ESA Discovery and Preparation – OSIP

Campaign on Remote Sensing of Plastic Marine Litter

PLASTIC MONITOR

Detecting riverine plastic conglomerations, fluxes and pathways in Indonesia

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Executive Summary

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Executive Summary

1 Introduction

Plastic litter pollution is a complex societal issue. Due to the extensive use and persistent nature of plastic, plastic litter can leak from a multitude of sources and, once in the environment, be subject to many physical processes that affect its distribution and fate. While intensive research and *in situ* monitoring efforts generate an immense amount of data on the quantities and composition of (marine) plastic pollution, data are still limited in capturing the complexity of factors at play. Estimations of plastic leakages and discharges into the marine environment present high degree of uncertainty, while concentrations of plastic in aquatic environments vary widely in time and space, which hinders baselining and clear trends to be derived.

Plastic in rivers remains understudied compared to marine plastics but interest and research in this domain are gaining momentum. Rivers constitute pathways of transport of plastic from land-based sources into the sea. In countries such as Indonesia, most inputs of marine plastic litter from land-based sources are discharged via rivers. For this reason, "Plastic Monitor" focused on riverine litter in Indonesia, a country that is considered one of the global hotspots of plastic pollution.

In the last few years, there has been a strong impetus within the scientific community to prospect the potential application of remote sensing (RS) to marine plastic litter. ESA's Discovery Campaign has been a strong catalyser in these efforts and there are clearly high expectations from society on what RS can deliver. Satellite detection of plastic litter, particularly in aquatic environments, is challenging because of the variety of plastics in terms of sizes, types and material properties, and the characteristics of the surrounding environment. Concentrations of plastic in aquatic bodies are very variable but tend to be generally too low to be captured by current satellite sensors. However, it is expected that sufficiently large plastic accumulations introduce spatial (and/or temporal) anomalies in receivers' signal.

2 Objectives of the project "Plastic Monitor"

"Plastic Monitor" (2021-2022) was one of the projects of ESA's Discovery Campaign on Remote Sensing of Plastic Marine Litter, funded by the Discovery Element of the ESA's Basic Activities. This project aimed at assessing the feasibility of detection of heavy plastic pollution loads in an Indonesian river by using satellite imagery and to demonstrate how RS can enhance the quantification and monitoring of plastic input into the marine environment.

The specific objectives of the project were to:

1. Characterize floating debris and plastic litter composition in accumulation patches in the Indonesian Citarum river;
2. Deploy time-lapse cameras over the river, and develop debris detection techniques to characterise fluxes of floating debris, and have additional field data to monitor the debris accumulations;
3. Analyse satellite imagery targeting known floating debris accumulation patches in the river, against known debris composition;

4. Discuss the potential of RS platforms in enhancing the knowledge of plastic pollution and particularly for policy formulation;
5. Provide recommendations for future satellite sensors tailored for detecting plastic pollution.

3 Study area and methodology

3.1 Study site

The project focused on the heavily polluted Indonesian Citarum river, in West Bandung regency, in West Java, where a riverine litter clean-up system by RiverRecycle initiative was deployed. The project intended to make use of this system as a way to accumulate large amounts of floating riverine debris in known locations in the river, while having access to sample these debris composition. The boom catchment system was installed near Cihampelas village and four study sites were defined for the data collection.

3.2 Methodology

The project collected two types of data, temporally aligned (Figure 1):

1. *In situ* data: sampling and characterization of riverine floating debris accumulations in four sites, complemented with time-lapse camera images deployed on the riverbank or from a bridge;

2. Earth Observation (EO) data targeting the four sites: from Copernicus' Sentinel-2, Sentinel-1 and commercial satellites WorldView-3 and ICEYE.

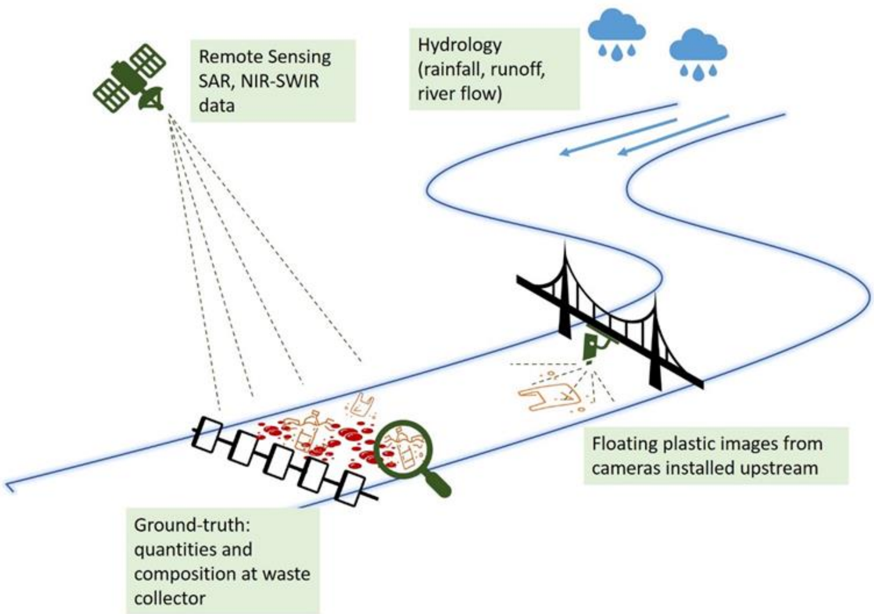

Figure 1 - Concept of "Plastic Monitor" experimental setup in the Indonesian river.

3.2.1 *In situ* litter sampling and time-lapse camera

In situ characterization of accumulated floating riverine debris was carried out from October 2021 until August 2022, to cover both the rainy season and the dry season. Sampling of debris was done in all four sites but in different days and time periods, due to local circumstances. Floating debris was semi-randomly collected by field operators, counted, (wet) weighted and classified in categories of materials and plastic types.

Time-lapse cameras were mounted in poles in Sites 1 and 3, pointed towards the river surface area (at a 45° angle to water surface) and suspended from a bridge in Site 2 (at a 30° angle to water surface). Images were geo-referenced and calibrated to cater for lens distortion. A prototype software was developed, using computer vision techniques and pixel-based detection to extract statistics on floating debris in Site 2. The software generates a video highlighting the debris passing through the selected zone in the frame, as well as statistics of the total number of debris items, total area (in pixels or areal units), maximum flux of debris items and maximum areal flux of debris items.

3.2.2 Satellite imagery analysis

The field data were compared to data from the main high-resolution Copernicus monitoring satellites, Sentinel-2 and Sentinel-1, to check their potential for plastic detection. Their resolution could be sufficient to detect large accumulations of floating matter, the periodicity of data acquisition enables planning of fieldwork, and they carry very accurate instruments.

Reflectances from Sentinel-2A and 2B multispectral instruments (MSI) were used to extract spectra from matchup and reference water and water hyacinth pixels. Various well-known indices were calculated, such as the Floating Debris Index (FDI, from Biermann et al., 2020[1]), and subsequently dynamic thresholding was tested for creating plastic litter maps. In addition, possibilities to use Sentinel-1 radar (SAR) in case of cloudy conditions, and WorldView-3 and ICEYE for higher resolution were explored.

4 Key results

4.1 Riverine debris composition

Plastic Monitor field observations reveal the prevalence of plastic litter in this part of the Citarum river, which constituted 74% of all the floating debris collected and analysed (from a total of 58,000 items sampled) (Figure 2). The composition results also provide evidence on how policies that target production and recycling influence how much plastic ends up and remains in the environment: the shares of PET[2] (e.g. plastic drink bottles) and HDPE[3] in total plastic abundance in all sites remain fairly low, since these are the types of plastic with highest recycling value and, as such, are intensively scavenged by the local waste pickers. Contrastingly, multi-layered plastics (which are massively used in Indonesia as single units packaging) and EPS[4] are difficult to recycle and therefore are not collected by waste pickers and represent the most abundant plastic types in the riverine study sites. EPS, also used abundantly in packaging, is a very lightweight and easily fragmented material. This may help

[1] Biermann et al., 2020. Sci. Rep. 10.
[2] Polyethylene therephtalate
[3] High density polyethylene
[4] Expanded polystyrene, "Styrofoam"

explaining the high proportion of EPS pieces found during the rainy period of the study (Figure 3) and suggests that better prevention and management of this type of waste is needed, even if EPS is partially banned in the Bandung regency since 2016. Interestingly, different plastic types also have slightly different spectral signatures. Thus, large seasonal and even regional differences in plastic litter composition could potentially be captured by RS.

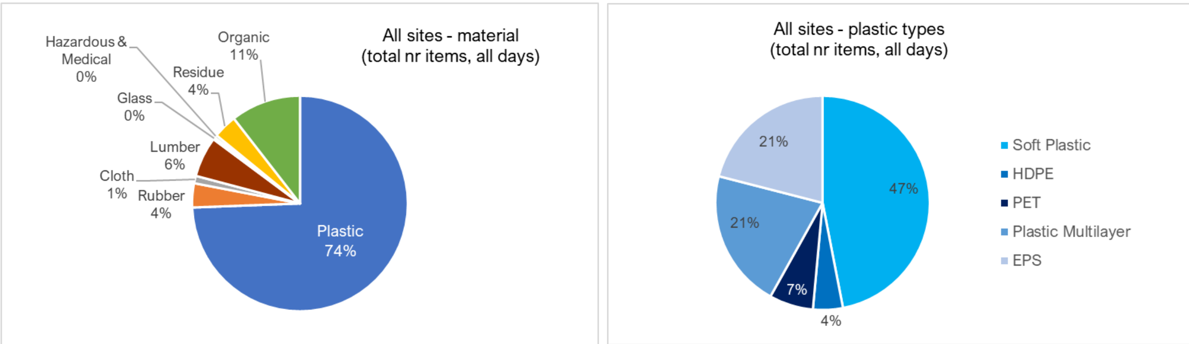

Figure 2 - Composition of riverine floating debris (left) and plastic types (right), collected between October 2021 and August 2022 (based on aggregated items collected in all four sites, total items sampled: 57,957). Note: the category "soft plastic" includes a mix of plastic items (e.g. bags) for which polymers were not determined.

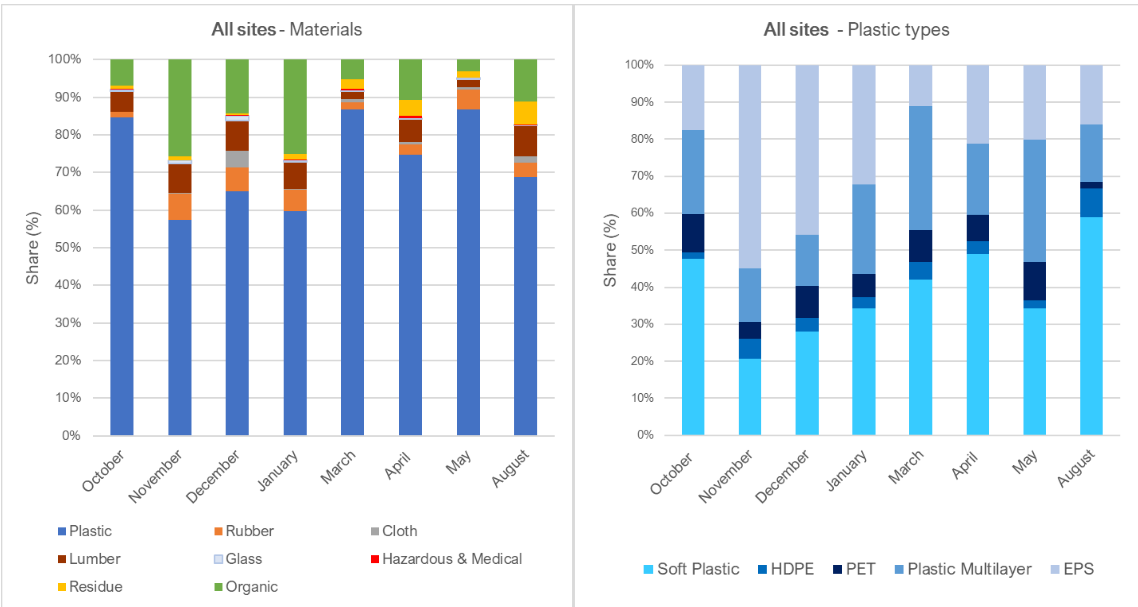

Figure 3 - Monthly variation in the share (%) of materials of riverine floating debris (left) and types of plastic (right), between October 2021 and August 2022 (based on aggregated total number of items collected in all four sites).

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4.2 Determining riverine fluxes with time-lapse camera

The application of the software prototype developed in Plastic Monitor reveals a very large variability in the fluxes of floating debris in this section of the river, within very short periods of time (see example in Figure 4).

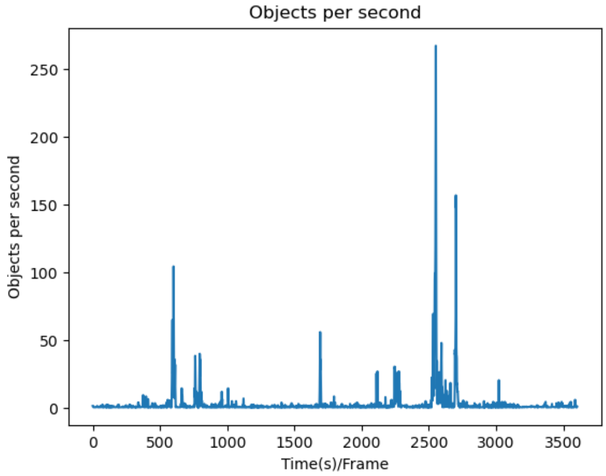

Figure 4 – Example of timeseries output from the software showing the high temporal variability of floating debris detected (image acquisition rate: one frame per second).

The automated detection by the software can, however, be affected by sunglint or very high river flow rates that exceed the frame rate of the camera. Nevertheless, this pixel-based method of detecting floating items is less labour-intensive in preparation than using segmentation and machine learning for classification, since no labelling of objects is needed. The prototype software developed is freely available[5] for further development and applications e.g. by citizen-science initiatives.

4.3 Capturing riverine plastics through earth observation (EO)

Information from monitoring satellites such as Sentinel-2 and Sentinel-1 is useful for generating inventories of relatively large accumulations of floating matter – with likelihood to contain litter - along global rivers or worldwide coastal areas. These satellites also enable to monitor significant changes over time, e.g. for large dumpsites and landfills. But can we use them to reliably identify floating plastic against a background of complex river water with other floating debris, and water hyacinth? We used thresholding on different spectral indices to map accumulations of floating debris, and floating plastic litter.

From mid-March to end of May 2022, debris was sampled from areas of 1 m^2 dimensions, in 10 replicates at different locations in and along the patch of the accumulated debris. For these "matchups", the pooled organic and pooled plastic components of the *in situ* samples were regressed against the normalised difference vegetation index (NDVI) and floating debris index (FDI) from Sentinel-2 L2A data (Figure 5). Correlation of the total organic items with NDVI is slightly higher than with FDI. Correlation of the total plastic items with FDI is slightly higher than with NDVI. The linear

[5] https://github.com/Deltares/plastic-monitor

models explain only a small percentage of the variation of the dependent variables. How to interpret these results? The scale between samples and EO is very different. Floating organic litter is not always healthy vegetation, some plastics are known to have high NDVI, and both organic and plastic items might be covered by dirt. The total amount of organic items is less than the total amount of floating debris items sampled. The correlation of the total plastic item with FDI is higher when the number of items is more than 100.

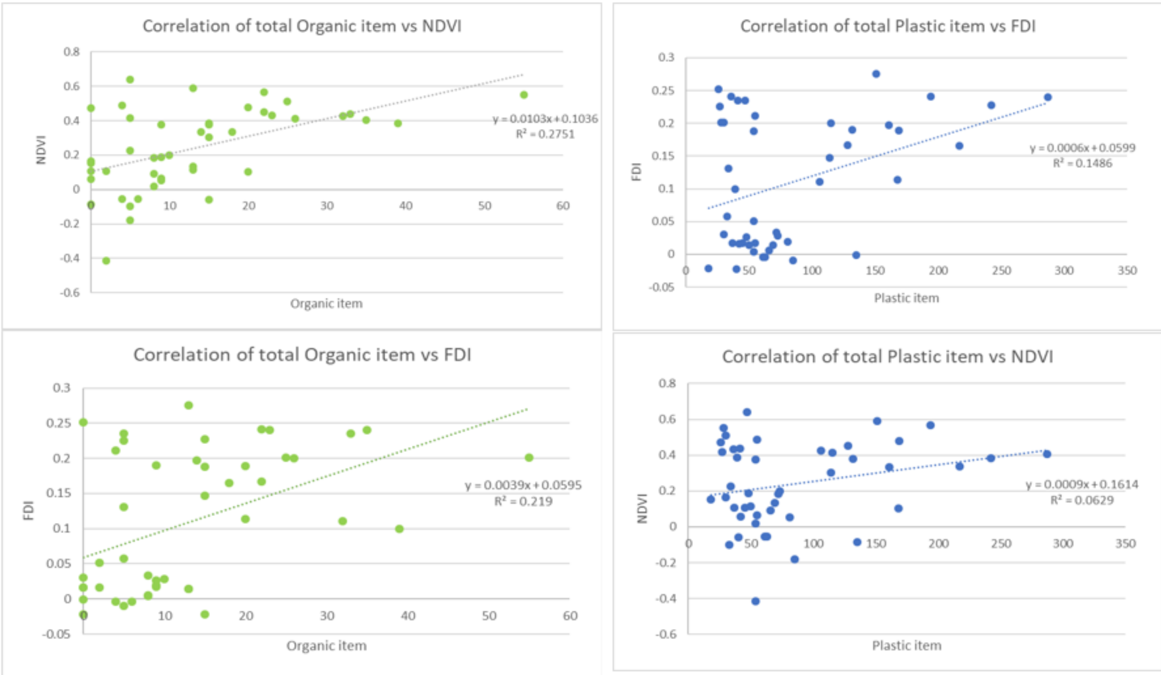

Figure 5 - Regression analysis of in situ organic and plastic items against the Earth Observation NDVI and FDI indices.

Spectra from river water and water hyacinths were also extracted from individual Sentinel-2 Level 2A images. Their FDI and NDVI values were plotted together with the FDI and NDVI of floating debris (plastic, and other floating objects). Figure 6 shows the extracted FDI and NDVI from different sampling days from mid-March to end of May 2022, and hence from images collected under different view angle, solar angle, atmospheric, weather and river conditions. Nevertheless, by grouping in the main classes, water, water hyacinth and floating debris can be discerned.

We also added data from August (orange and red dots) when we performed a controlled experiment, by using a 10 m x 10 m bamboo frame (covered in black cloth) containing mostly riverine plastic. Note that with a theoretical 100% plastic cover in the 10 m x 10 m frame, we would still have only max. 25% plastic coverage within the 20m x 20m pixel that we used for mapping. A plastic map for 22 August 2022 (Figure 7) also resulted from thresholding on NDVI and FDI.

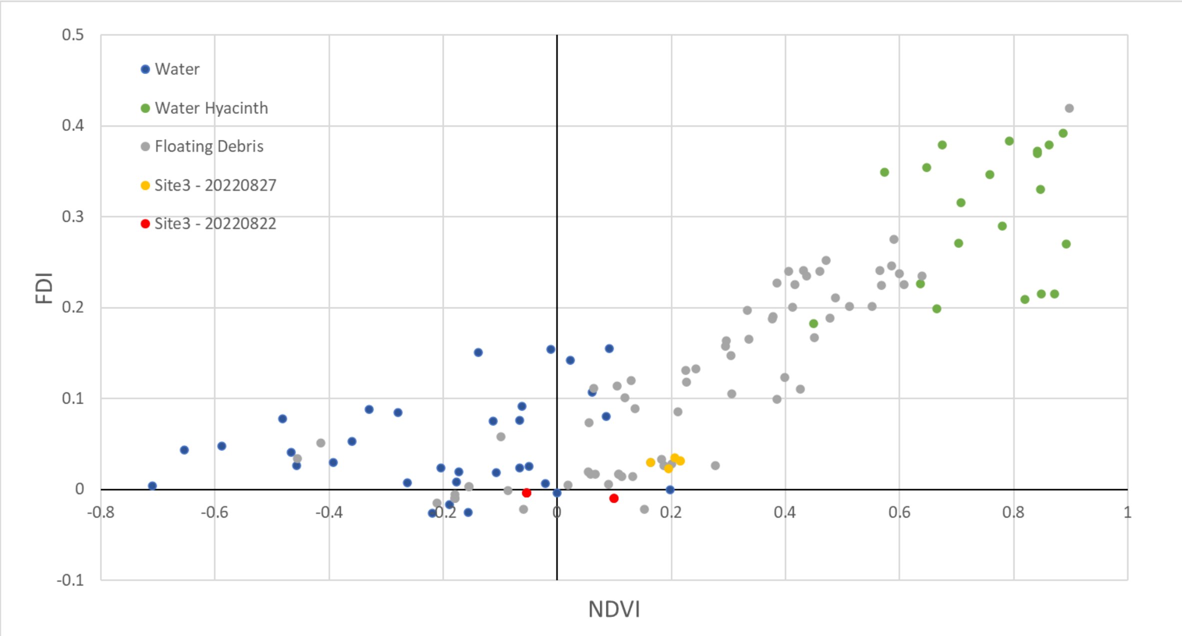

Figure 6 - Plotting Earth Observation vegetation and floating debris spectral indices for extracted points. Several points for Site 3 contained high concentrations of plastic within the manufactured 10 m x 10 m bamboo frame.

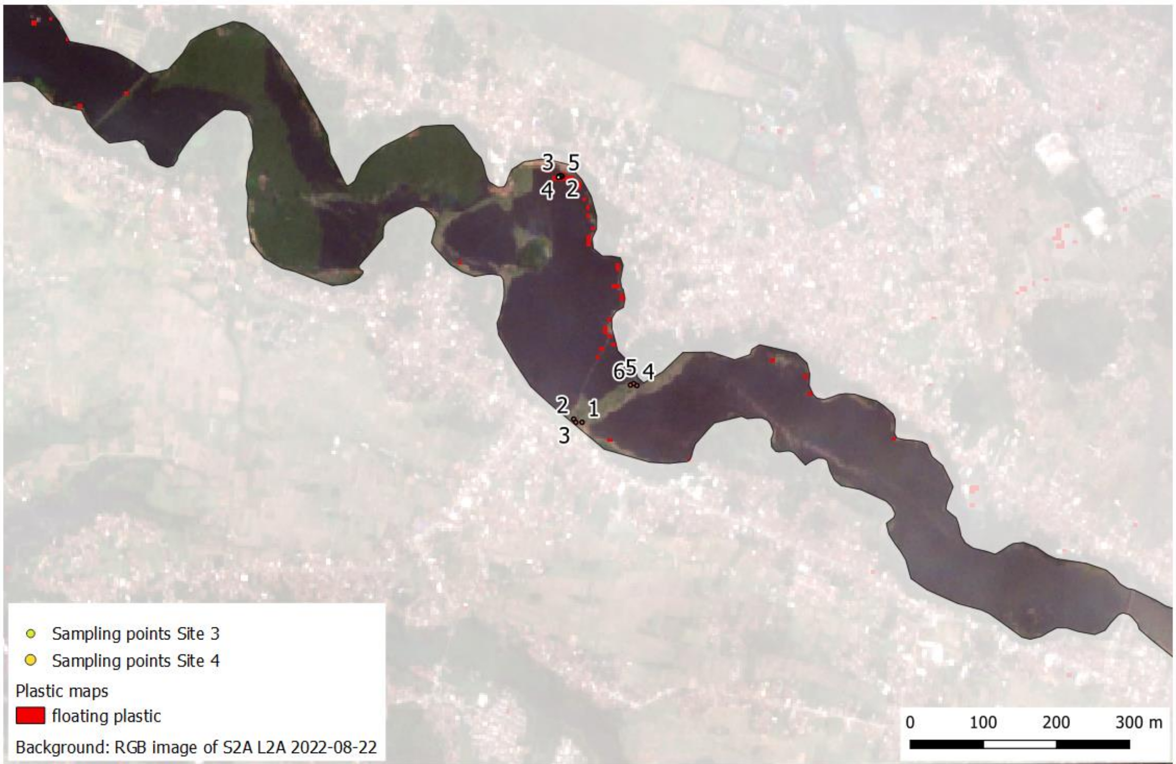

Figure 7 – Red areas indicate high concentrations of floating plastic from thresholding of indices derived from surface reflectance of Sentinel-2 L2A on 22-08-2022 (Source: Map contains modified Copernicus Sentinel data, 2022). The numbered points (2-5) indicate sampling in the frame and (1-6) indicates sampling points at an accumulation site with mixes of debris and water hyacinth.

Sentinel-1 images registered litter accumulation as high backscatter (Figure 8), but often in co-occurrence with water hyacinth in various densities. Our experiment with the frame enabled to concentrate plastic and exclude water hyacinth. High concentrations of riverine plastic inside this 10 m x 10 m frame, covered in black cloth, also scatter (Figure 9). Considerable efforts are still needed to investigate if it is possible to differentiate scattering from plastic, floating debris (including plastic), hyacinth, and hyacinth carrying plastic.

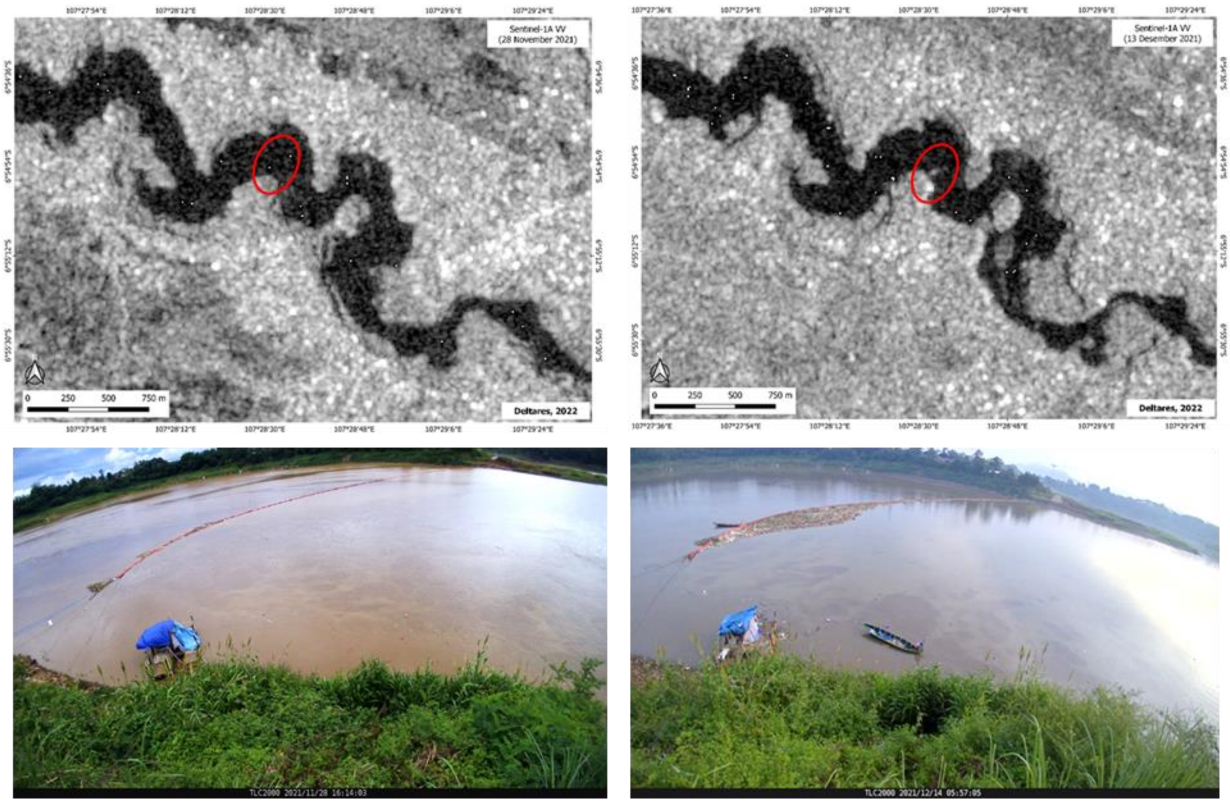

Figure 8 - Sentinel-1 IW GRD file, C-band SAR VV images of the radar backscatter coefficient (σ°) in decibels (dB) of 28-11-2021 (top left), and 13-12-2021 (top right). A red ellipse (top left) indicates the trash boom. (Source: Maps contain modified Copernicus Sentinel data, 2021). Images from the time-lapse camera at Site 1, (bottom left) showing absence of accumulated debris in the boom on 28-11-2021 and a (bottom right) patch of accumulated debris at the boom on 14-12-2021.

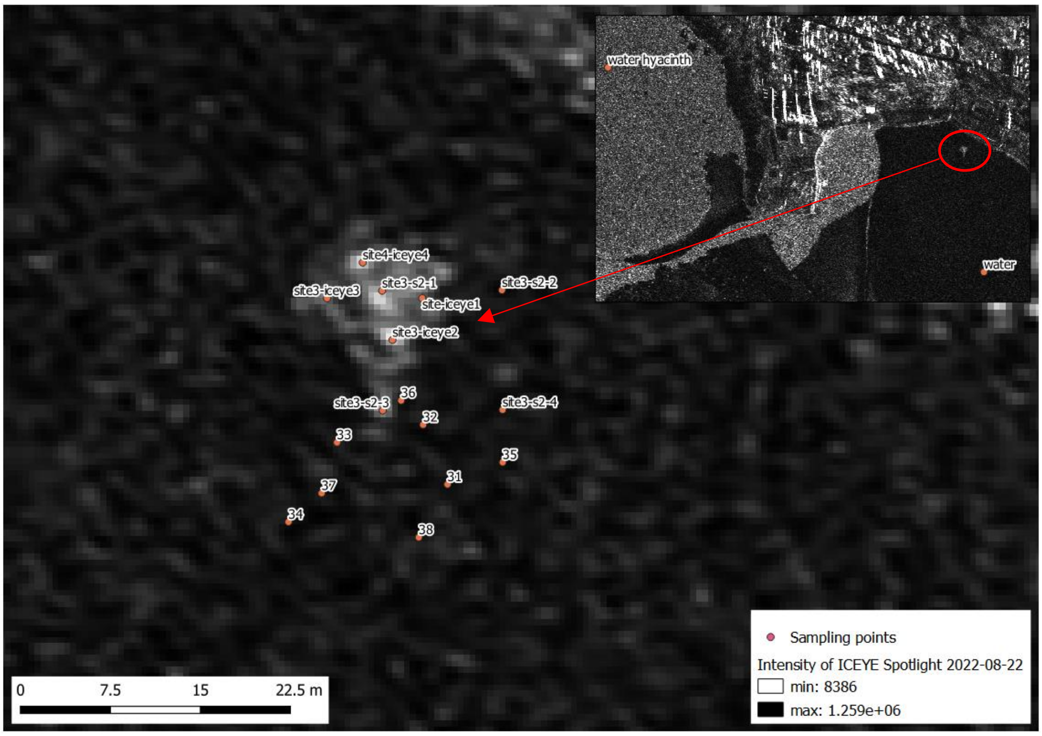

Figure 9 - Scatter from the cloth covered bamboo frame filled with riverine plastic in an ICEYE Spotlight file, X-band VV image of 22-08-2022 (Source: ICEYE).

5 Interfacing with policy - how RS can contribute to address key knowledge gaps

Different RS platforms have distinct applicability and limitations but can complement current *in situ* observations and assessment tools, and provide valuable data to fill in particular knowledge gaps on plastic pollution (Figure 10). Both remote sensing and *in situ* monitoring can benefit from cloud-based big data processing and virtual labs to analyse the data.

- Ground stations/platforms (for both optical and microwave-based sensors): continuous measurements and detailed data (e.g. individual floating litter items) but are limited in the area covered. High spatio-temporal resolution data can thus provide insight into important processes such as fluxes of floating plastic in rivers (as demonstrated in this project), dispersion and leakage of plastic from point sources, as well as the identification of most abundant types of litter in the targeted area.
- Airborne platforms as drones and planes (optical and microwave-based sensors): high spatial resolution, periodic measurements possible, flexibility in selecting the area of interest, fairly large area covered, although sometimes restricted. Can be applied to determine spatial patterns in terms of abundance of litter and even generic concentrations (e.g. qualitative assessments of state of pollution on coastlines). In the case of drones, similarly to ground platforms, detailed data on individual items can be generated.
- Satellites (optical and microwave-based sensors): wide coverage, suitable for large scale analysis but limited spatial resolution. Can therefore be applied to large accumulations of

floating litter/deposited at the land surface and not individual items. Examples of useful applications include the mapping of dumpsites (point sources of plastic litter).

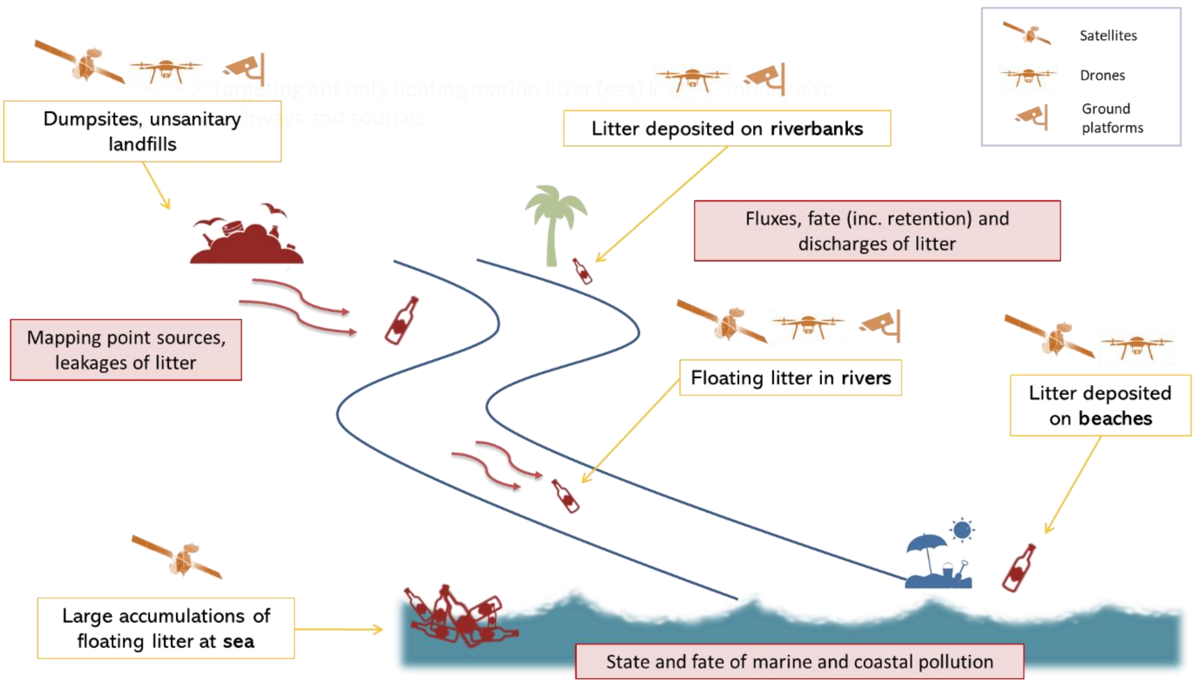

Figure 10 - Examples of targets for remote sensing platforms across land-rivers-sea to enhance knowledge of plastic pollution.

Applying these technologies to riverine litter may be particularly relevant for countries such as Indonesia, but also because rivers are connectors between the land and sea and constitute pathways of transport of land-generated marine plastic litter. Rivers are closer to land-sources and are unidirectional in flow. Therefore, measurements of plastic in rivers can better reflect the amounts of plastic waste that is leaking from land and possible changes in those leakages. In this sense, rivers can work as plastic leakage "sentinels" and allow to assess where policies are most needed and monitor whether measures are effective.

6 Concluding remarks and outlook on a future satellite sensor

The study showed that large accumulations, and a target containing high concentration of riverine plastic litter, can be detected by satellite. Clustering of the plastic and other debris class in the feature space of simple spectral indices gives some confidence that plastic, and mixtures with plastic, can be separated from other endmembers, but this remains to be tested along the river, as well as in different rivers. An immediate follow-up step would be to test the sensitivity of thresholding to the background.

Satellites with spectral band settings targeting the diagnostic plastic absorption bands, or hyperspectral satellites, with suitably high Signal-to-Noise-Ratio (SNR) and spatial resolution, could detect the presence of plastic accumulations down to a fraction of the area identified by the Ground

Sample Distance (GSD), provided of course the signal is not degraded by clouds, or aerosol and water vapour absorbance in the atmosphere. In water, or on land when wet, the diagnostic SWIR bands absorption signals get obscured by water absorption. The strength of the plastic signal for these bands depends on the SNR and percentage surface coverage by dry plastic in a pixel.

In the riverine environment, C-band and X-band microwave-based sensing show debris accumulations primarily as rough patches, also when they contain a very high fraction of plastic litter. For further analysis, capturing the dominant plastic scattering against various backgrounds, wave and current conditions is key for future inverse modelling.

6.1 Recommendations for future satellite sensing strategies

Multiple dedicated instruments on one platform, possibly in constellation with the Sentinel-2 or Sentinel-1 monitoring satellites, would be ideal for monitoring landfills, accumulations or hotspots of plastic litter in polluted rivers (and also coastal areas). Sentinel-2 and Sentinel-1 can provide detection of “anomalies” with likelihood to be debris accumulations, while the data processing of the multi-sensor platform (with high spatial and spectral resolution and SNR) could focus on such anomalies to limit processing resources.

If the SNR is sufficiently high, hyperspectral, or multispectral sensors with well-chosen narrow absorption and reference bands in visible, near-infrared and shortwave infrared, might work for detecting plastic in widely extended landfills and for large accumulations in rivers. Microwave-based sensors showed higher backscatter for debris and plastic compared to the river water surface (which is typically less affected by several tidal and wind waves than sea and ocean surfaces). Radar data provide the additional advantage to be less or not sensitive to cloud cover.

The concept of developing an integrated marine debris observing system (IMDOS), integrating *in situ* and remote sensing observations, and modelling has been described by Maximenko et al. (2019)[6]. We reiterate that a similar framework should be developed for monitoring riverine litter, including the interface with land (from which most plastic leakages originate), as well as integrating all the environmental domains in the continuum land-rivers-sea.

Acknowledgements

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[6] Maximenko et al., 2019. Front. Mar. Sci. 6