak: Methodology, Writing - Review & Editing, Data collection & analysis. Paul Vriend: Writing - Review & Editing, Conceptualization. Mengru Wang: Writing - Review & Editing, Conceptualization. Jikke van Wijnen: Conceptualization, Methodology, Validation, Writing - Review & Editing. Maryna Strokal: Conceptualization, Methodology, Validation, Writing - Original Draft, Supervision, Visualisation, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare no conflicts of interest.

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Supplementary Material

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