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Engaging Communities in Sulawesi Island, Indonesia: A Collaborative Approach to Modelling Marine Plastic Debris through Open Science and Online Visualization

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Impact Statement

Computer models, including those which simulate physical ocean conditions and track pieces of plastic pollution throughout the environment, often require specialist skills to operate or are hidden behind proprietary software. Ocean models can provide long-term and comprehensive estimates reducing the need to rely on costly, resource-intensive and irregular in-person monitoring. Indonesia, which is both a high emitter of plastic pollution and particularly vulnerable to non-domestic sources of marine litter as an archipelagic state, requires a cross-discipline and cross-sector approach if sources and impacts are to be addressed efficiently. Considering these synergies, this study has modelled surface microplastic transport around Sulawesi Island in central Indonesia across the monsoon-driven wet and dry seasons. We have also demonstrated a replicable framework and methodology to engage interested parties in the results of marine litter modelling. Through a combination of outreach and engagement activities, the impact and relationships of this study has far surpassed its initial funding duration - as evidenced by the continued use and engagement in its outputs. Not only does this study build upon evidence that plastic concentrations in the region are highly influenced by seasonality but also provides recommendations on funding structures, project development and international collaboration to create more impactful, inclusive, and symbiotic research.

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Abstract

Marine litter poses a complex challenge in Indonesia, necessitating a well-informed and coordinated strategy for effective mitigation. This study investigates the seasonality of plastic concentrations around Sulawesi Island in central Indonesia during the monsoon-driven wet and dry seasons. By using open data and methodologies including the HYCOM and Parcels models, we simulated the dispersal of plastic waste over three months during both the southwest and northeast monsoons. Our research extended beyond data analysis, as we actively engaged with local communities, researchers, and policymakers through a range of outreach initiatives, including the development of a web application to visualize model results. Our findings underscore the substantial influence of monsoon-driven currents on surface plastic concentrations, highlighting the seasonal variation in the risk to different regional seas. This study adds to the evidence provided by coarser resolution regional ocean modelling studies, emphasizing that seasonality is a key driver of plastic pollution within the Indonesian archipelago. Inclusive international collaboration and a community-oriented approach were integral to our project, and we recommend that future initiatives similarly engage researchers, local communities, and decision-makers in marine litter modelling results. This study will work to support in the application of model results in solutions to the marine litter problem.

Keywords
`plastic pollution', `open access', `transport modelling', `outreach', `Indonesia'

1. Introduction

The issue of plastic debris in the Indonesia Seas is a complex and multifaceted problem. It transcends national boundaries, originating from both local waste mismanagement and neighbouring countries (Purba et al., 2021) and is influenced by intricate ocean circulation patterns within Southeast Asia (van Calcar and van Emmerik, 2019). These circulation patterns vary seasonally and interannually, and are susceptible to more pronounced shifts as a result of climate change which in turn will modify the distribution of the debris and may destabilise already vulnerable ecosystems (Browne et al., 2015; Ford et al., 2022; Lincoln et al., 2022). Addressing such a complex issue necessitates a coordinated approach between communities, researchers and policy-makers. As a result, Indonesia has taken the lead by becoming the first national government to develop a formal National Action Plan (NAP) aimed at reducing marine plastic debris by 70% by 2025 and to 0% by 2040 (Purba et al., 2019). This NAP relies on inter-agency cooperation, science-based management, and the combined efforts of society. However, the lack of comprehensive data on the amount and distribution of marine plastic debris poses challenges to understanding and implementing effective mitigation strategies (Vriend et al., 2021) and ultimately calls into question whether these ambitious targets are realistic especially given the ever-shortening time frame.

Ocean modelling and particle tracking modelling have been widely used to simulate plastic dispersal across space and time including throughout Indonesia, identifying the Java and Banda seas as particularly vulnerable to plastic exported from local rivers (Dobler et al., 2022; Iskandar, Cordova and Park, 2022). Although the outputs of these tools are of great interest to the public, they often require high levels of computer literacy and understanding, limiting the involvement of various interested parties in their application. Indonesia has previously been named as one of the regions where levels of mismanaged plastic waste are among the highest in the word (Jambeck et al., 2015). While this point remains contested due to the lack of in-situ data, the management of marine plastic debris and the need for accessible methodologies and data-sharing remains crucial to address this challenge. Furthermore, previous studies in the region have often neglected the importance of open access data and methodologies (open access is defined as the free access to information and unrestricted use of electronic resources for everyone (UNESCO, 2024)), which hinder the establishment of a lasting knowledge-sharing legacy. To address these gaps, this study brought together research teams from the United Kingdom (UK) and Indonesia to share methodologies to quantify marine plastic debris in Indonesia and develop a collaborative platform for disseminating results and engaging communities and stakeholders. Focussing on Sulawesi Island, Indonesia, at the core of this study is a novel web-based visualization platform that empowers non-scientists to visualize, explore, and comprehend the pathways of plastic debris from coastal sources to both coastal- and offshore sinks.

The overarching goal of this study was to coordinate research efforts and raise awareness about the current and potential future source-sink pathways of marine plastic debris in the Sulawesi Island region of Indonesia. To achieve this, we employed a combination of ocean and particle tracking models, developed a user-friendly web-based visualization platform, conducted outreach activities targeting

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schools and communities (specifically in Selayar Island, South Sulawesi (see Figure 1) and fostered collaborative relationships between researchers from the UK and Indonesia. In this paper, we present a framework and methodology that actively engages stakeholders and enables their participation in understanding and using ocean modelling results for effective marine debris management that can be transferred to other regions globally.

1.1 Study Site

Situated in the northern Flores Sea, Selayar Islands Regency is a part of Sulawesi Island located in South Sulawesi Province (Figure 1). The island is to the west of Taka Bonerate National Marine Park and UNESCO Biosphere Reserve, surrounded by a diverse marine ecosystem, serving as a habitat for various marine species including coral reefs, seagrass beds, and mangrove forests. Despite its protected status, it has a growing record of plastic marine debris (Hermawan, Damar and Hariyadi, 2017). Moreover, Selayar Island has a strong connection to local communities that rely on the marine environment for their sustenance and economic activities, including fishing and tourism (Ferse et al., 2012; Hakim, Soemarno and Hong, 2012). This geography was selected based on previous work undertaken by Aquatera and the Centre for Sustainable Energy and Resources Management (https://cserm.unas.ac.id/profile/). Engaging with communities allows for a better understanding of their perspectives, the challenges, and any potential solutions related to marine plastic debris (Bracic, 2018). The island's ecological importance, exposure to plastic pollution and climate-related challenges, and the involvement of local communities make it an ideal location to conduct research and implement targeted interventions aimed at mitigating these environmental issues.

The physical oceanography of the surrounding sea of Indonesia plays a crucial role in shaping the transport and distribution of marine plastic debris. Differences in temperature between the ocean and region's landmasses drive the monsoon system, which is characterized by distinct wet (northeast (NE) monsoon) and dry (southwest (SW) monsoon) seasons (Schott, Xie and McCreary, 2009). During the wet monsoon season (December through April), the region receives heavy rainfall and experiences strong winds, resulting in increased freshwater runoff from rivers and enhanced ocean currents which flow predominantly towards the east. This period is associated with higher river discharge, which can carry significant amounts of land-based debris, including plastic, into the marine environment (Kurniawan and Imron, 2019). In contrast, the dry monsoon season (June through October) is characterized by reduced rainfall and weaker winds. During this period, ocean currents are reversed compared to the wet season, and flow predominantly towards the west.

The surrounding oceanography connects Sulawesi Island to other regions of the archipelago due to the Indonesian Through Flow, which is strongest during the SW monsoon (Sprintall et al., 2009), and other regional surface currents Figure 1). These seasonal variations in precipitation, wind patterns, and ocean currents influence the input and transport of marine plastic debris in the surrounding sea (Cordova and Nurhati, 2019). Understanding the influence of the monsoon on the physical oceanography of the study site is vital for comprehending the dynamics of plastic

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debris (Pattiaratchi et al., 2022). Furthermore, the influence of the monsoon on the coastal morphology, sediment transport, and water quality can contribute to the distribution and retention of plastic debris in the nearshore and offshore areas (VishnuRadhan et al., 2015; Clift, 2020). Oceanic scale particle tracking studies have illustrated that the monsoon's reversing currents transport buoyant plastic between eastern and western regions of the Indian Ocean (Van Der Mheen, Van Sebille and Pattiaratchi, 2020), however knowledge on how plastic debris is transported within the Indonesian archipelago itself is still limited.

2. Methods

2.1 Project conception and development

A workshop titled "Addressing Marine Plastic Waste as a Climate Change Adaptation Priority", funded by the Newton Fund British Council and facilitated by Aquatera, was conducted from August 31st to September 2nd, 2021. Aquatera's ABCG (Academia-Business-Community-Government) partnership model is a key component in these processes. The premise that delivery shared between these sectors is a fundamental basis for this research. The workshop brought together academic and industry partners from the UK and Indonesia to assess the compounding impacts of climate change and marine plastic pollution in Indonesia. Participants engaged in presentations and discussions of these issues from academic, business, industry, and governmental perspectives. Following the workshop, this study was formed involving international and transdisciplinary teams, focusing on the complex issue of the distribution of marine plastic litter in and around Indonesia. The study was structured into three work packages: (1) a particle tracking study and web-based visualization platform, (2) local school outreach activities, and (3) an academic knowledge exchange workshop.

2.2 Plastic dispersal modelling and interactive web-based application development

Existing hydrodynamic model outputs for Indonesia were used to conduct a Lagrangian particle tracking study in the region surrounding Sulawesi Island. The modelling exercise was designed to simulate the present-day pathways of marine plastic debris from source to sink. Hydrodynamic data covering one year (November 2020 - October 2021) was obtained from the HYCOM GOFS 3.1 Analysis model, with a spatial resolution of 1/12° and a temporal output resolution of 3 hours (https://www.hycom.org/dataserver/gofs-3pt1/analysis). HYCOM model is the US Navy's operational global ocean nowcast/forecast system including three-dimensional ocean temperature, salinity, and current structure, surface mixed layer depth, and the location of mesoscale features. For further information on the model set-up and application see Cummings and Smedstad, (2013) and Metzger et al., (2014). The eastward and northward water velocities within our selected domain (longitude: between 93° and 141°, latitude: between -14° and 10°) were downloaded from the HYCOM server and these velocities served as the hydrodynamic basis for the particle tracking simulations. These simulations were performed using the open-source Parcels model (Delandmeter and van Sebille, 2019). Two-dimensional

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(ocean surface layer) dispersal simulations were configured to release 80 virtual particles, representing neutrally buoyant plastic, from each of the 13 discrete locations representing major rivers mouths across the Sulawesi Island (Figure 1). These were released at 24-hour intervals over a span of three months (totalling 94,640 particles), run for both the wet and dry seasons. The two 90-day simulations represent surface ocean transport of plastic debris from coastal sources. We find this assumption to be acceptable as microplastic residence times in the surface ocean is estimated to be approximately 2.4 years (Weiss et al., 2021). Particles were 'deleted' once they hit or exceeded the model boundary, and thus assumed they did not return into the domain.

2.3 School Outreach Activities

The school outreach activities aimed to raise and assess awareness of plastic debris and climate change in Indonesia. Activities were conducted over three days in the Benteng Region, Selayar Island for 10-20 in-person university students from Bandung, and 20-30 remote students and researchers from across Indonesia in January 2022. These activities were attended by a total of 43-45 students and 18 teachers from six secondary schools around the capital, Benteng, alongside other participants from local NGOs (Selayar Bebas Sampah Plastik (SBSP)) and local government (Environment Department). These activities were covered by a local TV channel, LTTV, thus reaching a wide audience.

2.4 Academic Knowledge Exchange Workshop

The academic knowledge exchange workshop was designed to connect researchers between UK and Indonesia with a shared interest in simulating marine debris pathways, and to share methodology from the particle tracking modelling used here. We aimed to introduce and demonstrate the functionality of a numerical modelling tool for marine debris pollution examples to Indonesian university students and researchers through facilitating a three-day 'hybrid' workshop, conducted in person in Bandung, West Java (January 2022). The session was also available to researchers throughout Indonesia with interest in simulating marine litter dispersal in the marine environment.

This workshop, led and facilitated by Indonesia- and UK-based researchers, introduced the fundamentals of ocean modelling (day 1), and then introduced programming and particle tracking fundamentals (day 2). Following short demonstrations students then used these methods to apply to their own small research projects. All data and modelling tools were open-access, and the workshop tutorials remain free to view online to maintain a positive project legacy (https://bit.ly/marineplasticseminar).

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3. Results

3.1 Particle Tracking Study and Web-based visualisation platform

The particle tracking study was conducted to demonstrate the dispersal of marine litter in surface waters around Sulawesi Island and the impact of seasonality on this dispersal. During the wet season (November-March), the particles released tended to be transported eastwards of Sulawesi Island, and ultimately concentrating in the Ceram and Banda seas (Figure 2a). Conversely, in the dry season (April-October), the particles exhibited a wider distribution, spanning a larger area, with a notable proportion of particles accumulating to the west in the Java Sea (Figure 2c). Particles in the dry season had a longitudinal range of 47.9°, compared to particles in the wet season with a range of just 24.2°. Notably, both seasons' particle releases resulted in high concentrations of plastic around the coast of Sulawesi Island with over 30% of particles released concentrating around the northern coast of Sulawesi during the dry season (Figure 2d). No particles were simulated dispersing north or northeast into the South China Sea. There was a relatively limited dispersion of particles beyond the Indonesian regional seas throughout the three-month simulations. A total of 4720 particles, representing 2.5% of total particles released during both simulations, exited the domain.

Following the simulations, we created an open-access interactive visualization tool ("app") for non-modelers to explore simulated pathways of marine plastic debris around Sulawesi Island, and to compare the present coastline of Selayar Island against an approximated future coastline given 0.9 meters of sea level rise. The user is greeted with a "Welcome" page describing the project, then is guided through simulation parameter selection, including one of thirteen river mouth particle release sources, season, and days since release. For the data back end, we converted raw simulation matrices of shape ‘i’ sites by ‘j’ positions into "long" dataframes, where each row was a single latitude and longitude observation of a given particle at a given time step. We further divided the data into separate files by release source and dry season; upon user selection, the app loads only the appropriate file for animation to save memory. To improve app performance, we down-sampled data spatially (included one in eighty particle replicates) and temporally (reduced time steps from hourly to every two hours). The app is written in the R programming language (R Core Team, 2021), based on the open source R Shiny application framework (Chang et al., 2023), and presents interactive animated maps using an R wrapper for the Leaflet Javascript library (Cheng, Karambelkar and Xie, 2022). The app is hosted on a Shiny server and is accessible via https://rstudio.bangor.ac.uk/shiny/microplastics-indonesia/. Code for the application is accessible on GitHub via https://github.com/nwgiebink/microplastics-indonesia/tree/main.

3.2 School Outreach Activities

The first day commenced with a questionnaire to determine attendees' existing knowledge of marine plastic and its impacts, followed by an information session on marine plastic and climate change including how to use GPS and safely collect litter. Average scores of two initial questionnaires on the topics of marine/coastal litter and climate change were 50.16% and 51.56% respectively, allowing for activity facilitators to assess pre-existing knowledge and engage participants on these topics effectively. On the second day, the participants conducted a beach clean including collecting, sorting, and identifying plastic litter. The third day involved 'plogging', the combined activity of plastic litter picking while jogging along the coast, to continue to raise awareness and expand participants to include members of the general public (see local news coverage here: https://bit.ly/LTTVselayar).

3.3 Academic Knowledge Exchange Workshop

There were 12 in-person Academic Knowledge Exchange Workshop participants, and 20 online participants. The participants included undergraduate/postgraduate students, lecturers from several universities around Indonesia, as well as researchers and professionals. By the end of the workshop, 95% of the participants indicated that they had already benefited from attending the workshop and 96% of participants indicating the lesson material was 'good' or 'very good' (Figure 4).

To ensure that the benefits of this workshop extended beyond the immediate audience, the workshop was recorded and subsequently made freely available on YouTube (which now has over 1400 views at the time of writing). This decision not only allowed the original participants to revisit and reinforce the presented material but also opened the door for a wider audience to access and engage with marine litter transport modelling.

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4. Discussion

The main objective of this study was to create accessible tools and share knowledge on how ocean models can play a role in engaging diverse audiences on the issue of marine litter with an aim to increase awareness around this complex issue. From project conception to dissemination of results, we prioritised inclusivity and open access science through communicating advanced modern methods and engaging new audiences. As a result, we successfully demonstrated that surface-level plastic pollution concentrations around Sulawesi Island were strongly influenced by seasonal current direction related to the monsoon season. Irrespective of season, simulated plastic concentrations remained high around coastal areas of Sulawesi Island with the dry season seeing a greater longitudinal spread of particles. Results also indicated the impact of marine litter released from Sulawesi Island on individual regional seas differs between seasons with a greater amount of litter within the Java Seas during the dry season, and the Banda and Ceram seas during the wet season after six months of dispersal. These results, which highlight the important influence of the monsoon currents, agree with Van Der Mheen, Van Sebille and Pattiaratchi (2020) and provide an important regional perspective to marine litter. While knowledge on this topic is growing, greater effort needs to be made to communicate this information to key local practitioners, policymakers and social organisers who can fast-track impact within their local communities.

The models in this study were intentionally kept straightforward and open access, due to time limitations and the need to communicate the results clearly to all interested parties. Particle tracking simulations were kept two-dimensional, as very few buoyant particles are expected to fall out of the surface layer within 6 months (Weiss et al., 2021), and beaching and aggregation behaviour were not parametrized. As concentrations around Sulawesi Island remained high, future studies, including higher resolution ocean models, should look at the impact of beaching plastic on coastal environments and how this is also affected by varying monsoon currents and winds.

We were able to share the methods used through free and accessible workshops to provide local students and researchers with the ability to begin developing projects and answering research questions which are of local interest. To engage local young people in the issue of marine litter prior higher education through fun and unusual outreach activities including community litter picks and 'plogging' were also conducted in local schools to improve awareness and understanding of the issue. The project and its outcomes received positive feedback from attendees both during and after the activities. Moreover, the project's initiatives garnered a positive response from both local and international collaborators and participants during a virtual end-of-project meeting, which included project researchers, funding agencies, and local government officials. All parties involved in the project expressed satisfaction with the outputs and acknowledged the lasting impact it had achieved. The project development and funding structure brought together multidisciplinary teams with expertise in particle tracking, modelling, and visualization, alongside specialists in addressing marine litter issues within local communities, regional oceanography, and the model domain. This framework served as a conduit for the exchange of modelling and coding knowledge among international institutions,

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fostering a two-way dialogue to establish best-practice methodologies for engaging communities in tackling the marine litter crisis. This study underscores the indispensable contributions of both the UK and Indonesia teams to the project's success, demonstrating that innovative leadership and modern online collaboration tools can effectively minimize the environmental footprint associated with international travel. For future projects necessitating extensive international collaboration, a similar structure is recommended, ideally featuring shared formal leadership roles across participating countries.

To ensure continuous engagement with this important subject matter, the online visualization platform remains accessible and free of charge. This commitment helps to maintain open lines of communication surrounding the environmental issues addressed by the project. The project's lasting impact is evident through regular emails received from individuals, particularly students, who have discovered the workshop and visualization tool online and now express their interest in using these valuable resources themselves. This study, along with its outreach efforts, was carried out over a 12-week funding period. The impact and use of the tools, examples, and relationships established during this project have far surpassed the initial funding duration. We partly attribute this impact to our commitment to open science principles and our deliberate choice to employ accessible methodologies and data. Moving forward, we strongly recommend that funding bodies prioritize supporting international and cross-disciplinary teams that deliver accessible outputs. These principles have been proven to be socially, economically, and academically successful (Tennant et al., 2016). This becomes increasingly important as plastic pollution cements itself as fundamentally linked to other issues like climate change which require massive international collaboration if national and global emissions targets are to be met (Ford et al., 2022).

This project was developed as a pilot study. Further work is now required to communicate more comprehensive (e.g., long timescales, higher spatial resolution etc.) plastic pollution transport models to relevant interested parties. These methods can communicate regional and local variability of plastic pollution as well as the impact of current and future waste management methods. Due to the short timeframe, this study was unable to assess whether there was a long-term positive impact on the understanding of coastal pollution by activity and outreach participants. Future work using these methods should investigate how they can contribute to increased understanding and impact over longer timescales. Plastic transport studies also require greater analysis of how future environmental change may impact pollution transport which would support just and efficient adaptation measures.

5. Conclusion

This study aimed to increase awareness and knowledge of the complex issue of plastic debris in the Indonesia Seas. The project successfully used particle tracking models to simulate the pathways of marine plastic debris and to visualize the impact of seasonality on its dispersal around Sulawesi Island, Indonesia. Engaging local communities and schools in Selayar Island through outreach activities further contributed to raising awareness and understanding of marine litter and

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environmental change. The web-based visualization platform developed as part of this project facilitates accessible viewing and comprehension of the particle tracking results, promoting inclusivity in addressing environmental issues. The project's positive reception from diverse interested parties, both locally and internationally, highlights the significance of open access science and collaborative efforts in tackling plastic pollution. To enhance future similar initiatives, it is essential for funding bodies to prioritize supporting international and cross-disciplinary teams, like the ABCG (Academia-Business-Community-Government) model, that can deliver accessible outputs, enabling comprehensive research on plastic pollution and its relationship to other environmental challenges. As this project was a pilot study conducted within a limited timeframe, further efforts are required to communicate higher resolution plastic pollution transport models in a similar manner and analyse the impact of environmental changes on pollution transport on a larger scale. Ultimately, building upon the lessons learned from this project and fostering a lasting knowledge-sharing legacy will contribute to addressing regional marine litter issues more effectively in the future.

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Author Contribution

Conceptualisation: all authors; Particle Tracking Modelling: NHJ, SLW; App Development: NG, SLW, NHJ; Outreach and Workshops: NPP, MBP, IF, NHJ, DC; Writing – original draft: NHJ, SLW, DC.; Writing – review and editing: all authors.

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Conflict of Interest Statement

Conflict of Interest: None

Ethics Staement

This work received ethical approval from the faculty of Fishery and Marine Science, Universitas Padjadjaran.

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Figure 1

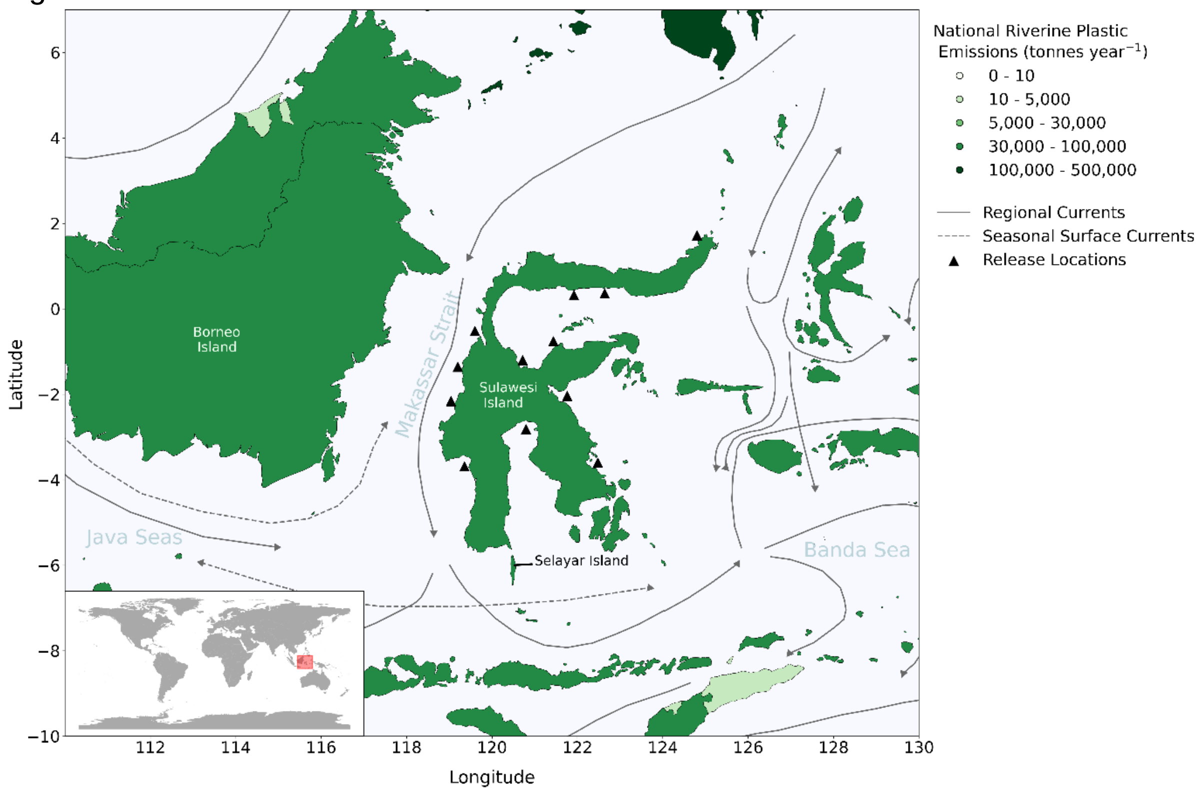

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Figure 2

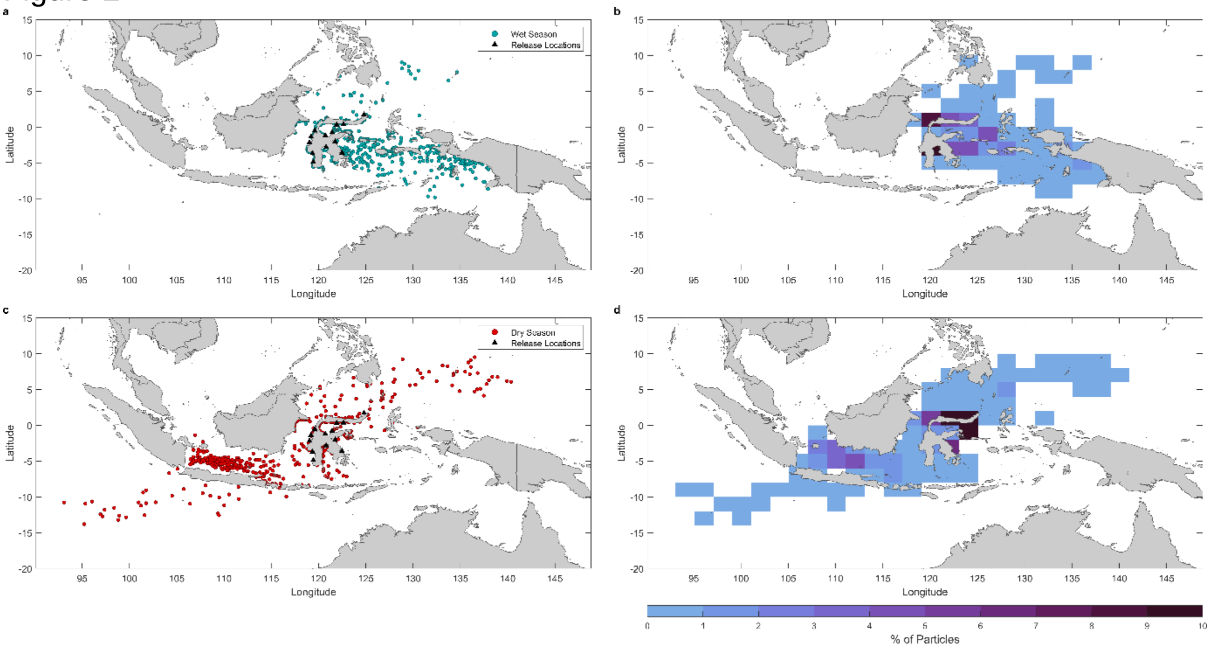

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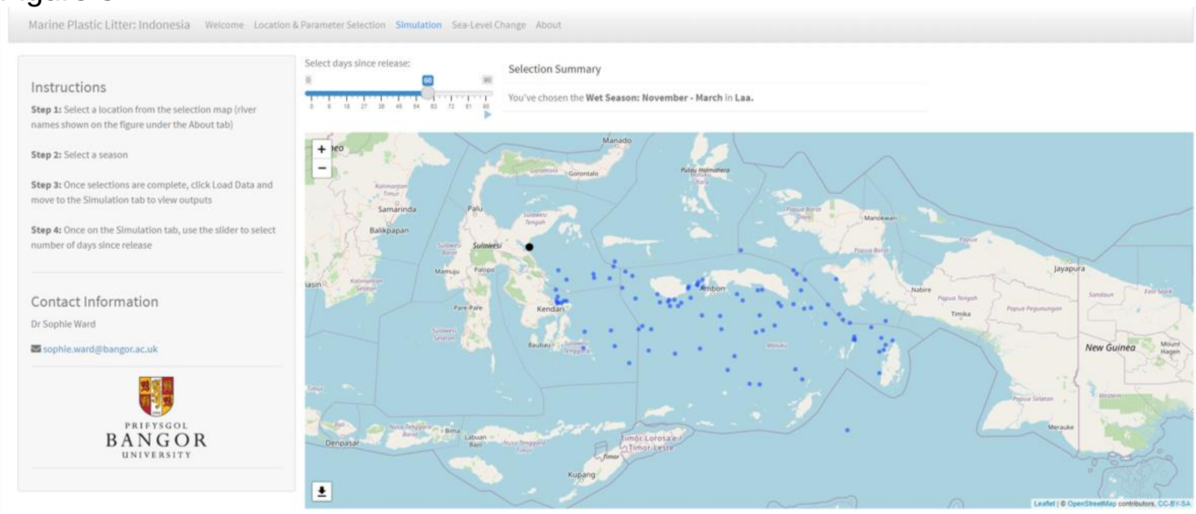
Figure 3



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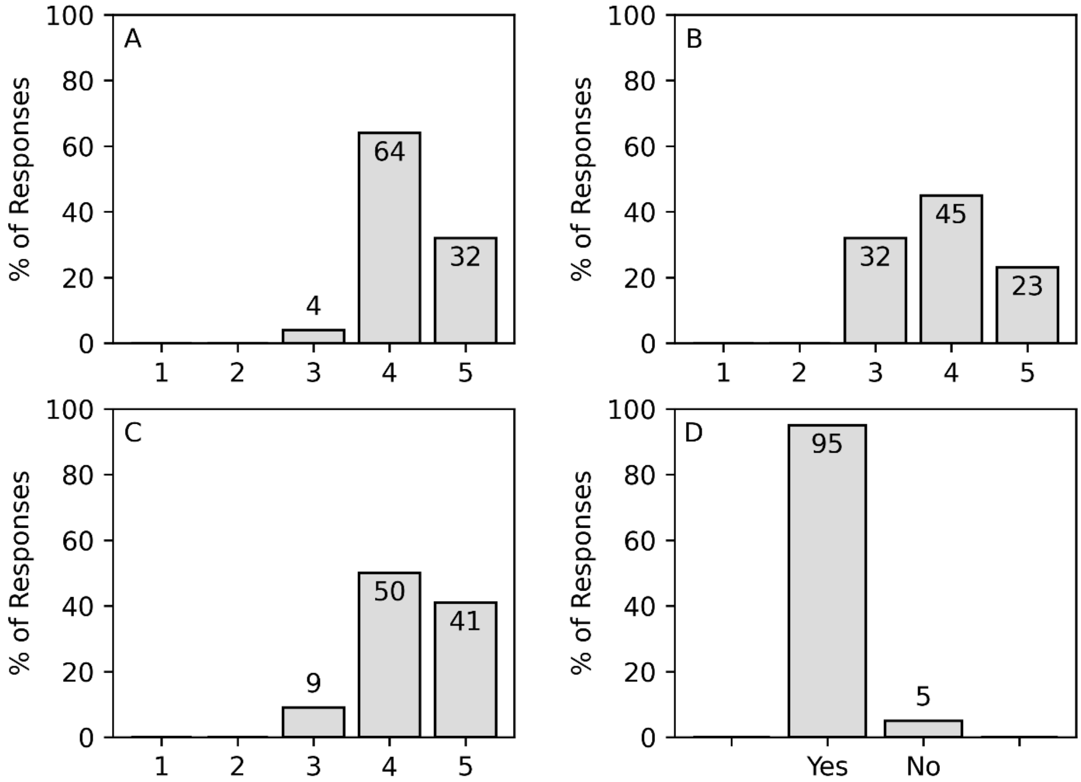
633 Figure 4



634

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