Supporting Information

MANUSCRIPT TITLE: Global Riverine Plastic Outflows

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NO. OF TEXTS: 4

NO. OF TABLES: 7

NO. OF FIGURES: 7

NO. OF PAGES: 26

Text S1. Riverine plastic outflow versus riverine plastic input to the ocean

Plastic waste derived from land-based activities can be flushed into rivers via surface/subsurface runoff. In the journey to the ocean, plastic waste in rivers may partially be buried in the river bed through sedimentation, ingested by aquatic organisms, deposited along river shores, and inevitably fragmented to undetectable fine particles. The remaining portion eventually reaching the ocean is defined as riverine plastic input. On the other hand, the amount of riverine plastics measured at a specific sampling point is defined as riverine plastic outflow, which is obviously equal to riverine plastic input plus the amount of plastic waste lost during transport from the sampling point to the ocean. Riverine plastic outflow instead of riverine plastic input is used throughout the entire paper as the lost portion is not accounted for.

Text S2. The definition and calculation of Human Development Index (HDI)[1]

The Human Development Index (HDI) is a composite index focusing on three basic dimensions of human development: the ability to lead a long and healthy life, measured by life expectancy at birth; the ability to acquire knowledge, measured by mean years of schooling and expected years of schooling; and the ability to achieve a decent standard of living, measured by gross national income per capita.. The HDI is a broad measurement of human development that measures the average progress of a country from above three basic dimensions of human development.

Before calculating the HDI, an index has to be built for each dimension. To calculate the index of each dimension, the maximum and the minimum values have to be defined (Table S1). As a result, the index of each dimension will be a value between 0 and 1, by applying the following equation:

$$\text{Index of each dimension} = \frac{\text{Actual value-Minimum value}}{\text{Maximum value-Minimum value}} \quad (1)$$

The HDI can be calculated from the arithmetic mean value of these indexes of all three dimensions. The values of HDI and its parameters for each country/region can be found at http://hdr.undp.org/en/content/table-1-human-development-index-and-its-components-1.

Text S3. Overestimation of plastic outflows by MPW-based modeling: The case of Changjiang

The large difference in the estimated riverine plastic outflows of Changjiang is worth further discussion. Zhao et al.[2] conducted a sole sampling event in 2014 and obtained a number microplastic concentration of 4140±2460 particles m^{-3} with a size range of 60 μm–5 mm using 100 L of bulk water. This value was used to calculate the total plastic concentration in the MPW model, based on a particle microplastics to plastic debris ratio of 0.04 in oceans and rivers (size range of 0.3–5 mm using trawling nets).[3] In 2019, Zhao et al.[4] revised the number and mass concentrations to 45.4–123 particles m^{-3} and 0.033 mg $particle^{-1}$, respectively, upon completion of an extensive field sampling campaign at the Changjiang Estuary. Use of the conversion ratio (The mass ratio of microplastic to plastic debris is at a median of 2.2%) reported in our previous study[5] yields a mass concentration range of 68–186 mg m^{-3} for plastic debris in Changjiang, which are substantially lower than 40800 mg m^{-3} which was estimated by Lebreton et al.[3] It should be noted that Lebreton et al.[3] actually obtained substantially different correlation coefficients of field measured plastic riverine outflows with catchment characteristics (mass of MPW × riverine runoff discharge) with (0.999) and without (0.174) the Changjiang data point. This should also invalidate the measurement conducted by Zhao et al.[2] in 2014.

Text S4. Management of available plastic waste in China

Waste management has been substantially improved in the past decades. Herein, we take China as an example to illustrate the improvements in past ten years (only ten years data are available). Data of domestic waste generation and treating efficiency from 2003–2017 are provided by China Statistical Year Book (2004–2018).[6] Percent of plastic in the total solid waste is estimated to be 11%.[7] Plastic waste generation in China has increased dramatically in recent years. With rapid development of waste treatment facilities, the gap between waste generation and adequately treated amount is narrowing, resulting in a decrease on inadequately treated waste. This development was also confirmed by Geyer et al.,[8] who reported that the recycling and incineration rates in 2014 in China reached 25% and 30%, respectively, only lower than those in Europe (30% recycling rate and 40% incineration rate). Meanwhile, the global average recycling and incineration rates accounted for 18% and 24%, respectively, of all waste generated in 2014, which are lower than those in China.[8] The important development in China reflects the change of HDI value, which has increased from 0.502 (lower than the world average HDI of 0.598) in 1990 to 0.752 (higher than the world average HDI of 0.728) in 2017 (Figure S5).

Table S1. The Maximum and Minimum Values Used for HDI Calculation.[1]

dimension	Indicator	minimum	maximum
Health	Life expectancy (years)	20	85
Education	Expected years of schooling	0	18
	Mean years of schooling	0	15
Standard of living	Gross national income per capita (purchasing power parity dollars)	100	75,000

Note: This table was adopted from the Training Material for Producing National Human Development Reports (http://hdr.undp.org/sites/default/files/hdi_training.pdf) which was originally sourced from UNDP (2014), Technical Note 1. p.2 (http://hdr.undp.org/sites/default/files/hdr14_technical_notes.pdf).

Table S2. Conversion of Field Measured Plastic Concentrations in Rivers from Literature Studies

river	micro ($n\ m^{-3}$)	micro ($mg\ m^{-3}$)	macro ($n\ m^{-3}$)	macro ($mg\ m^{-3}$)	total ($mg\ m^{-3}$)
Patapsco	8.72	0.51	**0.61**	**72.6**	73.1
Patapsco	1.99	1.6	**0.139**	**16.6**	18.2
Patapsco	0.399	0.071	**0.0279**	**3.32**	3.39
Patapsco	0.886	0.54	**0.062**	**7.38**	7.92
Magothy	0.661	0.12	**0.0463**	**5.51**	5.63
Magothy	1.73	1.6	**0.121**	**14.4**	16
Magothy	0.369	0.18	**0.0258**	**3.07**	3.25
Magothy	0.24	0.035	**0.0168**	**2**	2.03
Rhode	0.249	0.023	**0.0174**	**2.07**	2.1
Rhode	0.88	0.37	**0.0616**	**7.33**	7.7
Rhode	0.546	0.063	**0.0382**	**4.55**	4.61
Rhode	0.124	0.021	**0.00868**	**1.03**	1.05
Corsica	0.617	0.13	**0.0432**	**5.14**	5.27
Corsica	0.364	0.077	**0.0255**	**3.03**	3.11
Corsica	0.0714	0.018	**0.005**	**0.595**	0.613
Corsica	0.0369	0.027	**0.00258**	**0.307**	0.334
Po	7.06	0.955	**0.494**	**59**	60
Po	14.3	3.2	**1.00**	**119**	123
Po	0.892	0.625	**0.062**	**7.43**	8.06
Po	0.797	0.467	**0.056**	**6.64**	7.11
Po	0.718	0.104	**0.05**	**5.98**	6.08
Po	0.307	0.050	**0.021**	**2.56**	2.61
Po	2.049	0.338	**0.143**	**17.07**	17.41
Po	0.096	0.285	**0.007**	**0.8**	1.09
Bio Bio	0.05	**0.0085**	**0.0035**	**0.417**	0.425
Maipo	0.647	**0.11**	**0.0453**	**5.39**	5.5
Maule	0.74	**0.126**	**0.0518**	**6.16**	6.29
Elqui	0.129	**0.0219**	**0.00903**	**1.07**	1.1
Ofanto	4.2	**0.714**	**0.294**	**35**	35.7
Rhine	5.5	**0.935**	**0.385**	**45.8**	46.8
Rhine	6.3	**1.07**	**0.441**	**52.5**	53.6
Rhine	5	**0.85**	**0.35**	**41.7**	42.5
Rhine	3.5	**0.595**	**0.245**	**29.2**	29.8
Yangtze	0.9	**0.153**	**0.063**	**7.5**	7.65
Delaware	1.24	**0.211**	**0.0868**	**10.3**	10.5
Delaware	0.62	**0.105**	**0.0434**	**5.16**	5.27
Tamar	0.04	**0.0068**	**0.0028**	**0.333**	0.34
Pasig	1.32	**0.225**	**0.0926**	**11**	11.2
Danube	0.823	9.8	0.12	1.1	10.9
Danube	0.04	2	0.015	0.2	2.2

Note: Average numerical (n m^{-3}) and mass (mg m^{-3}) concentrations of micro (< 5 mm) and macro (> 5 mm) plastics were reported in field studies. Macro plastic numerical concentrations in bold were derived from microplastic concentrations using a median ratio of 0.07 between macro and micro plastic particle numbers. Mass concentrations in bold were derived from the numerical concentration using median particle masses of 0.17 and 119 mg for micro and macro plastics, respectively. These median values are obtained from 53 records of both micro and macro plastics observed in rivers.[9-11] The converted total concentrations are median values, which used for model calibration.

Table S3. Field Studies Used for Model Calibration

reference	sampling site	Q (km^3 day^{-1})	PD (capita km^{-2})	SWG[12] (kg $capita^{-1}$ day^{-1})	P	median C[a] (mg m^{-3})	HDI[1]	M_{out} (kg day^{-1})
Mai et al.[5]	Humen	5.48E-02	849	0.43	11%	8.37	0.869	4.59E+02
	Jiaomen	5.18E-02	248	0.43	11%	4.93	0.869	2.56E+02
	Hongqimen	8.44E-02	233	0.43	11%	2.15	0.869	1.81E+02
	Hengmen	7.65E-02	149	0.43	11%	6.31	0.869	4.83E+02
	Modaomen	1.23E-01	157	0.43	11%	3.91	0.869	4.81E+02
	Jitimen	8.89E-03	154	0.43	11%	0.52	0.869	4.58E+00
	Hutiaomen	2.72E-02	153	0.43	11%	0.8	0.869	2.17E+01
	Yamen	6.72E-02	159	0.43	11%	6.35	0.869	4.27E+02
	Humen	7.07E-02	849	0.43	11%	58.4	0.869	4.13E+03
	Jiaomen	7.87E-02	248	0.43	11%	15.3	0.869	1.21E+03
	Hongqimen	3.99E-02	233	0.43	11%	5.44	0.869	2.17E+02
	Hengmen	5.62E-02	149	0.43	11%	28.9	0.869	1.63E+03
	Modaomen	1.08E-01	157	0.43	11%	5.95	0.869	6.41E+02
	Jitimen	1.58E-02	154	0.43	11%	0.72	0.869	1.13E+01
	Hutiaomen	1.40E-02	153	0.43	11%	0.18	0.869	2.54E+00
	Yamen	1.88E-02	159	0.43	11%	1.17	0.869	2.19E+01
	Humen	1.94E-01	849	0.43	11%	49	0.869	9.50E+03
	Jiaomen	2.16E-01	248	0.43	11%	8.7	0.869	1.88E+03
	Hongqimen	1.10E-01	233	0.43	11%	6.91	0.869	7.57E+02
	Hengmen	1.54E-01	149	0.43	11%	8.39	0.869	1.29E+03
	Modaomen	2.95E-01	157	0.43	11%	2.31	0.869	6.83E+02
	Jitimen	4.34E-02	154	0.43	11%	4.58	0.869	1.99E+02
	Hutiaomen	3.84E-02	153	0.43	11%	2.54	0.869	9.74E+01
	Yamen	5.15E-02	159	0.43	11%	11.5	0.869	5.74E+02
	Humen	1.76E-01	849	0.43	11%	15.7	0.869	2.76E+03

176		Jiaomen	1.96E-01	248	0.43	11%	18.4	0.869	3.62E+03
177		Hongqimen	9.96E-02	233	0.43	11%	3.74	0.869	3.73E+02
178		Hengmen	1.40E-01	149	0.43	11%	11.3	0.869	1.59E+03
179		Modaomen	2.69E-01	157	0.43	11%	35	0.869	9.39E+03
180		Jitimen	3.95E-02	154	0.43	11%	2.47	0.869	9.75E+01
181		Hutiaomen	3.49E-02	153	0.43	11%	1.97	0.869	6.87E+01
182		Yamen	4.68E-02	159	0.43	11%	12.6	0.869	5.90E+02
183		Humen	6.17E-02	849	0.43	11%	29.5	0.869	1.82E+03
184		Jiaomen	5.84E-02	248	0.43	11%	2.32	0.869	1.36E+02
185		Hongqimen	9.51E-02	233	0.43	11%	1.3	0.869	1.23E+02
186		Hengmen	8.62E-02	149	0.43	11%	6.15	0.869	5.30E+02
187		Modaomen	1.38E-01	157	0.43	11%	1.02	0.869	1.41E+02
188		Jitimen	1.00E-02	154	0.43	11%	1.54	0.869	1.54E+01
189		Hutiaomen	3.06E-02	153	0.43	11%	6.15	0.869	1.88E+02
190		Yamen	7.56E-02	159	0.43	11%	5.4	0.869	4.08E+02
191	Yonkos et al.[9]	Patapsco	3.93E-04	550	2.24	12%	7.76	0.93	3.07E+00
192		Patapsco	4.75E-04	550	2.24	12%	18.2	0.93	8.55E+00
193		Patapsco	6.06E-04	550	2.24	12%	3.39	0.93	2.06E+00
194		Patapsco	8.84E-04	550	2.24	12%	7.92	0.93	6.98E+00
195		Magothy	4.14E-05	351	2.24	12%	5.63	0.93	2.32E-01
196		Magothy	4.97E-05	351	2.24	12%	16	0.93	7.95E-01
197		Magothy	6.90E-05	351	2.24	12%	3.25	0.93	2.28E-01
198		Magothy	7.45E-05	351	2.24	12%	2.03	0.93	1.49E-01
199		Rhode	8.71E-06	64	2.24	12%	2.1	0.93	1.83E-02
200		Rhode	1.14E-05	64	2.24	12%	7.7	0.93	8.78E-02
201		Rhode	2.35E-05	64	2.24	12%	4.61	0.93	1.08E-01
202		Rhode	4.02E-05	64	2.24	12%	1.05	0.93	4.42E-02
203		Corsica	2.13E-05	36	2.24	12%	5.27	0.93	1.13E-01
204		Corsica	1.84E-05	36	2.24	12%	3.11	0.93	5.70E-02
205		Corsica	3.10E-05	36	2.24	12%	0.61	0.93	1.89E-02

	Corsica	4.56E-05	36	2.24	12%	0.33	0.93	1.50E-02
Vianello et al.[13]	Po River Delta	2.26E-01	226	1.12	6%	60	0.88	1.36E+04
	Po River Delta	2.26E-01	226	1.12	6%	123	0.88	2.78E+04
	Po River Delta	2.26E-01	226	1.12	6%	8.06	0.88	1.82E+03
	Po River Delta	2.26E-01	226	1.12	6%	7.11	0.88	1.61E+03
	Po River Delta	1.54E-01	226	1.12	6%	6.08	0.88	9.39E+02
	Po River Delta	1.54E-01	226	1.12	6%	2.61	0.88	4.02E+02
	Po River Delta	1.54E-01	226	1.12	6%	17.4	0.88	2.69E+03
	Po River Delta	1.54E-01	226	1.12	6%	1.09	0.88	1.68E+02
Rech et al.[14]	Bio Bio	8.24E-02	83	1.05	11%	0.43	0.843	3.50E+01
	Maipo	8.64E-03	467	1.05	11%	5.5	0.843	4.75E+01
	Maule	4.79E-02	41	1.05	11%	6.29	0.843	3.01E+02
	Elqui	8.64E-04	26	1.05	11%	1.1	0.843	9.47E-01
Campanale et al.[15]	Ofanto	1.30E-03	104	1.34	5%	35.7	0.88	4.63E+01
Mani et al.[16]	Rhine	1.91E-01	249	1.44	19%	46.8	0.931	8.91E+03
	Rhine	1.43E-01	249	1.44	19%	53.6	0.931	7.65E+03
	Rhine	2.21E-01	249	1.44	19%	42.5	0.931	9.39E+03
	Rhine	2.25E-01	249	1.44	19%	29.8	0.931	6.69E+03
Xiong et al.[17]	Yangtze	2.47E+00	312	0.43	11%	7.65	0.752	1.89E+04
Cohen et al.[18]	Delaware	2.74E-02	290	2.24	12%	10.5	0.924	2.89E+02
	Delaware	2.74E-02	290	2.24	12%	5.27	0.924	1.44E+02
Sadri et al.[19]	Tamar	8.50E-03	6	1.83	11%	0.34	0.939	2.89E+00
Deocaris et al.[20]	Pasig	1.81E-05	4038	0.34	14%	11.3	0.699	2.03E-01
Lechner et al.[21]	Danube	5.75E-01	113	0.69	12%	10.9	0.811	6.27E+03
	Danube	5.75E-01	113	0.69	12%	2.2	0.811	1.27E+03

Note: [a] Median plastic concentrations after sensitive analysis for uncertain factors.

Acronyms: Q: water discharge; PD: population density; SWG: solid waste generation; P: percent of plastic waste; C: Concentration of plastics; M_{out}: calculated plastic input.

Table S4. Data Sources for Various Parameters Used in the HDI Model

model parameter	data source
Water discharge (Q)	(n = 1,252) Milliman and Farnsworth[22]; (n = 266) Discharge data calculated from regression model in Figure S3
Population density (PD)	(n = 1,357) Schmidt et al.[23] and world population density increasing rate from 1960–2018 (World Bank); (n = 161) Average population density of the country (World Bank)
Plastic waste generation per capita (SWG × P)	(n = 1518) Kaza et al.[12] for solid waste generate and Jambeck et al.[7] for percent of plastics
HDI	United Nations Development Program (UNDP) 2018 update[1]

Note: SWG: solid waste generation; P: percent of plastics in SWG.

Table S5. Comparison of Field Measurements and HDI Model Estimates for Riverine Plastic Outflows

reference	river	region/country	measured outflow(s) (MT $year^{-1}$)	lower estimate (MT $year^{-1}$)	median estimate (MT $year^{-1}$)	upper estimate (MT $year^{-1}$)
Zhao et al.[4]	Changjiang	China	24,400–41,000	6750	17000	33600
Xiong et al.[17]	Changjiang	China	~18,900	6750	17000	33600
Mani et al.[24]	Rhine	Europe	~8160	178	1990	6210
Vianello et al.[13]	Po	Italy	~6120	43.5	330	892
Mai et al.[5]	Zhujiang	Asia	2,400–3,800	855	2160	4290
Lechner et al.[21]	Danube	Europe	~1,530	388	1470	3280
Rech et al.[14]	Maule	Chile	~301	4.25	22.4	53.9
Cohen et al.[18]	Delaware	the USA	~217	24	255	786
Faure et al.[25]	Rhône	Europe	~208	37.7	399	1230
Eo et al.[26]	Nakdong	Asia	193–301	16.2	153	446
Rech et al.[14]	Maipo	Chile	~47.5	20.5	107	260
Campanale et al.[15]	Ofanto	Italy	~46.3	0.076	0.57	1.52
Rech et al.[14]	BioBio	Chile	~35	12.4	63.7	154
Gasperi et al.[27]	Seine	France	27 (22–36)	13.5	124	357
Sadri et al.[19]	Tamar	England	~2.89	0.036	0.49	1.77
Rech et al.[14]	Elqui	Chile	~0.95	0.032	0.167	0.402

Deocaris et al.[20]	Pasig	the Philippines	0.2	5.6	11.8	21.9

Note: Measured outflows are calculated from data in the literature. For Seine River, an median annual outflow of 27 MT plastics was reported based on a six-year field monitoring campaign for floating debris from 2008 to 2013.[27] For Danube River, a daily plastic outflow of 4.2 MT was obtained based on three and four sampling events in 2010 and 2012, respectively.[21] A daily plastic outflow of 570 kg from the Rhône River to the Mediterranean Sea was acquired.[25] Only microplastic annual outflows (53.3–118 MT or 5.4–11 trillion particles) were reported for Nakdong River from field sampling in four seasons.[26] Annual outflows of meso-plastics from Nakdong River were estimated at 75–116 MT based on the outflows of microplastics and the conversion method established by Lebreton et al.,[3] resulting in annual plastic outflows of 193–301 MT from Nakdong River. Plastic outflows from Changjiang are converted from microplastic outflows based on the ratio of microplastics to plastics in Chinese waters.[28] For other rivers, the median values derived from the conversion in Table S1 are used for calculating the field-measured outflows. Some European rivers flowing through two or more countries, therefore, Europe is used for the region of these rivers.

Table S6. Comparison of the Median Estimates (MT year^{-1}) in Different Models for the Top Ten Rivers with the Highest Annual Riverine Plastic Outflows to Oceans

Schmidt model[23]				Lebreton model[3]			HDI model		
river	location	estimate 1 (MT year^{-1})	estimate 2 (MT year^{-1})	river	location	estimate (MT year^{-1})	river	location	estimate (MT year^{-1})
Changjiang	Asia	1540000	155000	Changjiang	Asia	333000	Changjiang	Asia	17000
Indus	Asia	176000	24400	Ganges	Asia	115000	Brahmaputra	Asia	10400
Huanghe	Asia	134000	19200	Xi	Asia	73900	Ganges	Asia	7880
Haihe	Asia	99400	14900	Huangpu	Asia	40800	Vaippar	Asia	6200
Nile	Africa	91800	14000	Cross	Africa	40300	Amazon	South America	5670
Bramaputra	Asia	79100	12300	Brantas	Asia	38900	Bekasi	Asia	3770
Zhujiang	Asia	57800	9400	Amazon	South America	38900	Vaigai	Asia	3630
Amur	Asia	42000	7140	Pasig	Asia	38800	Mekong	Asia	3400
Niger	Africa	38700	6650	Irrawaddy	Asia	35300	Irrawaddy	Asia	3230
Mekong	Asia	36800	6370	Solo	Asia	32500	Congo	Afria	2830

Table S7. Riverine Plastic Outflows from Different Continents

region	total discharge (km^3 $year^{-1}$)[22]	HDI[1]	population density (capita km^{-2})	lower estimate (MT yr^{-1})	median estimate (MT yr^{-1})	upper estimate (MT yr^{-1})
Asia	11000	0.74	100	43000	92800	173000
SA	10000	0.74	56	6860	17300	34300
NCA	4600	0.86	81	2290	9600	24800
Europe	4000	0.75	57	1040	7360	21000
Africa	2600	0.56	7	3730	6730	11100
Oceania	1100	0.86	5	303	628	1170

Note: Population density data are adopted from the World Bank 2018 at https://data.worldbank.org/. SA: South America; NCA: North and Central America.

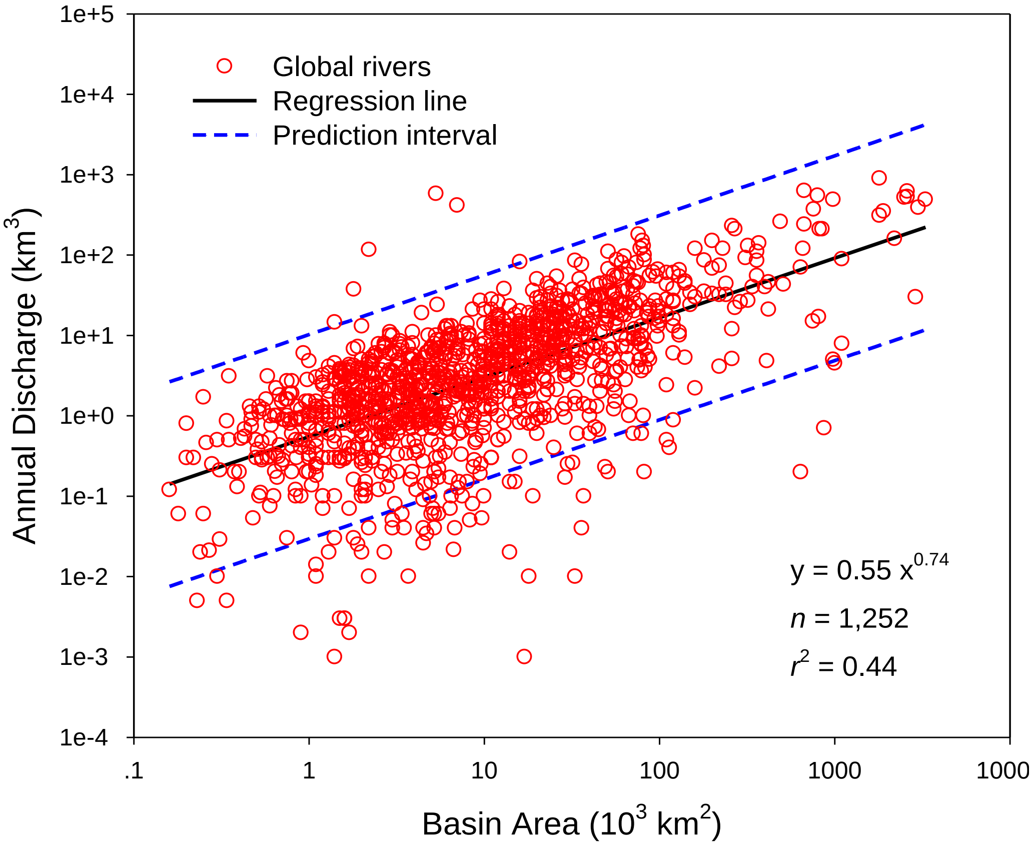

Figure S1. Correlations between the annual water discharge and basin areas from 1,252 rivers draining to global oceans. The data are derived from Milliman and Farnsworth[22]. The regression is shown as a solid black line and the prediction intervals shown as blue dash lines.

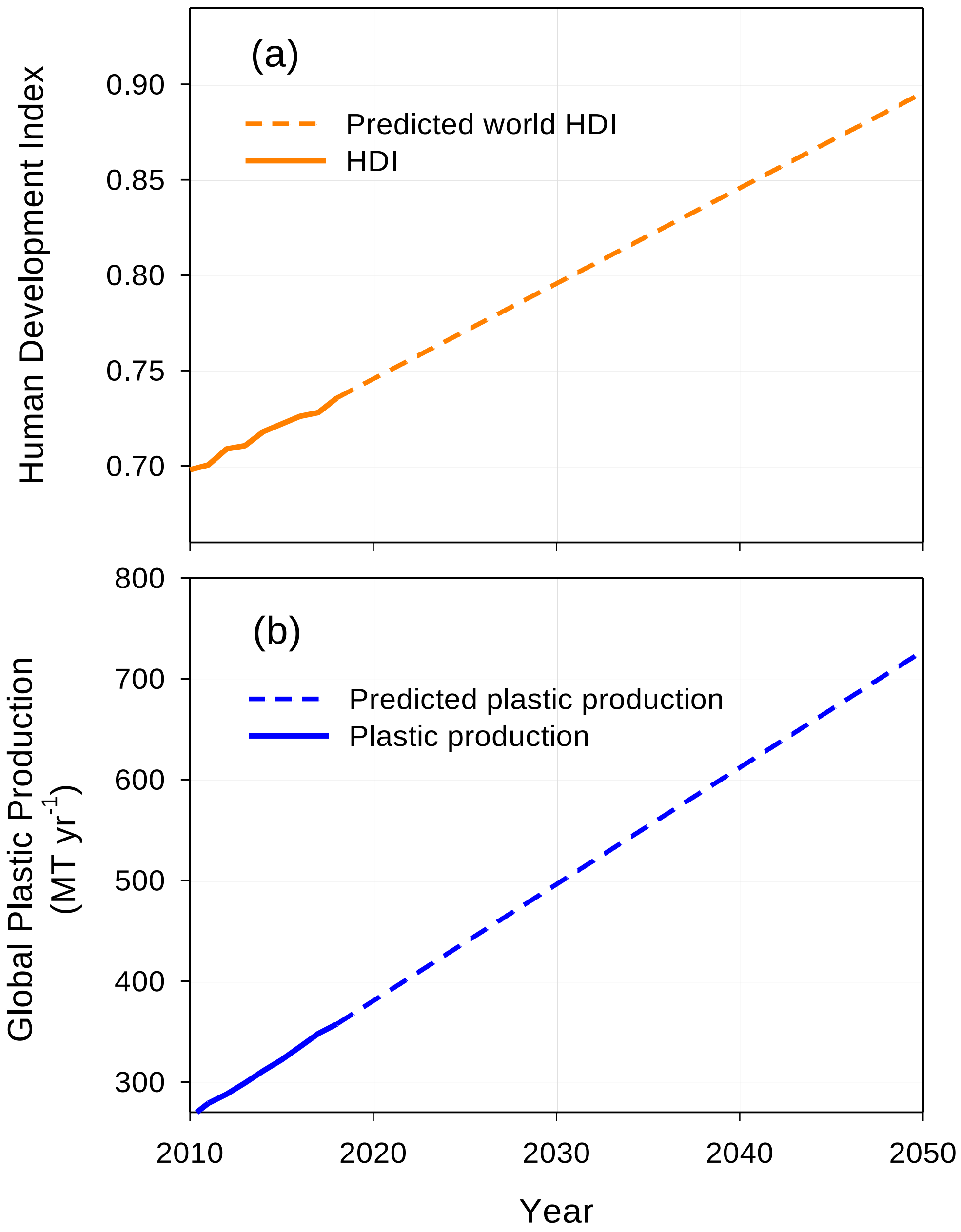

Figure S2. Temporal trends of global plastic production and world HDI from 2010 to 2050. (a) Changing HDI values from 2010 to 2018 are adopted from the United Nations Development Program (orange solid line) and predictions to 2050 (orange dash line) are assumed with the current increase rate. (b) Plastic production in the past years (blue solid line) is adopted from Plastic Europe[29-31] and predictions to 2050 (blue dash line) are programed under the current increase rate.

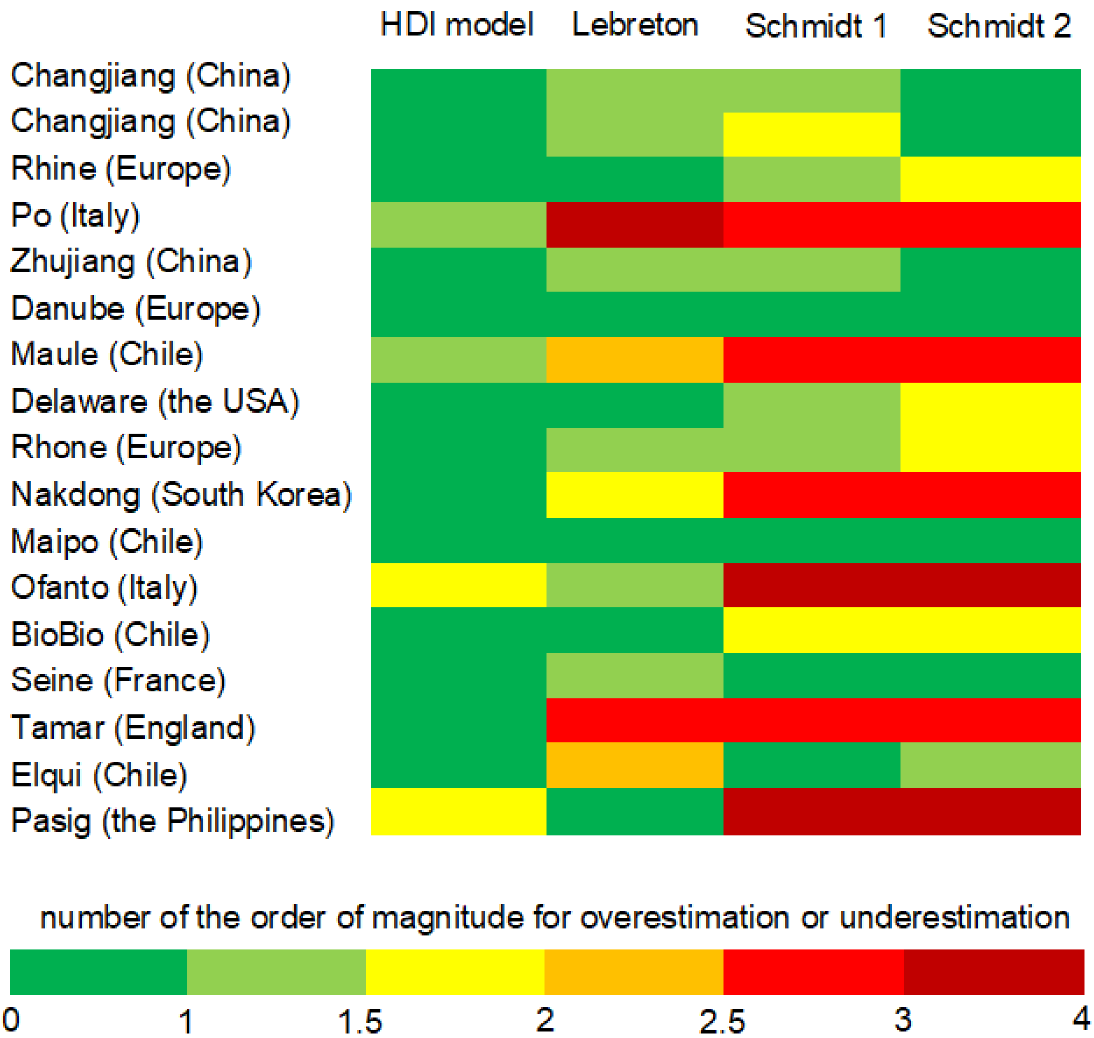

Figure S3. The over- or under-estimations by both HDI-based and MPW-based models against field measurements in observed rivers, presenting as the number of order of magnitude.

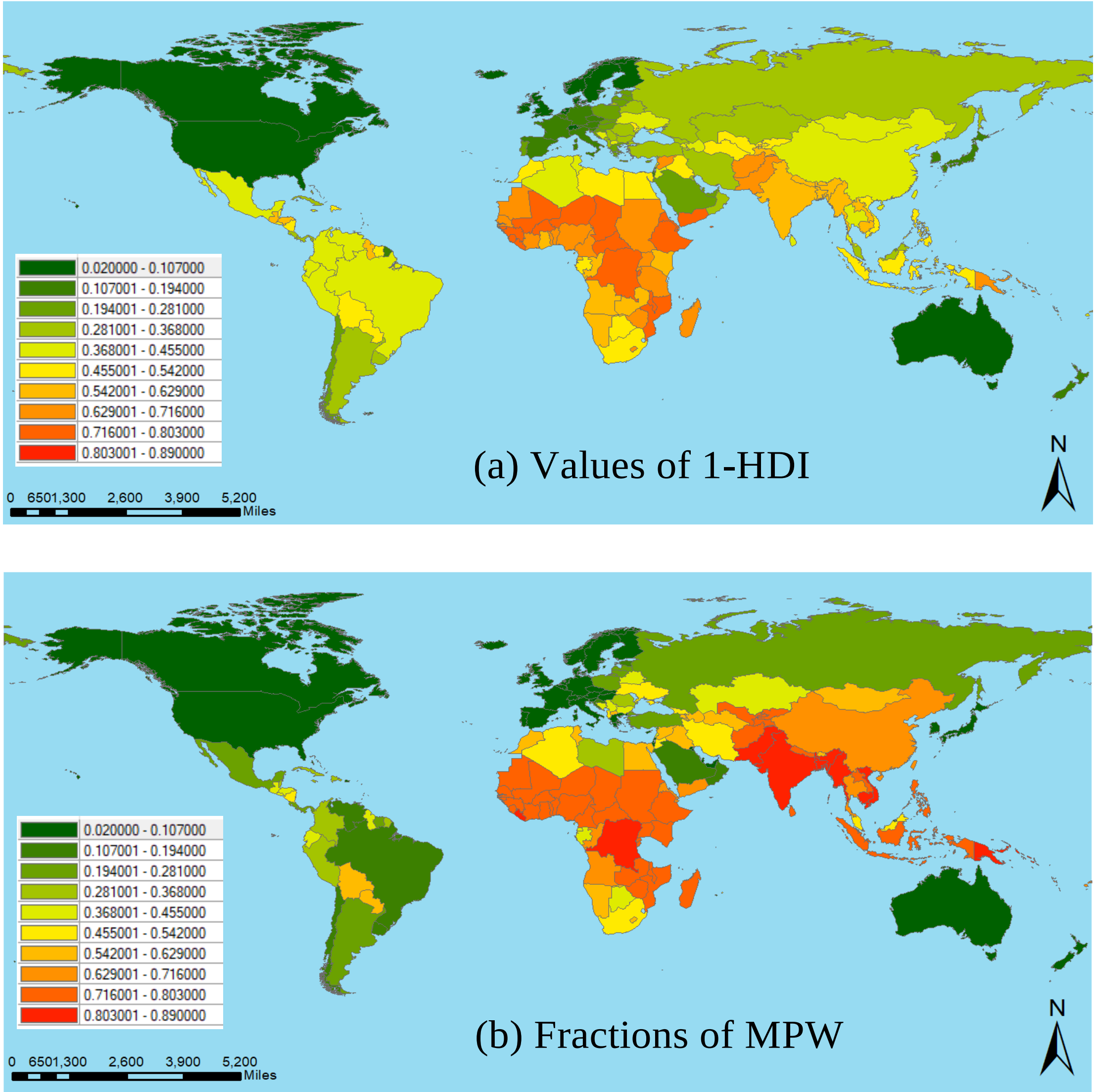

Figure S4. The spatial comparison between available plastic waste (APW) and mismanaged plastic waste (MPW), which is displayed as the (a) values of 1-HDI and (b) fractions of MPW.

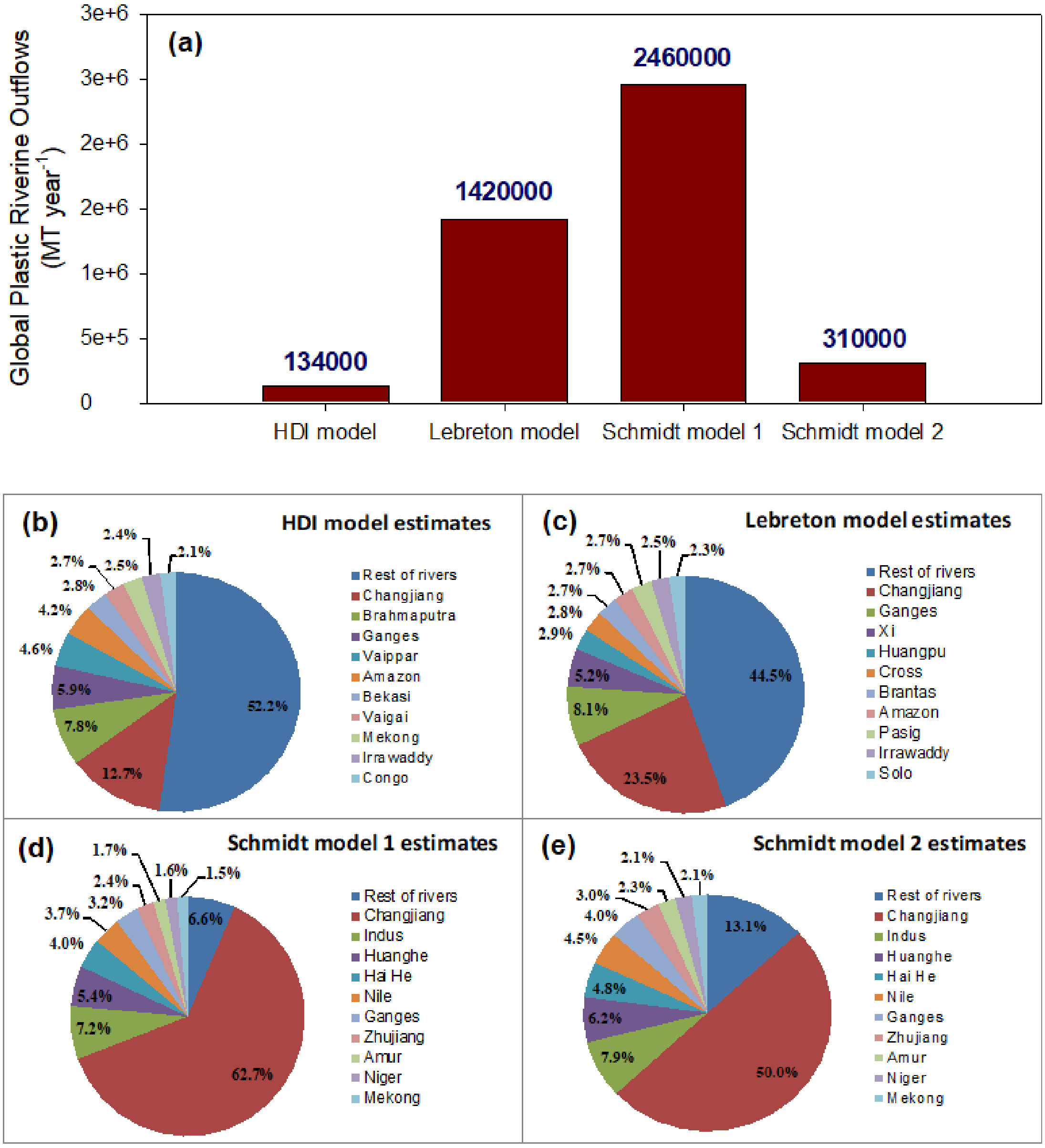

Figure S5. Global plastic riverine outflows in different model estimates. (a) Gross estimates of global rivers; and the share of top ten polluted rivers in the total global rivers estimated by (b) HDI model, (c) Lebreton model, (d) Schmidt model 1 and (e) Schmidt model 2.

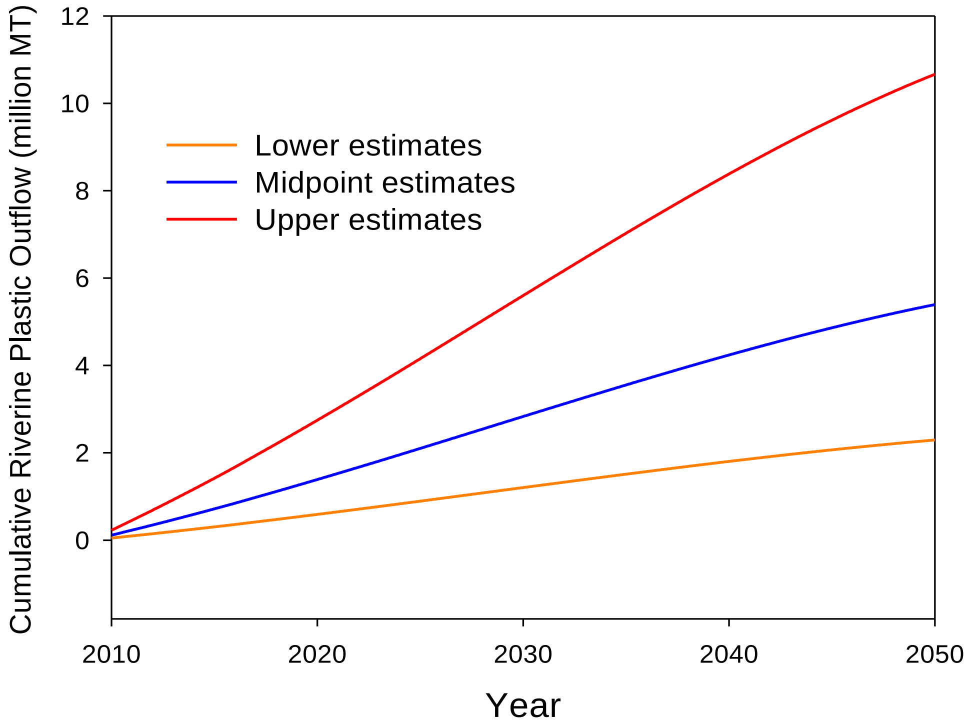

Figure S6. Estimated cumulative riverine plastic outflows (million metric tons (MT)) from 2010 to 2050. Lower, median, and upper values are derived from the estimated range presented in the main text.

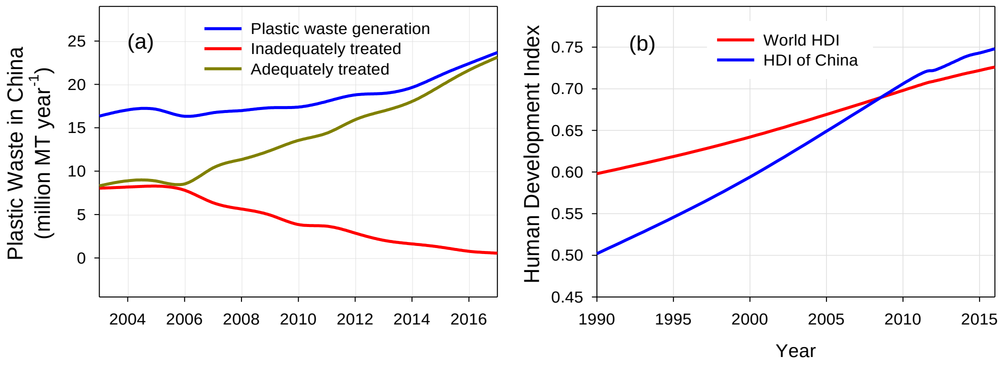

Figure S7. Temporal trends of plastic waste management and human development index (HDI) in China. (a) Plastic waste generation (blue line), adequately treated waste (brown line), and inadequately treated waste (red line). (b) World HDI (red line)[1] and HDI for China (blue line).

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