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Pacific Conservation Biology

Supplementary Material

Decision-science navigates trade-offs between environmental and socio-economic objectives for marine debris mitigation

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S1 Data preparation

Because the plastic transport model is based on a rasterized seascape, where movement is modelled from each individual cell to its neighboring cell in every time step, all data need to be prepared in a way that assigns spatial information on the source of plastic as well as value at destination sites to each individual cell. A fishnet grid that matched and aligned with the model resolution of ocean currents was created in ArcGIS, and all vector and point data was intersected with this grid to create quantitative data in each cell of the grid.

Location of source rivers

Raster data for the location of sources was based on modeled input from rivers (Lebreton et al., 2017). Coordinates at the location of the river mouths represented the over 80.000 individual rivers in the data set, and 7180 were located in the model domain. A limit of 65 tons per year in the mid or high estimates of debris load was used as a threshold as it is the capacity of some of the clean-up devices that are already operating in Thailand and India (personal communication with two project teams from Benioff). We assumed it to be unlikely that locations with the same cost of operation but lower efficacy would be chosen. After applying the threshold, 683 rivers remained in the model domain. In total, this subset of 683 rivers carries 700.000 tons between June and September, which is half of the 1.400.000 tons which are carried annually by all 40764 rivers in Lebreton's global dataset. All individual 8 x 8 km cells containing information on ocean currents (hereafter water cells) that contained a point of Lebreton's data set were assigned the modeled volume of debris from this river. If multiple rivers were located in one cell, their load was summed. The volume of debris from points that were located outside of the water cells were assigned manually to the nearest cell within the downstream estuary based on visual judgment on a topographic basemap in ArcMap. When an estuary was larger than one cell, volume was assigned to one cell in the middle of river mouths for any estuary under 100km width along the shoreline, and equally split across three points for estuaries wider than 100km, at left, center and right of the estuary along the shorline. This process resulted in 542 source cells for plastic debris in the 721 x 649 cells of the model domain.

Location of downstream receiving sites

Raster data for the location of habitats was based on available data on marine protected areas, coral reefs, and key biodiversity and bird areas. All cells along the shoreline were considered as a potential receiving location as well (Martin et al., 2020; Schernewski et al., 2020). To create the cell-based information, all vector files of habitat were first dissolved, and then unioned with each other to create a layer with one feature for each unique combination. This layer was then intersected with the fishnet grid. Individual units were assigned IDs based on the combination of habitat type in any 8 x 8 km cell and its direct neighbors. Cells at the border of the model domain were used to quantify the amount of debris that leaves the area. This process led to the designation of 4444 patches of one or more cells that could function as receiving sites for marine debris.

S2 Plastic transport model

Assessment of potential other hydrodynamic models and hydrodynamic parameters

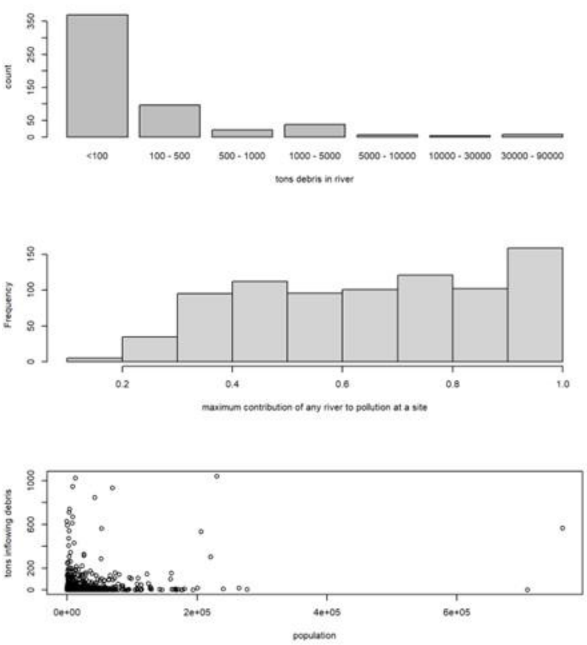
While our study primarily aims to provide a concise overview of necessary steps in the decision process, and the main linkages between the Structured Decision Making framework with the problem of site selection to remove plastic debris from sites to minimize negative impacts on a range of values, we have settled on a well-tested hydrodynamic model for which ready-made tools and workflows exist (see for example http://mgel.env.duke.edu/mget/ for creating connectivity output based on ocean currents within the ArcGIS software). However, if skill and expertise allow, alternative models can be selected for the best suitability for the seascape and scale of the region for which mitigation measures have to be assessed, or ensembles of a set of different models can be used to reduce uncertainty. Hydrodynamic models come in different resolutions, and with different inbuilt physical parameters that drive the modelled movement direction between the cells in a grid or mesh. See for example (van Sebille et al., 2020) as an overview of parameters that can be important when modeling movement of drifting plastic debris in different environments. Our study aimed to asses broad patterns within the larger seascape around the Coral Triangle, and a finer resolution than provided by the HYCOM model would be advisable in regional or even national decision making. We used a drift time of 60 days, however, there is no clear guidance on the most informative window of time for floating plastic debris, and studies with shorter as well as longer drift time exist (Critchell et al., 2015; van Sebille et al., 2020).

Network analysis and visualisation

In our network analysis, a node is any source river or downstream site of value, and an edge is any connection between any source river and downstream site of value. The weight of the edge in the visualization is calculated as the probability of this connection happening across all simulations, multiplied with the volume of plastic debris carried by the source river.

First the analysis identifies which connections exist, then it can be calculated how many rivers contribute to the total amount of inflowing debris at specific downstream sites, and which rivers are particularly important when the inflow needs to be reduced by a specific order of magnitude.
The available R-code on figshare (https://doi.org/10.6084/m9.figshare.26491714.v1) provides an annotated workflow that starts with tables generated by the transport model that provide the probability of transport from source river to downstream site of value, multiplies this probability with the volume of pollution in each river for each simulation, and calculates each metric described in Equations 1-4. The workflow ends with statistics for specific source rivers and downstream sites, as well as a shapefile that can be imported into GIS software to visualise the connections between source rivers and downstream sites of value as bendy arcs.

Figure S1: Summary statistics for all impact metrics. Panel A shows a histogram of volume in each river (Equation 4), panel B a histogram of total downstream pollution (Equation 3), panel C the volumetric impact at receiving sites (Equation 2), panel D the relative impact at receiving sites (Equation 1), and panel E the correlation between inflowing debris and population density at the receiving site.



S3 Parallel ranking of source rivers for all metrics

The parallel ranking (Table S2) reveals that rivers contributing the largest fraction of the pollution that impacts downstream sites (ranking highest for *total downstream impact across all receiving sites,* Table S2, column 3) did not rank high for other objectives. However, several rivers ranking high for high pollution at individual downstream sites (columns 7,9 and 11) also ranked high for multiple other objectives. Many of the 30 rivers carrying the highest volume of plastic debris impacted a large number of sites to a lesser degree but were not the main contributor of inflow for any of the most polluted sites (Tables S2 & S3). The rivers that carry a high load and also rank high for environmental or social impact can be further evaluated by comparing the different metrics on type and magnitude of impact to enable better judgment on the relative difference between the ranks (Annex S3). The selection of options to compare in more detail is to a certain degree subjective and depends on the values of the decision makers and the weight they want to give to specific objectives. For example, river #255 ranks only high for 6 out of 12 objectives, but if coral reefs seem to be of high value, the most important pollution source should be included in the more detailed assessment. River #298 is an example of a source that ranks high for many objectives and is not included for further detailed analysis because it appears consistently in lower ranks than rivers Song Hau (#95) and Irrawaddy (#29).

Table S1: Parallel ranking of river IDs for multiple objectives and metrics, enabling the identification of clean-up locations that would benefit multiple objectives. Each column shows the top 30 source river IDs for one metric, ranked from 1-30. Blue fields in heading highlight social objectives, green fields environmental objectives. Color code highlights the number of co-benefits, with darker colors for river IDs that rank high for several metrics. Bold text = high ranks for 8 out of 12 metrics, light green fields = high ranks for 9 out of 12 metrics, medium green fields = high ranks for 10 out of 12 metrics, dark green fields = high ranks for 11 out of 12 metrics. River 255 ranks only for 6 objectives, but is the most important source of pollution for coral reefs.

Rank	1: Eq_1: relative impact on downstream site [%]	2: Eq2: volumetric impact on downstream site [t]	3: Eq_3: total downstream impact across all sites [t]	4: Eq_4: impact at source / load in river [t]	5: Eq_{2a}: volumetric impact on downstream site [t], discounted for population	6: Eq_{1a}: relative impact on downstream site [%] discounted for population	7: Eq_{2b}: volumetric impact on most polluted downstream reefs	8: Eq_{2b}: volumetric impact on all downstream reefs	9: Eq_{2c}: volumetric impact on most polluted downstream Marine Protected Area	10: Eq_{2c}: volumetric impact on all downstream Marine Protected Areas	11: Eq_{2d}: volumetric impact on most polluted downstream Key Biodiversity Area	12: Eq_{2d}: volumetric impact on all downstream Key Biodiversity Areas
1	243	195	**196**	195	146	146	255	255	**197**	**197**	195	16
2	273	**196**	**197**	196	196	196	146	146	**15**	**15**	**196**	17
3	278	**197**	195	**197**	195	195	298	298	**196**	**196**	16	195
4	76	146	146	146	197	197	95	95	146	146	17	**196**
5	288	16	**15**	15	149	149	**126**	29	**123**	**123**	**15**	**15**

6	541	17	**255**	16	255	255	29	323	122	95	29	29
7	311	**15**	16	17	17	17	174	**126**	95	122	**208**	241
8	384	29	29	29	**208**	**208**	25	507	**126**	**126**	241	**208**
9	471	255	17	255	95	95	78	373	88	88	**223**	31
10	245	149	**208**	149	16	16	447	174	298	298	31	**223**
11	531	95	**123**	95	**15**	**15**	27	25	87	87	99	368
12	330	**208**	126	**208**	**123**	**123**	373	27	**208**	447	162	99
13	29	**123**	95	**123**	162	162	507	78	263	353	447	447
14	329	140	**162**	140	**223**	**223**	442	447	282	507	368	162
15	247	**126**	149	**126**	9	9	323	442	447	**208**	183	**197**
16	177	162	**223**	162	80	80	380	243	507	90	174	174
17	284	257	122	257	29	29	**223**	277	501	263	**123**	183
18	246	**223**	263	**223**	140	140	245	276	90	501	**197**	**123**
19	507	189	160	189	**126**	**126**	248	354	471	471	361	361
20	146	241	257	241	474	474	276	245	296	500	39	39
21	529	122	241	122	177	177	309	380	323	282	203	203
22	537	263	298	160	263	263	287	**223**	353	296	442	442
23	368	99	168	263	257	257	329	309	418	323	298	298
24	34	80	170	99	183	183	243	329	500	86	369	369
25	9	177	140	80	19	19	335	248	376	376	**146**	**146**
26	241	9	125	177	170	170	354	335	86	34	173	173
27	263	168	215	9	442	442	52	287	34	535	76	351
28	95	298	173	168	298	298	334	474	56	241	357	76
29	318	170	99	298	99	99	500	500	241	418	343	357
30	27	173	189	145	122	122	471	52	535	56	351	343

S4 Metrics for highly polluted sites and their sources of pollution

Many of the most polluted sites receive inflow from multiple rivers but seem to have one or few dominant sources (Table S2, column count of polluting sources and flows). Only some of the most polluted sites have either larger areas of environmental value or high population density (Table S2). Of the 542 potential sites within rivers available for site selection in our case study, only 32 contributed more than 100 tonnes to the accumulating plastic debris across all receiving sites. An inflow of debris was found for 4008 receiving sites, and the volume of plastic debris arriving at each site varied substantially. 1770 sites received less than 100 kg, and 2925 sites received less than 1 tonne of plastic debris. Only 703 sites received between 1 to 10 tons of plastic debris, 380 sites between 10 and 100 tonnes of pollution, 77 sites received between 100 and 1000 tonnes of plastic debris, and two sites received more than 1000 tonnes of plastic debris (Table S1, Table S2). Hundreds of sites received a large contribution of the incoming debris from one main source. Half of the 30 most polluted receiving sites did not contain any mapped areas of value, 14 of these located along the coastline, and one at the border of the modeled seascape. None of the 30 most polluted sites contained any reef, 13 contained key biodiversity areas, and 6 contained marine protected areas. The size of receiving sites in terms of the number of cells was not related to the volume of debris arriving, as a third of the 30 most polluted sites were single model cells. Sites with a high probability of receiving a large volume of debris were mostly sites in the direct vicinity of a source river. There was no correlation between the inflow of plastic debris to receiving sites and the coastal population density (Figure S1).

Table S2: Contextual information for some of the 30 receiving sites with the highest total inflow of plastic debris. Orange cells highlight variability in inflow (column *Flows*) from sources within the same estuary, dark blue cells highlight high social benefit from a smaller estuary, albeit stretched over a long area of coastline (*coast)* without any mapped reefs (*reef*), marine protected areas (*mpa*) or key biodiversity areas (*kba)*, all abbreviated info on habitat values in second last column. The full list of top 30 polluted sites is shown in table S1.

	Information on receiving site				**Information on main sources of pollution**				**Information on values**	
Rank Main source name	**Site ID**	**Site area [km^2]**	**Pollution at site [t]**	**Count of polluting sources**	**Main three sources**	**Fractions [t]**	**River load [t]**	**Flows [t]**	**Mapped ecological value and area [km^2]**	**People within 8 km vicinity**
1 Yangtze	675	6272	1041	101	196, 197, 195	0.36, 0.34, 0.24	82921, 82921, 82921	373, 355, 261	coast (6272 km^2)	230.609
2 Yangtze	647	2688	1023	42	196, 197, 195	0.36, 0.36, 0.26	82921, 82921, 82921	376, 373, 271	coast (99 km^2) mpa (67 km^2) coast + mpa (65 km^2) coast + bio (65 km^2) mpa + bio (5 km^2) coast + mpa + bio (91 km^2)	13.077
3 Yangtze	662	256	945	46	195, 196, 197	0.39, 0.36, 0.23	82921, 82921, 82921	371, 348, 224	bio (149 km^2)	8800
11 Modao-men Shidao	906	10.944	567	140	146, 149, 140	0.47, 0.17, 0.06	59003, 21698, 8440	268, 98, 38	coast (10.944 km^2)	763.172
17 Ganges	591	2624	404	16	197, 196, 195	0.67, 0.28, 0.03	82921, 82921, 82921	271, 119, 13	mpa (1870 km^2)	2575
19 Ganges	947	1792	325	27	15, 16, 13	0.49, 0.48, 0.01	35420, 35420 1915	160, 158, 4	coast (171 km^2) coast + mpa (3 km^2) coast + bio (274 km^2) coast + mpa + bio (<1 km^2)	25.794
20 Ganges	946	640	312	26	16, 15, 17	0.51, 0.47, 0.01	35420, 35420 35420	160, 147, 1	bio (442 km^2)	25.897
25 Modao-men Shidao	146	64	254	78	146, 145, 162	0.99, 0.00, 0.00	59003, 2775, 7622	252, 1, 0.1	coast (64 km^2)	1532
45 Bay of Manila	1256	1600	159	47	255 257 256	0.73, 0.19, 0.04	25992, 7314, 1798	117, 31, 7	coast (317 km^2) coast + reef (2 km^2) coast + mpa (<1 km^2) coast + bio (<1 km^2) coast + mpa + bio (<1 km^2)	28.715

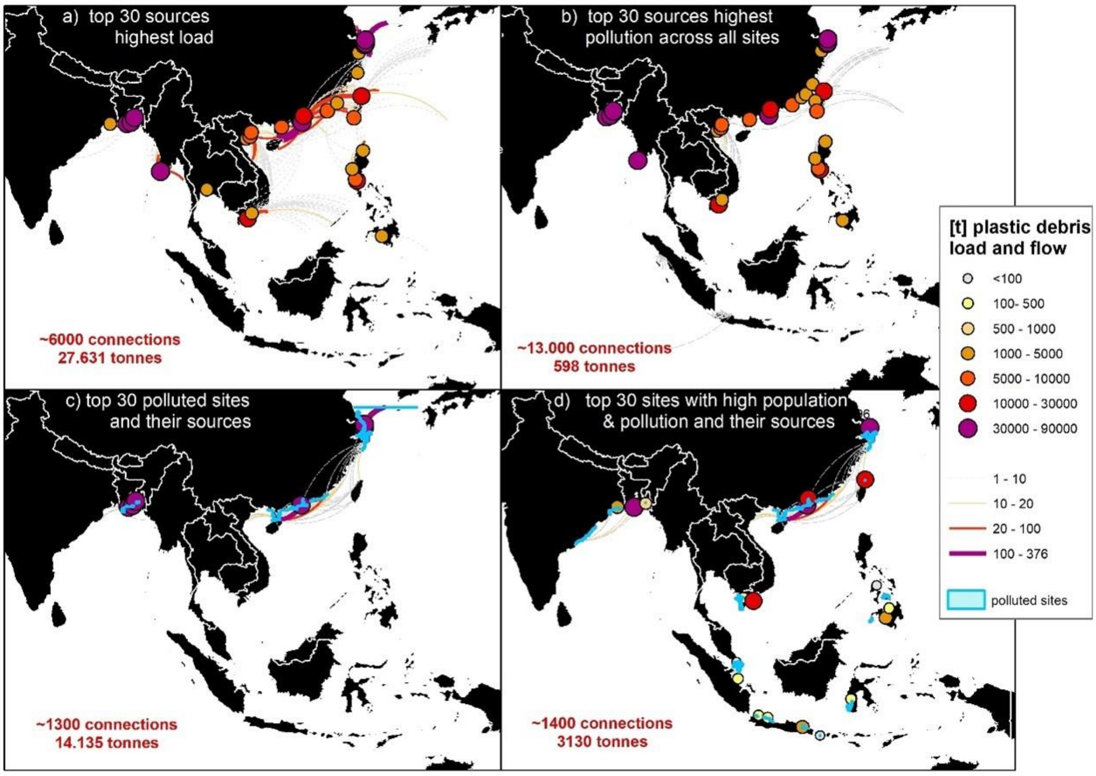


Figure S2: Top 30 sources of plastic debris from ranking for different objectives, with connections to downstream receiving sites. Volume at source (a), top sources regarding total downstream impact in volume across all sites (b), top sources regarding highest volumetric impact at the most polluted downstream sites (c), top sources regarding volumetric impact at most polluted downstream sites relative to population density (d).

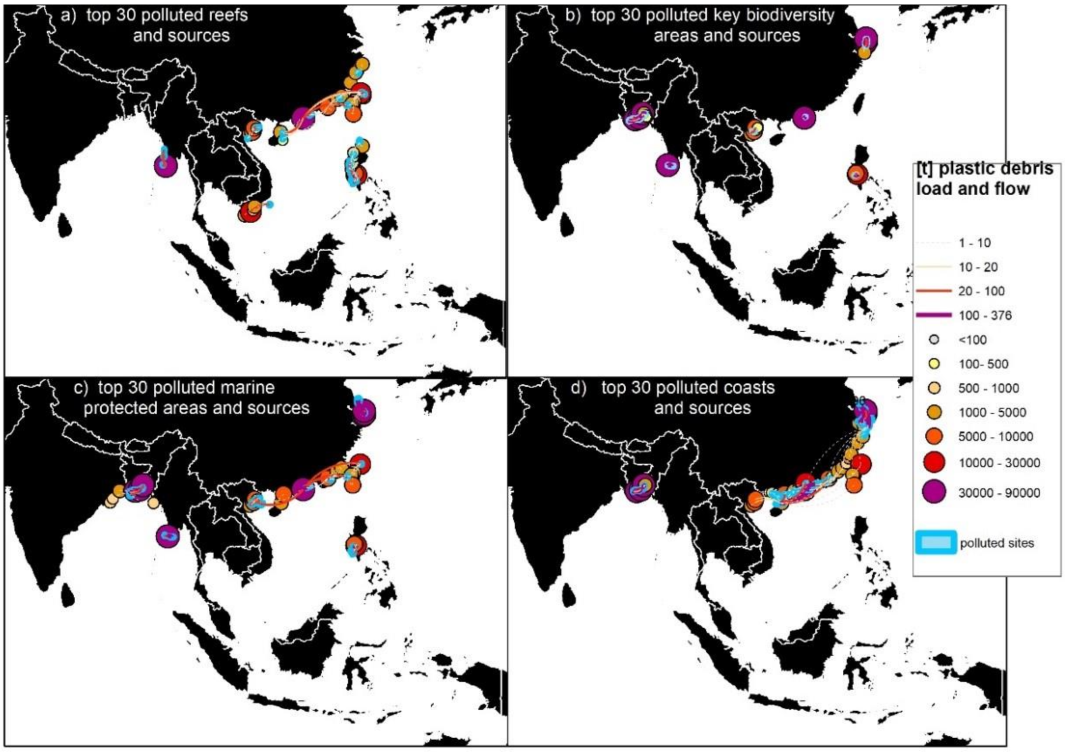


Figure S3: The top 30 most polluted sites for each ecological value and general coastline, with the main sources of pollution.

S5 Sensitivity of metrics to different model scenario settings

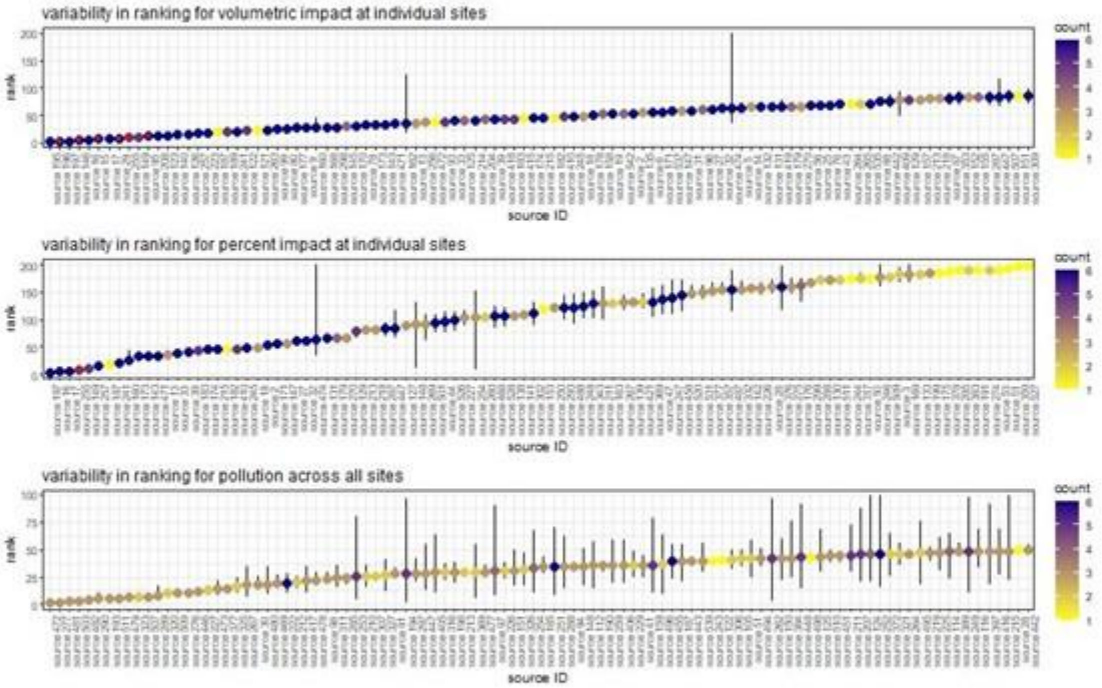


Figure S4: Variability in ranking in the first 100 ranks based on variability in the reduction of variability in reduction in volume of inflow (Equation 2, top panel, relative inflow (Equation 1, middle panel)) and variability in volume of debris in the source river (Equation 3, bottom panel), across 6 different scenarios (shallow and deep currents, high and average load of plastic debris in rivers, high and low settlement rates). A count of 6 indicates that a high rank is robust under the full range of parameters across all scenarios, while a count of 1 indicates that a source is only ranking among the top 100 under a narrow range of conditions. Error bars indicate the magnitude of variability in ranks across all scenarios.