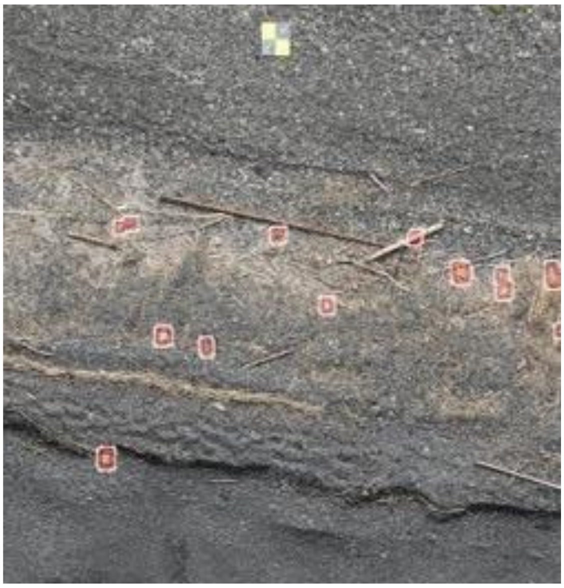
The Guidelines for Harmonizing Marine Litter Monitoring Methods Using Remote Sensing Technologies



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The Guidelines for Harmonizing Marine Litter Monitoring Methods Using Remote Sensing Technologies

Member of International Expert Meeting on Marine Litter Monitoring Methods by Using the Remote Sensing Technologies:

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Note that Annex and Appendix of ver.1.0 introduce beach litter monitoring survey using "UAVs (drones)", while ver.2.0 adds beach and litter monitoring survey using "stationary cameras" (see the table "Revision history of the guidelines" below).

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Experts and companies with experience in UAV litter surveys that cooperated in the inquiry survey conducted in the preparation of Annex Section I. Plan, preparation, and implementation of monitoring surveys for each remote sensing technology 1.1. Beach litter monitoring survey using UAV

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Revision history of guidelines

Version	Publication Date	Revised Part	Main Revisions
1.0	July 2024	-	Initial Release
2.0	July 2025	Main body	− Clarify the definition of remote sensing platforms in these guidelines (1.3) − Revise the scope covered by these guidelines (1.5 Table 3) − Add a table of sensors that can be mounted on satellites to detect litter (1.5 Table 4) − The evaluation of the technical maturity level (TRL) of monitoring methods: Changed from inclusion of the main text of the guidelines to reference material at a separate URL (Ministry of the Environment website) (3.1) − Added a column titled “Current Status and Future Prospects of Marine Litter Monitoring Using Satellites” (3.2) − Added content regarding the sharing of datasets for AI machine learning in image analysis and the collection of continuous learning data using applications (3.2)
		Annex	− Added item of “Data needed for quantification of beach litter Record” regarding UAV-based beach litter monitroing (1.1) − Added a part “Beach litter monitoring survey using stationary camrera” (1.2) − Added a part “River litter monitoring survey using stationary camrera” (1.3) − Expanded content on image analysis (2.1)
		Appendix	− Add Appendix 2 “Result of demonstration test for beach litter survey using stationary camera” − Add Appendix 3 “Result of demonstration test for river litter survey using stationary camera”

* For details of the revisions, refer to the “Comparison table”.

CONTENTS

The Guidelines ver.2.0

Chapter I Introduction

1.1 Background

There is a growing international interest in addressing marine litter, including plastics, and discussions are underway at the Intergovernmental Negotiating Committee (INC) on the creation of an international legally binding instrument to end plastic pollution. Under these circumstances, the need for monitoring is emphasized as a means of establishing scientific knowledge to serve as a basis for planning and assessing countermeasures, and the establishment of research/monitoring methods that enable continuous and efficient monitoring over wide areas is essential. Therefore, in order to further improve the comprehensiveness and efficiency of marine litter monitoring, we have developed new international guidelines for marine litter monitoring and image analysis methods using remote sensing technology. Such technology has been increasingly studied in recent years, and relevant knowledge and experience are being accumulated (see Table 1).

Table 1. Number of major studies on marine litter monitoring using remote sensing technology (Kako et al. 2025, draft paper).

Fields	Data Acquisition Methods (Remote Sensing)							Image Analysis Methods			
	Platform							Manual (Visual)	Automatic		
	Stationary camera	UAV*1	Balloon	Aircraft	Satellite	Vessel	Others		Object Detection by Bounding Box	Semantic Segmentation	Others
	Sensor										
	RGB	RGB	RGB	Multispectral/Hyperspectral, LIDAR	Multispectral/Hyperspectral	RGB, LIDAR					
Beach (Dune)*2	3	22 (7)	2	2				13 (2)	6 (1)	6 (2)	10 (2)
Sea Surface		7	1	5	10		1	8	1		14
Estuary Surface											
Riverbank/Lake Beach	1	1						1	1		1
River Surface	2	6					1	4	2	1	4
Land											
Others*3							3	3			2

Notes:

The numbers above are the number of papers listed as references in Kako et al. (2025, draft paper) . The numbers in this table are subject to change after the paper is published.

*1 UAV: Uncrewed Aerial Vehicle

*2 In the guidelines, the term “beach” not only refers to the area of the shoreline covered with sand or pebbles, but also includes dunes and vegetation such as mangroves. The numbers in parentheses are the number of literatures that cover dunes in the measurement area.

*3 "Others" indicates fields for which research cases have not been sufficiently confirmed (e.g. river and sea water columns / floors).

1.2 Structure of the guidelines

These guidelines consist of 3 parts: the main body, the Annex, and the Appendix. The main body provides a general overview of the measurement methods of marine litter using multiple remote sensing technologies. The detailed methodology for each remote sensing technology in the Annex, and the Appendix presents the results of a demonstration test conducted to ensure the practicality of the methodology in the Annex.

1.3 Definitions and terminology

The terms used in the guidelines are defined as follows.

(i) Remote sensing

Remote sensing technologies are used to gather and process information about an object without direct physical contact (ASPRES https://www.asprs.org/organization/what-is-asprs.html accessed 2024-6-30). Remote sensing platforms are defined as vehicles (Jafarbiglu and Pourreza 2022) or other stationary objects that can carry or mount sensing devices to perform remote measurement operations.

The guidelines cover remote sensing methods using the following platforms. It should be noted that the methods to be covered may change in the future.

- Stationary camera: It is defined as a camera installed in the environment, e.g., installed on a shoreline with scaffolding, fixed on a bridge, to acquire time series image data at the same location. It does not include a camera fixed on a vehicle, such as an aircraft or a vessel.
- Uncrewed Aerial Vehicle (UAV)
- Aircraft
- Satellite
- Vessel

For reference, Table 2-1~Table 2-5 show examples of each platform.

(ii) Image processing and analysis

The data obtained by remote sensing is processed to certain images, and then the type or amount of litter can be automatically detected by image analysis methods. Relevant terms in the guidelines are defined as follows:

- **Image processing**

  Means processing captured images taken by remote sensing methods into forms that allow litter detection. It includes color correction, noise reduction, orthorectification, and composite processing with other images (such as orthomosaiccking).

- **Orthoimage**

  Mean aerial images taken by remote sensing methods, which have been corrected for the shooting position, lens distortion, and shooting direction to align the image with ground coordinates. Unlike uncorrected aerial images, orthorectified images can accurately represent the true distance to the Earth's surface.

- **Orthomosaic**

  Mean created images by mosaicking multiple overlapping orthoimages and ensuring that the brightness and color values are consistent across the entire area.

- **Image analysis**

  Means extracting litter information from processed images, such as identifying the types, quantities, or numbers of litter items.

  In recent times, machine learning and deep learning-based image processing techniques for plastic litter quantification have emerged. These methodologies utilize large datasets to develop models capable of detecting complex features—such as colors and shapes—in images, allowing for more flexible litter detection (Kako et al. 2025, draft paper). Such image analysis methods include “object detection by bounding box” and “semantic segmentation”, both of which are briefly described in Figure 1. The term “image analysis” also includes manual litter detection from images.

(iii) Survey and monitoring

In the guidelines, “survey” is defined as the measurement conducted to provide a snapshot of environmental conditions at the time. On the other hand, “monitoring” is defined as the repeated measurement of a characteristic of the environment, or of a process, to detect a trend in space or time (GESAMP 2019).

(iv) Litter

The monitoring targets addressed in the guidelines are litter in the environment (including marine litter).

- **Litter in the environment**

  Includes mismanaged waste (e.g., waste open-burned and dumped in uncontrolled dumpsites), macro plastic litter that will fragment into microplastics in the environment, and leakage and accumulation of other objects that can adversely affect humans and the living and non-living environment.

- **Marine litter**

  Litter in the environment that is persistent, manufactured, or processed solid material that is directly or indirectly discarded, disposed, or abandoned into the open ocean, coastal, or inland aquatic environment (UNEP 1995).

Table 2-1. Monitoring example: stationary camera

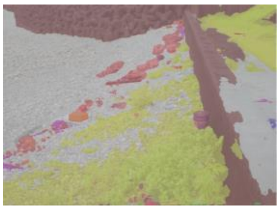
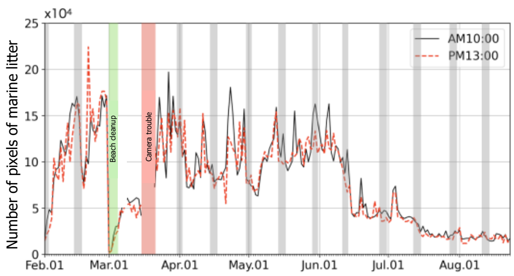
Case	Kagoshima University "Research Chair of Plastic Litter Monitoring System from the City, Sea, and Space" Website. https://pmd.oce.kagoshima-u.ac.jp/ / (accessed 2025-1-31)
Survey Objectives and Overview	The temporal images of beach litter were taken by stationary cameras. The images were processed by the image processing method of “semantic segmentation”. Since time series litter information is obtained, it can be used to understand changes in litter over time and determine the timing of cleanup activities.
Place and Time (Duration, Frequency)	The beaches in Japan 26th January (2022) ~ Pictures were taken every hour between 6 a.m. and 7 p.m. daily
Area Coverage	Approximate 100 m^2
Camera	HykeCame LT4G (RBG camera)
GSD (Ground Sample Distance)	> 1 mm
Litter Information	Number of pieces, covered area, type of litter
Images	(a)  (b)  (a) An image taken by a stationary camera (b) its semantic segmentation  Time series litter data  Stationary camera

Table 2-2. A survey example: UAV

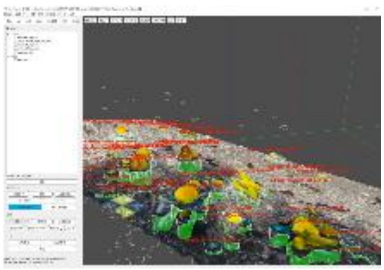
Case	Demonstration test for beach litter survey using UAVs conducted by Dr. Kako lab, JANUS Co. Ltd., Futaba Inc (The details are described in the Appendix 1).
Survey Objectives and Overview	To ensure the practicality of the guidelines, a demonstration test was conducted (details are described in the Appendix 1). Photographs of beach litter including driftwood were taken by UAV. The imagery data was processed for merging those images. Beach litter was detected automatically using AI developed by Dr. Kako, after which the number of pieces, area coverage, and beach litter volume were estimated.
Place and Time (Duration, Frequency)	The beaches in Japan A: Gravel beaches in Iyo city, Ehime: 8 a.m. (low tide), 24th July 2023 B: Uwajima city, Ehime: 9 a.m. (low tide), 27th July 2023
Area Coverage	Photographing area: A: 5,180 m^2 B: 706 m^2 Survey area: A: 50 x 17.1 m B: 20 x 4.3 m (longshore x cross-shore)
Camera	DJI Zenmuse P1 (RBG camera)
GSD	5 mm/pix
Litter Information	Number of pieces, covered area, volume
Images	 UAV  UAV takeoff  UAV imagery  Result of beach litter detection  Volume estimation image

Table 2-3. A survey example: aircraft

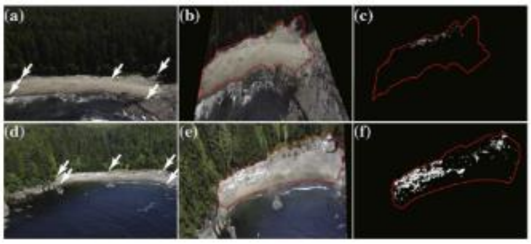
Case	Kataoka et al. (2018)
Survey Objectives and Overview	The photographs taken from an aircraft at oblique angles were processed for georeferencing. Thereafter, pixels of marine litter were extracted based on their color differences from the background beaches. The litter abundance can be evaluated by the ratio of an area covered by marine litter to that of the beach (coverage). The estimated coverage is useful information to determine priority sites for mitigating adverse impacts across broad areas.
Place and Time (Duration, Frequency)	The beaches in Canada − The west coast of Vancouver Island: October 7 and December 3, 2014 − The central coast of British Columbia and Haida Gwaii: January 30 and March 2, 2015
Area Coverage	Over 1,500 km of British Columbia's coastline
Camera	Nikon D750 (RGB camera)
GSD	0.1 x 0.1 m
Litter Information	Covered area
Images	 Aerial imagery Acknowledgement: Lightspeed Digital for Government of Japan/North Pacific Marine Science Organization (PICES 2015)  Image processing to (a, b, and c) Cheewat Beach, and (d, e, and f) Clo-ose Beach. (a) and (d): Original aerial photographs taken by the aerial photography. The white arrows denote the five reference points required for the projective transformation. (b) and (e): The projective transformation method was applied to the images (a) and (d). (c) and (f): The pixels of marine debris shown by the white pixels were extracted by the image processing described in the text. The red outlines in the images (b), (c), (e), and (f) denote the beach areas defined to compute the percent cover. (Kataoka et al. 2018 Fig. 2.)

Table 2-4. A survey example: satellite

Case	Themistocleous et al. (2020)
Survey Objectives and Overview	This is a pilot study to determine if plastic targets on the sea surface can be detected using remote sensing technologies with Sentinel-2 data. A target made up of plastic water bottles with a surface measuring 3 m x 10 m was created, which was subsequently placed on the sea surface (Themistocleous et al. 2020 Figure 3). Spectral signatures of the water and the plastic litter were obtained by Sentinel-2. By using the specific wavelength identified from the spectral signatures, the “Plastic Index” (equation) was established to identify plastic effectively.
Place and Time (Duration, Frequency)	The sea surface in Cyprus 15th December (2018)
Area Coverage	-
Camera	SVC HR-1024 spectroradiometer (multispectral camera)
GSD	While spatial resolution of Sentinel-2 is 10 x 10 m^2, the study shows a smaller target (3 x 10 m) was able to be identified by setting the Plastic Index.
Litter Information	Type of litter (plastic)
Images	 Figure 3. Divers moving target 200 meters from shoreline. Kyriacos Themistocleous A 3 x 10 m plastic litter target (Themistocleous et al. 2020 Figure 3)  Figure 11. Plastic index (PI) was used to identify the target, which is circled in yellow. The identified image using Sentinel-2 data Plastic Index (PI) was used to identify the target, which is circled in yellow. (Themistocleous et al. 2020 Figure 11)

Table 2-5. A survey example: vessel

Case	Papachristopoulou et al. (2020)
Survey Objectives and Overview	Images were obtained through a vessel-based photography survey for a total of 62 beaches, merged into seamless panoramas (photomosaics), and manually processed to quantify beach litter abundance. At four of the beaches selected detailed *in situ* litter sampling surveys were carried out to calibrate and validate the proposed vessel-based method.
Place and Time (Duration, Frequency)	The beaches in Greece 20 working hours (The total period of this study including *in situ* sampling was August (2017) ~ August (2018))
Area Coverage	Coastline extension approx. 8.5 nautical miles (approx. 15.7 km)
Camera	Nikon D80 (RGB camera)
GSD	-
Litter Information	Type, Number of items
Images	 Fig. 2. Example of photomosaic digitizing process in QGIS environment. Black points represent the BL items registered in the A-B area. White squares indicate zoomed example areas, while 1–9 numbers show samples of different identified item categories. 1: Plastic water bottle, 2: Plastic cap/lid drink, 3: Plastic cup, 4: Rope, 5: Cigarette filter, 6: Straw, 7: Float for fishing net, 8: Plastic cup and 9: Cup lid. Example of photomosaic digitizing process (Papachristopoulou et al. 2020 Fig. 2.)

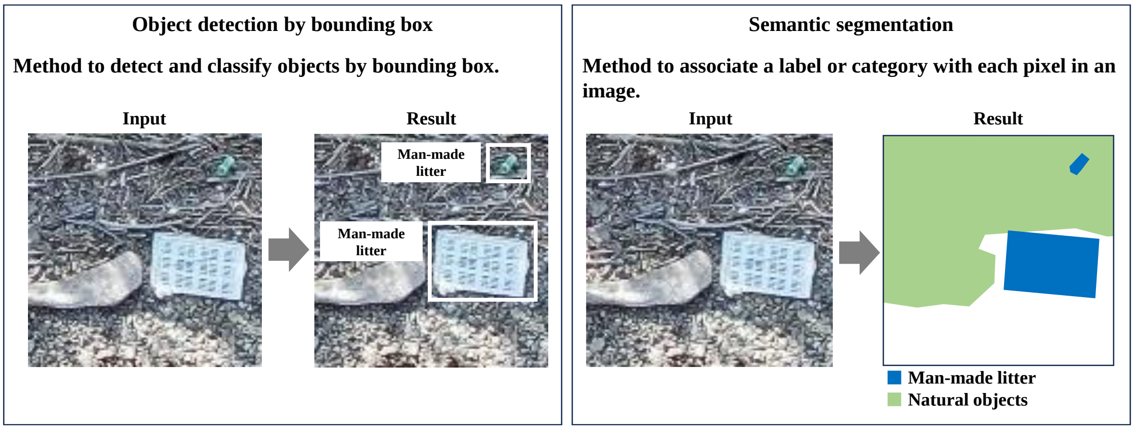


Figure 1. Description of image analysis methods.

1.4 Purpose of the guidelines

To develop and guide the comprehensive use of harmonized monitoring methods using remote sensing technologies that provide continuous and efficient monitoring over wide areas, and to contribute to understanding of the current status of marine litter internationally.

1.5 Scope of the guidelines

1.5.1 Monitoring fields, data acquisition methods, and image analysis methods

The scope of the guidelines is as follows (Figure 2, Table 3). It will be scaled up and updated based on the best available science. The guidelines are mainly aimed at utilization by academic and research institutions, private industries and NGOs, government agencies (policy makers), and citizen scientists.

Regarding marine area classification, the guidelines mainly cover coastal areas in order to avoid duplication with existing efforts on marine litter monitoring of other organizations such as The International Ocean Colour Coordinating Group (IOCCG).

In addition, a variety of sensors can be used on satellites, and a list of the sensors that can be installed on satellites is shown in Table 4.

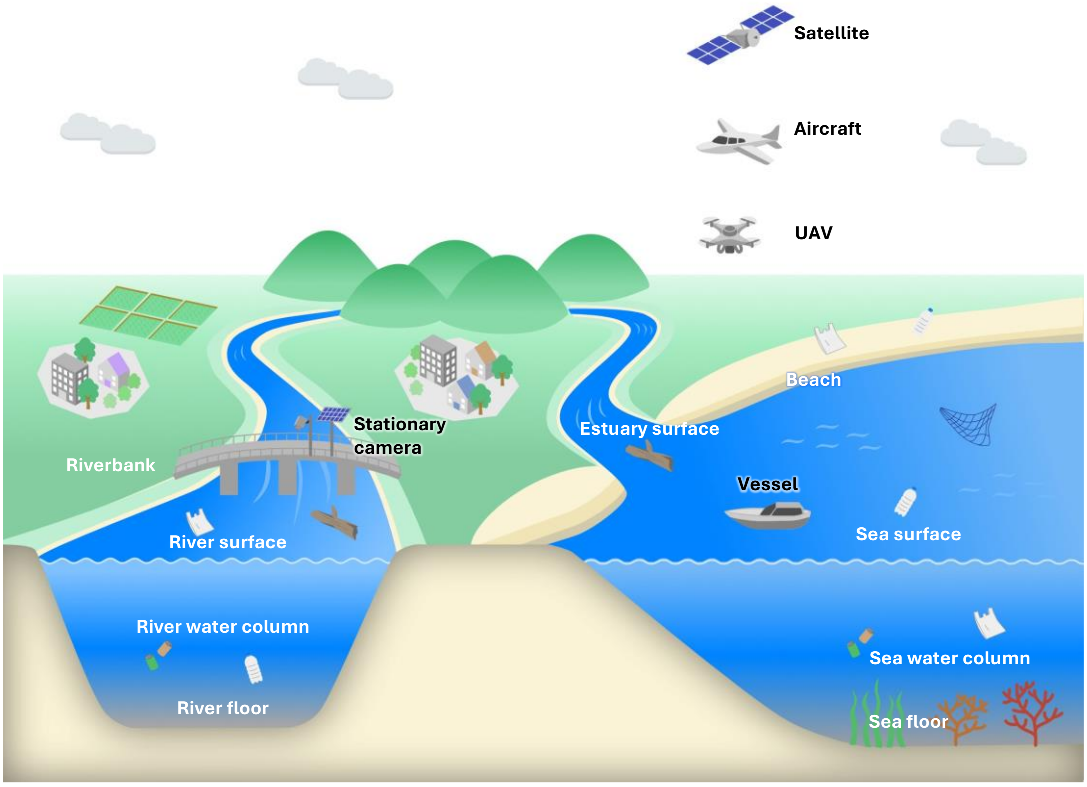


Figure 2. Diagram of the monitoring fields and the data acquisition methods.

Table 3. The scope of monitoring fields, data acquisition methods, and image analysis methods in the guidelines.

Fields	Data Acquisition Methods						Image Analysis Methods			
	Remote Sensing						Manual (Visual)	Automatic		
	Platform									
	Stationary Camera	UAV*1	Aircraft	Satellite	Vessel	Others		Object Detection by Bounding Box	Semantic Segmentation	Others
	Sensor									
	RGB	RGB	Multispectral/ Hyperspectral, RGB, LIDAR	Multispectral/ Hyperspectral	RGB, LIDAR					
Beach (Dune)										
Sea Surface		●	●	●						
Sea Water Column		●	●	●						
Estuary Surface										
Riverbank/Lake Beach										
River Surface										
Land										
Others*2										

Listed in the guidelines Version 2.0 Annex
To be discussed

Notes:
Regarding plastic litter monitoring, the areas are being discussed by other initiatives (e.g., IOCCG Task Force on Remote Sensing of Marine Litter)

*1 UAV: Uncrewed Aerial Vehicle

*2 "Others" indicates fields for which research cases have not been sufficiently confirmed (e.g. river and sea water columns / floors).

Table 4. List of sensors that can be mounted on satellites to detect litter.

Type of Sensor					Field		Target		Examples of Sensors That Could Be Used to Detect Marine			
Passive/ Active	Sensor	Image Sensor	Spectral Range	Spectral Resolution	Dry (Beach, Riverbank, Land)	Wet (Sea Surface, Water Column, River Surface)	Object (Anomaly*1, Plastic Detection, Plastic Characterisation)	Proxy (e.g. Sea Current, Wind)*2	Name of Sensor (Available Satellite)	Spatial Resolution (GSD in m)	Type of Orbit	Revisit Time Interval
Passive	Panchromatic	CCD, CMOS	200-1000nm		Yes	No	Anomaly	No	Planet, SuperDOVE	3-5		
	Multispectral			50-100nm	R&D	R&D	Anomaly	R&D	MSI (Sentinel-2)	10 (max)		5 days
	(Narrow band)			10-20nm	No	R&D	Anomaly	R&D	OLCI (Sentinel-3)	300 (max)		1 day
	Hyperspectral			10nm	R&D	R&D	R&D	R&D	PRISMA	30		7-14 days
			420-1000nm	6.5nm	R&D	R&D	Anomaly, plastic detection, plastic characterization	No	EnMap	30		4-21 days
			900-2450nm	10nm								
		CMOS	400-970nm	10nm	R&D	R&D		No	HISUI	20-310		-*3
		MCT	900-2500nm	12.5nm								
	Microwave radiometer								DMSP-SSM/I TMI (TRMM)		Sun-synchronous sub-recurrent orbit Others (near equator)	
Active	LIDAR				No	No	No	No	CALIOP (CALIPSO)			
	Synthetic aperture radar (SAR)		L: 15-30cm C: 3.75-7.5cm X: 2.4-3.75cm		R&D	R&D	R&D	R&D	TanDEM-X SAR (TanDEM-X)			

Notes:
- Yes: practical stage, No: challenging stage, R&D: research and development stage
- List of sensors expected to be used for marine litter detection within 3-5 years from 2024.
- Spectral ranges and resolutions in the table are typical.
- Reference: Goddijn-Murphy et al. (2024), Tanii et al. (2022)

*1 Anomaly: A signal that is different from the background (or expected value) that can be an indicator of the presence of marine plastic litter (Goddijn-Murphy et al. 2024).
*2 Proxy: One or a combination of indirect variables that correlate with the presence of marine plastic litter (Goddijn-Murphy et al. 2024).
*3 HISUI is installed on the International Space Station (ISS), and since it is not in a sun-synchronous orbit, it does not have a fixed revisit time.

1.5.2 Targeted audiences

The following tables (Table 5-1, Table 5-2) summarize the organizations that are mainly expected to refer to the description of each technology in the guidelines at this time. These tables are created based on the actual surveys and research on marine litter monitoring using remote sensing methods that have been conducted by organizations.

Table 5-1. Targeted audiences of the guidelines.

Organizations	Remote sensing					Image Analysis Methods	
	Stationary Camera	UAV	Aircraft	Satellite	Vessel	Manual*1	Automatic*2
Academic and research institutions	■	■	■	■	■	■	■
Private industries and NGOs	■	■	■	■		■	■
Government agencies	■	■	■	□		□	□
Citizen scientists		□		□		□	□

■Organizations that are mainly expected to refer to the information on the guidelines

□Organizations that are expected to refer to the information on the guidelines to a limited extent

Notes:

Depending on the skills, resources, and the purposes of use, a wider range of users may utilize each technology.

*1 Manual：Extraction and identification of marine litter by visual inspection from images can be implemented by a wide range of users. However, location surveying techniques are required to quantitatively determine the amount of litter per unit area, thus the cooperation of academic institutions or specialized companies is generally considered necessary.

*2 Automatic：If there are user interfaces (UI) and applications that users can operate with simple adjustment of threshold values and images, the method can be used by a wide range of users. However, if UIs or existing applications are not available and specialized skills (e.g., programming or machine learning models) are required, the cooperation of academic institutions or specialized companies are generally considered necessary.

Table 5-2. The reasons why each technology targets the specific organizations mentioned in Table 5-1.

Remote sensing	**Cost** (Cost for Image Analysis Not Included)	**Expertise**	**Compliance Requirements** (Difficulty in Licensing Procedures and Precautions in Implementation)	**Accessibility** (Indicating the Number of Existing Survey Cases and the Ease of Obtaining Platforms and Services)
Stationary camera	Relatively low if the system is installed and operated.*1	Some skills are required for setup and maintenance during camera installation.	Permits and approvals are required for camera installation in some cases.	Commercially available products can be used.
UAV	Relatively high if the system is installed and operated.*2	It is expected to be utilized by a wide range of users, since an autonomous flight can be easily performed by using dedicated applications. However, it is necessary to process positional information correction using surveying technology, if the device is not equipped with RTK (Real-time kinematic)*5.	Permits and approvals are required for flights in some cases.	Commercially available products can be used.
Aircraft	The cost of outsourcing each survey is high.*3	Special skills and licenses are required (generally outsourced).	Permits and approvals are required for flights (generally outsourced).	Although there are few survey cases concerning marine litter, the technology to capture images with a camera fixed to an aircraft is widely used in aerial surveys.
Satellite	There are data sources that can be utilized free of charge or for a fee of several hundreds of dollars for the smallest unit of data (it depends on the measurement range, resolution, etc.).	With regard to understanding the dynamics of litter or estimation of area coverage by litter, people without specialized skills and knowledge can utilize the data. In contrast, regarding the classification of litter, studies are being conducted mainly by academic institutions and specialized companies.	No permits or approvals are required to use data.	Some sources are easily accessible via the Internet.
Vessel	The cost is relatively low when vessels are chartered (it varies depending on the type of vessel).*4	Some skills are required to set up shooting conditions and to take pictures on board while the ship is in motion. (It is considered that in many cases, the operation of vessels is outsourced.)	Licenses and permits may be required depending on the location and size of the vessels. (It is considered that in many cases, the operation of vessels is outsourced.)	Since the number of survey cases is currently very limited and the method is not widely used, it is mainly considered to be utilized by academic institutions. However, it can be effective in environments where it is difficult to conduct aerial photography or human surveys on land (e.g., mangrove forests).

Notes:
The description above is only a guide and might vary by methods, countries, regions, or environment of survey fields.
The operation of the platforms can be outsourced depending on user skills or budgets.

*1 In typical cases in Japan, the introduction cost is about 300,000-400,000 yen ($1,900-$2,500), and the operational cost is about 50,000 yen/year ($300).

*2 In typical cases in Japan, the introduction cost is about 2,000,000-3,000,000 yen ($12,000-19,000), and the operational cost is about 200,000-300,000 yen/year ($1,200-1,900/year).

*3 In typical cases in Japan, the cost of outsourcing per flight is about 2,000,000-3,000,000 yen ($12,000-19,000).

*4 In typical cases in Japan, the cost of chartering a vessel per trip is about 10,000-50,000 yen ($100-300), and the cost of a camera is about 200,000-300,000 yen ($ 1,200-1,900).

*5 RTK is centimeter-level accuracy positioning in real-time based on GPS measurements (or more generally on GNSS (Global Navigation Satellite System) measurements) (Source: IAG (International Association of Geodesy) website).

USD = 161.07 yen (To convert yen to USD, we used the table of exchange rates for yen (TTM) on June 30, 2024. Decimal values resulting from the conversion were rounded off.)

Chapter II Purpose of monitoring and how to select the survey methods

2.1 Purpose and goals of monitoring

The major purposes of monitoring with the harmonized methodology are to utilize the monitoring results in addressing policy-related issues, including policy makings (e.g., understanding of the current status of pollution, estimation and identification of sources and hotspots), regulations (e.g., market restrictions on single-use plastics, extended producer responsibility etc.), public awareness (e.g., environmental education), beach clean-up activities, and verifications of the effectiveness of mitigation measures.

The goals of monitoring of litter in the environment are considered as follows:

- To reveal the abundance of litter
- To reveal the types of litter
- To reveal dynamics (mobilization and deposition) of litter
- To identify litter accumulation sites

2.2 How to select the monitoring methods

Figure 3-1, Figure 3-2 shows how to select an appropriate platform based on the survey recommendations for each purpose.
Image resolution obtained by surveys and the spatial coverage of a survey area are generally inversely proportional. It is important to select appropriate remote sensing methods depending on survey purposes.
Manual surveys are recommended in detailed litter composition analysis because of the limited ability of remote sensing methods to detect and identify objects. However, the results obtained by remote sensing methods could be used for broader purposes depending on the survey designs or combinations with other survey results.

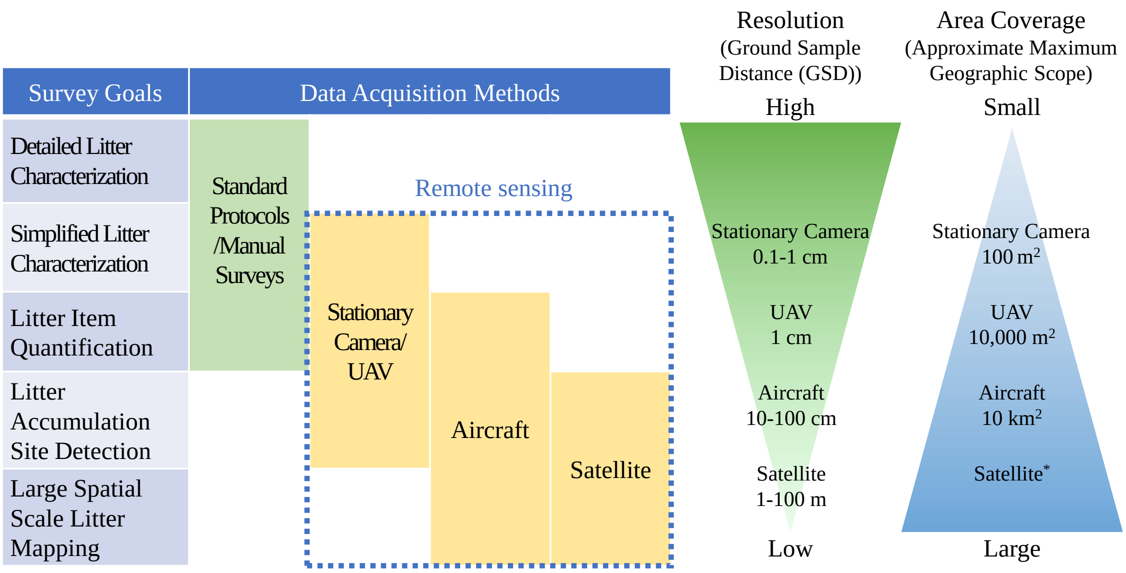
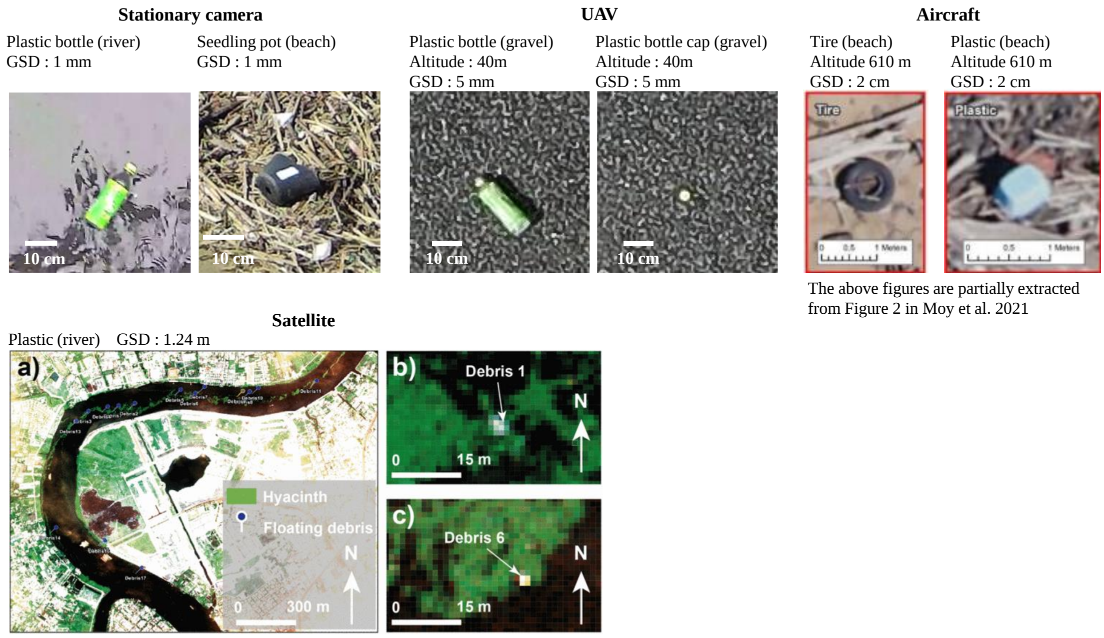


Figure 3-1. Approximate resolution, area coverage and purposes of surveys using each platform.

Notes:
Typical resolutions and area coverages for studies using each platform are shown, in orders of magnitude.
* Satellites are expected to be utilized over a narrow area, such as a specific river or coast, as well as over a larger area, such as an entire global unit.



(Schreyers et.al. 2022 Fig .1) Direct detection of floating debris in the Saigon river. a) overview of identified floating debris. b) c) zoomed-in view of two floating debris. The satellite scene is displayed in true color composite. Source: worldview-3 image from 4 March 2020. © 2020 maxar

Figure 3-2. Examples of common images produced by each platform.

In addition to the survey purposes in Figure 3-1, stationary cameras and satellites are considered to be suitable for surveying the dynamics (mobilization and deposition) of litter in the environment) because of their high frequency observations.
For the suitable observation time interval of each platform: see Kako et al. (2025, draft paper).

Regardless of the resolution, it is possible to determine the litter material composition of plastics (e.g., polyethylene, polypropylene), depending on the range of observation wavelengths of the sensors installed in each platform.

2.3 Overview of monitoring methods to meet policy-related issues.

Table 6. Examples of policy-related issues and output image.

What Do You Want to Know? *	Why Do You Want to Know?	Methods to Address Policy-Related Issues	How to Address Policy-Related Issues
Abundance of marine litter in seas under national jurisdiction	To manage the progress of countermeasures, to understand the impact	-	-
Type and origin of marine litter	To develop effective and efficient mitigation measures against marine plastic pollution	-	-
The effectiveness of mitigation measures		Stationary camera @river	Identify trends of increase/decrease in river runoff from land areas
Identification of accumulations	To assess the current status of plastic pollution, prioritize countermeasures, and promote efficient measures (including improving the efficiency of clean-up activities)	UAV @beach	Identify the distribution of marine plastics on major shorelines on a prefectural scale and clarify priorities for clean-up activities
		Aircraft @beach	Identify the distribution of marine plastics on all shorelines on a prefectural scale and clarify priorities for clean-up activities
		Stationary camera @beach	Identify detailed litter increase/decrease trends for specific shorelines to improve the efficiency of the limited number of clean-ups

* The left column of the table is based on GESAMP (2019).

Chapter III Monitoring methods

3.1 Technological maturity of current monitoring methods

The purpose of the guidelines is to provide a broad audience and users with information on current state of the art monitoring methods that enable them to obtain high resolution spatio-temporal information and to contribute to further current knowledge and understanding litter pollution in the environment. Therefore, detailed monitoring methods for multiple remote sensing platforms are described in the Annex in a stepwise manner, starting with those that have a high level of technological maturity and practicality.

Following recent research on technological solutions to tackle marine litter related issues a Technological Readiness Level (TRL) * assessment was used as a quantitative approach to establish technological maturity and readiness (Bellou et al. 2021). There are nine technological readiness levels. TRL 1 is the lowest and TRL 9 is the highest. In the guidelines, the definition of TRLs for remote sensing methods for litter monitoring was set as shown in Figure 4. TRLs of the technologies were assessed based on the existing marine litter surveys and researches referred to in Kako et al. (2025, draft paper) and other confirmed cases, under the definition in Figure 4.

As a result, the following technologies were evaluated as relatively high TRL and being highly practical: beach litter monitoring using UAVs, and beach and river surface litter monitoring using stationary cameras. These monitoring methods are described in detail in the Annex. The specific TRL figures for each platform as of April 2025 are shown on the Ministry of the Environment website (https://www.env.go.jp/page_00929.html). For image analysis technology, Table 7 summarizes the applications (tasks) that are commonly used at this time. It should be noted that research in this field has been accelerating in recent years, and the maturity of the methods may change in the future.

* TRL is a type of indicator developed by NASA (National Aeronautics and Space Administration) to assess the maturity of technologies and is commonly applied to various technical fields.

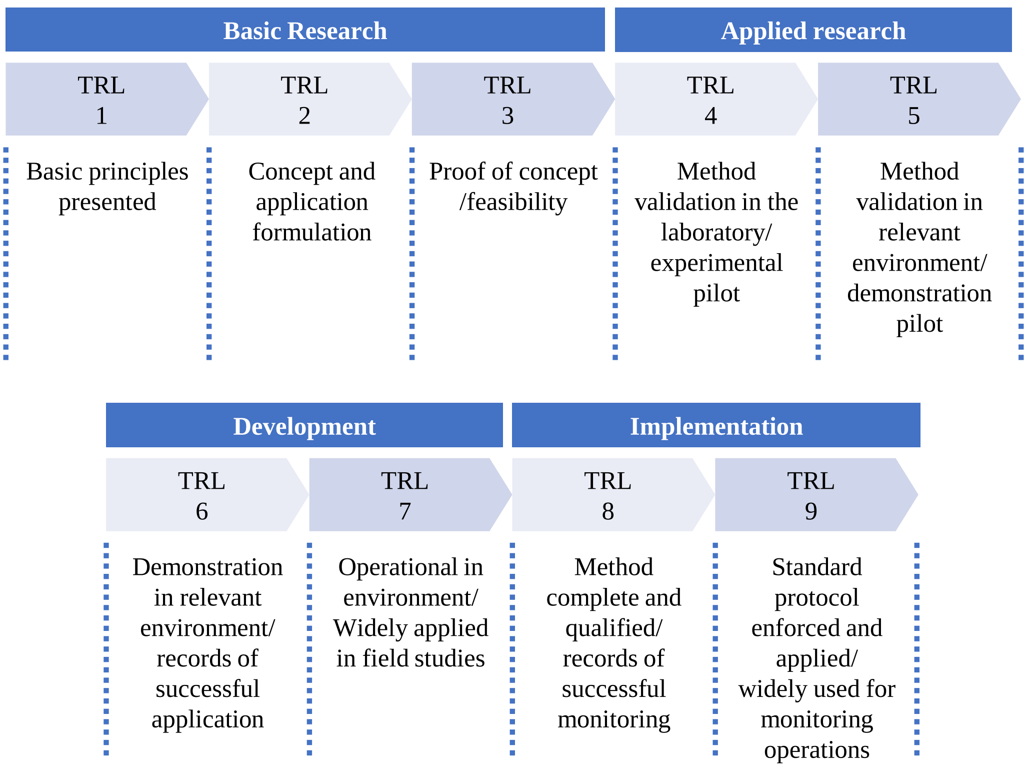


Figure 4. Description of the technological readiness level (TRL) scale on remote sensing technologies used in litter monitoring (Aliani et al. 2023).

Table 7. Correspondence table between tasks and image analysis technologies.

	Object Detection by Bounding Box	Semantic Segmentation
Evaluation of litter area (Estimation of volume and mass of litter)	N/A (Not applicable)	++[*1]
Counting the number of litter items	++	N/A
Classification of litter	++	+[*2]

Notes:

*1 Estimating area (Hidaka et al. 2022) and volume (Kako et al. 2020) requires information on the number of pixels per unit length and surveying techniques. To estimate mass, it is necessary to collect litter and determine its mass per volume on site (Kataoka et al. 2020).

*2 The classification of man-made and natural objects is accomplished, but no further detailed classification has not yet been achieved at this time (Kako et al. 2025, draft paper).

3.2 Current technical difficulties and future steps

3.2.1 Remote sensing platforms

As described in Figure 3-1, the image resolution obtained by surveys and the spatial coverage of a survey area are generally inversely proportional. The major advantage of remote sensing is its ability to enable continuous observation over short periods and batch observation over wide areas, which is not practically feasible manually, although it is difficult to classify litter in as much detail as manual surveys due to the issue of image resolution. In addition, combining different platforms offers advantages in observing plastic litter across varying spatiotemporal scales (Kako et al. 2025, draft paper). Typical technical difficulties of remote sensing methods and future steps are shown in Table 8.

Table 8. Typical technical difficulties and future steps of remote sensing methods.

<table>
<tr><th></th><th>Typical Technical Difficulties</th><th>Future Steps</th></tr>
<tr><td>Stationary camera</td><td>Stationary camera has a limited angle of view and cannot capture an entire beach. Also, installation constraints of the stationary camera restrict observations to locations where instrument installation is feasible on the observation region of interest, such as beach and river.</td><td rowspan="2">The stationary camera offers a real-time observation to obtain the temporal variation of litter abundance, while UAV can be used for obtaining snapshots at specific intervals to record the spatial distributions of litter abundance. Combining both platforms complements each other’s shortcomings and provides new insights into spatiotemporal variations over large areas, such as entire beaches.</td></tr>
<tr><td>UAV</td><td>UAV surveys typically require at least two operators—a pilot and an assistant—for each observation. These constraints considerably limit the feasibility of conducting frequent observations, such as every few days.</td></tr>
<tr><td>Aircraft, Satellite</td><td>No guidelines have yet been established for using RGB cameras or other instruments in an extensive aircraft or satellite system to observe plastic litter.</td><td>Since both platforms clearly offer bulk observations over broad areas, the proposed approach involves using UAV to collect ground truth data, to evaluate accuracy at multiple locations where litter tends to accumulate, as identified in images captured by aircraft and satellite systems.</td></tr>
</table>

Reference: Kako et al. 2025, draft paper

Column

Current Status and Future Prospects of Marine Litter Monitoring Using Satellites

(i) Current Status

Satellite monitoring has gained attention as an efficient method for tracking marine litter because it covers vast areas, including the entire global unit, in a single instance. This capability sets it apart from other methods such as stationary cameras, UAVs, and aircraft. However, there are several challenges associated with satellite monitoring:

- **Resolution:**
  In the past, the ground sample distance (GSD) of satellite imagery was around 60 m, but recent advancements in commercial satellite technology have improved this to resolutions as fine as 3.5 m (Goddijn-Murphy et al. 2024). Despite these improvements, it remains difficult to detect smaller litter, particularly those less than a few meters in size. Additionally, satellites face challenges in distinguishing between different types of litter.
  Marine litter often consists of both natural and man-made objects, making it hard to differentiate between them. It is especially difficult to identify plastics specifically within this mix, and to distinguish between different types of plastic based on their material properties (Zhu and Kanaya 2023).
- **Accuracy:**
  Ocean waves, sun glint, and other environmental factors make it difficult to detect litter, leading to a potential risk of false detections.
- **Cost:**
  Satellites have traditionally required significant expenses, with development costs exceeding several hundred million dollars and satellites weighing between 300 kg and several tons[*1].

(ii) Future Prospects

Technological advancements in satellites are progressing rapidly, and monitoring capabilities for marine litter are also evolving, with further innovations expected in the following areas:

- Regarding the distribution of large clusters of marine litter, whereas NASA’s Landsat could observe once every 16 days[*2], it is now possible to conduct daily observations, up to once per day (Maximenko et al. 2019).
- One example of existing technology is "target pointing," which allows the satellite's camera to focus on a specific direction[*1]. This technology has the following features:
  - It enables pinpoint observations, minimizing the amount of data obtained.
  - It can minimize false positives due to the sun glint.
  - The observation range is 20 times larger than traditional satellites.
- Additionally, regarding quantifying a plastic litter water column, combining differential absorption spectroscopy with NIR-SWIR hyperspectral imaging techniques is expected to allow for classification of plastics by material (Zhu and Kanaya 2023). In the future, not only sea/river surface monitoring, but also water column measurements and identification of litter types will become possible.
- On the cost front, recently developed ultra-small satellites weigh around 50 kg, and development costs have been reduced to 3 million dollars, which is 1/100th of the traditional cost[*1]. This will make the use of satellites for marine litter monitoring more feasible in the future.

*1 Hokkaido University. https://sdgs.hokudai.ac.jp/approach-to-sdgs/interview/itw-3405/ (accessed 2025-1-31)
*2 NASA https://landsat.gsfc.nasa.gov/satellites/landsat-next/ (accessed 2025-1-31)

3.2.2 Image analysis

Machine learning and deep learning-based image processing model was developed, which utilizes large datasets and can detect complex features—such as colors and shapes—in images, allowing for more flexible litter detection. Details on image analysis methods and data disclosure are provided in Annex Section II of these guidelines.

While manual methods can identify objects of all size ranges, image processing methods struggle to predict relatively small or obstructed objects (Kako et al. 2025, draft paper).

The development of image analysis technology based on deep learning requires specialized knowledge and the preparation of data to be used for training, and the assignment of information such as the location and classification of marine litter to that data (annotation work). Since current image analysis requires manual verification and annotation of all collected data and given the significant time and cost associated with creating training data, it is essential to share these datasets regardless of the remote sensing platform (Kako et al. 2025, draft paper).

Regarding the sharing of datasets, there are examples of the use of cloud computing (a technology for sharing work and data via the Internet) for annotation in the field of marine ecology. For example, the web applications shown in Table 9 are provided to experts partly free of charge.

Some services are equipped with programs that automatically detect objects in uploaded images and classify them by pixel unit through image segmentation. Users of such a service can upload images onto a web application, annotate them with the automatically detected objects, and share them online. Shared label data can be reclassified to ensure consistency in data classification. The above applications are also used in the marine litter. Specifically, BIIGLE, shown in Table 9, has been used in research to analyze the spatial and temporal variability of litter accumulated on the sea floor, and marine litter label data has been shared (Tekman et al. 2017).

Once marine litter label data is shared, the collection and accumulation of data necessary for image analysis and automatic object detection of litter by AI will take place through the application. It would facilitate data integration across different remote sensing platforms, as the collected label data could be reclassified. The data accumulated through the application can be used to create and develop AI that automatically detects and classifies litter in images or videos collected by remote sensing.

Table 9. Examples of cloud computing services for annotation.

Service	Application Features	URL
BIIGLE	Image segmentation enables automatic detection of objects on a pixel unit.	https://biigle.de/ (accessed 2025-1-31)
SQUIDLE	API (a mechanism for calling application functions from the outside) allows integration with other web applications (e.g., maps).	https://squidle.org/ (accessed 2025-1-31)
CoralNet	It is a web application specialized in image analysis of coral.	https://acceso.coralnet.co/ (accessed 2025-1-31)

3.2.3 Continuous collection of training data using smartphone applications

For monitoring methods for rivers and sea, plastic litter quantification methods are being developed as indicated in these guidelines. On the other hand, it is difficult to collect accurate data on litter in areas where there is a lot of human traffic, buildings, and other obstacles. Regarding the development of data analysis methods, the detection, classification, and quantification of litter using AI is expected due to its efficiency, and to improve its accuracy, it is desirable to have a large amount and continuous availability of image data of litter taken in various fields as training data.

Therefore, activities by citizen scientists using smartphone applications are being used to collect data. The user of the application can upload images of litter taken along with location information onto the server and share them with other users. Smartphone applications are useful for permanent and extensive data collection because they can be used without special skills and collect large amounts of data from users. It is also possible to map litter in the environment based on the location recorded on the smartphone. Smartphone applications that are being used to collect data on litter in the environment are shown in Table 10.

Table 10. Examples of applications used to collect data on litter in the environment.

Applications	Application Features	URL
Pirika	It functions as a social networking service, allowing communication among users.	https://corp.pirika.org/en/sns-pirika/ (accessed 2025-1-31)
Open Litter Map	The collected data is available to the public and anyone can use the data.	https://openlittermap.com/ (accessed 2025-1-31)
Planet Patrol	The collected data is verified and the data is reliable.	https://planetpatrol.co/ (accessed 2025-1-31)
Marine Litter Reporter	Specializes in collecting data on marine litter.	https://www.cleanatlantic.eu/ (accessed 2025-1-31)

Pirika, shown in Table 10, has been collecting images of litter in the environment along with location data since 2018, and more than 1 million images have been uploaded into the application over a period of about 6 years until 2024. The collected data is used for image analysis based on deep learning to quantify and analyze the distribution of litter in the environment (see Figure 5), and also as training data for deep learning.

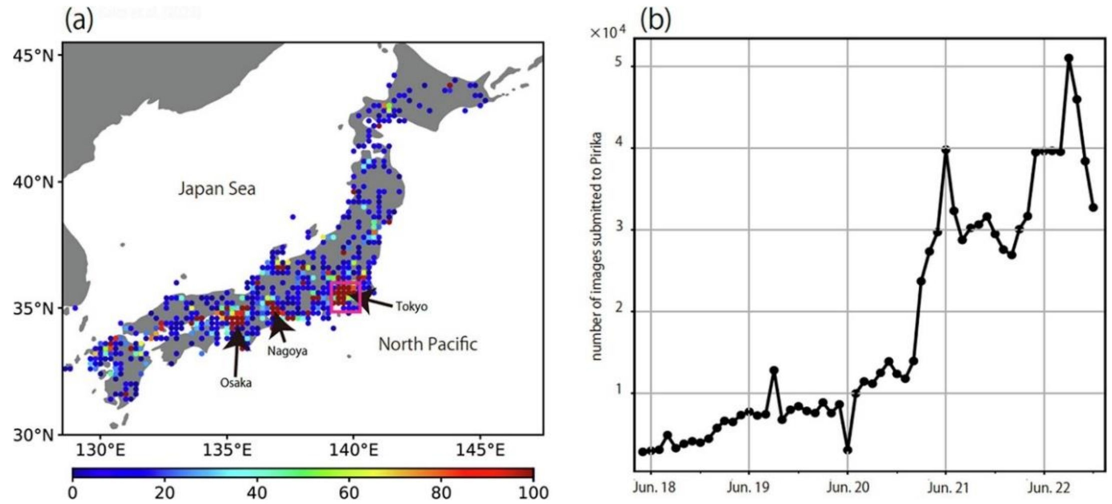


Figure 5. An example of a litter survey using a smartphone application.

(a) Average number of images submitted on September 2022 aggregated per 20-km grid. The pink square indicates the Kanto region shown in Figure 5. Time series of the number of images submitted to Pirika between May 2018 and December 2022. (For interpretation of the references to color in this figure legend, the reader is directed to the web version of this article.) (Kako et al. 2024)

On the other hand, data collection by citizen scientists using smartphone applications faces challenges regarding data quality. As Pirika is a free application, some images submitted were expected to be unsuitable for quantifying litter (Kako et al. 2024). Such images shown in Figure 6 are of low brightness, have small object sizes compared to the background ground, or are out of focus, challenging object detection. The low-quality images submitted are probably because of the lack of guidance when capturing images (Kako et al. 2024). In some cases, all uploaded images are verified for data quality control purposes, but such an operation is very time-consuming and costly (Stanton et al. 2022). Therefore, the application could incorporate guidelines into the smartphone application's camera interphase to encourage users to capture photos suitable for surveying litter in the environment to accumulate clear street litter images (Kako et al. 2024).

Figure 6. Example of low-quality images unsuitable for object detection and quantification (Kako et al. 2024).

3.2.4 Overall monitoring using remote sensing technologies

One of the ultimate goals of quantification through monitoring would be to elucidate the flow of litter, such as the extent to which litter from land areas is discharged into the ocean via rivers. To achieve this, it is necessary to standardize the units for quantification, which is currently difficult because data obtained from various platforms differ in GSD and the information obtained (e.g. with or without altitude) (Kako et al. 2025, draft paper).

Different technologies can be utilized for monitoring depending on the expertise or available resources of users (see Table 5-1, Table 5-2). It is important to understand the characteristics, advantages, and disadvantages of each technology, and to select appropriate methods depending on their survey purposes or situations. It should be noted that the use of each technology and those who can easily access it may change as the technology develops in the future.

3.3 Future revision of the guidelines

The guidelines will be updated periodically in line with the development of remote sensing technologies. As shown in Table 3, the technical details on platforms other than UAVs and stationary cameras will be added to the Annex as necessary.

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