FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Exploratory Visual Data Analysis of Maritime Plastics Pollution Events

Ana Sofia Oliveira Teixeira

Mestrado em Engenharia Informática e Computação

Supervisor: Prof. Alexandre Miguel Barbosa Valle de Carvalho

February 13, 2026

© Ana Sofia Oliveira Teixeira, 2026

Exploratory Visual Data Analysis of Maritime Plastics Pollution Events

Ana Sofia Oliveira Teixeira

Mestrado em Engenharia Informática e Computação

Approved in oral examination by the committee:

President: Prof. António Fernando Vasconcelos Cunha Castro Coelho
Examiner: Prof. Hugo Alexandre Paredes Guedes da Silva
Supervisor: Prof. Alexandre Miguel Barbosa Valle de Carvalho

February 13, 2026

Resumo

A poluição marinha por plásticos, em particular a acumulação de resíduos plásticos, representa uma ameaça ambiental crescente, com consequências ecológicas e sociais significativas, afetando ecossistemas marinhos e atividades humanas dependentes destes. Devido à natureza complexa, dinâmica e de grande escala dos dados oceanográficos, a análise e interpretação da distribuição e dispersão de plásticos continua a ser um grande desafio. Técnicas eficazes de visualização são, por isso, essenciais para apoiar a análise exploratória, melhorar a compreensão de padrões espaçotemporais e informar a tomada de decisão por públicos diversos.

Esta dissertação investiga a aplicação da análise exploratória de dados visuais à poluição marinha por plásticos, com foco na dispersão de plásticos nos oceanos. Foi realizada uma revisão sistemática da literatura, seguindo a diretriz PRISMA, que analisou modelos de transporte de plásticos, simulações numéricas e visualização de dados oceanográficos. A revisão identificou técnicas de visualização comuns, principais tarefas analíticas e limitações nos métodos atuais e na avaliação centrada no utilizador, as quais informaram os requisitos do sistema.

Com base nestes resultados, foi desenvolvido um protótipo de visualização interativo para a web, utilizando HTML, CSS, JavaScript e a biblioteca *Leaflet*. O protótipo integra dados de simulação *OpenDrift*, incorporando correntes marinhas, vento e condições de ondulação referentes a janeiro de 2020. Vários modos de visualização (animações de partículas, mapas de calor e representações vetoriais) apoiam a exploração da dispersão de plásticos em diferentes regiões e fontes, incluindo zonas costeiras, fluviais, atividades de pesca e praias. A interface foi concebida com foco na usabilidade, legibilidade e acessibilidade.

O protótipo foi avaliado com 32 participantes, recorrendo a métricas quantitativas, métodos qualitativos, questionários padronizados (SUS e PREVis) e registo dos movimentos do rato. Os resultados indicam uma elevada usabilidade e legibilidade globais. O desempenho nas tarefas não apresentou uma relação significativa com o conhecimento prévio do domínio ou com a literacia informática, demonstrando um apoio eficaz a utilizadores não especialistas. Os desafios identificados incluíram a interpretação das legendas, a perceção das cores e a complexidade de algumas codificações visuais.

Esta investigação demonstra o valor de uma avaliação multimétodo, contribui para a compreensão da interação de utilizadores não especialistas com visualizações ambientais e fornece orientações práticas de *design*. Trabalhos futuros incluem o aperfeiçoamento iterativo do protótipo, a incorporação de processos ambientais adicionais e o suporte para comparações globais e multirregionais.

Palavras-chave: Visualização da Informação, Visualização da Poluição Marinha, Visualização Científica, Análise Espaçotemporal, Sistemas de Monitorização de Partículas, Visualização Interativa, Dispersão de Plásticos

Abstract

Marine plastic pollution, particularly the accumulation of plastics, represents a growing environmental threat with significant ecological and societal consequences, affecting both marine ecosystems and human activities that depend on them. Due to the complex, dynamic and large-scale nature of oceanographic data, analysing and interpreting plastic distribution and dispersion remains a major challenge. Effective visualisation techniques are therefore essential to support exploratory analysis, improve understanding of spatiotemporal patterns and inform decision-making for diverse audiences.

This dissertation investigates the application of exploratory visual data analysis to marine plastic pollution, focusing on plastic dispersion in ocean environments. A systematic literature review following PRISMA guidelines examined plastic transport modelling, numerical simulations and oceanographic data visualisation. The review identified common visualisation techniques, key analytical tasks and limitations in current methods and user-centred evaluation, which informed the system requirements.

Based on these findings, an interactive web-based visualisation prototype was developed using HTML, CSS, JavaScript and the *Leaflet* library. The prototype integrates *OpenDrift* simulation data incorporating ocean currents, wind and wave conditions from January 2020. Multiple visualisation modes (particle animations, heatmaps and vector representations) support exploration of plastic dispersion across regions and sources, including coastal, riverine, fishing-related and beach. The interface was designed with a focus on usability, readability and accessibility.

The prototype was evaluated with 32 participants using quantitative metrics, qualitative methods, standardised questionnaires (SUS and PREVis) and mouse tracking. Results indicate high overall usability and readability. Task performance was not significantly related to prior domain knowledge or computer literacy, demonstrating effective support for non-expert users. Identified challenges included legend interpretation, colour perception and the complexity of certain visual encodings.

This research demonstrates the value of multi-method evaluation, contributes to understanding non-expert interaction with environmental visualisations and provides practical design guidance. Future work includes iterative refinement, incorporation of additional environmental processes and support for global and multi-region comparisons.

Keywords: Information Visualisation, Marine Pollution Visualisation, Scientific Visualisation, Spatiotemporal Analysis, Particle Tracking Systems, Interactive Visualisation, Plastic Dispersion

UN Sustainable Development Goals

The Sustainable Development Goals (SDGs) are objectives adopted by the United Nations in 2015 with the aim of being achieved by 2030. These goals seek to eradicate poverty and protect the planet by balancing social, economic and environmental sustainability.

The work presented in this dissertation makes a modest contribution to achieving a small portion of these broader goals, ultimately working toward a better future for the world.

The specific Sustainable Development Goal addressed in this project is as follows:

SDG 14 Life Below Water: Protect and manage the oceans, seas, and marine resources

The specific contributions of this project are described in the table below.

SGD	Target	Contribution	Performance Indicators and Metrics
14	14.1	One of the indirect impacts of this project is its potential to help visualise information aimed at reducing plastic concentrations in the ocean	The creation of visualisations to effectively observe and analyse data on the distribution of plastics in the ocean
	14.2	An indirect impact of this project could be utilising this work to contribute to the protection of marine and coastal ecosystems	Creating visualisations of plastic dispersion provides insights into pollution's impact and supports conservation efforts
	14.5	An indirect impact of this project could be using it to provide valuable information for the conservation of coastal and marine areas	Development of visualisations and their effectiveness in simulating plastic dispersion
	14.8	This would be the primary contribution of this work, as the project developed aims to enhance the understanding of plastic distribution in the ocean. It would have a significant impact on how researchers can visually analyse large amounts of data, enabling them to monitor and even simulate conditions to predict future behaviours	The creation of new information and valuable research, along with the development of visualisation technologies for plastic monitoring
	14.A	One of the indirect impacts of this project is to assist in the visualisation of information crucial for implementing and enforcing international maritime law	Development of visualisations that simulate plastic dispersion and provide data for informed decision-making

Acknowledgements

As I reach the final stage of this dissertation, marking the conclusion of a year's work and of a course that has challenged me considerably, I am grateful for having chosen the optional curricular units most suited to my interests. The path that led me to this topic began in one of the units I most enjoyed throughout my degree. In that unit, I was introduced to three distinct Advanced Topics in Interaction and Multimedia.

Although I initially focused that semester on my second favourite topic, I had always known that my first choice was the one that truly captured my interest. Since I was drawn to this topic, I asked Professor Alexandre Valle de Carvalho, who had introduced it, to supervise my dissertation. I can only thank him for taking a chance on me, even when it seemed an unpromising choice at the outset. Now, as I complete this work, I know that I could not have chosen a topic more aligned with my interests, nor found supervision that fitted so well with what I value most. Thank you sincerely for your guidance, your constant attention and your consistent presence throughout this process, which allowed me to appreciate this area of informatics all the more deeply.

To the 2+32 individuals who generously devoted twenty minutes of their time to testing my prototype and who took the task seriously, I extend my sincere thanks. This work was only possible because of your collaboration.

I would also like to express my gratitude to INESC TEC for the support and resources that contributed to this dissertation.

As I bring my course at FEUP to a close, I wish to extend my acknowledgements to reflect my entire journey. To my friends, thank you for your support, encouragement and companionship throughout these years. To my family, my deepest gratitude for your unconditional support, for the education and values that have shaped me and for inspiring me to reach further than I ever thought possible. Your guidance and belief in me have been the foundation of my academic journey and have made this milestone possible.

Sofia Teixeira

"Recomeça....
Se puderes,
Sem angústia e sem pressa"

Miguel Torga, Sísifo

This dissertation was written and edited by the student. To improve the clarity and accuracy of the English language, which is not the student's native language, the text was subsequently refined with the assistance of a large language model (LLM). All ideas, arguments and content remain entirely the work and authorship of the student. Original drafts of the text can be provided upon request by contacting the student.

Contents

1 Introduction **1**
- 1.1 Context and Motivation . . . 1
- 1.2 Problem Identification . . . 2
- 1.3 Research Questions . . . 2
- 1.4 Dissertation Structure . . . 3

2 Literature Review **4**
- 2.1 Introduction . . . 4
- 2.2 Data Sources . . . 4
- 2.3 Search Query Refinement . . . 6
- 2.4 Search Process . . . 7
- 2.5 Inclusion and Exclusion Criteria . . . 8
- 2.6 Identification . . . 9
- 2.7 Results . . . 10
  - 2.7.1 Content Assessment . . . 10
  - 2.7.2 Quality Assessment . . . 12
- 2.8 Critical Analysis . . . 13
  - 2.8.1 Trends and Patterns . . . 13
  - 2.8.2 Gaps Identified . . . 14
- 2.9 Summary . . . 15

3 State of the Art **16**
- 3.1 Introduction . . . 16
- 3.2 Numerical Modelling . . . 16
  - 3.2.1 Lagrangian Particle Tracking Models (LPTMs) . . . 16
  - 3.2.2 Eulerian Transport Models (ETMs) . . . 17
  - 3.2.3 Lagrangian vs Eulerian Models . . . 17
  - 3.2.4 Transport Model Frameworks . . . 17
  - 3.2.5 Influence of Input Data on Models . . . 18
- 3.3 Influencing Factors of Plastic in the Ocean . . . 18
  - 3.3.1 Advection by Currents . . . 19
  - 3.3.2 Turbulent Dispersion . . . 19
  - 3.3.3 Wind Action . . . 20
  - 3.3.4 Beaching and Refloating . . . 20
  - 3.3.5 Fragmentation and Size Distribution . . . 20
  - 3.3.6 Interaction with Chemical Contaminants . . . 21
- 3.4 Visualisation of Oceanographic and Environmental Data . . . 21
  - 3.4.1 Common Data Types . . . 21

3.4.2 Tools . . . 21
3.4.3 Visualization Techniques Applied to Ocean Plastic Pollution . . . 23
3.5 Summary . . . 30

4 Approach **31**
4.1 Introduction . . . 31
4.2 User-Centered Design Considerations . . . 31
4.3 Solution Requirements . . . 34
4.3.1 Taxonomy Table of Topics . . . 34
4.3.2 Narrowing to Design Objectives . . . 35
4.3.3 Final Selection . . . 40
4.4 Design Process . . . 42
4.4.1 Low-Fidelity Prototyping . . . 42
4.4.2 High-Fidelity Prototyping (Mockups) . . . 43
4.5 Functional Prototype . . . 50
4.5.1 Technology Selection . . . 52
4.5.2 Database Design . . . 53
4.5.3 Prototype Development . . . 58
4.6 Summary . . . 65

5 Experimental Design **68**
5.1 Introduction . . . 68
5.2 Objectives of Usability Testing . . . 68
5.3 Participants . . . 69
5.3.1 Target Population . . . 69
5.3.2 Recruitment . . . 69
5.3.3 Collected Characteristics . . . 69
5.3.4 Sample Size . . . 69
5.3.5 Ethical Considerations . . . 69
5.4 Test Design Methodology . . . 70
5.4.1 Study Design . . . 70
5.4.2 Evaluation Methods . . . 70
5.4.3 Variables . . . 71
5.4.4 Data Types . . . 71
5.5 Tasks . . . 71
5.5.1 Task Design . . . 71
5.5.2 Task Descriptions . . . 71
5.6 Test Moderator . . . 74
5.7 Apparatus . . . 75
5.7.1 Hardware and Software . . . 75
5.7.2 Experimental Materials . . . 75
5.8 Experiment Protocol . . . 75
5.9 Pilot Tests . . . 76
5.10 Summary . . . 76

6 Results and Discussion **77**
6.1 Introduction . . . 77
6.2 Outliers Identification . . . 77
6.3 Participant Overview . . . 79
6.4 Quantitative Results (Summative) . . . 80
6.4.1 Task Performance . . . 83
6.4.2 Mouse Tracking Analysis . . . 91
6.4.3 Accessibility Challenges . . . 96
6.4.4 System Usability Scale (SUS) . . . 99
6.4.5 Perceived Readability Evaluation for Visualizations (PREVis) . . . 101
6.4.6 Observed System Errors . . . 103
6.5 Qualitative Results (Formative) . . . 104
6.5.1 Participant Feedback . . . 104
6.5.2 Observed Behaviors . . . 107
6.6 Discussion . . . 109
6.6.1 Task Performance and Data Interpretation . . . 110
6.6.2 Usability and User Acceptance . . . 110
6.6.3 Perceived Readability . . . 111
6.6.4 The Legend . . . 111
6.6.5 Visualisation Mode and Interface Design . . . 111
6.6.6 Interaction Behaviour . . . 112
6.6.7 Accessibility . . . 112
6.6.8 Technical Performance . . . 113
6.6.9 Contributions and Significance . . . 113
6.7 Summary . . . 114

7 Conclusions **115**
7.1 Addressing Research Questions . . . 115
7.2 Limitations . . . 117
7.3 Final Remarks . . . 118
7.4 Future Work . . . 119

References **121**

A Quality Assessment - Problem **128**

B Quality Assessment - Approach **134**

C Quality Assessment - Method/Experimentation **141**

D Quality Assessment - Dataset **150**

E Quality Assessment - Technologies **156**

F Quality Assessment - Limitations **163**

G Quality Assessment - Validation **170**

H Questionnaires **177**

I Moderator Guide **197**
I.1 Before the Session 197
I.2 Welcome Script 197
I.3 Questionnaire 198
I.4 Familiarization Phase 198
I.5 Task Instructions 198
I.6 During Tasks 198
I.7 Debrief Script 199

List of Figures

2.1 PRISMA Workflow for the Systematic Literature Review. 5
2.2 Number of Articles Published per Year. 10
2.3 Number of Articles per Publishing Platforms. 11
2.4 Number of Conferences per Country. 12
2.5 Word Cloud with the Most Frequent Occurring Keywords. 12

3.1 3DGIS Interface Visualised with Cesium [32]. 23
3.2 Overview of the COVE System [29]. 24
3.3 Example Interface of the COVERAGE Data Viewer [48]. 24
3.4 Main Visualisation Interface of the CleanUpOurWorld Platform [44]. 24
3.5 Comparison of Flow Field Representation Methods [49]. 25
3.6 Priority Area Maps (PAMs) for different stakeholders [23]. 26
3.7 3D Dynamic Visualisation of Ocean Oil Spills [36]. 27
3.8 Overview of the OceanVive Immersive System [39]. 29
3.9 Web-based Visualisation Platform for Plastic Particle Tracking Results [24]. . . . 29

4.1 Design Framework. 32
4.2 PlasticAdrift Web Interface [54]. 33
4.3 Copernicus MyOcean Pro Viewer Interface [55]. 33
4.4 Low-Fidelity Prototype. 43
4.5 First Screen. 44
4.6 Study Selection Screen. 44
4.7 Region Selection Screen. 45
4.8 Animation Screen 1. 46
4.9 Animation Screen 2. 46
4.10 Animation Screen 3. 47
4.11 Animation Screen 4. 47
4.12 Map Screen. 48
4.13 Map Screen Sidebar 1. 48
4.14 Map Screen Sidebar 2. 49
4.15 Map Screen Sidebar 3. 49
4.16 Colour Screen. 50
4.17 Colour Screen Info. 51
4.18 Particle Screen. 51
4.19 Vector Screen. 52
4.20 plasticParcels simulation. 55
4.21 OpenDrift simulation. 57
4.22 Package Diagram. 58

4.23 Class Diagram. 59
4.24 plasticParcels Initial Map Integrations with Leaflet. 60
4.25 Prototype Map with Controls. 61
4.26 Initial legend and Colour Mapping. 61
4.27 Adjusted Legend with Regional Value Scaling. 62
4.28 Heatmap View. 63
4.29 Animation View of OpenDrift Simulation. 63
4.30 Final Colour Scale and Dark Mode. 64
4.31 Accessibility Features. 65
4.32 Mouse Event Tracking Tool Class Diagram. 66

6.1 Boxplot of Overall SUS Score. 78
6.2 Boxplot of Score by each PREVis Scale. 79
6.3 Pie Chart Count of Gender. 79
6.4 Boxplot of Age. 80
6.5 Bar Count of Education Level. 81
6.6 Bar Count of Occupation or Study Field. 81
6.7 Stacked Bar Count of Background Knowledge by Score. 82
6.8 Bar Count of Accessibility Problem Type. 82
6.9 Bar Count of Responses for Task A. 84
6.10 Bar Count of Responses for Task B. 84
6.11 Bar Count of Responses for Task C. 85
6.12 Frequency of Incorrect Responses per Participant. 86
6.13 Completion Time Analysis per Task: (top) Boxplots and (bottom) Stacked Histogram of Response Time Frequencies. 87
6.14 Heatmap of Spearman Correlations between Domain Knowledge Variables and Task Performance. 89
6.15 Task Completion Time by Accuracy for Each Task. 90
6.16 Heatmap of Spearman Correlations between Number of Help Requests and Task Performances. 92
6.17 Aggregated Mouse Cursor Heatmap. 94
6.18 Heatmap of Click Events for All Participants. 95
6.19 Heatmap of User Hesitation. 96
6.20 Reported Colour Perception Difficulties Among Participants. 97
6.21 Reported Reading and Comprehension Difficulties Among Participants. 98
6.22 SUS Scores per Question. 100
6.23 PREVis Scores per Question. 102

List of Tables

1.1 Research Questions. . . . 2

2.1 Search Queries. . . . 7
2.2 Number of Search Query Results Across Data Sources. . . . 8
2.3 Impact of Year Filter on Article Count. . . . 8
2.4 Impact of Keyword Filter on Article Count. . . . 9

4.1 Taxonomy Table of Topics. . . . 35
4.2 Design Objectives. . . . 39
4.3 Final Selection. . . . 41
4.4 Summary of Datasets. . . . 56

6.1 Task accuracy results for Tasks A, B and C. . . . 83
6.2 Distribution of the number of incorrect responses. . . . 85
6.3 Descriptive Statistics for Task Completion Times (in minutes). . . . 86
6.4 Spearman's ρ Correlations between Domain Knowledge Variables (N = 32). . . . 88
6.5 Spearman's ρ Correlations between Number of Help Requests and Task Accuracy (N = 32). . . . 91
6.6 Cross-tabulation of Self-Reported Colour Blindness and Experienced Colour-Related Difficulties (N = 32). . . . 98
6.7 Transposed Cross-Tabulation of Dyslexia Status and Reported Reading-Related Difficulties (N = 32). . . . 99
6.8 Descriptive Statistics for SUS items 1–10. . . . 100
6.9 Descriptive Statistics for SUS Overall Score. . . . 101
6.10 Descriptive Statistics for PREVis Questionnaire Items. . . . 101
6.11 Descriptive Statistics for PREVis Scales. . . . 103
6.12 Spearman's ρ correlations between pre-visualization measures and total correct responses (N = 32). . . . 103

A.1 Problem per Article. . . . 133

B.1 Approach per Article. . . . 140

C.1 Method/Experimentation per Article. . . . 149

D.1 Dataset per Article. . . . 155

E.1 Technologies per Article. . . . 162

F.1 Limitations per Article. . . . 169

G.1 Validation per Article. 176

List of Acronyms

2D	Two-Dimentional
3D	Three-Dimentional
4D	Four-Dimentional
ACM	Association for Computing Machinery
AI	Artificial Intelligence
AR	Augmented Reality
CSV	Comma-Separated Values
CMV	Coordinated Multiple Views
ETM	Eulerian Transport Model
FFT	Fast Fourier Transform
GIS	Geographic Information System
GPU	Graphics Processing Unit
IEEE	Institute of Electrical and Electronics Engineers
LCS	Lagrangian Coherent Structures
LLM	Large Language Model
LPTM	Lagrangian Particle Tracking Model
MP	Microplastic
NEMO	Nucleus for European Modelling of the Ocean
OpenGL	Open Graphics Library
OSG	OpenSceneGraph
PAM	Priority Area Map
PREVis	Perceived Readability Evaluation for Visualizations
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
ROMS	Regional Ocean Modeling System
RQ	Research Question
SDG	Sustainable Development Goal
SST	Sea Surface Temperature
SUS	System Usability Scale
UN	United Nations
USA	United States of America
VR	Virtual Reality
WebGIS	Web-based Geographic Information System
WebGL	Web Graphics Library
WebGPU	Web Graphics Processing Unit
WWW	*World Wide Web*
XML	Extensible Markup Language
XR	Extended Reality

Chapter 1

Introduction

1.1 Context and Motivation

Plastic, first discovered in the early 20th century, has become the most widely used material by humans [1] due to its affordability and versatility. Many traditional materials such as wool, iron and glass have been replaced by plastic across various industries. Its applications span a wide range of areas, including packaging, consumer goods, healthcare, construction, transportation, textiles, agriculture and fishing. Humans come into contact with plastic primarily through cosmetics, dietary consumption, dust particles and direct use of plastic products [2].

However, plastic pollution has emerged as a significant environmental issue, particularly affecting aquatic ecosystems. Plastics from various industries and daily use are frequently disposed of inappropriately, leading to their accumulation in lakes, rivers and oceans. Since plastic does not decompose easily, it remains in those water bodies for extended periods, exposed to environmental agents such as ocean gyres, wind and weather conditions. These forces contribute to the breakdown of larger plastic materials into smaller fragments, known as microplastics.

Microplastics are classified as particles in size from 1μm to 5mm. They originate from two main sources: primary microplastics, which are manufactured at small sizes, such as microbeads in cosmetics and secondary microplastics, which result from the degradation of larger plastic items, according to Issac and Kandasubramanian [2]. These microplastic particles are distributed across ocean surfaces and water columns, with some sinking into sediments due to their relative density, increasing their concentration in marine environments.

The accumulation of plastic is particularly severe in certain geographic locations, where oceanic currents create garbage patches. These are areas where plastic waste congregates in vast quantities. Some of the most well-known include the Great Pacific Garbage Patch (between Hawaii and California), the North Atlantic Garbage Patch (between the United States of America East Coast and Europe) and the South Pacific Garbage Patch (off the coast of South America). Additionally, regions with higher population densities and advanced industrial activities contribute significantly to water pollution, further deteriorating marine ecosystems [1].

1.2 Problem Identification

Plastic and microplastic pollution have far-reaching environmental and biological consequences. Microplastics alter marine habitats, disrupt food consumption patterns in animals and interfere with the broader food chain. These particles provide surfaces for microbial growth and are often mistaken for food by marine organisms due to their appearance and smell [2].

Microplastics are also a growing concern for human health. Although research is still in its early stages, studies have detected microplastic particles in human placenta and suggested potential links to reproductive, digestive and respiratory health issues, including a possible correlation with colon cancer [3]. Despite growing awareness, the harmful impacts of microplastics remain underexplored.

Assessing the microplastic dispersion behaviour is crucial because microplastic pollution is an escalating environmental crisis with direct implications for marine ecosystems and human health. The presence of these particles in the ocean is widespread, yet their detection and monitoring remain a challenge. Addressing this issue is relevant for policymakers, environmental scientists and public health researchers. Identifying an effective method for visualising plastics at both macro and micro levels can significantly aid in mitigation strategies.

Beyond monitoring, advanced visualisation techniques can also play a critical role in simulating scenarios to predict how plastics disperse over time, how they accumulate in different environments and what interventions may be most effective. By using imaging technologies and computational models, researchers can gain insights into the movement of plastics in marine systems, assess the impact of potential policy measures and develop targeted cleanup efforts.

1.3 Research Questions

To further investigate the issue and expand knowledge on the visualisation techniques for addressing plastic dispersion in the ocean, the topic can be divided into the research questions presented in Table 1.1.

RQ1	What visual information techniques are currently used in this context and are there comparable approaches in other domains?
RQ2	What techniques and methods are employed to create both macro and micro visualisations?
RQ3	What tasks are considered essential in the process of visualising plastic data over time?
RQ4	How can environmental and weather factors be visually represented to enhance scenario simulations?

Table 1.1: Research Questions.

By addressing these questions, this study seeks to contribute to the development of better monitoring and mitigation strategies for plastic pollution, helping to protect marine ecosystems and public health. Additionally, integrating these visual techniques into simulation models will

enhance understanding of plastic distribution patterns, aiding in the development of proactive environmental policies and interventions.

1.4 Dissertation Structure

In addition to this introductory chapter, this dissertation is organised into six additional chapters.

Chapter 2 presents a systematic literature review conducted in accordance with the PRISMA methodology, providing an overview of existing research on plastic pollution, numerical modelling and visualisation techniques. This chapter establishes the theoretical foundation for the study and identifies gaps in the current literature.

Chapter 3 presents the state of the art, building on the literature review through a thematic analysis of plastic transport mechanisms in the ocean, numerical modelling approaches and visualisation methods applied to marine pollution data.

Chapter 4 describes the proposed approach, including user-centred design considerations, system requirements, the design process and the development of the visualisation prototype.

Chapter 5 details the experimental design, outlining the objectives, participants, methodology, tasks and evaluation procedures used to assess the developed prototype.

Chapter 6 presents and discusses the results obtained from the experimental evaluation, combining quantitative and qualitative analyses to interpret usability, performance and accessibility outcomes.

Chapter 7 concludes the dissertation by addressing the research questions, summarising the main contributions, discussing limitations and outlining directions for future work.

Chapter 2

Literature Review

This chapter describes the work carried out to complete the literature review for this dissertation. The literature review provides an overview of published works on a specific topic, enabling the identification of current knowledge, relevant theories, research methods and gaps in the existing literature.

2.1 Introduction

This systematic literature review was conducted following the PRISMA [4] (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. While the process was adapted to align with the specific requirements of this dissertation, the principles of PRISMA were consistently followed to ensure methodological rigour. The following sections present the structure of the literature review, along with the content and quality assessments carried out to extract as much relevant information as possible. These steps were essential in supporting the development of the state of the art section of this dissertation.

Figure 2.1 illustrates the PRISMA workflow followed in this systematic literature review. The diagram outlines the main stages of the process, including study identification, screening, eligibility assessment and final inclusion and shows how records were progressively filtered according to predefined criteria. Sections 2.2 to 2.6 provide a detailed description of each stage of this process.

2.2 Data Sources

The initial phase of the literature search was carried out using Google Scholar [5], which provides a broader range of results and has a search style more similar to what someone without a research background might be used to. During this stage, it became easier to recognise certain patterns, such as which keywords produced more relevant results and which ones led to a more scattered and less useful set of articles.

After these initial tests, the search process moved to IEEE Xplore [6] to become more familiar with a research-focused database. Some initial queries were used to check whether the results

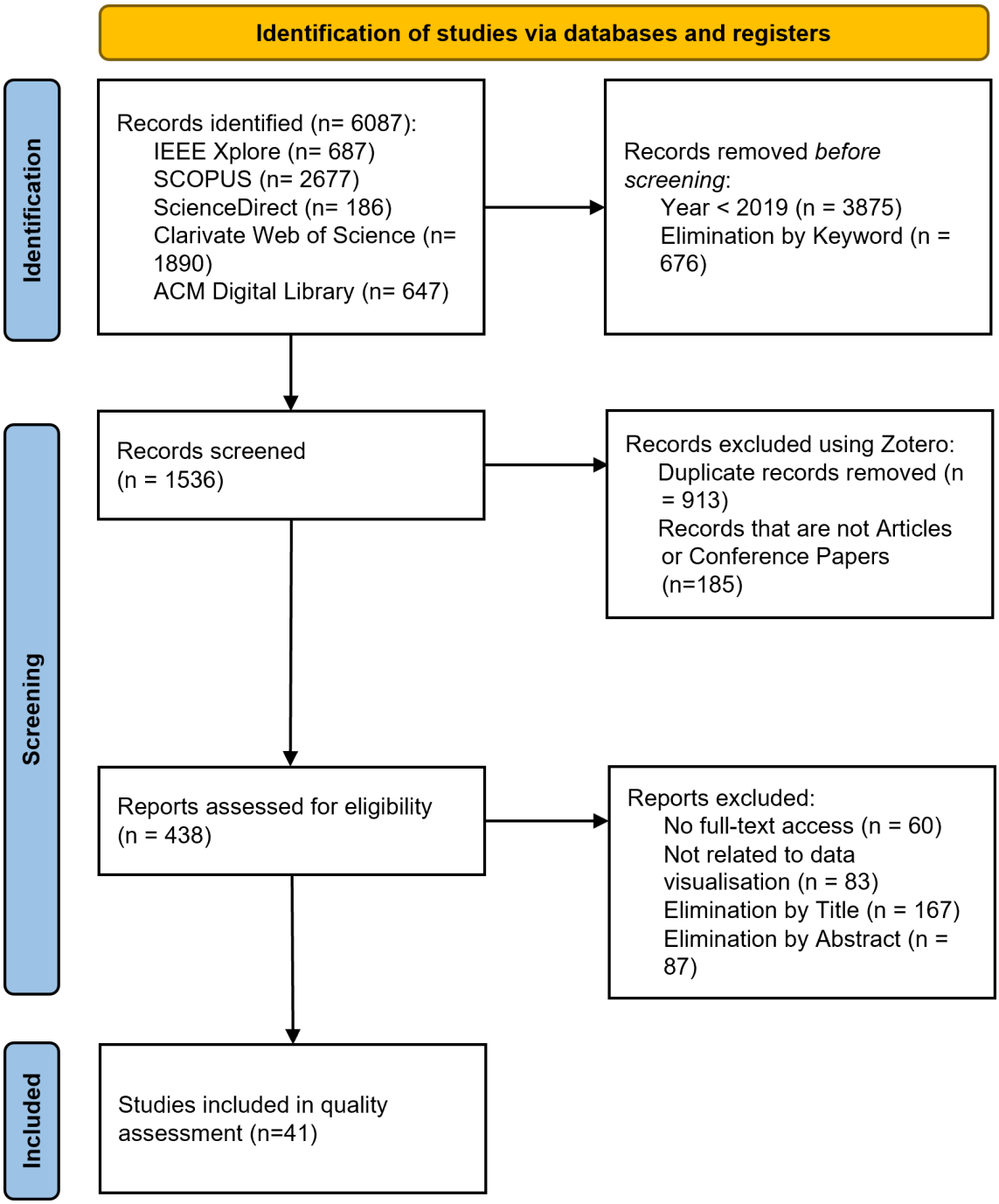


Figure 2.1: PRISMA Workflow for the Systematic Literature Review.

were similar to those found through Google Scholar or if there were clear differences. The queries were then refined and following this, the range of databases used was expanded. In addition to Google Scholar and IEEE Xplore, the search was extended to include SCOPUS [7], ScienceDirect [8], Clarivate Web of Science [9] and the ACM Digital Library [10].

2.3 Search Query Refinement

The formulation of search queries was initiated with the primary objective of addressing the research questions presented in the previous chapter. From these research questions, a set of key compound terms was extracted to guide the retrieval of relevant literature.

Initial tests were conducted using Google Scholar and IEEE Xplore with the following search queries:

1. Temporal Scientific Visualisation
2. Spatio Temporal Scientific Visualisation
3. Oil Spill Visualisation
4. Dispersion Scientific Visualisation
5. Scientific Visualisation Meteorological Factors
6. Scientific Visualisation of Plastics
7. Visualisation of Floating Objects

These initial tests revealed that several of the search terms were too broad or inadequately specified. The first two queries produced an excessive number of results, many of which were outside the scope of this study. The third query was more effective and provided insight into relevant approaches in analogous domains. The fourth query was also overly general. The fifth query was the result of a translation error during the formulation process. Due to incorrect phrasing in English, the query did not accurately reflect the intended concept and, as a result, produced only a small number of relevant results. The sixth query returned limited but relevant material. Notably, the seventh query proved to be among the most productive. Based on the insights gained from this preliminary phase, additional search terms were developed and refined to improve the relevance and specificity of the results. The improved terms include:

1. Scientific Visualisation Meteorological Data
2. Scientific Visualisation Marine Pollution
3. Contour Visualisation Plastic Dispersion
4. 3D Oceanographic Data Visualisation

5. Modelling Plastic Dispersion
6. Ocean Pollution Dynamic Visualisation Techniques
7. Volume Rendering Ocean Pollution
8. Ocean Visualisation Particle System Dispersion

At this stage, more concrete and relevant results were obtained. Consequently, the refined terms were transformed into effective search queries, better suited for use in advanced academic databases. In the initial phase, each of the eight revised phrases was individually converted into specific search queries. However, upon reviewing them collectively, it became evident that some of the queries could be combined without altering their intended meaning. This allowed for a reduction in the total number of queries required while still preserving the breadth and relevance of the results. The final set of queries presented in Table 2.1 reflects this consolidation and optimisation process.

SQ1	"scientific visuali?ation" AND ("meteorological data" OR "climate data" OR "weather data")
SQ2	(visuali?ation OR "data visuali?ation") AND ("ocean pollution" OR "marine debris" OR "plastic pollution")
SQ3	("contour visuali?ation" OR "3D visuali?ation" OR "volume rendering") AND (ocean* OR marine)
SQ4	(model* OR simulation OR "particle system*") AND ("plastic dispersion" OR microplastics OR "plastic pollution") AND (ocean* OR marine)
SQ5	("dynamic visuali?ation" OR "temporal visuali?ation" OR animation) AND (ocean* OR marine)

Table 2.1: Search Queries.

2.4 Search Process

The search process was carried out individually within each selected data source, requiring some adaptation of the queries to match the specific requirements and limitations of each platform. The initial iteration of results, along with the number of results retrieved from each database, is presented in Table 2.2.

For IEEE Xplore, the queries were used exactly as described in the table 2.1. In SCOPUS, the searches were conducted within the article title, abstract and keywords. For ScienceDirect, wildcard characters are not supported therefore, the terms were used in their singular form. Additionally, the search was limited to the title, abstract and author-specified keywords with the access type filtered to include only "Open access & Open archive" content. In Clarivate Web of Science, the queries were applied as specified in table 2.1. For the ACM Digital Library, the term "animation" had to be excluded from the search query. Including that term resulted in an overwhelming number of irrelevant results (2618), compared to a more focused and relevant set of 98 results

Search Query	Data Source				
	IEEE Xplore	SCOPUS	ScienceDirect	Clarivate Web of Science	ACM Digital Library
SQ1	15	15	85	15	114
SQ2	64	55	25	43	77
SQ3	208	287	10	351	250
SQ4	124	1795	26	951	77
SQ5	276	525	40	530	99
Total	687	2677	186	1890	617

Table 2.2: Number of Search Query Results Across Data Sources.

when the term was removed. The majority of results, including "animation", were outside the scope of this dissertation.

This approach ensured that the search process was applied as consistently and fairly as possible across all data sources, taking into account their inherent differences in query syntax and filtering mechanisms. All retrieved metadata were stored in CSV files and subsequently filtered using a standardised set of inclusion and exclusion criteria, applied uniformly to every query and across all data sources.

2.5 Inclusion and Exclusion Criteria

The articles retrieved from the initial search were processed through a series of filtering steps to reduce the dataset and ensure that the results aligned with the scope of this dissertation. Upon exporting the results from the selected data sources, initial inclusion criteria were applied: only articles with full-text access and those published in English were considered. Following this, the first exclusion criterion was implemented: all articles published before 2019 were discarded from the dataset. This step led to a significant reduction in the number of eligible articles. The impact of this reduction is shown in Table 2.3.

	Data Source				
	IEEE Xplore	SCOPUS	ScienceDirect	Clarivate Web of Science	ACM Digital Library
Start	687	2677	186	1890	617
After Step 1	276	1930	94	1204	372

Table 2.3: Impact of Year Filter on Article Count.

Following the previous filtering stage, the keywords of all remaining articles were manually reviewed to identify those most relevant to the focus of this dissertation. Specifically, articles containing keywords such as "information visualisation", "data visualisation", "visualisation", "visualisation techniques", "3D visualisation" or "volume rendering" were retained. Articles associated with unrelated terms, such as "neural networks", "artificial intelligence", "machine learning",

"augmented reality (AR)" or "virtual reality (VR)" were excluded, as these topics fall outside the scope of this research. This filtering step further reduced the number of relevant articles, as shown in Table 2.4.

	Data Source				
	IEEE Xplore	SCOPUS	ScienceDirect	Clarivate Web of Science	ACM Digital Library
Start	687	2677	186	1890	617
After Step 1 and 2	163	84	30	33	367

Table 2.4: Impact of Keyword Filter on Article Count.

In the next phase, the remaining articles were imported into the Zotero [11] reference management application to facilitate the identification and removal of duplicates. During this process, 913 duplicate entries were detected and subsequently discarded. Additionally, only articles or conference papers were included in the final selection and only final versions of documents were considered. As a result of applying these criteria, 185 records were discarded during this phase. This ensured the quality and relevance of the dataset used for the next stages of the analysis.

2.6 Identification

After the removal of duplicate entries, all remaining records were manually screened to verify whether the downloaded files were fully accessible. In this step, 60 records were excluded because either the full text was not available or parts of the article were missing. Subsequently, all articles were examined to confirm their relevance to the topic of data visualisation. Articles that indicated an unrelated focus with terms such as "underwater", "deep-sea" or references to vertical water-column imaging were excluded, as these topics fall outside the scope of this dissertation.

After this step, 83 additional articles were identified as unrelated and were removed. A staged screening procedure was then applied in the following sequence:

1. Title
2. Abstract
3. Introduction
4. Conclusions
5. Full Text

Each stage involved reading the specified section and determining whether the content was relevant to the research objectives. This sequential approach is both time-efficient and effective: initial sections are more concise, enabling quicker exclusions, while subsequent sections provide

more detailed information to support the decision-making process. As a result of this screening, 167 articles were excluded based on their titles and an additional 87 articles were discarded after reviewing their abstracts.

During this stage, annotations were recorded to support subsequent analysis and to inform the development of the dissertation's state of the art review.

2.7 Results

2.7.1 Content Assessment

From the results obtained, an analysis of the metadata was conducted to extract relevant information about the collected articles.

Initially, the publication year of each article was evaluated to determine whether the publications are more recent or older and to observe the evolution of research within the scope of this dissertation. A graph was created to visualize these data. As shown in Figure 2.2, the number of publications in 2020 is notably lower, which can be attributed to the global impact of the COVID-19 pandemic that caused disruptions. Similarly, the year 2022 also shows a reduced number of publications, although the reasons for this are unclear. The data for 2025 is limited, as the year is only partially complete, so a lower number of publications is expected. For the other years, publication counts are relatively consistent, with a slight increase observed before the pandemic. However, it is important to note that definitive conclusions cannot be drawn based on a single year of data.

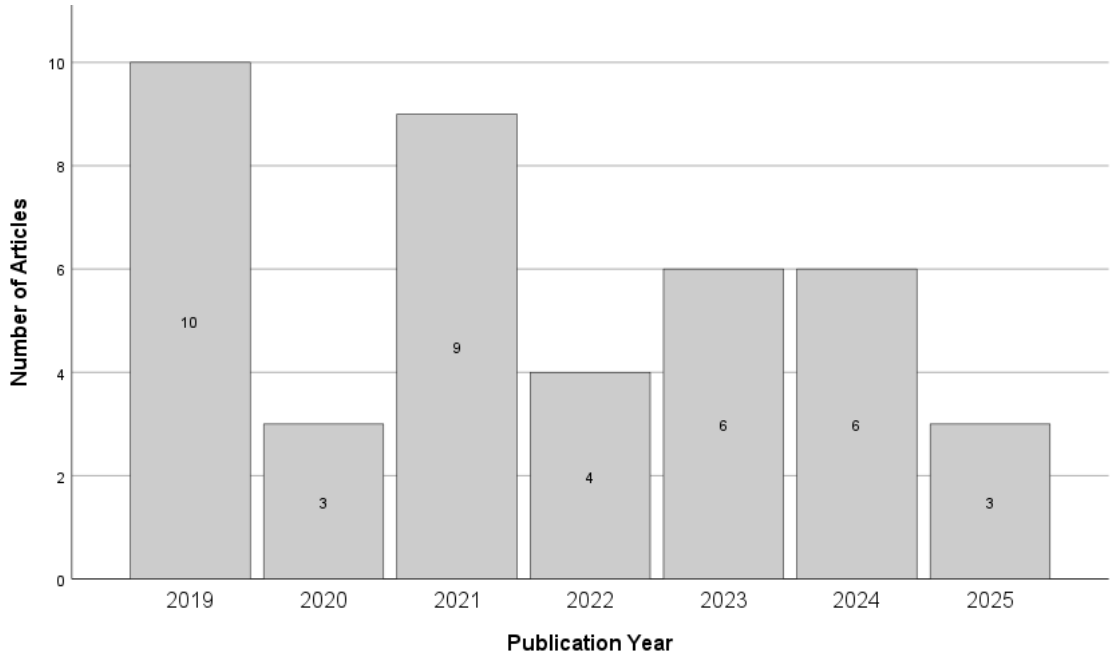


Figure 2.2: Number of Articles Published per Year.

Next, the types of publications were analysed. The retrieved articles consist of approximately 73,2% journal papers and 26,8% conference papers. Journal articles typically represent more extensive, long-term investigations and undergo a more rigorous peer-review process, often reflecting more mature research. Conference papers, on the other hand, tend to present preliminary findings or ongoing research and usually focus on more recent developments. This distinction does not imply that conference papers are of lesser quality, but rather that the collected articles predominantly reflect established research, with conference papers contributing insights into emerging topics.

In this phase, data regarding the publishing platforms from which the articles were retrieved were collected. Their distribution is illustrated in Figure 2.3. Publication platforms with more than one article are displayed individually in the figure, whereas those represented by only one article each are grouped under the “Other” category. In total, 28 additional platforms were identified that contributed a single article each. Subsequently, the locations of the conferences were identified, resulting in the graph presented in Figure 2.4. The data shows that the United States of America (USA), China and France host the majority of these conferences, which may indicate that these countries play a leading role in research and innovation related to marine science and environmental preservation.

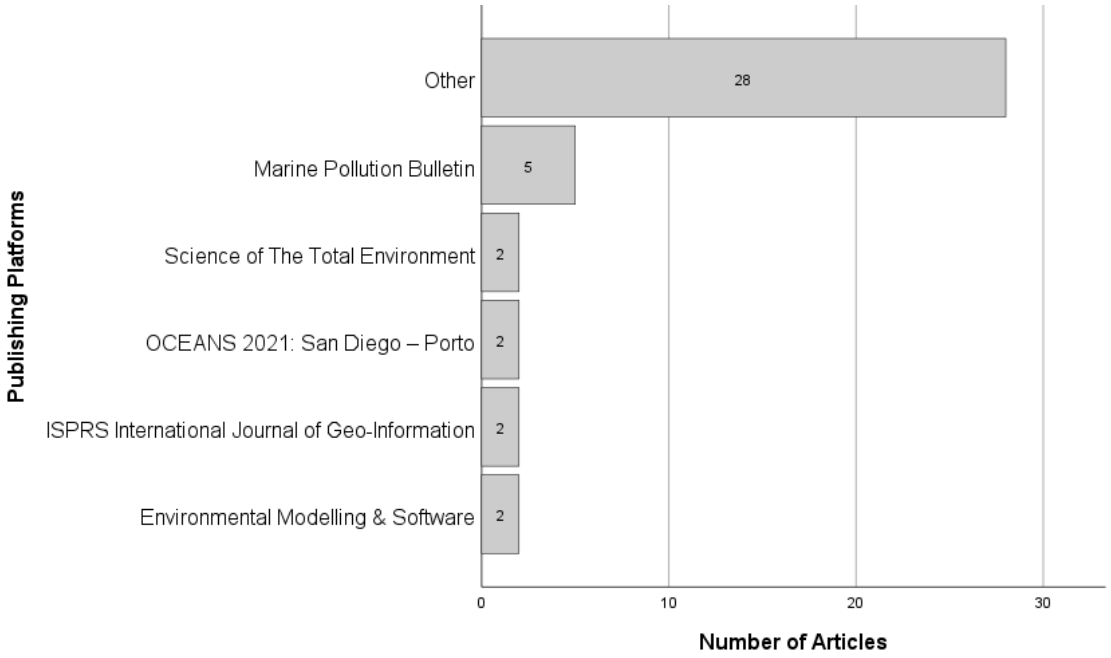


Figure 2.3: Number of Articles per Publishing Platforms.

Following this phase, the keywords from the articles were extracted and a word cloud was generated to provide an overview of the most frequently occurring terms, summarising the collected literature. The word cloud in Figure 2.5 reveals that terms such as "microplastics" and "oceans" appear most prominently, followed by "visualisation", "data visualisation" and "sea surface". Additionally, words like "pollution", "monitoring", "plastics", "ocean data" and "three-dimensional displays" are noticeably frequent. This distribution of keywords suggests that the retrieved articles

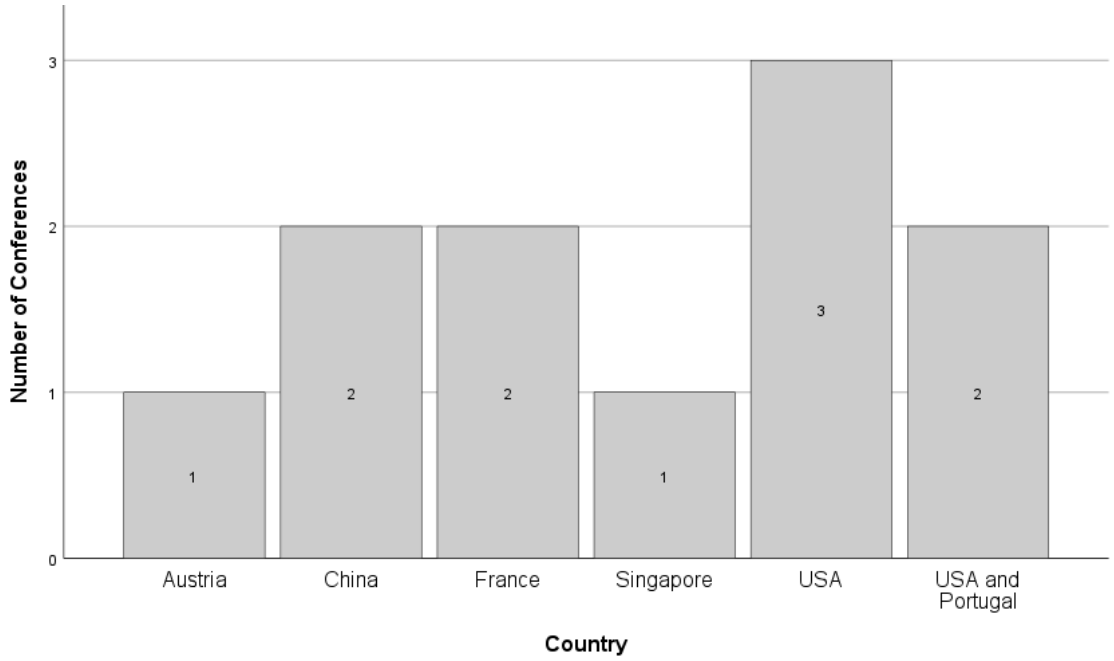


Figure 2.4: Number of Conferences per Country.

are closely aligned with the research topics targeted in this study.

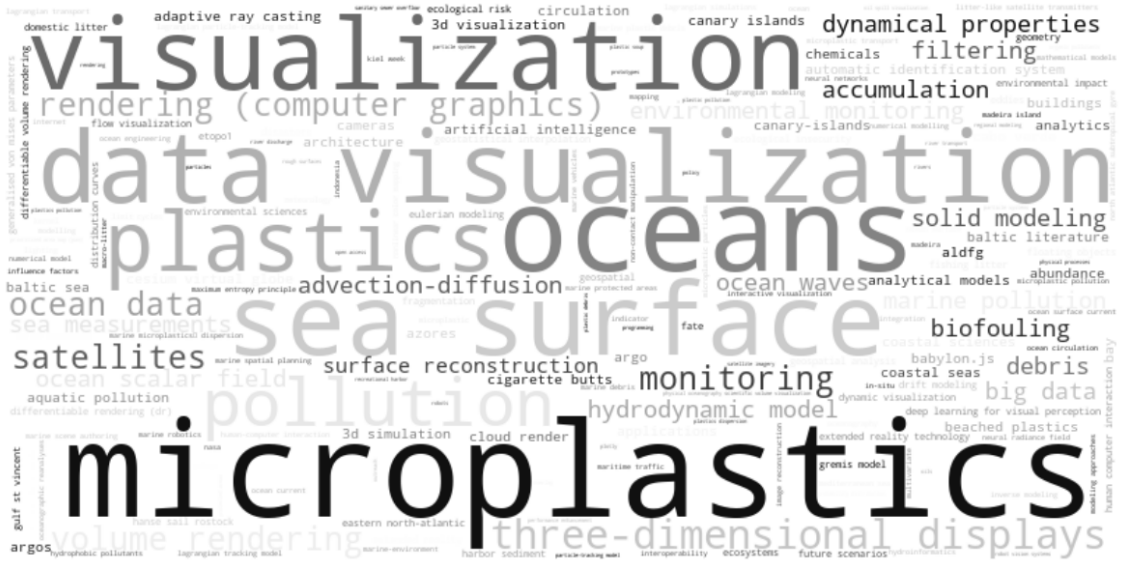


Figure 2.5: Word Cloud with the Most Frequent Occurring Keywords.

2.7.2 Quality Assessment

The articles were analysed with a focus on topics that would be useful for future work, particularly in the context of developing the state of the art. This analysis was organised into the following

categories: problem, approach, method/experimentation, dataset, technologies, limitations and validation. A detailed description of each of these categories is provided in the appendices A to G.

2.8 Critical Analysis

After completing the entire selection process and thoroughly examining the article's metadata, the focus shifts to an in-depth analysis of the content itself. This section of the chapter presents a critical review of the articles, including observations on emerging trends and patterns, as well as a discussion of identified gaps in the literature.

2.8.1 Trends and Patterns

The analysis of the selected articles revealed several recurring themes and methodological approaches that reflect current trends in the study of marine pollution, with a particular focus on plastics and their visualisation.

A dominant theme across the literature is the concern with plastics and marine litter. The increasing awareness of these pollutants has led to research efforts aimed at understanding their sources, transportation mechanisms, behaviour and environmental impact. Specific areas of interest include source identification and contamination pathways [12] [13] [14] [15], influence of physical and biological processes on dispersion, complex ocean dynamics, including currents, tides, waves and vortices [13] [16] [12] [17] [18] [19], plastic fragmentation and degradation [18] [20] [19] [13] [15], consequences for marine ecosystems and human health [15] [21] [12] [18] [13] [22], the need for improved monitoring, modelling and management strategies [12] [13] [23] [24].

The literature demonstrates a convergence around three main methodological approaches. Numerical modelling studies frequently rely on advanced oceanographic models to simulate plastic transportation with techniques such as Lagrangian particle tracking [13] [19] [25], Eulerian field-based simulations [13] [26] [27] and coupled models integrating both approaches [25] [26] [13]. Visualisation plays a central role in interpreting and communicating modelling results with interactive visual analytics [28] [27] [29], 3D [30] [31] [32] [33] and 4D (spatiotemporal) visualisations [34] [28] [32] [35] and applications of digital twins [36] [27] [37] and extended reality environments [38] [39] [37]. Although some articles incorporated machine learning or AI techniques [12] [40], these were not the primary focus of the studies.

Common experimental and simulation practices include plastic transportation modelling incorporating biofouling, degradation, beaching, sediment interaction and dynamic environmental parameters [17] [19] [13] [18] [20] [12] [21] [16], wave and current modelling, particularly using directional spectrum estimation and controlled laboratory setups [41] [20] [19] [42] [13], simulation and performance analysis, including particle behaviour, system efficiency and size-based tracking [42] [19] [13] [18] [20].

The studies reviewed rely on a variety of datasets to support modelling and analysis. Oceanographic datasets from platforms such as NEMO-MEDUSA, SMOC and HYCOM provide temperature, salinity and velocity fields [13] [15] [16] [43] [24] [24] [42] [31] [27] [21], observational data including *in situ* measurements and satellite imagery [15] [12] [16] [23] [44] [34] [45], marine debris and plastic data addressing particle characteristics and incorporating survey results and beach cleanup data [12] [18] [13] [15] [20] [19] [46] [47] [21], supplementary data sources such as national statistical data and vessel tracking information, particularly from fisheries [18] [13] [15] [22] [26] [48].

The implementation of research methodologies was supported by several key technological tools, such as programming environments (Python [46], Parcels [13] [26] [38] [33], OpenDrift [46], MATLAB [30] [27], TrackMPD [13] [19], PaTATO [19]), which were the most commonly used for simulations and modelling. Visualisation libraries and platforms such as Matplotlib and Plotly for 2D and interactive charts [28] [27] [32] [24], OpenGL and WebGL/WebGPU for web-based 3D rendering [30] [32] [36] [33]. For digital twin tools, Unity3D as well as VR and AR frameworks were used for immersive visual representations and simulation interfaces [38] [36] [39] [37].

To ensure reliability and accuracy, various validation techniques were employed, such as comparison with *in situ* data or historical measurements [12] [13] [43] [32] [47] [45], sensitivity analyses and comparison with peer-reviewed models or simulations [19] [25] [13] [29] [33], evaluation by domain experts to verify scientific accuracy [39], user studies assessing the usability and clarity of visual outputs, particularly in interactive or immersive environments [24] [36] [39].

2.8.2 Gaps Identified

Following the detailed analysis of the selected articles, several key gaps in the existing literature were identified. These limitations highlight areas where further research is necessary to improve the accuracy and reliability of current models and approaches in the study of plastics in marine environments.

One of the main gaps is the limited availability of empirical measurement data to support and validate plastic transportation models, particularly in regions such as the deep ocean, where data on microplastic release points and distribution patterns are especially lacking [13] [46] [21].

Another recurring issue is the oversimplification in the parameterisation of plastic behaviour [13] [15]. Several studies rely on general assumptions that limit the representation of the complexity of microplastic interactions with the environment. For example, many models adopted simplified debris geometries, commonly representing particles as spheres, which fail to account for the diverse shapes and material properties of actual marine debris [17] [19]. Moreover, it is common for transport parameterisations to be adapted from models developed for other substances, such as sediments or oil spills, which may not accurately reflect the dynamics of plastics [13] [19] [21].

Furthermore, particle release mechanisms in simulation studies are often basic [16]. Many models use a limited number of particles or assume a uniform distribution across a region, which does not align with observed release patterns influenced by various anthropogenic and environmental factors [13] [16] [25].

One notable gap consistently observed across the literature is that the potential influence of marine organisms on plastic transportation has not been incorporated into existing models [13] [19]. This represents a significant oversight given the growing recognition of the role of biotic processes in ocean dynamics.

In addition to these modelling challenges, limitations in visualising oceanic data also affect the study of plastics. Technical constraints, such as inefficient algorithms and limited GPU use, make it difficult to interact with large datasets in real time [33]. Cognitive and perceptual issues, including the frequent use of rainbow colour maps [28], low-resolution temporal animations causing "time cracks" [35], ambiguous flow representations with arrows or streamlines and difficulties in comparing multiple variables [49], can confuse interpretation and obscure key patterns, making it harder to identify trends and hotspots in plastic transport.

These identified gaps have direct implications for the accuracy and reliability of plastic transport projections and visualisations. Inconsistencies between modelled outcomes, visualisation challenges and real-world observations highlight the need for improved data collection, enhanced modelling techniques and broader interdisciplinary integration in future research.

2.9 Summary

This chapter presented a systematic literature review conducted according to the PRISMA methodology, focusing on numerical modelling and visualisation techniques for plastic dispersion in marine environments. The review reveals that, although modelling approaches are well-established, many studies rely on simplified assumptions and limited empirical validation. At the same time, visualisation methods are often fragmented and rarely evaluated from a user-centred perspective. These limitations reveal clear research gaps and motivate the need for more integrated visualisation solutions.These findings inform the state of the art presented in the next chapter and support the definition of the proposed approach.

Chapter 3

State of the Art

The following chapter presents the state of the art, built upon the literature reviewed and discussed in the previous chapter.

3.1 Introduction

The following chapter is structured around key thematic areas essential for the development of this dissertation. The work is guided by a thematic approach that encompasses the numerical modelling techniques used to simulate this transport, the influencing factors of plastic transport in the ocean and the visualisation methods used to represent the resulting data.

3.2 Numerical Modelling

Plastic pollution in marine environments is among the most pressing environmental challenges today [12], exacerbated by the continuous and drastic increase in global plastic production. To enhance the understanding and prediction of the sources, trajectories and final destinations of plastic debris, including microplastics, numerical modelling has emerged as an essential tool. At present, two principal approaches are employed in numerical modelling to simulate the transport and fate of microplastics in marine environments: Lagrangian and Eulerian models.

3.2.1 Lagrangian Particle Tracking Models (LPTMs)

This model focuses on the trajectory of individual particles, making them particularly advantageous for simulating microplastic dispersion in complex flow fields. These models allow for the resolution of sub grid scale particle displacements while maintaining manageable computational demands. LPTMs assume that particles do not interact with one another and that particle velocity is equal to the fluid velocity at the particle's location. They are especially useful for modelling microplastic quantities in terms of particle count. However, their application typically requires a high number of simulated particles, leading to increased computational complexity due to the

necessity of small time steps and high spatial resolution. Consequently, this approach can become resource intensive [13].

3.2.2 Eulerian Transport Models (ETMs)

The Eulerian model describes particle behaviour in terms of mass or volume concentration rather than individual trajectories. This makes them better suited for representing large scale patterns and for simulating macroscopic changes such as spatial concentration distributions and transport volumes. ETMs offer higher computational efficiency and are particularly appropriate for three dimensional distribution modelling that involves mean flow and vortex interactions. They are well aligned with methods that measure microplastic mass, thereby avoiding the uncertainties involved in converting particle counts into mass estimates. However, ETMs do not track individual microplastic particle pathways and, as such, may overlook microscale dynamics that are crucial in certain contexts [13].

3.2.3 Lagrangian vs Eulerian Models

Some studies explicitly compare the two approaches for different purposes: Lagrangian models are often used to trace point-source plastics or microplastic plumes, whereas Eulerian models are more appropriate for representing the transport of dissolved or particulate chemical contaminants, such as organic pollutants, in the water column [26].

3.2.4 Transport Model Frameworks

Numerous frameworks have been developed to support both Lagrangian and Eulerian modelling of microplastic transport. Regarding the first, the identified frameworks are:

- TrackMPD: A 3D framework specifically designed for marine plastic debris modelling, incorporating relevant physical processes such as advection, dispersion, windage, sinking, settling, stranding, resuspension, biofouling and degradation states [19].
- Parcels: A Python-based, open-source toolkit that enables customisable Lagrangian particle tracking simulations using various ocean circulation models. It is suitable for simulating the transport of plastics, water masses, plankton [13] and other marine particles, with a strong emphasis on near-surface dynamics [42].
- Ichthyop: Commonly used to simulate microplastic transport pathways, seasonal variations and coastal accumulation zones [13].
- Pol3DD: A model focused on surface dispersion of floating particles, often coupled with HYCOM (Hybrid Coordinate Ocean Model) velocity data [13].
- OpenDrift: An open-source Python framework that integrates ocean currents and atmospheric forcing to simulate particle trajectories [15] [46].

- SLIM Plastic Oceanography Model: Designed to predict microplastic behaviour in specific coastal environments such as the Bohai Sea in China [13].
- Mobidrift: Eemploys a 2D Lagrangian advection scheme with Monte Carlo ensemble simulations and is forced by satellite-derived surface currents and wind data to probabilistically estimate debris pathways and accumulation hotspots [50].

In what concerns Eulerian Modelling tools, the surveyed frameworks are:

- NEMO (Nucleus for European Modelling of the Ocean): Used to investigate global 3D dispersion of microplastics with varying densities throughout the water column [13].
- HYDROTAM-3D: A transport sub-module tailored for enclosed coastal regions, accounting for wind and wave-driven currents [13].
- FSK-MPTM: Developed within the Delft3D-WAQ framework, this model includes biofouling effects, microplastic interactions with fine sediments and can simulate a wide range of particle classes with varying polymer densities [13].

3.2.5 Influence of Input Data on Models

Accurate estimation and prediction of microplastic sources, pathways, distribution and accumulation zones depend heavily on the availability and precision of *in situ* measurements used to define model parameters [19] [23]. Despite ongoing advancements, many modelling efforts remain unvalidated due to the scarcity of reliable empirical data. The parameterisation of complex behaviours, such as biofouling [17], degradation and fragmentation [20], continues to require significant improvement and further experimental validation. In many cases, parameter values and transport equations are adapted from models developed for other substances, such as sediments or oil spills, which may not fully represent the behaviour of microplastics [13] [19]. Accurately quantifying input sources remains a critical challenge in the field, limiting the predictive power of even the most sophisticated models [13].

3.3 Influencing Factors of Plastic in the Ocean

The transport and fate of microplastics in the marine environment are influenced by a combination of factors that can be broadly grouped into several key areas, which are discussed in the following subsections. These include environmental influences, such as currents, wind, beaching and refloating processes and turbulent dispersion, as well as particle specific properties and interactions with chemical contaminants.

3.3.1 Advection by Currents

One of the primary drivers of microplastic transport is advection by ocean currents. Lagrangian numerical particle tracking, combined with ocean circulation modelling, is widely used to predict the potential sources and destinations of microplastic particles. Ocean current characteristics vary significantly across regions, influencing transport patterns and accumulation zones. Large-scale horizontal advection, Ekman drift (the movement of surface ocean layers caused by wind stress), geostrophic currents (large scale ocean currents that flow steadily in a roughly straight path, mainly driven by the slope of the sea surface), mesoscale and submesoscale eddies (rotating structures with scales ranging from hundreds of kilometers down to 1-10km) and Stokes drift (transport of water and particles in the direction of wave propagation, resulting from differences in velocity experienced by particles at wave crests versus troughs) are all relevant mechanisms [13]. For instance, the combination of Ekman drift and geostrophic currents provides a plausible explanation for the accumulation of floating plastics in subtropical gyres, often forming large "garbage patches" [21]. The advection of plastics is also influenced by seasonal variability driven by monsoons, particularly in archipelagic regions such as Indonesia [24] and by internal waves and tidal dynamics, which contribute to vertical redistribution across the water column [34]. In this context, the directional wave spectrum constitutes a fundamental quantity for the calculation of pollutant and sediment transport in the marine environment. Particle motion is not governed solely by surface currents, but by the complex interaction between waves and the surrounding hydrodynamic conditions [41].

In coastal environments, microplastic transport is influenced by factors such as river plumes, coastal currents, turbidity currents, wind, internal waves and extreme weather events, including tides and typhoons [16]. Barotropic tidal currents (tidal flows that move uniformly throughout the entire water column, with minimal variation in velocity or direction with depth and driven by sea-level oscillations rather than density differences), in particular, play a significant role in the transport and accumulation of floating microplastics in coastal and semi-enclosed waters [15]. Plastic retention within estuaries is a critical factor that is often underestimated in transport models. Events such as sewer overflows and stormwater discharge represent the most important pathways for the input of visible plastics into the marine environment, particularly following intense rainfall [47]. Effective modelling of microplastic transport requires accurate representation of local hydrodynamic conditions [13], including vertical shear in current profiles, where current speed and direction vary with depth and strongly influence particle mixing and vertical redistribution [19].

3.3.2 Turbulent Dispersion

Turbulent dispersion is another key physical process incorporated into plastic transport models such as TrackMPD [19]. Horizontal dispersion facilitates mixing with other substances, such as pollutant spills or biological matter and is strongly influenced by underlying flow dynamics. Lagrangian Coherent Structures (LCSs) serve as transport barriers in unstable flow fields, accumulating or dispersing material [34]. These structures represent the fundamental pathways of

Lagrangian transport and define the main transport routes [45]. In regions where diffusion dominates, the accumulation of floating microplastics tends to increase [21]. Some models address sub-grid scale processes through stochastic zero-order Markov models using horizontal diffusion coefficients [15].

3.3.3 Wind Action

Wind plays a significant role in the transport of floating materials in surface waters [19]. This is integrated into models like TrackMPD through the use of windage coefficients assigned to virtual particles [45]. These coefficients simulate the direct drag effect of wind over particles with varying levels of buoyancy and surface exposure [15].

Wind effects are critical in determining microplastic distribution. Windward beaches often accumulate more debris than leeward beaches, with higher rates of stranded materials [13]. In addition, specific wind events can alter coastal circulation patterns and trap riverine plastic plumes, preventing them from reaching open bays [34]. Wind also affects Lagrangian Coherent Structures, thereby influencing the fate of pollutants and other marine debris [45]. Particles with high windage are more likely to escape oceanic gyres and travel across broader ocean regions [15]. However, wind-driven currents predominantly affect only the ocean's uppermost layers [46].

3.3.4 Beaching and Refloating

Beaching and refloating processes (microplastics alternately accumulate on shorelines and are later remobilised back into the ocean) are essential for determining microplastic load concentrations in both open ocean and coastal waters [12]. These processes are complex and influenced by external factors such as tidal regimes, wave direction and human activities, making them difficult to incorporate into numerical models [25]. Tools like TrackMPD employ probabilistic (Monte Carlo) approaches to replicate beaching and refloating behaviours. During high tides, debris stranded on beaches can be returned to the ocean and potentially follow similar transport paths [13].

Model results often suggest that beaching predominantly occurs within the first weeks following particle release [21]. Coastal zones and semi-enclosed waters are recognised as hotspots for plastic accumulation due to increased beaching activity. Windward coasts, in particular, tend to exhibit higher concentrations of stranded debris [12]. Beaching serves as a significant sink for microplastics, although it remains one of the least accurately represented processes in current models, highlighting the need for more extensive *in situ* research [13] [15].

3.3.5 Fragmentation and Size Distribution

The fragmentation of macroplastics is the main source of microplastics in rivers and coastal areas, but the rate of fragmentation strongly depends on the environmental conditions [14]. Recent modelling approaches, based on statistical mechanics, have shown that there are fewer small fragments than would be expected from uniform breaking. This is because fragmentation into smaller sizes

requires exponentially rarer "crushing energy" in the environment, which is often not available in typical river or coastal conditions [18].

3.3.6 Interaction with Chemical Contaminants

Microplastics do not travel through the ocean in isolation, they act as vectors for Plastic-Related Organic Pollutants (PROPs) through adsorption and desorption processes [26]. The dynamics of these pollutants are often decoupled from the microplastic particles themselves, as their diffusion and chemical interactions follow different transport laws. As a result, Eulerian advection-diffusion models are frequently employed to simulate the distribution of PROPs in combination with Lagrangian particle tracking of plastics, providing a more complete picture of chemical and physical transport in marine environments [26].

3.4 Visualisation of Oceanographic and Environmental Data

In this section, given that the focus of the dissertation is the visualisation of oceanographic and environmental data alongside plastic dispersion, it is important to review the common data types used in previous projects, the tools employed in these studies and the visualisation techniques applied to represent ocean plastic pollution.

3.4.1 Common Data Types

Oceanographic and environmental datasets are inherently complex, vast, heterogeneous and multidimensional. They capture dynamic interactions across multiple spatial and temporal scales [28]. These datasets include scalar variables, such as temperature, salinity, water depth, pressure, humidity, wind speed and precipitation [29], as well as vector fields representing ocean currents and wind [29]. Gridded data derived from forecasting systems and satellite imagery are often structured in 3D arrays [32]. In addition, simulated data are generated from coupled ocean-atmosphere models, hydrodynamic simulations and Lagrangian particle tracking models [29]. Observational or *in situ* data are collected via satellites, ships, buoys, drifters, fixed sensors, coastal surveys and sediment sampling [27] [50]. These datasets are frequently heterogeneous and multidimensional, combining diverse sources, formats and resolutions [28] and often include time varying information, such as long term sea surface temperature (SST) records, ocean forecasts and maritime traffic observations [35].

3.4.2 Tools

Given the scale and complexity of these datasets, advanced tools and frameworks are required for effective visual representation. Key tools used in oceanographic data visualisation include:

- VisAD: Among the earliest platforms for multidimensional marine data visualisation [28].

- Geospatial Platforms (e.g., Google Earth, NASA World Wind, Microsoft Virtual Earth, Cesium): These support the display of remote sensing data in interactive 3D environments. Cesium, an open-source JavaScript library, offers advanced 3D rendering capabilities [32]. Figure 3.1 presents the 3DGIS interface using Cesium Version 1.56.
- Skyline (Hainan Provincial Digital Ocean 3D Visualisation System): Integrates DEM (Digital Elevation Model), DOM (Digital Orthophoto Maps), vector data and multiple ocean environment parameters on a digital earth sphere model [51].
- ESRI ArcGIS: Widely applied in oceanographic research for spatial data analysis [28].
- GeoZui3D: A specialised 3D system enabling multi-source ocean data visualisation with zoom focus and coordinated views [29].
- COVE (Collaborative Ocean Visualisation Environment): Facilitates large scale observatory design and data layering using XML based structures [29]. Figure 3.2 illustrates the system, highlighting the exploration of multiple properties.
- Maritime Traffic Visualisation System: Uses AIS (Automatic Identification System) data to display spatio-temporal vessel trajectories and traffic density, supporting monitoring, hotspot identification and collision avoidance [52].
- COVERAGE Data Viewer: An integrated system designed for combined satellite and *in situ* datasets, allowing seamless visualisation of multi-source oceanographic information [48]. Figure 3.3 presents a screenshot of the data viewer displaying an ecological dataset, showing the spatial distribution of tuna fishery catch per unit effort overlaid with satellite derived oceanographic variables
- CleanUpOurWorld: A scalable database platform for ocean plastic tracking and environmental monitoring, enabling large-scale data exploration and visualisation [44]. Figure 3.4 shows the main visualisation interface of the platform, highlighting (a) the highest level spatial overview and (b) the street level visualisation.
- VAPOR: A platform tailored for the visualisation and analysis of Earth system simulation data [32].
- ParaView: Suitable for end users needing to visualise and interact with large volumetric datasets [32].
- WebGIS: Integrates GIS functionality with web technologies for accessible, interactive mapping [32].
- WebGL: Enables plugin-free 3D visualization directly in web browsers using GPU acceleration [32] [37].

- WebGPU: The next generation successor to WebGL, providing higher performance rendering and improved access to modern GPU features for web based visualisation of large-scale oceanographic datasets [33].
- Plotly.js: A powerful JavaScript library supporting both 2D and 3D plots, useful for dynamic volume rendering [32].
- Python Toolkits (e.g., Matplotlib, Plotly, PyQt): Widely used for preprocessing and visual analysis [27].
- Unity3D: Often employed for creating extended reality (XR) scenarios and immersive marine environments [38].
- OpenSceneGraph (OSG): Used for 3D ocean modelling, FFT-based sea surface simulation and cloud rendering [30].
- Other libraries: ECharts for temporal trend analysis [32] and FiPy for Eulerian advection and diffusion simulations [22].

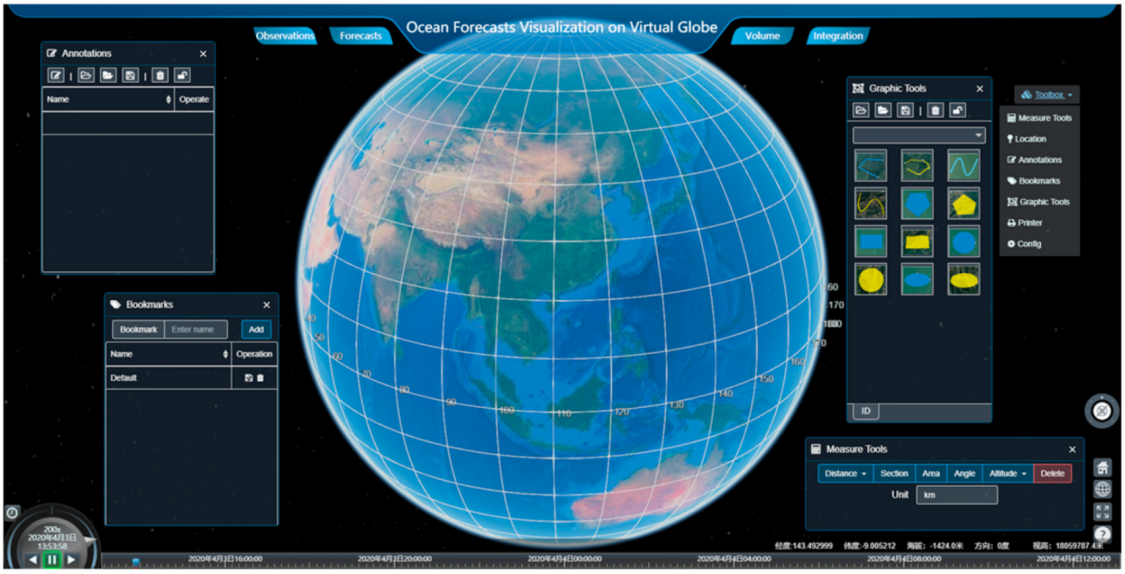


Figure 3.1: 3DGIS Interface Visualised with Cesium [32].

3.4.3 Visualization Techniques Applied to Ocean Plastic Pollution

The complex behaviour of microplastics in marine environments demands visualisation approaches that effectively capture their dynamic, multiscale nature. The following techniques have been widely adopted in both scientific research and environmental monitoring.

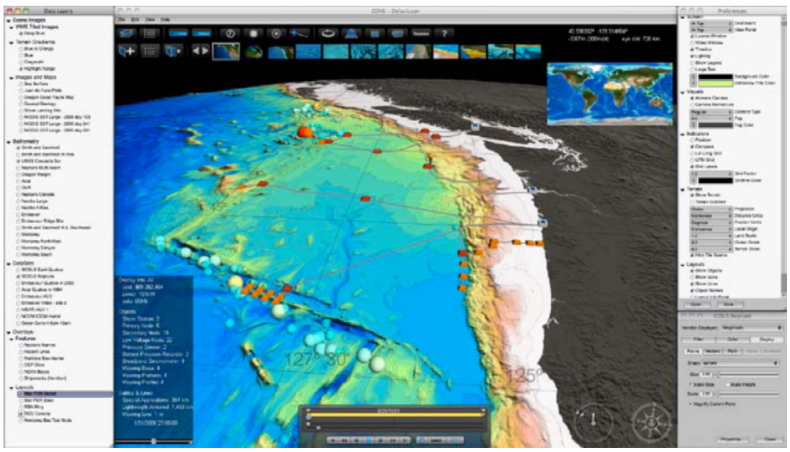


Figure 3.2: Overview of the COVE System [29].

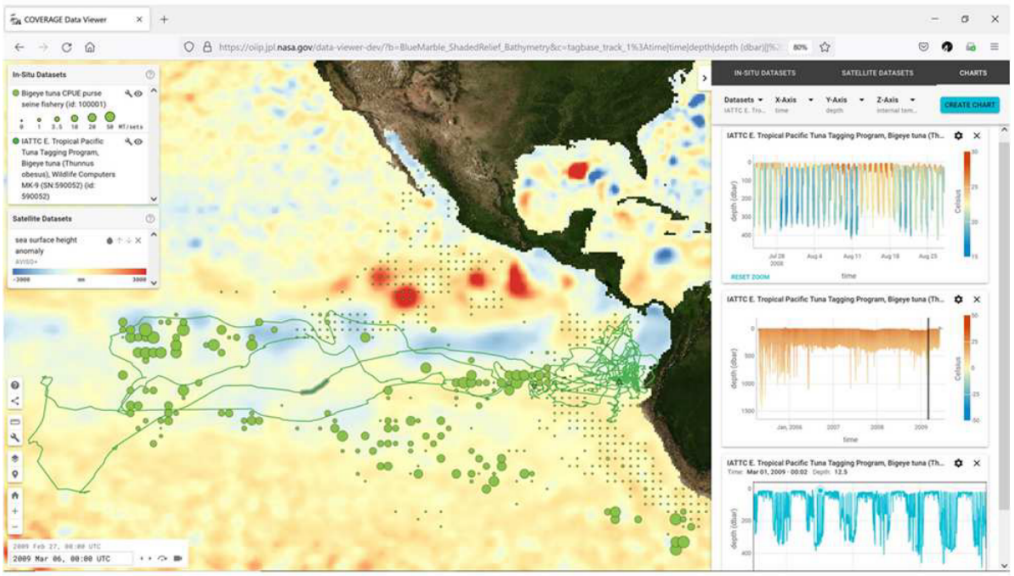
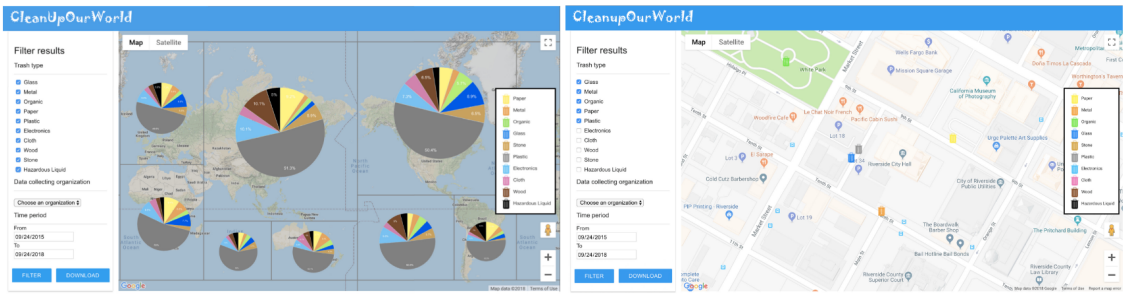


Figure 3.3: Example Interface of the COVERAGE Data Viewer [48].

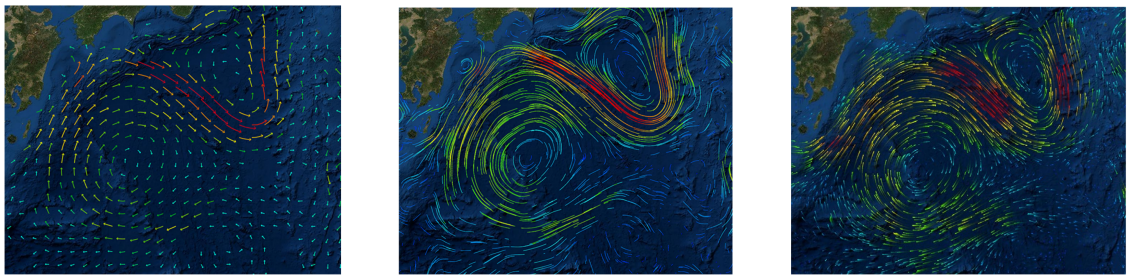


(a) Litter Data on Continent Level (b) Litter Data on Street Level

Figure 3.4: Main Visualisation Interface of the CleanUpOurWorld Platform [44].

3.4.3.1 Visualization of Plastic Dispersion and Trajectories

Visualising plastic transport typically involves flow field representations and Lagrangian particle tracking. Vector fields, represented with arrows indicating current speed and direction, provide a simple overview of transport patterns but can produce visual clutter in dense or multidirectional fields [49]. Streamlines offer a continuous and smooth representation of flow direction and structure [49] [32]. However, their readability depends heavily on the placement of seed points, which can lead to occlusion or misinterpretation. The use of asymmetrical glyphs, such as teardrop shapes, can help resolve directional ambiguity [49]. Particle systems simulate the movement of individual particles over time, displaying attributes such as velocity, lifespan and direction. These systems generate high contrast visuals with reduced clutter and can dynamically incorporate shape, transparency and colour to indicate movement characteristics. Some particle systems are also adapted for 3D and spherical visualisation environments [49]. Trajectory Maps show cumulative particle paths over seasonal or annual periods, aiding in the identification of accumulation zones and transport connectivity. Techniques such as adjoint marginal sensitivity analysis can be used to detect critical source areas for plastic release [43]. Figure 3.5 illustrates the visual outcomes of three flow field representation techniques: (a) the direct vector based method, (b) the streamline method and (c) the dynamic stremlet method based on the particle system.



(a) (b) (c)

Figure 3.5: Comparison of Flow Field Representation Methods [49].

3.4.3.2 Visualisation of Distribution and Accumulation

Visualisation of distribution and accumulation relies on heatmaps, density maps and probability grids. Heatmaps use continuous colour gradients to reveal spatial distribution patterns and highlight concentration hotspots [25], providing an intuitive overview of areas with high particle density. Density maps emphasise regions of particle aggregation, which is particularly useful for detecting estuarine and coastal accumulation zones [25]. Source-to-sink pathway visualisations trace the movement of plastics from their input points to final destinations, supporting strategic management and pollution mitigation efforts [25]. Priority Area Maps (PAMs) are used to guide stakeholder decisions by highlighting zones of ecological or economic concern [23]. Figure 3.6 presents PAMs generated for three different stakeholders: (A) plastics, (B) ports and (C) ecological considerations. Subtropical gyres, often referred to as “garbage patches”, are frequently

visualised in this context due to their role as major plastic sinks, shaped by the combined effects of Ekman transport and geostrophic currents [13].

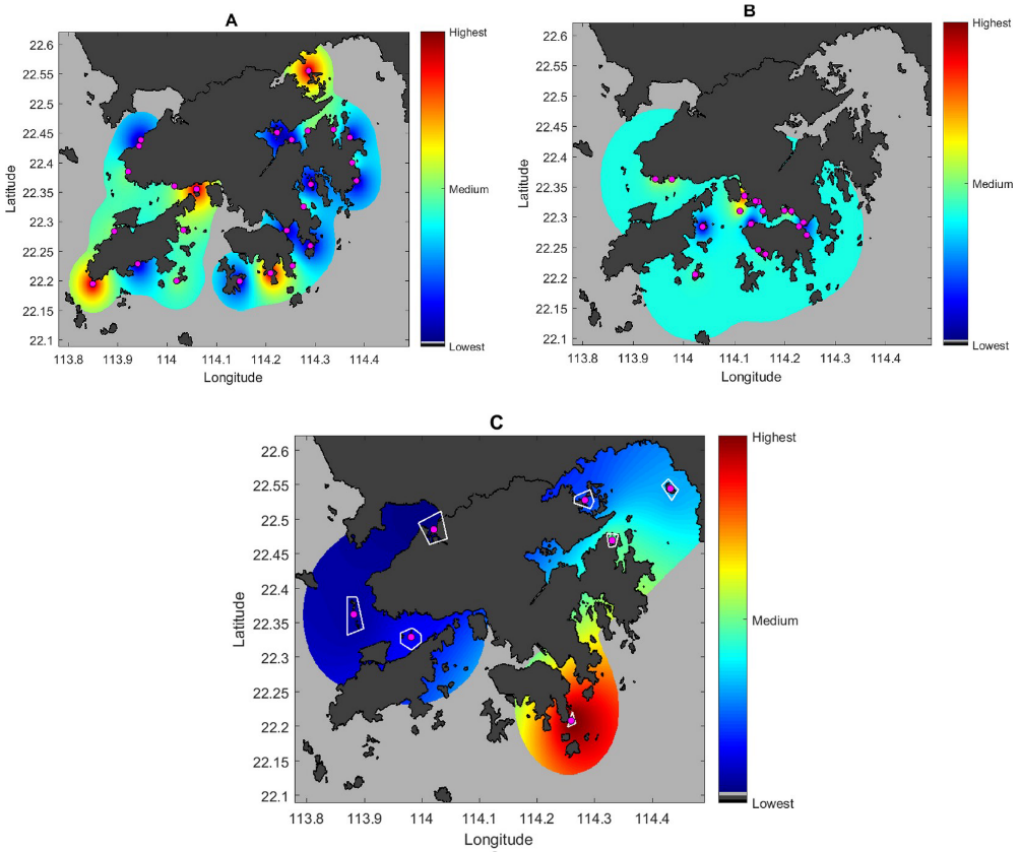


Figure 3.6: Priority Area Maps (PAMs) for different stakeholders [23].

3.4.3.3 Three-Dimensional Visualization (3D Surface and Volume Rendering)

Three-dimensional techniques provide essential insights into the vertical transport and distribution of plastics. 3D surfaces are commonly used to represent bathymetry or sea surface features, such as oil slicks and wave patterns [36]. Figure 3.7 illustrates a 3D dynamic visualisation system for simulating oil spills in the ocean. Isosurfaces show specific value thresholds within 3D scalar fields, for example, temperature or dissolved oxygen [27]. Volume rendering allows simultaneous visualisation of internal distributions of microplastics and oceanographic variables, with techniques such as texture slicing improving real time rendering performance [32]. Vertical profile visualisations illustrate particle sinking due to biofouling, changes in density and vertical mixing, revealing mechanisms behind subsurface plastic transport [15].

High-precision 3D visualisation requires the integration of scalar fields with seafloor topography to provide accurate spatial context. Adaptive ray casting methods can be employed to remove invalid sampling points located below the terrain, improving the fidelity of subsurface renderings.

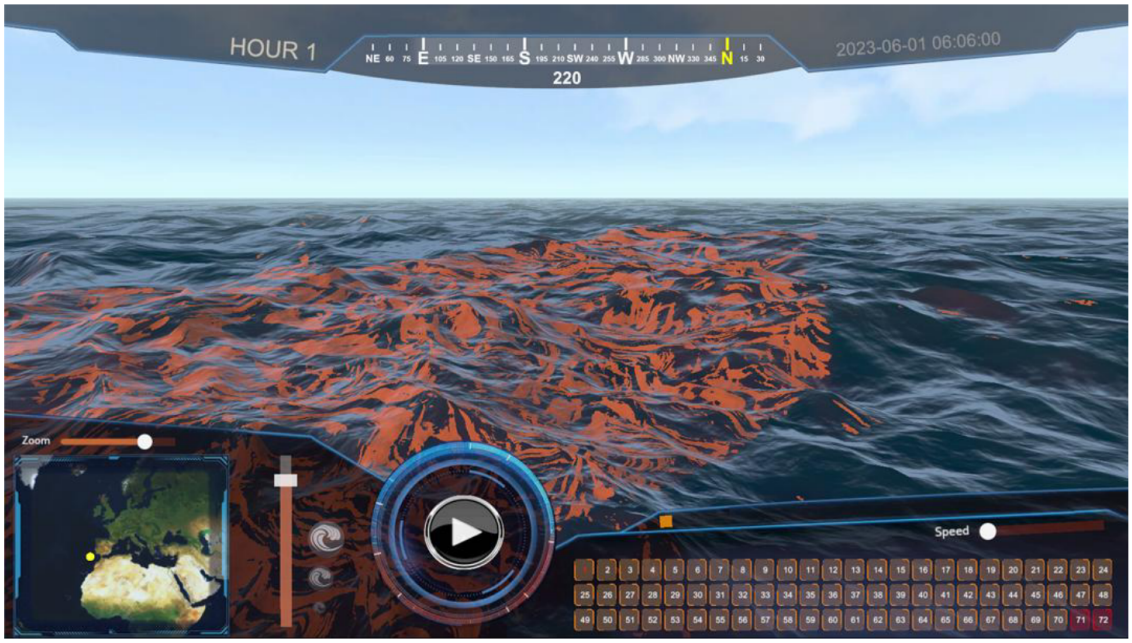


Figure 3.7: 3D Dynamic Visualisation of Ocean Oil Spills [36].

In addition, non-linear colour mapping, based on metrics such as obliquity or data skewness, optimises the representation of volumetric data and enhances the perception of complex features in both oceanographic and microplastic distribution datasets [31]. Emerging techniques, such as differentiable rendering, allow for surface reconstruction in three-dimensional ocean visualisation, which enables the self-supervised optimisation of ocean geometry. Unlike traditional rendering approaches, differentiable rendering captures visual information at pixel and sub-pixel scales by representing surfaces through hierarchical displacement, normal and roughness components [40].

Real world implementations illustrate the effectiveness of these techniques. For example, the Hainan Provincial Digital Ocean 3D Visualisation System integrates DEM, DOM, vector data and multiple ocean environmental parameters on a digital earth sphere model, providing interactive navigation, multi-temporal comparison and spatial overlay analysis [52]. Similarly, vessel traffic visualisation platforms leverage AIS trajectories with density maps and interactive dashboards for monitoring, anomaly detection and navigation support [51]. These applications demonstrate how large-scale observational data can be effectively rendered, explored and analysed, analogous to 3D visualisation of microplastic transport and environmental parameters. Overall, these methods integrate seafloor topography and scalar ocean fields to provide geographic context and enable data fusion.

3.4.3.4 Spatiotemporal and Dynamic Visualization

Dynamic and temporal visualisations play a crucial role in understanding the evolving nature of marine processes. Animations can represent variations in sea surface temperature, ocean currents

or particle dispersion over time, offering improved comprehension compared to static representations [29]. Coordinated Multiple Views (CMV) enable the simultaneous analysis of different variables or time frames, enabling more comprehensive scientific exploration [29]. Real time visual systems allow continuous updates of marine variables, such as chlorophyll concentration, salinity and wave height, which is valuable for operational oceanography. However, the implementation of such systems is challenged by the heterogeneity, volume and rapid temporal changes of the data [35]. Scalability and information overload remain key obstacles, requiring optimised data reduction and processing techniques.

3.4.3.5 Integrated and Interactive Visualization

Integrated and interactive visualisation plays a crucial role in enhancing analytical capabilities when dealing with complex oceanographic and environmental datasets. By combining diverse visual modalities, multi-view systems allow the simultaneous display of different data perspectives, such as salinity slices alongside flow fields, thereby revealing interdependencies and promoting a more comprehensive understanding of underlying processes [29]. User interaction features, including zooming, filtering and variable selection, empower users to explore and analyse data across multiple spatial and temporal scales, facilitating deeper insight and hypothesis generation [29]. Integrated visualisation frameworks further streamline this process by seamlessly linking data acquisition, processing and visualisation within a unified pipeline, thus supporting efficient and informed decision-making [28]. To manage the computational demands of large-scale oceanographic datasets, GPU-accelerated rendering techniques enable real-time visualisation performance, which is essential for dynamic monitoring and responsive analysis [29].

The future of oceanographic visualisation increasingly emphasises narrative-driven, navigable spatial environments. Immersive systems, such as OceanVive, employ large curved displays to communicate complex phenomena, including hypoxia or plastic accumulation, to non-scientific audiences, enhancing intuitive understanding of dynamic ocean processes [39]. Figure 3.8 illustrates the system, highlighting (A) the 180º panoramic curved display and (B) the exploratory interaction panel. In parallel, web-based platforms enable local communities and citizen scientists to explore real-time plastic drift trajectories and accumulation patterns, fostering collaborative engagement and public awareness [24]. Figure 3.9 presents a screenshot of the online visualisation platform used to communicate the results of particle tracking simulations to local communities. These approaches demonstrate the potential of combining immersive and web-based visualisation to bridge the gap between scientific research and societal understanding.

Immersive technologies, including virtual, augmented and extended reality (VR/AR/XR) provide intuitive, spatially enriched environments for interacting with complex marine systems [38]. These platforms enhance user engagement and spatial awareness, especially in highly layered or three-dimensional contexts, making them valuable tools for both scientific exploration and stakeholder communication.

Emerging interactive strategies extend these capabilities by supporting structured exploration and decision-making. Interface designs inspired by the visual search mantra guide users from an

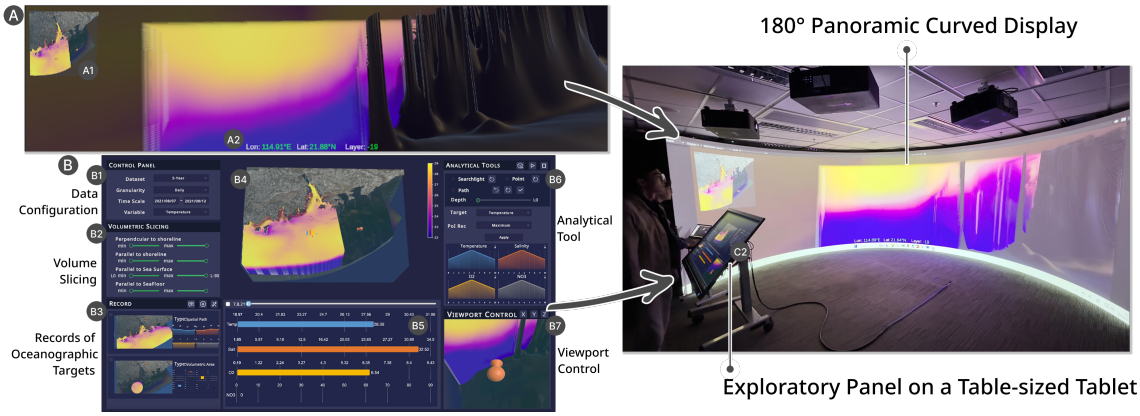


Figure 3.8: Overview of the OceanVive Immersive System [39].

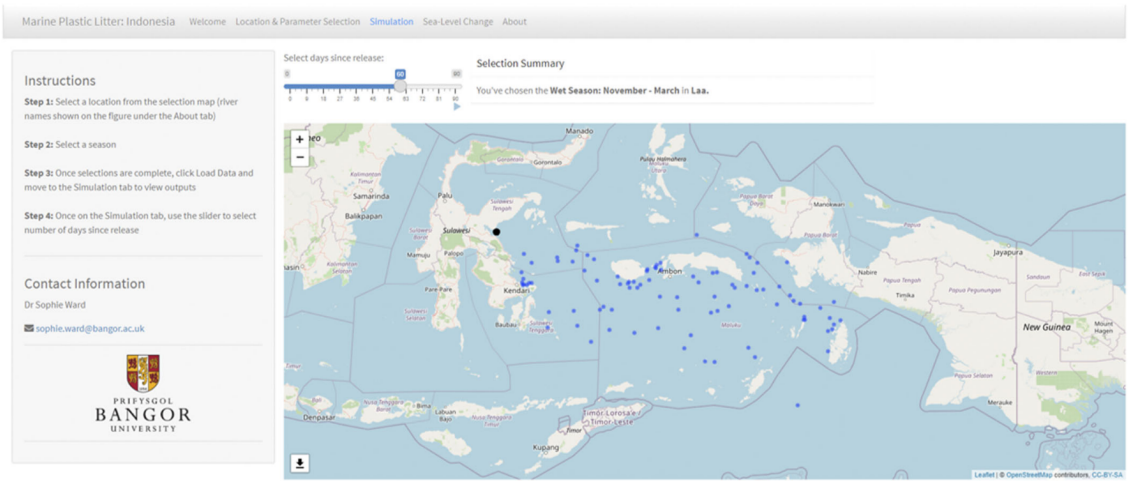


Figure 3.9: Web-based Visualisation Platform for Plastic Particle Tracking Results [24].

initial overview of the dataset through progressive zooming, filtering and access to detailed information, enabling efficient identification of patterns and anomalies in complex oceanographic data [37]. Serious games, such as the Iowa Watershed Decision Support System (IoWa DSS), introduce interactive and scenario based environments that engage stakeholders, including policymakers and resource managers, in collaborative planning and risk mitigation, offering an accessible means of exploring management strategies [37]. In addition, intelligent visual analytics systems integrate artificial intelligence techniques to automatically detect important features, such as anomalies in spatial or temporal data and guide users through interactive storytelling, reducing cognitive load and supporting data driven decision making [37].

By combining these interactive strategies with immersive and web-based visualisation approaches, modern visual analytics systems provide powerful tools for exploration, hypothesis generation, collaborative planning and public engagement, extending the impact of oceanographic research beyond the scientific community.

3.5 Summary

This chapter presents a comprehensive overview of the state of the art in modelling and visualising marine plastic pollution, highlighting both the maturity of existing approaches and the challenges that remain. Numerical modelling of plastic transport in the ocean is largely dominated by two paradigms: Lagrangian Particle Tracking Models and Eulerian Transport Models. Among these, Lagrangian Particle Tracking Models are more widely adopted due to their flexibility, intuitive representation of particle movement and suitability for simulating dispersion processes over time, while comparisons with Eulerian approaches reveal trade-offs in computational cost, scalability and physical detail.

The chapter emphasises that plastic dispersion in the marine environment is influenced by a complex combination of interacting factors, including ocean currents, turbulence, wind forcing, beaching and refloating processes, fragmentation and interactions with chemical contaminants. Accurately modelling these processes remains challenging and many existing models simplify or omit certain mechanisms, which can limit the realism and interpretability of simulation results.

From a visualisation perspective, a wide range of techniques is identified, including particle animations, vector fields, heatmaps, contour plots and three dimensional or immersive representations. While effective in conveying spatiotemporal patterns and large-scale trends, these approaches often prioritise technical sophistication over user centred evaluation and accessibility, limiting their suitability for non-expert audiences.

Overall, despite significant progress, a clear gap remains between complex simulation outputs and intuitive, accessible visual interfaces, motivating the need for interactive, web-based visualisation solutions that balance scientific accuracy with usability, readability and support for exploratory analysis. This knowledge is essential for formulating a concrete methodological plan to guide the development of the visualisations required to support and validate the work undertaken throughout the dissertation.

Chapter 4

Approach

The following chapter outlines the methodological approach adopted to develop a solution that addresses the problem identified in this study.

4.1 Introduction

In this chapter, building upon the insights obtained from the current state of the art, an approach to addressing the initially defined problem statement is established. To this end, key design considerations are visited, solution requirements are clearly defined and the design phase is initiated with the objective of producing a testable prototype supported by programmatic development. Each of these steps is described in detail in the following sections.

4.2 User-Centered Design Considerations

The development of an initial prototype required careful adherence to user-centred design principles. From the outset, all design considerations were made with the needs of the intended users in mind. This approach aligns with a user-centred design methodology, in which the prototype is conceived as an artefact to be evaluated and iteratively refined based on user testing and feedback.

This work follows the three-phase design framework described by Gould and Lewis [53]. The first phase corresponds to the requirements analysis presented in section 4.3, where the solution requirements for the intended prototype were defined with a strong focus on user needs. The target user is characterised as a non-expert individual with no prior experience in oceanographic or environmental data analysis, who may use the visualisation to gain insight into the dispersion of plastics in the ocean. The intended purpose of the visualisation is therefore not strictly scientific, but rather educational and exploratory, aiming to raise awareness of the issue and to support high-level understanding that may inform general decision-making related to monitoring and mitigation strategies.

A simplified diagram illustrating the design process framework is presented in Figure 4.1. This diagram provides a visual overview of the methodology and serves as a concise reference for the overall structure of the project.

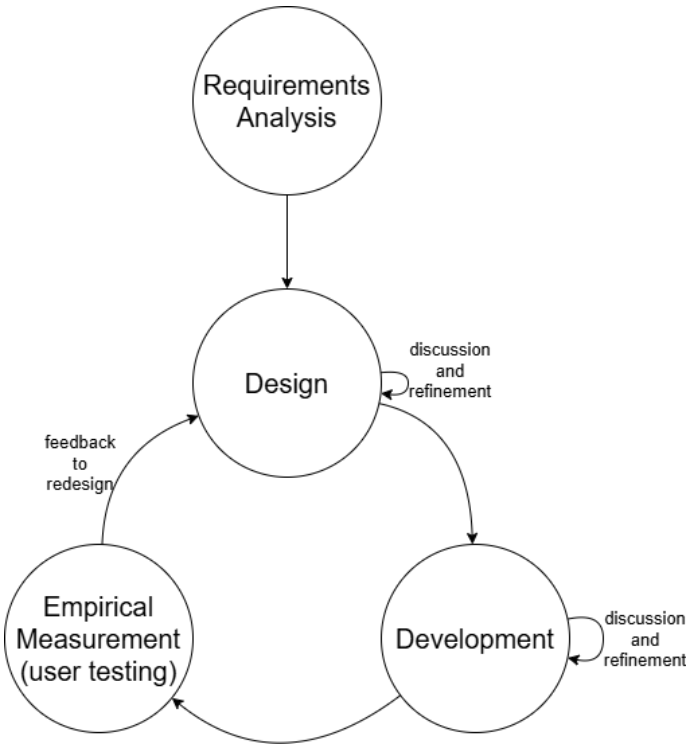


Figure 4.1: Design Framework.

Within the scope of this project, no preliminary user interviews or usability tests were conducted during this initial phase. This decision was influenced by time constraints and by the nature of existing tools considered for benchmarking, namely PlasticAdrift [54] and the Copernicus MyOcean Pro Viewer [55]. These platforms were assessed as being, respectively, too simplistic and overly complex for extracting meaningful and comparable insights from user testing that would be directly applicable to the objectives of this dissertation. Additionally, the Copernicus MyOcean Pro Viewer does not natively support the visualisation of plastic data, requiring the addition of a custom layer on top of the existing marine datasets. This limitation further reduced its suitability as a baseline for early-stage evaluation. Figure 4.2 illustrates a screenshot of the PlasticAdrift website, while Figure 4.3 presents a screenshot of the Copernicus MyOcean Pro Viewer.

Furthermore, given the complexity of the topic and the level of domain knowledge required to interpret ocean plastic dispersion data, it was considered that interviews without prior hands-on interaction with a prototype would be unlikely to produce actionable or reliable requirements within the available timeframe.

Following the initial requirements phase and the identification of the key tasks users would be expected to perform, the second phase of the design process involved the creation of an empirical measurement. This phase is detailed in section 4.4 and focuses on the development of the prototype

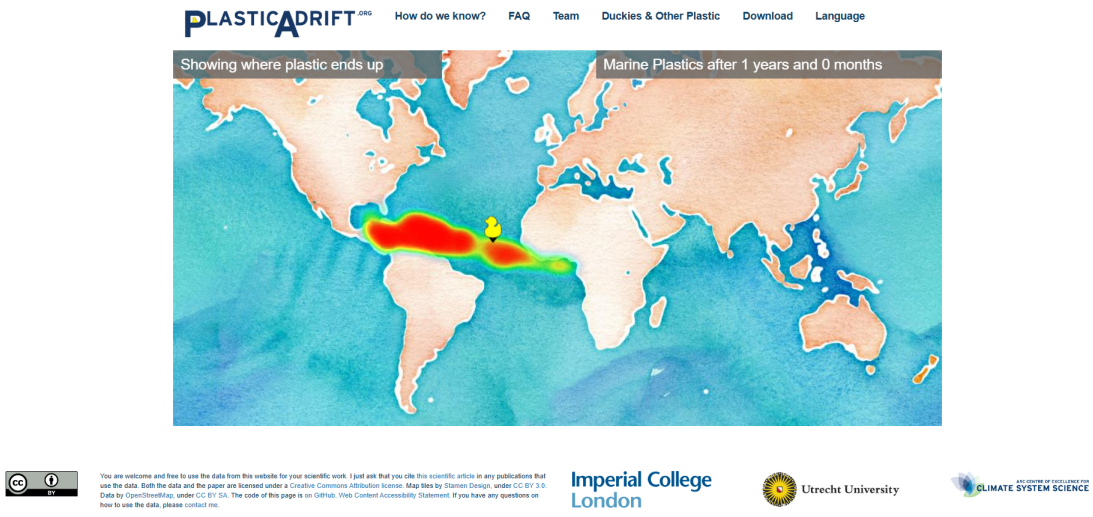


Figure 4.2: PlasticAdrift Web Interface [54].

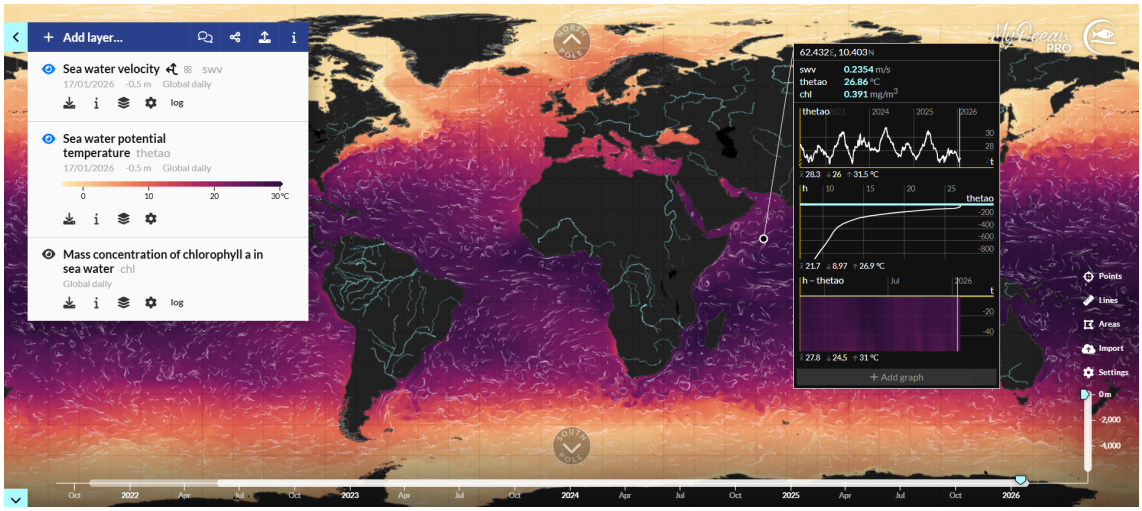


Figure 4.3: Copernicus MyOcean Pro Viewer Interface [55].

intended for user testing. The experimental design and testing methodology are described in detail in chapter 5.

Based on this framework, the project adopts an interaction design perspective in which user difficulties identified during testing inform subsequent design decisions. Although a full redesign and retesting cycle could not be completed due to time constraints, the first phase of user testing was conducted and produced initial results. These results validated the feasibility of the proposed prototype and identified areas for potential improvement. As such, the initial design cycle can be considered complete, providing a solid foundation for future iterative refinement. This establishes the work presented in this dissertation as a starting point for continued development, rather than a finalised solution and highlights its potential for extension through further cycles of evaluation and redesign.

4.3 Solution Requirements

To begin brainstorming how to design and develop a prototype for this visualisation, it is essential first to establish a clear understanding of the problem at hand. This foundational step enables the creation of a coherent conceptual framework for the prototype, clarifying what must be built and why each component is necessary. A central aspect of understanding the problem space is identifying users' needs and pain points [56] to focus on the underlying problems rather than prematurely considering potential solutions.

To support this process, a taxonomy table of relevant topics was created. These topics were subsequently organised into broader thematic categories related to the visualisation, referred to as design objectives. From these design objectives emerged three guiding questions that define the main areas of focus for this initial stage of prototype development, constituting the final selection of priorities for the project.

4.3.1 Taxonomy Table of Topics

To gain a clearer understanding of the objectives and key features to be incorporated into the prototype developed for this dissertation, a taxonomy table of topics was created. The table 4.1 presents the initial set of guiding questions, formulated with careful consideration of user needs and the types of actions users may wish to perform. For each question, the table also identifies the corresponding type of information that could be extracted, as well as the possible actions that could help users obtain those answers.

Question	Information Retrieved
On day A, which river region shows the highest concentration of plastics?	Filter by time and interpret the colour scale
During year B, which coast receives the greatest accumulation of particles?	Time, run the animation and interpret deposition
What is the main direction of plastics moving from location C on date D?	Using vector view and interpret directions
Which of the years E or F accumulates more plastics from fishing activity in country G?	Temporal comparison in the same region for fishing activity
Which hemisphere shows the greatest dispersion of plastics on date H?	Filtering by year and comparison between hemispheres
Which zone shows the highest rate of plastic dispersion between years I and J?	Multi-year animation and dispersion rate recognition
Which region of the ocean shows the greatest spatial dispersion of plastics on date K?	Switch to 3D, spatial perception of dispersion
During year L, the coasts of which continent receive the most plastic particles?	Coastal accumulation and comparison

Table 4.1: Taxonomy Table of Topics.

The topics captured in the table were organised into the corresponding user actions that they imply. These actions can be grouped into the following thematic categories:

- Filtering data by time
- Interpreting the colour scale
- Perceiving and comparing accumulation
- Running animations and interpreting deposition changes over time
- Viewing vectors and interpreting directional information
- Comparison of temporal data for the same region
- Understanding spatial dispersion with the aid of 3D rendering

4.3.2 Narrowing to Design Objectives

Table 4.1 was then expanded to include additional dimensions: the type of task required from the user, the justification for why each piece of information is necessary, the corresponding visualisation techniques recommended by the state of the art and the technique selected for the subsequent stage of the prototype design process.

The resulting structure is presented in table 4.2, where certain data values, locations and dates were created solely to simulate a realistic scenario for the formulation of the questions.

Example Question	**Task**	**Justification**	**Visual Representations (State of the Art)**	**Selected Representation**
Did the approximate plastic concentration near the coast of Portugal increase or decrease between 2020 and 2025?	Spatial Filtering + Value Retrieval/Estimation	Provides localised quantitative context (important to understand regional impacts)	- Spatiotemporal and Dynamic • Animations [29] • Coordinated Multiple Views (CMV) [29] • Real-Time Visual Systems [35] - Distribution and Accumulation • Heatmaps [25] • Density Maps [25] • Source-to-Sink Pathways [25] • Priority Area Maps (PAMs) [23]	Animation with heatmap (spatial distribution patterns and highlight concentration hotspots)
Which European Sea shows a concentration of more than 10^{-1} earliest in the timeline?	Temporal Filtering + Limit Detection	Detects critical regions (relevant for monitoring and prevention)	- Distribution and Accumulation • Heatmaps [25] • Density Maps [25] • Source-to-Sink Pathways [25] • Priority Area Maps (PAMs) [23]	Heatmap (spatial distribution patterns and highlight concentration hotspots)
Which ocean shows the highest concentration of plastic in 2020?	Hotspot Counting	Reveals spatial patterns (useful for prioritising intervention)	- Distribution and Accumulation • Heatmaps [25] • Density Maps [25] • Source-to-Sink Pathways [25] • Priority Area Maps (PAMs) [23]	Heatmap (spatial distribution patterns and highlight concentration hotspots)

Continued on next page

Example Question	Task	Justification	Visual Representations (State of the Art)	Selected Representation
In 2020, which region shows the most visible riverine particle emissions?	Temporal Filtering + Spatial Distribution	Identifies dominant riverine emissions (relevant for linking rivers to marine pollution)	- Dispersion and Trajectories • Vector Fields [49] • Streamlines [49] [32] • Particle Systems [49] • Trajectory Maps [15] - Distribution and Accumulation • Heatmaps [25] • Density maps [25] • Source-to-Sink Pathways [25] • Priority Area Maps (PAMs) [23]	Particle systems (particles advected over time displaying attributes such as velocity, lifespan and direction with reduced clutter and can incorporate shape, transparency, colour)
Where are fishing related emissions most concentrated in 2020?	Category + Spatial Distribution	Differentiates sources (relevant for fisheries management)	- Distribution and Accumulation • Heatmaps [25] • Density maps [25] • Source-to-Sink Pathways [25] • Priority Area Maps (PAMs) [23]	Particle systems (particles advected over time displaying attributes such as velocity, lifespan and direction with reduced clutter and can incorporate shape, transparency, colour)

Continued on next page

Example Question	**Task**	**Justification**	**Visual Representations (State of the Art)**	**Selected Representation**
How many distinct particle clusters are visible in the Atlantic Ocean in 2020?	Temporal Filtering + Aggregation Perception	Evaluates fragmentation vs concentration (important for dispersion analysis)	- Distribution and Accumulation • Heatmaps [25] • Density Maps [25] • Source-to-Sink Pathways [25] • Priority Area Maps (PAMs) [23]	Particle systems (particles advected over time displaying attributes such as velocity, lifespan and direction with reduced clutter and can incorporate shape, transparency, colour)
Which hemisphere shows more total emission particles in 2020?	Temporal Filtering + Aggregation Perception	Provides large-scale comparative insight (relates pollution to global circulation patterns)	- Distribution and Accumulation • Heatmaps [25] • Density Maps [25] • Source-to-Sink Pathways [25] • Priority Area Maps (PAMs) [23]	Particle systems (particles advected over time displaying attributes such as velocity, lifespan and direction with reduced clutter and can incorporate shape, transparency, colour)
Which coastal area is the primary origin for plastics entering the Atlantic Ocean in 2020?	Spatial and Temporal Filtering + Source Identification	Identifies main sources of pollution (mitigation policies)	- Dispersion and Trajectories • Vector Fields [49] • Streamlines [49] [32] • Particle Systems [49] • Trajectory Maps [15]	Vector Fields (represented with arrows indicating current speed and direction)

Continued on next page

Example Question	Task	Justification	Visual Representations (State of the Art)	Selected Representation
From which region do plastics most frequently flow into the Mediterranean Sea in 2020?	Spatial and Temporal Filtering + Source Identification	Pinpoints key entry sources (containment strategies)	- Dispersion and Trajectories • Vector Fields [49] • Streamlines [49] [32] • Particle Systems [49] • Trajectory Maps [15] - Spatiotemporal and Dynamic • Animations [29] • Coordinated Multiple Views (CMV) [29] • Real-Time Visual Systems [35]	Animation with Vector Fields (represented with arrows indicating current speed and direction)
Which current carries most plastics from Southeast Asia toward the Pacific?	Spatial Filtering + Vector Interpretation	Identifies dominant transport route	- Dispersion and Trajectories • Vector Fields [49] • Streamlines [49] [32] • Particle Systems [49] • Trajectory Maps [15]	Animation with Vector Fields (represented with arrows indicating current speed and direction)
What is the predominant direction of plastic flow from the Mediterranean Sea in 2020?	Spatial and Temporal Filtering + Vector Interpretation	Defines main exit routes (useful for predicting dispersion)	- Dispersion and Trajectories • Vector Fields [49] • Streamlines [49] [32] • Particle Systems [49] • Trajectory Maps [15]	Animation with Vector Fields (represented with arrows indicating current speed and direction)

Table 4.2: Design Objectives.

The visualisation techniques identified in the literature were used to guide the selection of representations according to the example questions defined in the design objectives. Techniques supporting distribution and accumulation, such as heatmaps and density maps, were favoured for tasks involving concentration comparison and hotspot detection. Particle systems were selected for representing dispersion, emissions and clustering, as they effectively convey trajectories and temporal evolution while reducing visual clutter through visual encoding. For tasks related to

transport direction and flow interpretation, vector fields, often combined with animation, were chosen to represent current-driven movement and dominant pathways. Interactive and spatiotemporal techniques further support flexible exploration across space and time, ensuring that each selected representation aligns with both the task requirements and the capabilities identified in the state of the art.

4.3.3 Final Selection

Following the alignment of table 4.2, it became evident that several questions were highly similar and addressed overlapping objectives. Retaining all questions would have introduced redundancy without providing additional insight into the design space. As a result and given the similarity among the selected solution approaches, a need emerged to consolidate and refine the set of questions. Therefore, the set was reduced to three representative questions, each capturing a distinct objective: limit detection, spatial distribution and vector interpretation. This reduction allowed the design process to focus on a manageable number of core tasks while still covering the key visualisation requirements identified in the state of the art. With this in mind, the final selection of user questions is presented in Table 4.3.

Example Question	**Task**	**Goal**	**Visual Representations (State of the Art)**	**Selected Representation**
Which European Sea shows a concentration of more than 10^{-1} earliest in 2020?	Temporal Filtering + Limit Detection	Detects critical regions (relevant for monitoring and prevention)	- Distribution and Accumulation • Heatmaps [25] • Density Maps [25] • Source-to-Sink Pathways [25] • Priority Area Maps (PAMs) [23] - Dispersion and Trajectories • Vector Fields [49] • Streamlines [49] [32] • Particle Systems [49] • Trajectory Maps [15]	Heatmap (spatial distribution patterns and highlight concentration hotspots) OR Particle Systems (particles advected over time displaying attributes such as velocity, lifespan and direction with reduced clutter and can incorporate shape, transparency, colour)

Continued on next page

Example Question	**Task**	**Goal**	**Visual Representations (State of the Art)**	**Selected Representation**
In 2020, which region is most likely to contribute plastic waste to riverine pathways that lead to the ocean?	Temporal Filtering + Spatial Distribution	Identifies dominant riverine emissions (relevant for linking rivers to marine pollution)	- Distribution and Accumulation • Heatmaps [25] • Density Maps [25] • Source-to-Sink Pathways [25] • Priority Area Maps (PAMs) [23] - Dispersion and Trajectories • Vector Fields [49] • Streamlines [49] [32] • Particle Systems [49] • Trajectory Maps [15]	Heatmap (spatial distribution patterns and highlight concentration hotspots) OR Particle systems (particles advected over time displaying attributes such as velocity, lifespan and direction with reduced clutter and can incorporate shape, transparency, colour)
From which region do plastics most frequently flow into the Mediterranean Sea in 2020?	Vector Interpretation	Pinpoints key entry sources (containment strategies)	- Dispersion and Trajectories • Vector Fields [49] • Streamlines [49] [32] • Particle Systems [49] • Trajectory Maps [15] - Spatiotemporal and Dynamic • Animations [29] • Coordinated Multiple Views (CMV) [29] • Real-Time Visual Systems [35]	Animation with Vector Fields (represented with arrows indicating current speed and direction)

Table 4.3: Final Selection.

The final set of questions provides a focused and representative basis for the design process,

covering key analytical tasks and visualisation requirements identified in the state of the art. These questions directly inform the design decisions and implementation choices described in the following section.

4.4 Design Process

For the development of the prototype, it is essential to consider the creation of a conceptual model, which is defined as:

> "a description of the proposed system in terms of a set of integrated ideas and concepts about what it should do, behave and look like, that will be understandable by the users in the manner intended." [56]

In designing a visualisation to represent plastics in the ocean, several initial elements were identified to support map-based representation, integrating all the information from the table 4.3. As discussed in the chapter 3, key elements include a map visualisation that incorporates particle systems, as well as streamlines that represent plastics flow. These streamlines illustrate the dispersion trajectories of plastics released from the coast, taking into account environmental factors such as wind, waves and tides. Additional visualisation components include heatmaps and spatiotemporal dynamics, such as animations that display changes over time.

Key user interactions were also considered, including zooming, filtering and variable selection. These interactions allow users to explore specific regions of the world and clearly differentiate the amount of plastics at individual data points.

The development process highlighted the need to create prototypes. Initially, a low-fidelity prototype was developed, which subsequently evolved into a high-fidelity prototype using mock-ups. These phases are described in detail in the following subsections.

4.4.1 Low-Fidelity Prototyping

Figure 4.4 presents the low-fidelity prototype developed to support the initial conceptualisation of the features identified in the previous chapter. The prototype serves as a conceptual representation of the intended system layout, interaction mechanisms and visualisation components.

To establish a spatial framework, the design was represented using a 2D map. Additionally, the data needed to be represented in a spatio-temporal context. Whilst the spatial variable is inherently incorporated through the map, the temporal variable required a dedicated mechanism. To address this, a bottom bar with a play button was created to start an animation, allowing the simulation of the passage of time to be visualised. Complementary buttons displaying specific dates were included to enable users to filter the visualisation according to the time periods of interest.

The prototype also explored ways for users to choose between alternative visualisation modes, with the selected option appearing on the map. Additional interactive elements considered included adjusting environmental parameters, such as wind speed and wave conditions, to illustrate

how these factors might influence the dispersion of plastics. Zoom functionality was also considered to allow both detailed and overview perspectives of the spatial data.

In this low-fidelity prototype, animation controls were conceptually placed at the bottom of the screen, while visualisation options were positioned on the right side, using slide bars and radio buttons. Zoom controls were suggested to be located above the map, which was centred on the screen. In the figure, the striped region is intended to represent land (specifically the Iberian Peninsula and part of northern Africa), while the unshaded areas represent the oceans and seas. The grey area indicates a heatmap-style visualisation, corresponding to the option selected via the "Colour Coded" radio button located on the right side of the screen.

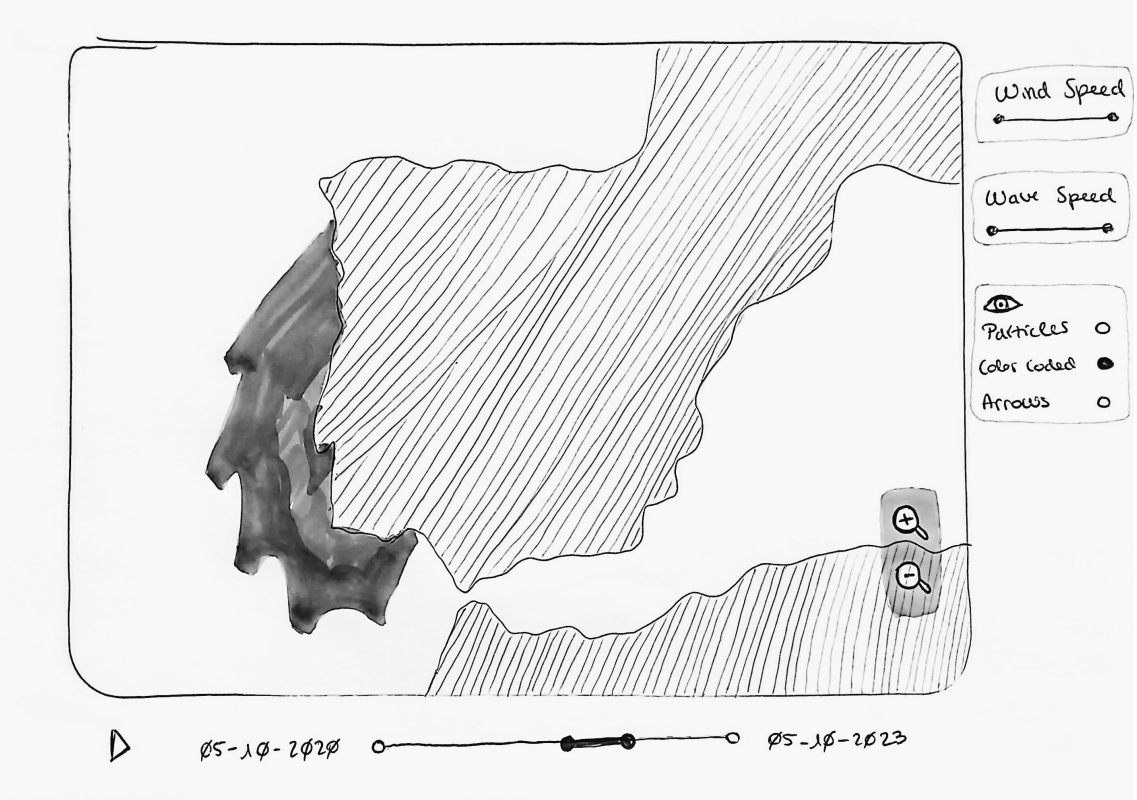


Figure 4.4: Low-Fidelity Prototype.

4.4.2 High-Fidelity Prototyping (Mockups)

Following the development of the low-fidelity prototype, it was determined that it provided a suitable foundation that served as a proof of concept for further development. A second iteration was therefore created, incorporating full functionality and interactivity to test the most effective design implementations for the initial programming prototype.

The initial screen (Figure 4.5) presents a conceptual globe, allowing the user to select the dataset to be explored. A side menu contains radio buttons for each dataset option.

Once a dataset is selected (Figure 4.6), the user can choose a region, corresponding to one of the continents of the globe (Figure 4.7).

Figure 4.5: First Screen.

Figure 4.6: Study Selection Screen.

Figure 4.7: Region Selection Screen.

After both the "Study" and "Region" selections are made, an animation initiates in which the globe rotates and zooms into the selected region (Figures 4.8-4.11). This demonstrates a simple overview + detail technique, where the overview is represented by the globe and, following the animation, a more detailed 2D map is presented, showing a subset of the data filtered by the selected region.

Upon zooming into the selected area, the globe transitions into a 2D map, as seen on Figure 4.12. In this screen, the map occupies the central portion of the page as a primary background. A bottom bar provides temporal controls, including buttons for selecting specific dates, a slider to adjust dates and a play button to animate the progression over time. On the right side of the screen, users can select their preferred visualisation type using a radio button, with three options available: "Particles", "Color" or "Vectors". Zoom controls are positioned at the top-right corner of the map.

During an early review session, it was suggested that users would benefit from a persistent reference of the overall map to maintain orientation while exploring detailed regions. To address this, a mini-map was added in the top-left corner of the screen, showing the full map with a highlighted rectangle indicating the currently viewed area. This modification demonstrates the iterative nature of the design process, in which feedback directly informed improvements to the prototype, ensuring better spatial awareness for the user, providing contextual information.

Additionally, a collapsible sidebar menu is available, which slides out of view but reappears when hovered over on the left side of the screen (Figure 4.13). This menu allows users to modify the initially selected study (Figure 4.14) and region (Figure 4.15), with the options mirroring those

Figure 4.8: Animation Screen 1.

Figure 4.9: Animation Screen 2.

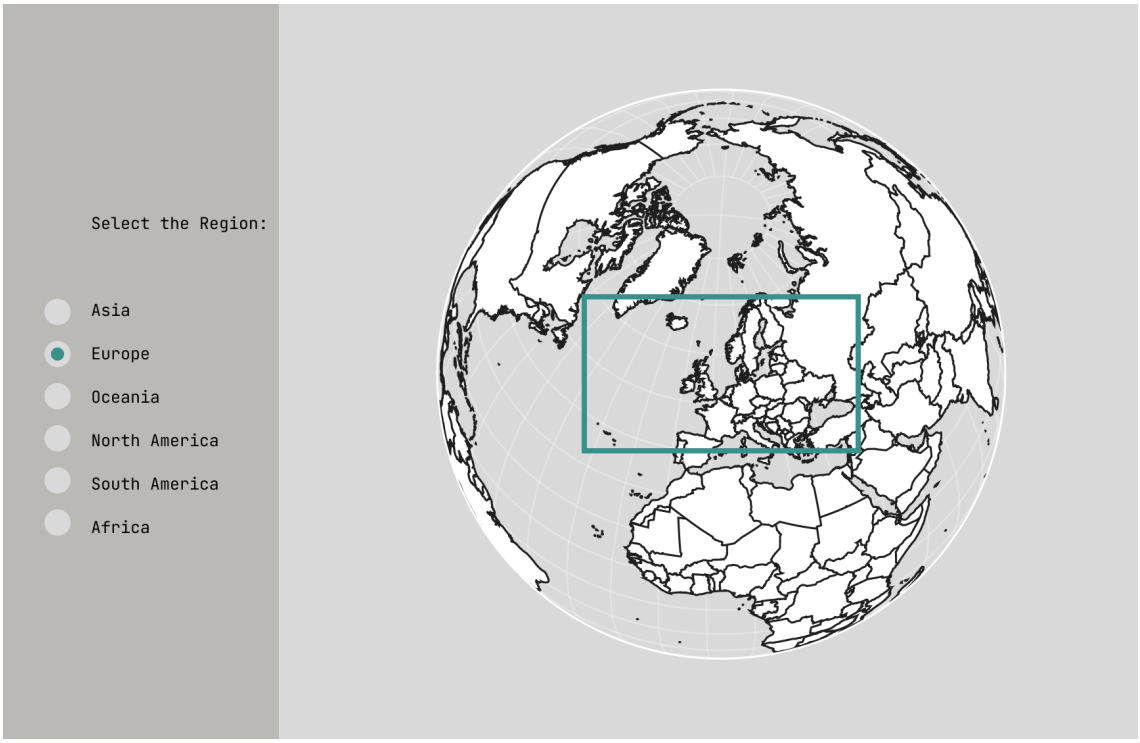


Figure 4.10: Animation Screen 3.

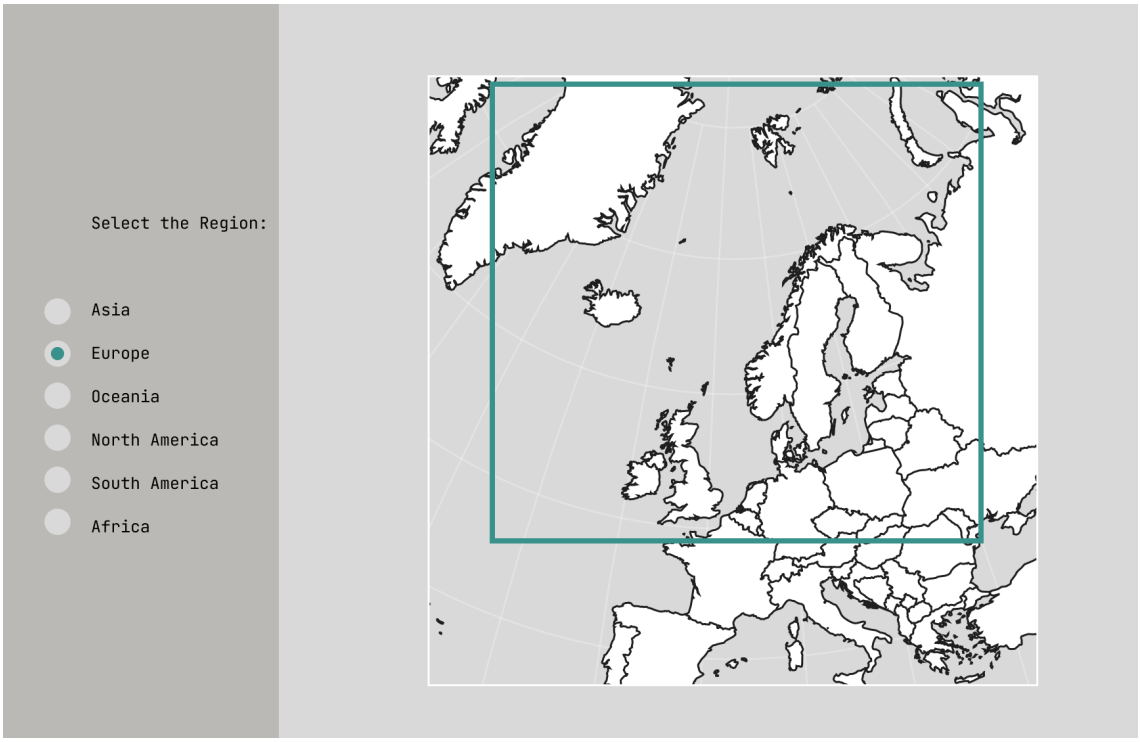


Figure 4.11: Animation Screen 4.

Figure 4.12: Map Screen.

on the initial screen.

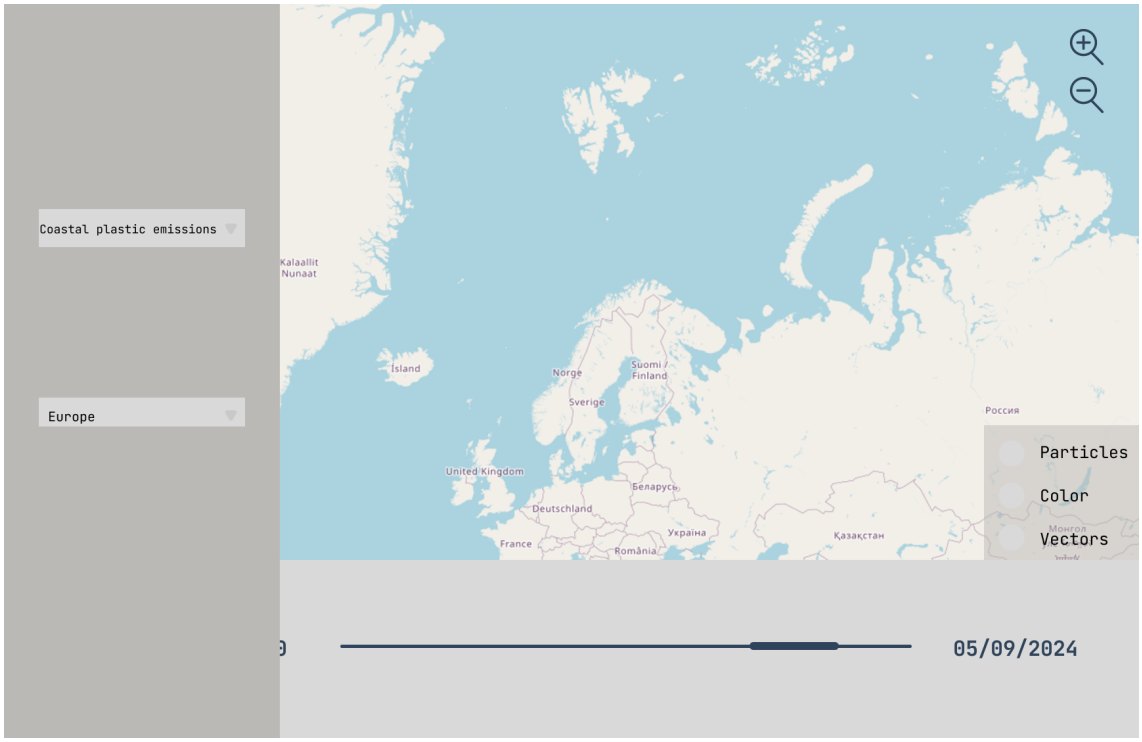


Figure 4.13: Map Screen Sidebar 1.

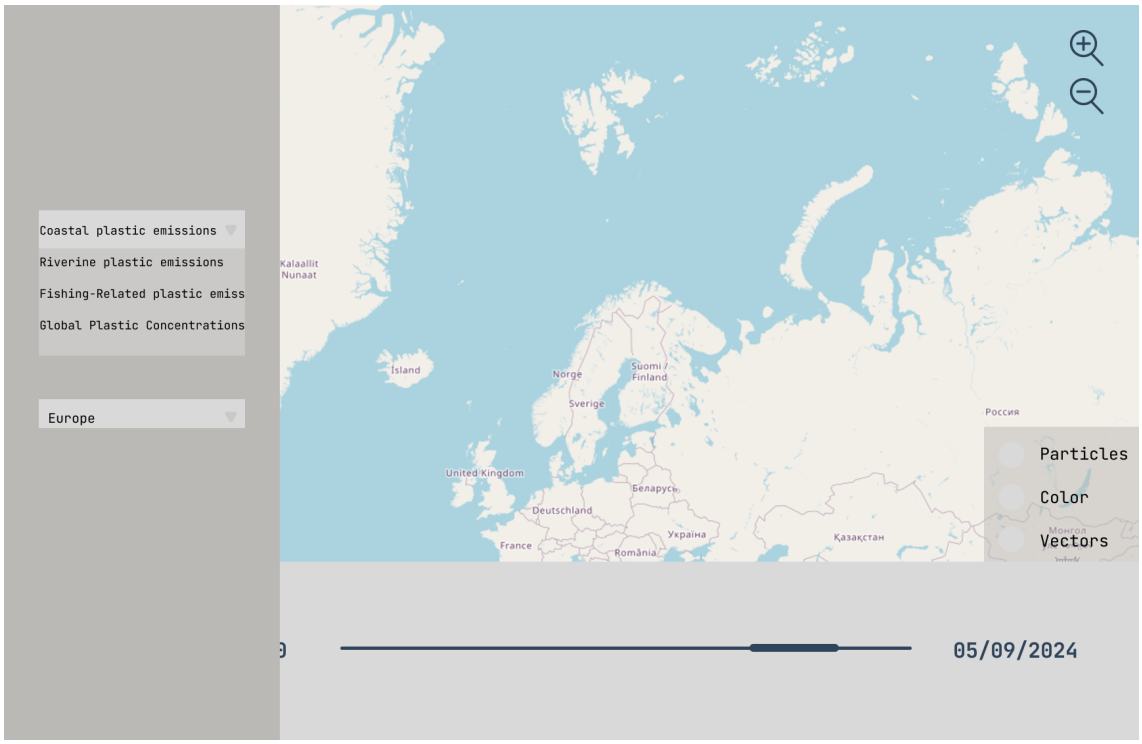


Figure 4.14: Map Screen Sidebar 2.

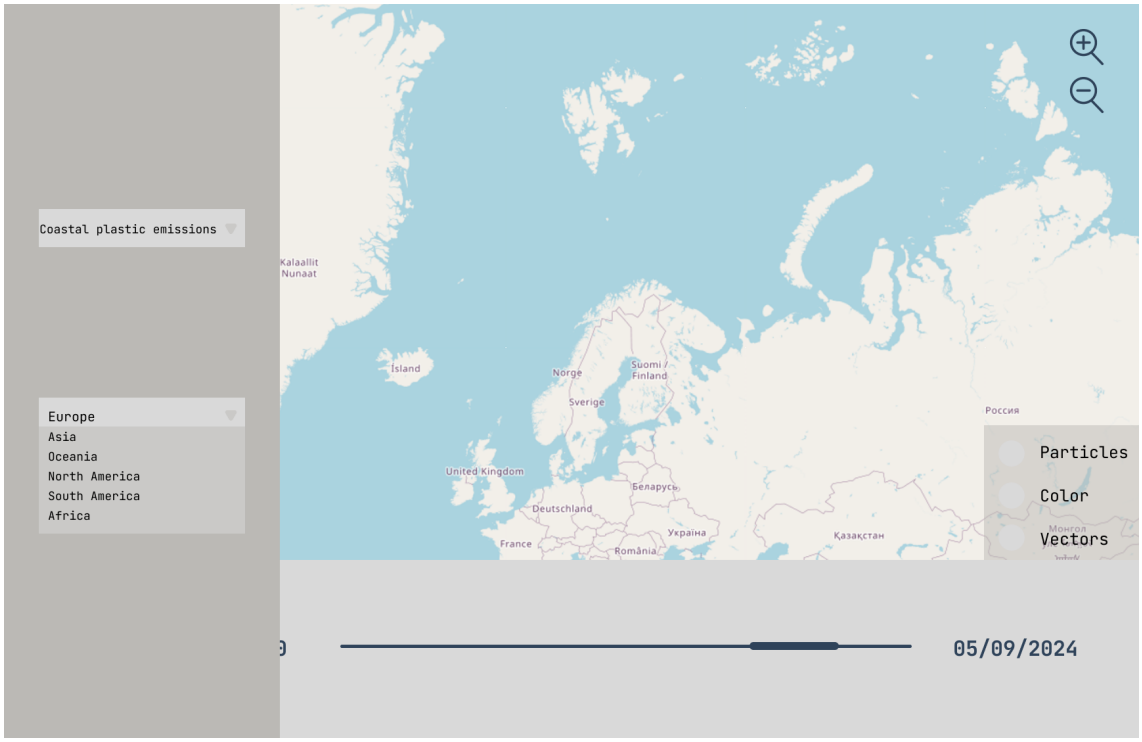


Figure 4.15: Map Screen Sidebar 3.

Selecting the "Colour" visualisation displays the plastics data as a heatmap with three distinct colours (Figure 4.16). Hovering over the information button provides a legend explaining the meaning of each colour (Figure 4.17).

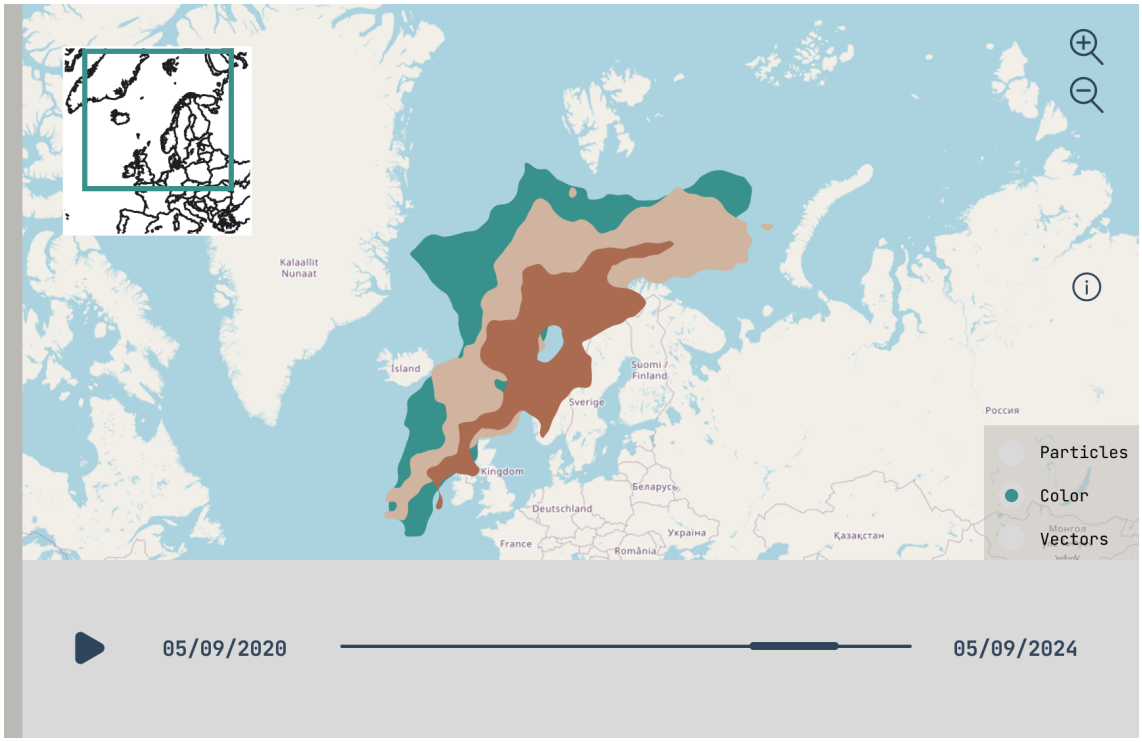


Figure 4.16: Colour Screen.

The "Particles" option visualises the data as individual points, with accumulation represented by the density of colored dots (Figure 4.18).

The "Vectors" option shows the calculated movement direction of particles, represented by arrows indicating orientation (Figure 4.19).

All of these interactions are demonstrated in a video of the high-fidelity prototype, which can be accessed via the following link:

`https://drive.google.com/file/d/1MjoctwUhSpxCjxbMxW3MQh-KMrr78fch/view?usp=sharing`

The prototype was developed using Figma [57], an interface design tool.

4.5 Functional Prototype

Following the initial design phase, in which the ideas for the prototype were defined, the next step involved progressing to the implementation phase to develop a programmable solution suitable for user testing. This required making informed decisions regarding both the technologies and the datasets used in the development of the prototype. The programming process and technical implementation of the testing prototype are described in detail in subsection 4.5.3.

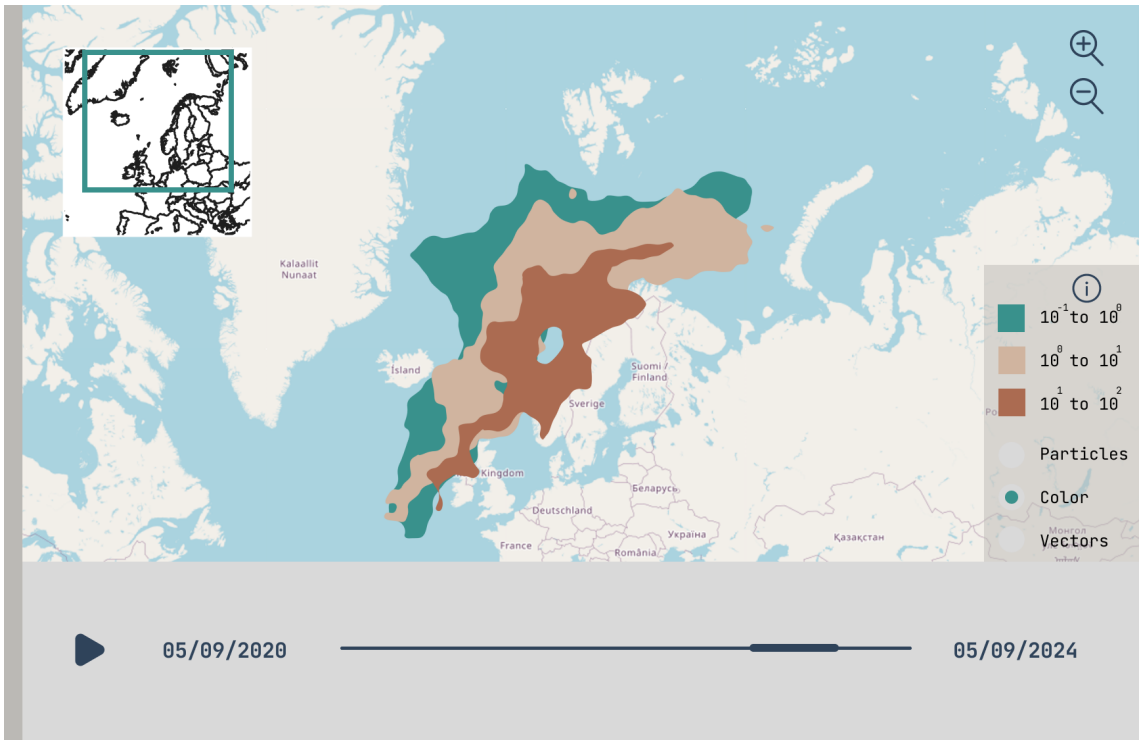


Figure 4.17: Colour Screen Info.

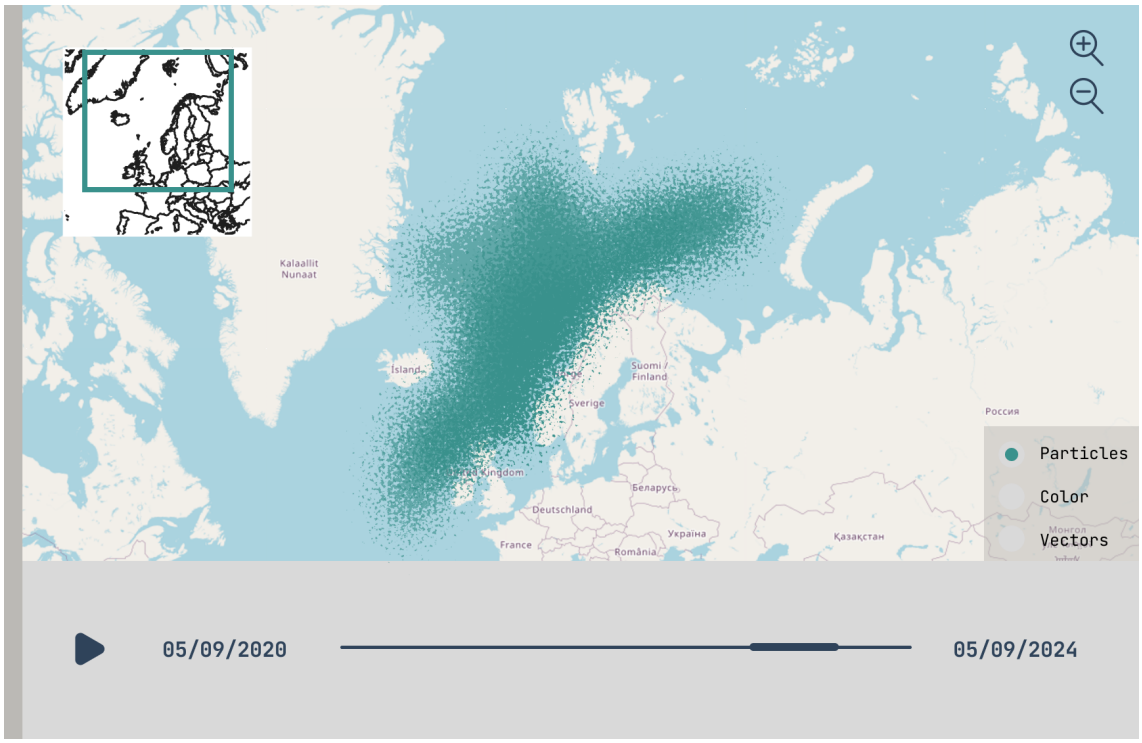


Figure 4.18: Particle Screen.

Figure 4.19: Vector Screen.

4.5.1 Technology Selection

Considering the main requirements defined for the prototype, it was essential to make informed decisions regarding the technologies to be used in the development of a programmatic solution suitable for user testing. To this end, a simple single-page web application was created to materialise the visualisation. This prototype was implemented using standard web technologies, namely HTML, CSS and JavaScript. These technologies were selected because the prototype phase did not require a complex technical infrastructure.

To make the web application accessible for the development phase and for user testing, it was run locally using the Live Server [58] extension for Visual Studio Code [59]. This solution enabled the application to be accessed in a browser without requiring a full production deployment. During development, the automatic page reloading triggered by file modifications proved essential, as it supported rapid iteration and simplified debugging. The simplicity, minimal configuration requirements and absence of performance or security constraints associated with this approach were all aligned with the goals of prototype development.

Given that modifications were expected after the first round of user testing, it was considered more appropriate to prioritise conceptual clarity over an overly complex technology stack. This choice also facilitated faster debugging during a phase characterised by frequent iterations and allowed for better control over performance by minimising external dependencies.

Despite the simplified approach, specific technologies were required to support the visualisation objectives, particularly regarding map-based representation. For this purpose, the Leaflet

[60] library was adopted. Leaflet was chosen due to its open-source nature, its JavaScript-based implementation and its seamless integration within the existing development environment. Although Leaflet places a strong emphasis on mobile applications, which was not a primary goal of this project, it offers a clean visual design, an intuitive API and a wide range of plugins, making it well-suited for rapid prototyping. To fully leverage the library's capabilities, geographic data were formatted using the GeoJSON standard to enable proper rendering and interaction within the map.

A central objective of the visualisation was to represent the dispersion of plastics in the ocean. In line with the state of the art reviewed for this project and considering existing technologies used for this purpose (Appendix E), the plasticParcels [61] Python package was initially selected to generate simulations of plastic transport and dispersion. The initial application setup was developed using this technology, however, integration issues related to wind and wave data prevented this solution from meeting the project's requirements within the available timeframe. As a result, an alternative simulation Python package, OpenDrift [62], was adopted. OpenDrift is open-source and designed to model the trajectories and fate of objects and substances drifting in the ocean and includes a dedicated class for plastic particles. Both plasticParcels and OpenDrift employ Lagrangian modelling approaches and are open-source, which were key factors in their selection. Although the integration issues with plasticParcels were later resolved following communication with its development team, only simulations generated using OpenDrift were ultimately tested by users in this study.

To support integration between the simulation outputs and the front-end visualisation, some data preprocessing was required. For this purpose, Python was used to perform lightweight data manipulation tasks. Python was also employed during early exploratory phases to test simulation outputs, run tutorial examples provided by the selected frameworks and generate initial static plots and maps to validate the results.

In addition to these technologies, Git was used for version control, backup and documentation of the project's development process. The repository was hosted on GitLab, which aligns with the infrastructure used at FEUP. The project repository is available at the following link:

`https://gitlab.up.pt/up201806629/feup_thesis`

4.5.2 Database Design

Since the data used in the prototype were not collected within the scope of this dissertation, it was necessary to identify datasets available online under open licenses or within the public domain. As the plasticParcels technology had already been selected for this project, the datasets required by this package were adopted [63]. PlasticParcels is designed to operate with data provided by the Copernicus Marine Service [64]. Consequently, several types of environmental data were required, namely hydrodynamic model data, biogeochemical model data, wave data and wind data. Some of the links originally provided by the plasticParcels framework were depracated and certain datasets differed from those initially required. The datasets ultimately gathered and used in this project are described below.

Hydrodynamic model data [65] This dataset consists of a global ocean physics reanalysis produced by Mercator Ocean and distributed through the Copernicus Marine Service. It is provided in NetCDF format and offers a daily mean, physically consistent 3D description of the ocean state, with separate files available for each day of 2020. The dataset includes 2D surface variables with dimensions of time, latitude and longitude, namely mixed layer thickness (mlotst, m), sea surface height above geoid (zos, m), sea floor potential temperature (bottomT, $^{\circ}C$), sea ice thickness (sithick, m), sea ice concentration (siconc, *dimensionless*), eastward sea ice velocity (usi, m/s) and northward sea ice velocity (vsi, m/s). In addition, 3D ocean interior variables are provided with dimensions of time, depth, latitude and longitude, including the potential temperature (thetao, $^{\circ}C$), salinity (so, *psu*), eastward ocean current velocity (uo, m/s) and northward ocean current velocity (vo, m/s).

Biogeochemical model data [66] This dataset contains surface biogeochemical variables extracted from a global reanalysis produced by Mercator Ocean within the Copernicus Marine Environment Monitoring Service (CMEMS). It is provided in NetCDF format and includes monthly data for the year 2020 on a regular latitude-longitude grid at a depth of $0.5m$, as the focus of this project is on surface plastic transport and dispersion. The variables include chlorophyll concentration (chl, mg/m^3), dissolved iron concentration (fe, $mmol/m^3$), nitrate concentration (no3, $mmol/m^3$), net primary production ($nppv$, $mg{\cdot}m^{-3}{\cdot}day^{-1}$, dissolved oxygen (o2, $mmol/m^3$), pH (ph, *dimensionless*), phytoplankton concentration in carbon (phyc, $mmol/m^3$), phosphate concentration (po4, $mmol/m^3$), silicate concentration (si, $mmol/m^3$) and surface partial pressure of CO_2 (spco2, Pa). All variables have dimensions of time, depth, latitude and longitude, except for spco2, which includes only time, latitude and longitude.

Wave data [67] Wave data were obtained from a global surface drift dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) [68]. The dataset is provided in NetCDF format and contains daily data for the year 2020 on a global latitude-longitude grid. The variables include mean wave period (mwp, s), peak wave period (pp1d, s), the U-component (eastward) Stokes drift (ust, m/s) and the V-component (northward) Stokes drift (vst, m/s).

Wind data [67] Global near-surface wind fields were also obtained from ECMWF. This NetCDF dataset provides daily data for the year 2020 on a global latitude-longitude grid and includes the neutral wind at $10m$ height, represented by the U-component (eastward) (u10, m/s) and V-component (northward) (v10, m/s) wind velocity.

In addition to these environmental datasets, the plasticParcels package provides four particle initialisation datasets representing different sources of plastic pollution: coastal emissions [69], riverine emissions [70], open-ocean emissions from fishing-related activities [71] and estimated concentrations of buoyant plastics on beaches worldwide [72].

The coastal dataset represents mismanaged plastic waste in kilograms per person per day ($kg/person/day$) and incorporates population density and economic status information.

The riverine emissions dataset quantifies plastic pollution entering the ocean through river systems and reports values in tonnes per year (*tonnes/year*).

The fisheries dataset quantifies plastic inputs based on monthly fishing effort measured in fishing hours, under the assumption that plastic waste generation is proportional to fishing activity.

The global beach concentration dataset reports accumulation in grams per meter of coastline (*g/m of coastline*). As indicated in the code provided by the authors of plasticParcels, the technology offers data for the year 2020 [73].

Table 4.4 summarises the main characteristics of these datasets, including their representation, plastic units, spatial and temporal coverage, variables and scale.

In order to use these datasets with the plasticParcels technology, several preprocessing steps were required. Specifically, the wave and wind data needed to be reoriented from south to north instead of north to south. Additionally, since the plasticParcels code was not updated for the latest datasets, modifications were necessary, including adjustments to fieldset construction, renaming of variables, unit conversions, coordinate alignment and the inclusion of placeholders for missing or inconsistent data. Temporal normalisation across all datasets was also performed. All models were converted to GeoJSON files to facilitate integration with the Leaflet library. For all simulations, the biogeochemical dataset was not used, therefore, biochemical factors and biofouling were not considered. An initial test simulation was run along the Italian coast to verify functionality.

In Figure 4.20, land is represented in grey, allowing the movement of particles to be observed relative to the coastline. Panel *a)* shows the trajectory map, which displays the individual paths of all particles, while panel *b)* presents the spatial concentration map, illustrating the density of particle positions. In this map, brighter yellow areas indicate regions with higher particle concentrations. The simulation represents a period of 20 days, starting from the first day of 2020. The code used for this simulation is available at the following link: `https://gitlab.up.pt/up201806629/feup_thesis/-/blob/main/src/data/tutporial.py?ref_type=heads`

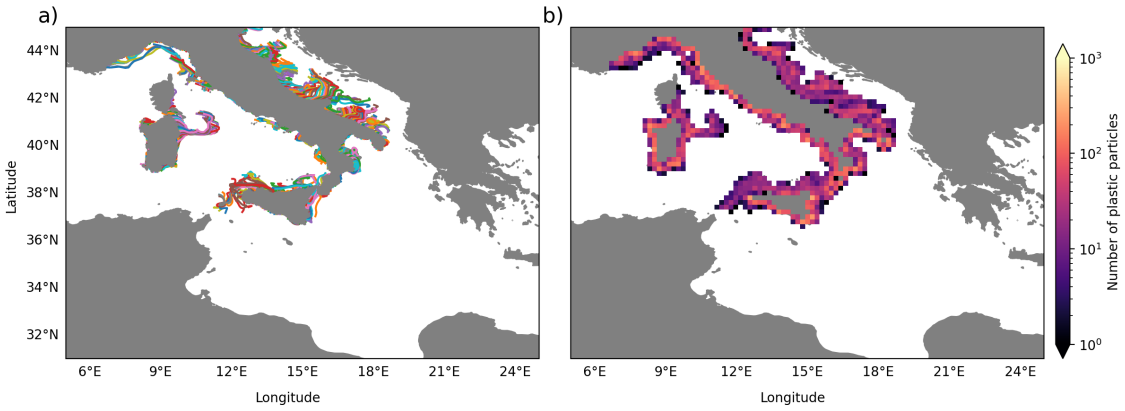


Figure 4.20: plasticParcels simulation.

Due to the time-intensive nature of this data preparation and the complications arising from integrating new datasets with the existing plasticParcels code, it was necessary to contact the original authors for clarification. The available documentation proved insufficient to resolve the issues.

Dataset	Representation	Plastic Units	Temporal and Spatial Coverage	Variables	Scale
Coastal	Estimates land-based plastic inputs from coastal populations using population density and mismanaged plastic waste rates	*kg/person/day*	Annual data for 2020; 193 countries (Africa, Antarctica, Asia, Europe, North America, Oceania, Seven seas – open ocean, South America)	continent, region, subregion, country, longitude, latitude, area [km^2], population density, economic status, mismanaged plastic waste [kg/person/day], MPW_Cell	87 859 rows
Rivers	Estimates plastic emissions entering the ocean via rivers, a major land-to-sea transport pathway	*tonnes/year*	Annual data for 2020; 139 countries (Africa, Asia, Europe, North America, Oceania, South America)	continent, region, subregion, country, longitude, latitude, emissions	31 819 rows
Fisheries	Global fishing activity as a potential ocean-based source of plastic pollution, quantified through fishing effort	*fishing hours*	Monthly data from January to December 2020; 130 countries (Africa, Asia, Europe, North America, Oceania, Seven seas – open ocean, South America)	longitude, latitude, flag, gear type, month, continent, region, subregion, country, fishing hours	5 975 970 rows
Ocean	Modelled marine plastic concentration fields, representing the spatial distribution of plastic already present in the ocean	*g/m of coastline*	Annual data for 2020; 181 countries (Africa, Antarctica, Asia, Europe, North America, Oceania, Seven seas – open ocean, South America)	continent, region, subregion, country, longitude, latitude, concentration, concentration type	7 670 612 rows

Table 4.4: Summary of Datasets.

Given the urgency of progressing with the experimental phase of the dissertation, an alternative solution was adopted using OpenDrift. Consequently, the final prototype tested with users and the data subsequently analysed in Chapter 6, relies exclusively on simulations conducted with OpenDrift rather than plasticParcels.

For the OpenDrift simulations, the same datasets were used as previously described. The pre-processing for OpenDrift involved reorienting the data from south to north, renaming variables to match OpenDrift's internal schema, temporal alignment and inclusion of placeholders. Additionally, a configuration was implemented to prevent particles from moving inland, ensuring that all particles remained in valid ocean positions. This required slightly nudging particles from land to ocean to conform to OpenDrift's schema, rather than the plasticParcels schema. The particle concentration was scaled down to maintain visual clarity and computational feasibility. The final particle trajectories were stored in NetCDF files, which were subsequently converted to GeoJSON format to facilitate integration with Leaflet. The code used for these simulations is available at the following link: https://gitlab.up.pt/up201806629/feup_thesis/-/blob/main/src/data/continentsOpenDrift.py?ref_type=heads

Initial test simulations were also plotted to verify the results, with examples shown in Figure 4.21.

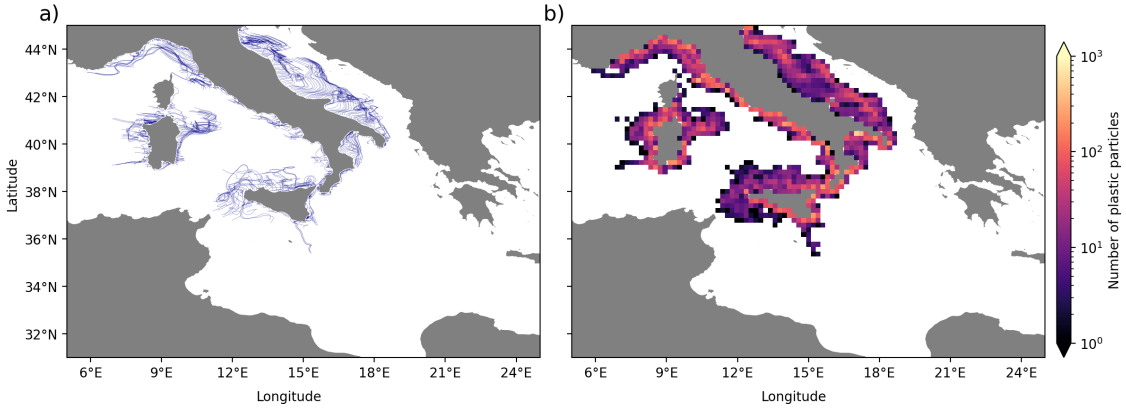


Figure 4.21: OpenDrift simulation.

Simulations were executed individually for each region-dataset pair, requiring filtering for each run. Because each simulation required approximately twenty minutes to run, it was not practical to generate data in real time for the frontend visualisation. Therefore, the results were precomputed and stored in GeoJSON files. For this dissertation, simulations were limited to thirteen days due to hardware limitations. The simulations were performed on the student's personal desktop computer (with a CPU of 1.80GHz and RAM of 8GB.

With these simulations completed, the dataset was considered ready for integration with the Leaflet-based visualisation, as described in the following subsection.

4.5.3 Prototype Development

The final structure of the programmatic prototype can be summarised with the UML Package Diagram in Figure 4.22. The Figure illustrates the architecture of the visualisation prototype, organised into four main components: the *Presentation Layer*, the *Application Core*, *External Libraries* and *Data Storage*. The *Presentation Layer* defines the user interface structure and styling, while the *Application Core* manages initialisation, user interactions, data processing and visualisation logic, with arrows indicating dependencies between modules. *External Libraries* provide additional functionality for mapping, heatmaps, sliders and fonts and the *Data Storage* component contains geographic and particle trajectory data used by the core modules to generate dynamic visualisations.

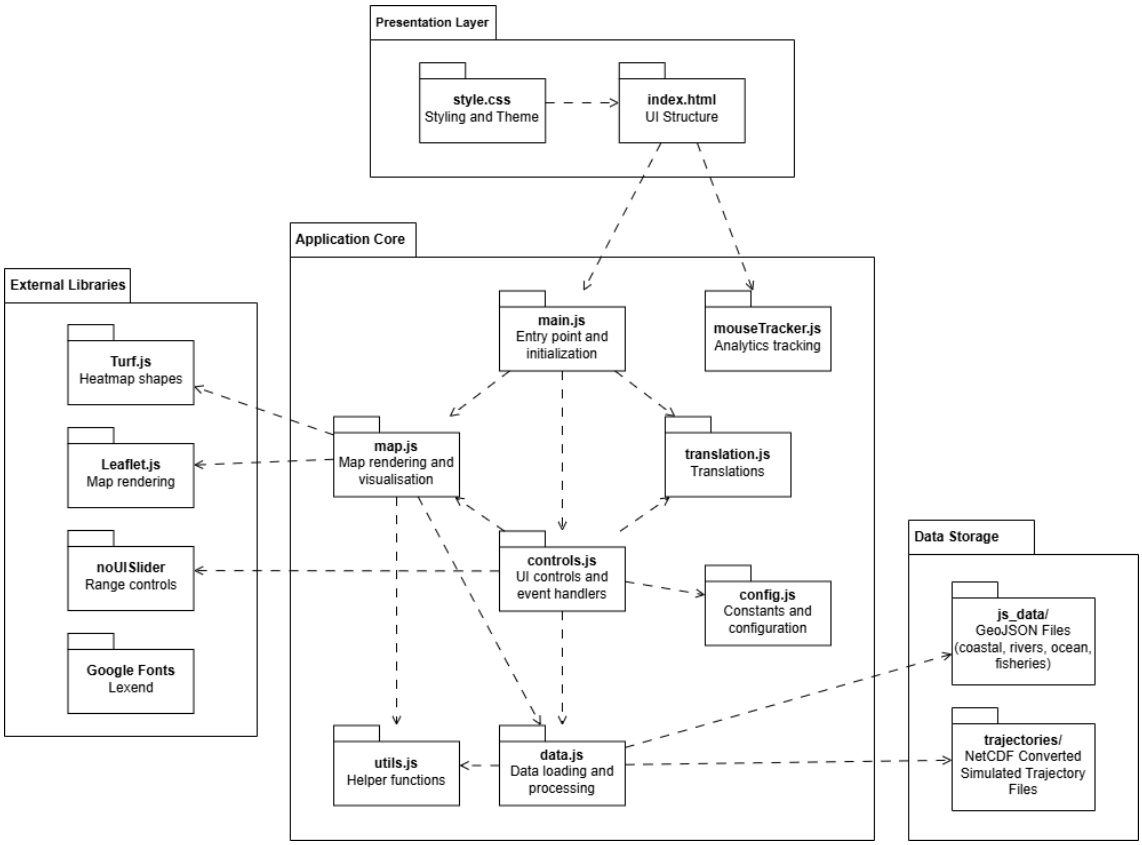


Figure 4.22: Package Diagram.

Additionally, a class diagram is provided in Figure 4.23 to give more detailed information on the relationships between elements. The figure presents the class and module architecture of the visualisation prototype, showing the interactions between the central *State* class and core modules such as *Main*, *ControlsModule*, *MapModule*, *DataModule*, *ConfigModule*, *UtilsModule* and *TranslationModule*. The *State* class maintains the active dataset, region, visualisation mode, trajectories and language settings, while data structures such as *FeatureCollection*, *Feature*, *Geometry*, *Properties* and *Trajectory* support consistent access to spatial and temporal information.

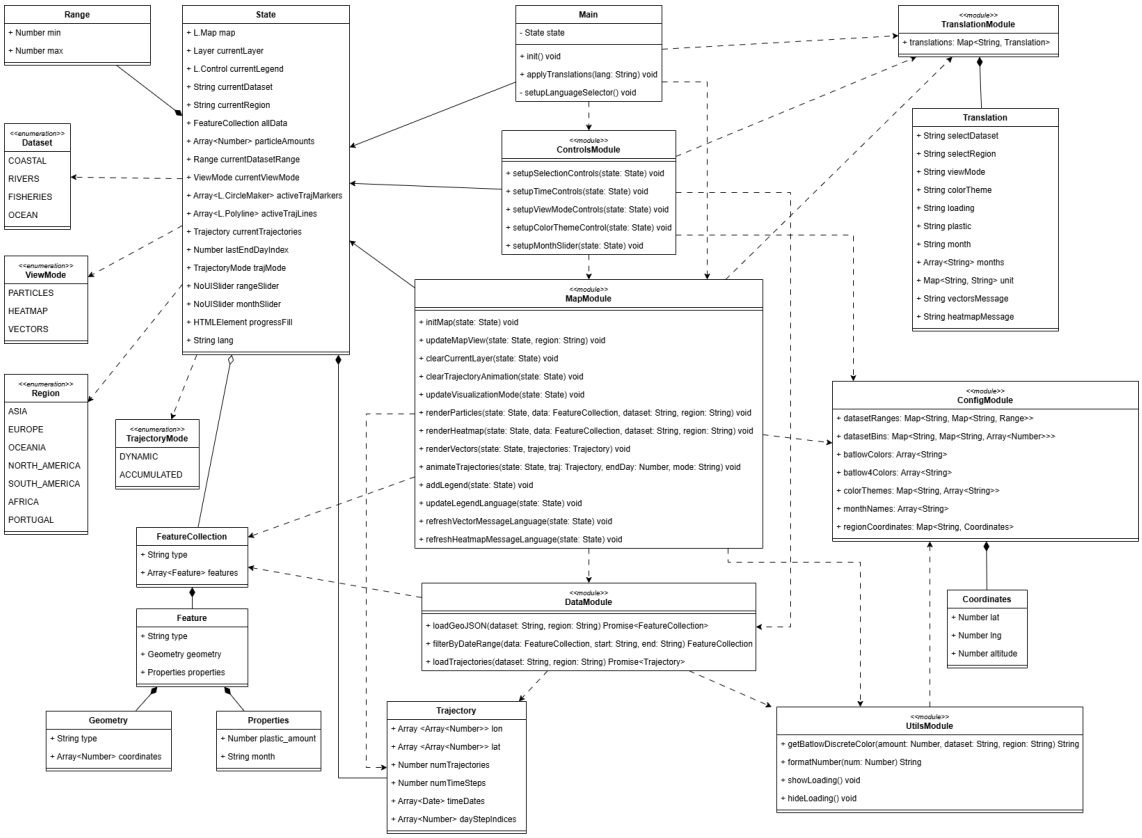


Figure 4.23: Class Diagram.

Although the complete code can be accessed at `https://gitlab.up.pt/up201806629/feup_thesis`, a detailed description of the development process and the evolution of the application to its final state is provided below. This phase was executed incrementally, with continuous discussion and refinements, as described in the design framework presented earlier 4.1.

An initial integration test with plasticParcels was performed to combine it with the Leaflet technology. The initialisation maps provided in the plasticParcels tutorial [74] were followed, resulting in an initial representation with both technologies working together, as seen in Figure 4.24.

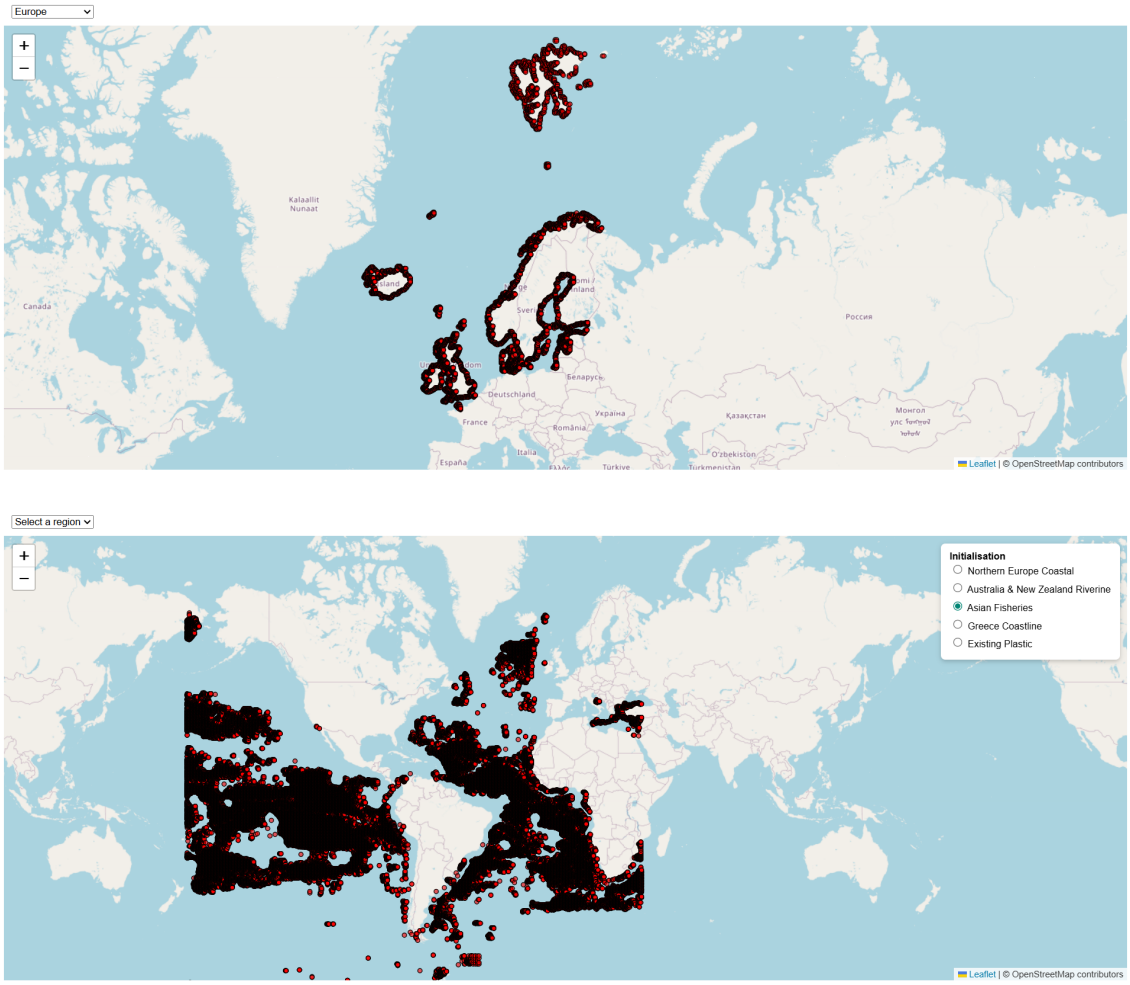


Figure 4.24: plasticParcels Initial Map Integrations with Leaflet.

The prototype was subsequently developed on top of this initial map. A radio button was added to allow users to select different datasets. Following the mockups, a globe animation was implemented to represent the initial overview before zooming into the map, using the GlobeGL [75] library. Integrating this 3D globe animation with Leaflet proved challenging, requiring additional code adjustments to achieve continuous animation. Bottom animation controls were then added according to the mockups, followed by zoom in/out buttons and the map legend, as can be

seen in Figure 4.25.

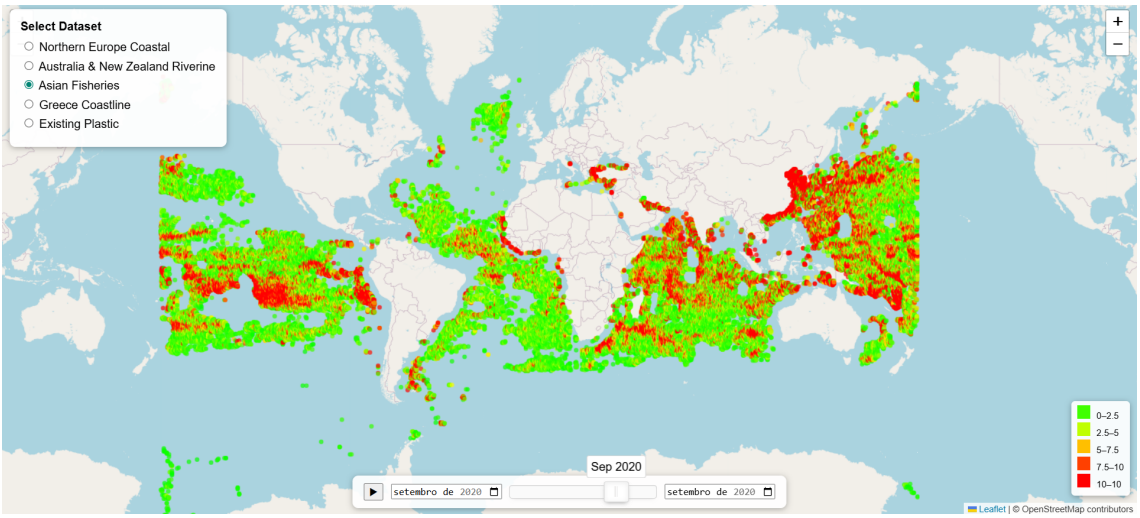


Figure 4.25: Prototype Map with Controls.

The initial use of a traffic light colour scheme was identified as problematic [76], as colour combinations involving red and green can be difficult to distinguish for users with colour vision deficiencies. In consideration of accessibility requirements, this colour scheme was replaced with the Batlow [77] colour map. Furthermore, the legend used the same value range for all regions within each dataset. This approach caused issues, as values within some regions were represented by the same colour despite differences in magnitude, as can be seen in Figure 4.26. To address this, a region-specific range was implemented, providing users with a perception of values relative to the selected region while allowing comparison across regions.

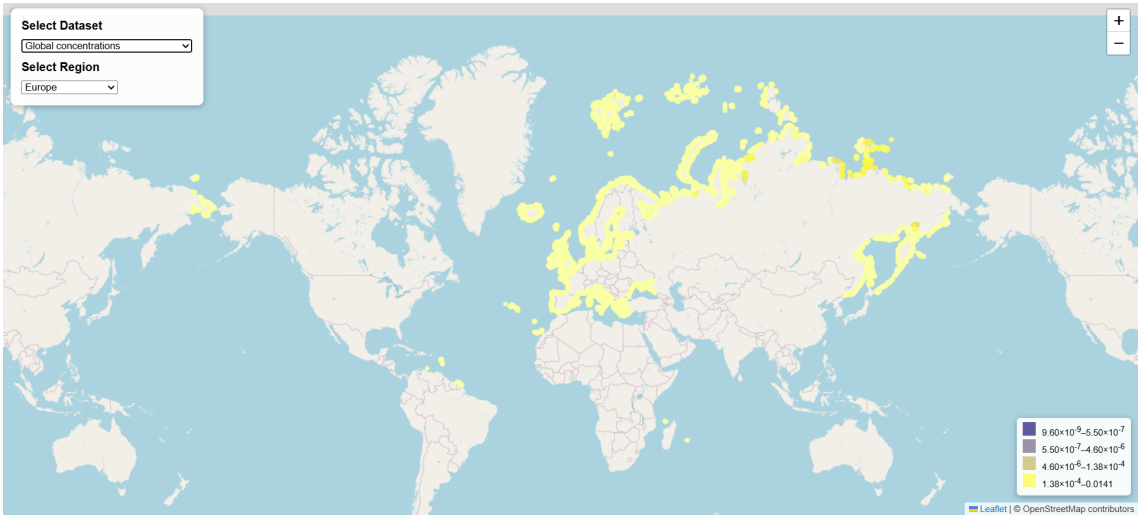


Figure 4.26: Initial legend and Colour Mapping.

A new linear scale with arrows was added to indicate minimum and maximum values for the current viewed region relative to all regions, as illustrated in Figure 4.27. While not entirely

intuitive for less focused users, it provided a functional workaround to the problem at hand.

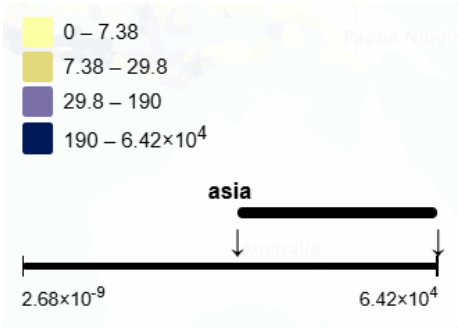


Figure 4.27: Adjusted Legend with Regional Value Scaling.

Following this initial implementation phase, a meeting was held with the supervisor and an additional INESC TEC investigator. The external contributor had no prior involvement with the project and was first exposed to both the prototype and its contextual information during this meeting. The discussion benefited from an impartial external perspective, which led to the removal of the initial globe animation. The use of a 3D representation without a clear functional purpose was considered unnecessary, as it introduced additional cognitive load and potential confusion for users. A conventional 2D map-based animation was deemed sufficient to convey the same information while supporting a more intuitive and coherent narrative.

In addition to this feedback, opinions were gathered informally from individuals without prior visualisation expertise, who provided brief qualitative input on the visual aspects of the prototype during its development. This decision further reinforces the user-centred design approach adopted through the project. Furthermore, the repeated world map pattern, where successive maps were displayed continuously, was removed due to computational limitations that negatively affected application responsiveness. This feature was also reported as confusing by external users exposed to this version of the prototype.

Subsequently, a visual indicator was introduced to inform users when data were being loaded. An option to switch between different visualisation modes was also implemented through radio buttons, allowing users to select between particle, heatmap or vector representations. Following this, the heatmap view was developed and a minimap reference was added in accordance with the previously defined mockups, as can be seen in Figure 4.28.

A vector-based visualisation was implemented using values derived from the previously described simulations, with the prototype displaying results generated using the OpenDrift model, that are illustrated in Figure 4.29.

During this stage, the use of the Batlow colour scale was found to be potentially confusing when applied to a limited four discrete values. In particular, the presence of two shades of blue and two shades of yellow tended to visually segment the data, which conflicted with the intended representation of a continuous scale. To address this issue, a custom, unique colour gradient was developed that maintained perceptual continuity while remaining accessible to users with common colour vision deficiencies.

Figure 4.28: Heatmap View.

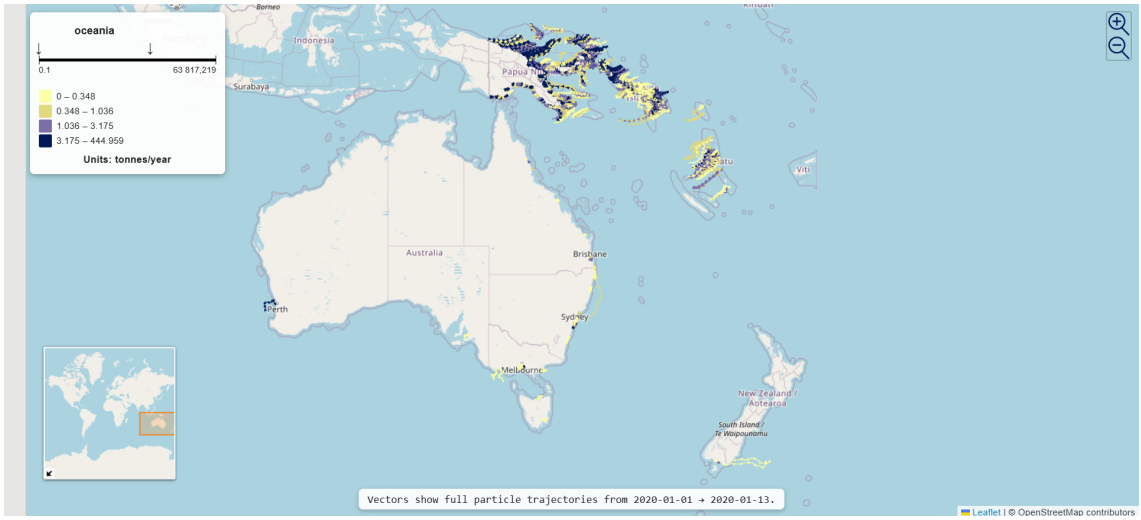


Figure 4.29: Animation View of OpenDrift Simulation.

In addition, a distinction was introduced between two animation modes: a dynamic simulation and an accumulated representation. The dynamic mode displays particle dispersion as it evolves, while the accumulated mode visualises the successive positions of particles, effectively illustrating their overall trajectories. As the datasets varied in their measurement units, the legend was updated dynamically to reflect the appropriate units for each dataset.

The initial vector visualisation included directional arrows, however, this approach proved to be visually cluttered and introduced unnecessary complexity. As a result, the arrows were removed. This decision was supported by the fact that particle motion generally progresses from coastal areas toward the open ocean and the animated movement itself sufficiently conveys directional information.

Finally, the overall visual appearance of the prototype was revised by adopting a dark mode interface. Since the primary objective of the visualisation is to highlight plastic related data, visual emphasis was shifted toward the particles, heatmaps or vector representations. Using darker tones for the land and ocean representations on the map and the minimised emphasis on map labels reduced visual competition with the data. This design choice enhanced contrast, with lighter colours representing higher values and darker tones (closer to the ocean background) indicating lower values. To further support user preferences and accessibility, an option was added allowing users to select between alternative colour schemes, including purple and green in addition to blue. The final colour scale and the dark mode modification can be viewed in Figure 4.30.

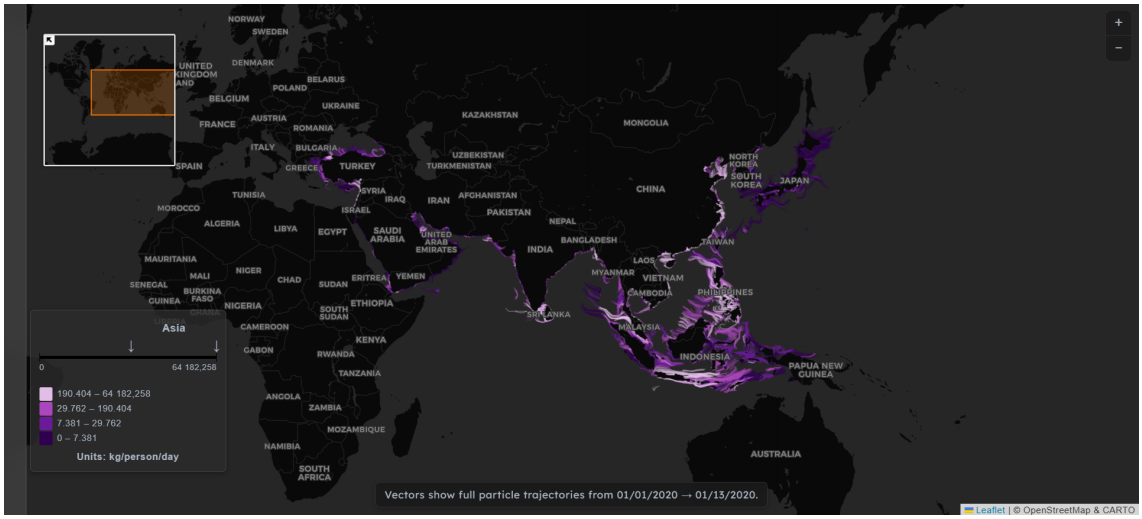


Figure 4.30: Final Colour Scale and Dark Mode.

An option to switch the prototype between Portuguese and English was added, as the testing was primarily conducted with Portuguese participants, who were the most available for the testing phase. Additionally, a dyslexia-friendly font was implemented for all textual information displayed on the map to address accessibility concerns, as shown in Figure 4.31.

The mouse tracking tool was also integrated for use during the testing phase of the project. A class diagram of this tool is presented in Figure 4.32. The diagram is a UML class diagram illustrating the architecture of the mouse tracking tool. At its core, the *MouseTrackerModule* controls

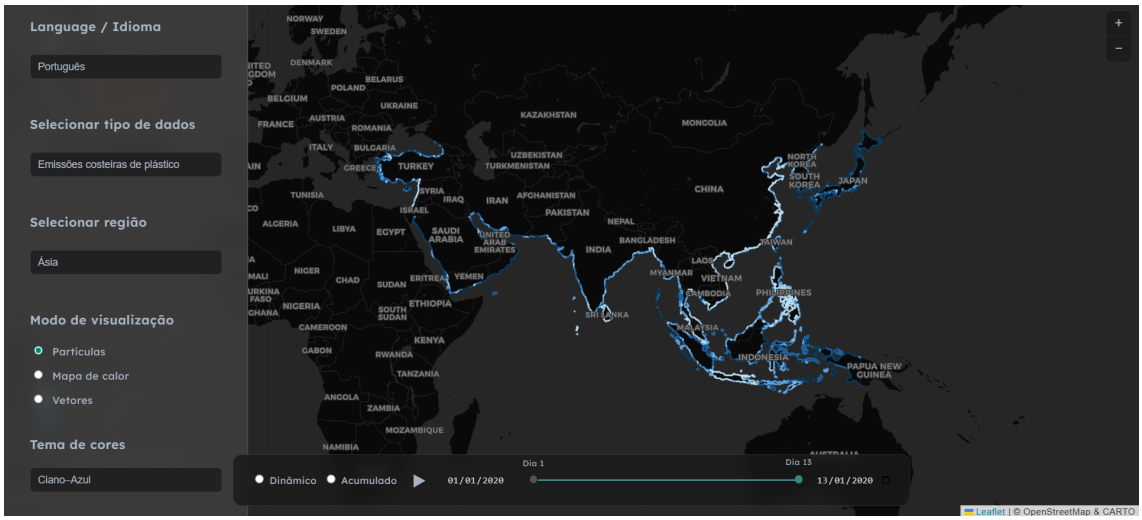


Figure 4.31: Accessibility Features.

data collection through *start()* and *stop()* methods and records interaction data in a central *SessionData* class, which stores session metadata and aggregates mouse movement, click, scroll and hover events. These interactions are represented by structured event classes (*MouseMove*, *ClickEvent*, *ScrollEvent* and *ScreenDimensions*), forming a composition logging architecture designed for systematic analysis of user behaviour.

With these enhancements and modifications applied from the initial mockups to the fully functional programmatic prototype, the solution was considered ready for the initial round of user testing. To make the web application available, visible and fully interactive for participants, the Live Server was once again used, as it proved well suited to the testing scenarios. The prototype's functionalities are illustrated in the following video:

https://drive.google.com/file/d/1K8wnELaS_qnBcHADTjocngKGlSlDmYTE/view?usp=sharing

4.6 Summary

Following the completion of these development steps, the prototype was prepared for detailed user testing, which represents one of the primary objectives of this dissertation. Insights gained from this testing can inform future design iterations, supporting the refinement of the solution to better meet user needs. A detailed description of the experimental design implemented is provided in the following chapter.

This chapter presented the approach adopted for the design and development of the proposed visualisation system for maritime plastic dispersion. Grounded in a user-centred design perspective, the chapter translated insights from the literature review and state of the art into concrete system requirements and design objectives. A structured design process was followed, progressing from low-fidelity prototypes to high-fidelity mock-ups and culminating in the implementation of a functional web-based prototype.

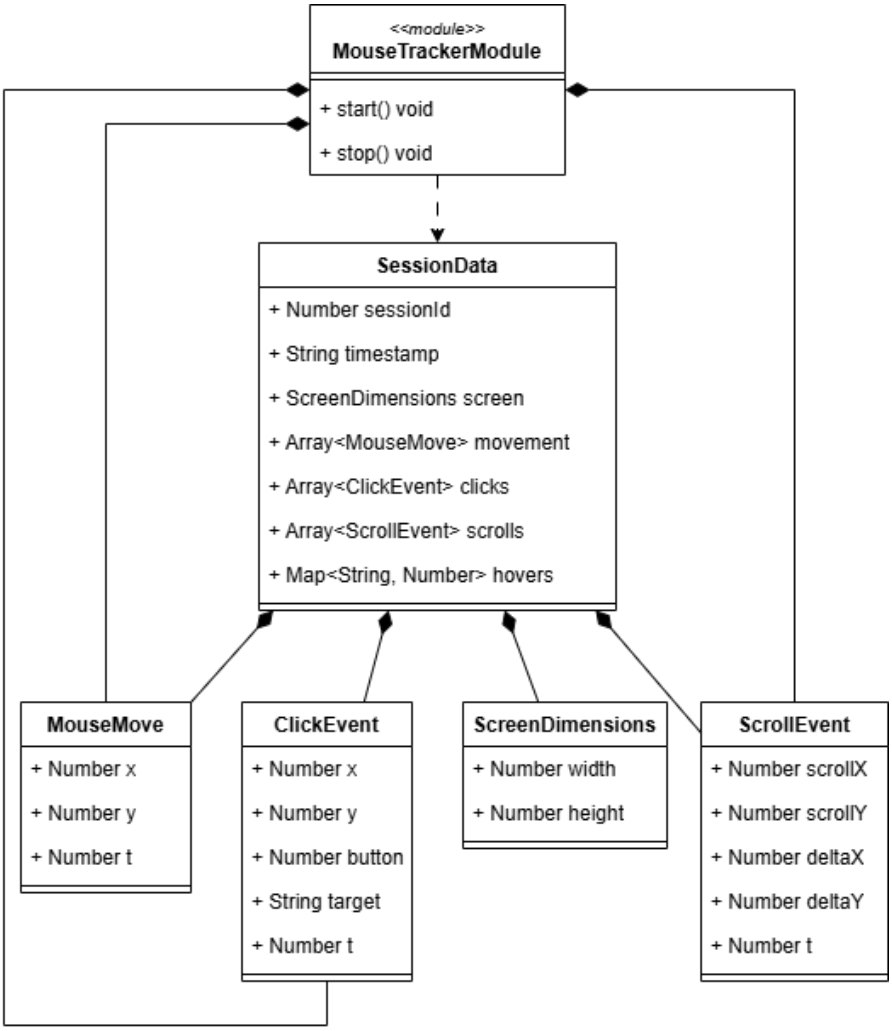


Figure 4.32: Mouse Event Tracking Tool Class Diagram.

The final solution integrates multiple visualisation modes, including particle animations, heatmaps and vector representations, enabling the exploration of plastic dispersion patterns across different regions, sources and temporal scales. Particular attention was given to usability, readability and accessibility, informing decisions related to interaction design, colour mapping, legends and interface layout. The use of OpenDrift simulation data and web technologies such as Leaflet supports interactive and dynamic exploration of complex spatiotemporal phenomena.

Overall, this chapter establishes a clear link between identified research gaps and the implemented solution, demonstrating how design choices address both analytical tasks and user needs. The resulting prototype provides the basis for the experimental evaluation described in the following chapter, where its usability, effectiveness and accessibility are systematically assessed.

Chapter 5

Experimental Design

The following chapter presents the experimental framework applied to evaluate the effectiveness of the proposed solution outlined in the previous chapter.

5.1 Introduction

This chapter presents the methodology to evaluate the effectiveness of the adopted approach. The main objectives of the usability testing are first outlined, followed by a detailed description of the study and its preparation for full implementation. Participant characteristics are examined, the design methodology is explained in detail and the tasks assigned to participants are described. Considerations regarding the test moderator are discussed and the apparatus and experimental protocol are presented. Finally, the pilot study is described and its influence on the design of the main experiment is explained.

5.2 Objectives of Usability Testing

To effectively apply the user-centred design principles described in the previous chapter (4), it was necessary to involve users in this phase of the project to gather insights directly from representative participants and draw informed conclusions about the developed prototype.

Usability testing is defined by Rubin [78] as

> "a process that employs people as testing participants who are representative of the target audience to evaluate the degree to which a product meets specific usability criteria." [78]

This type of study involves users interacting with the system to identify aspects of the prototype that require refinement, as well as elements that should be retained. In this specific case, user testing was conducted to assess whether participants could correctly interpret the data visualisations and provide accurate and timely responses to three questions related to plastic visualisation. Additionally, the testing aimed to identify usability issues in a formative manner and to measure user

performance in a summative way. The study also collected data to evaluate perceived usability and overall quality of the visualisations.

5.3 Participants

This section describes the characteristics of the study participants. The target population is defined, the recruitment process is outlined, the participant characteristics collected during the study are detailed, the sample size is justified and relevant ethical considerations are discussed.

5.3.1 Target Population

The target population consists of individuals without expert knowledge in oceanic or environmental data analysis, representing a general audience for data visualisation tools.

5.3.2 Recruitment

The recruitment of participants was partially influenced by the accessibility of potential users to the moderator. All participants volunteered to take part in the study. The majority were university students, most of whom had no prior experience with this type of data visualisation tool. Additional statistical details regarding the participants are provided in chapter 6.

5.3.3 Collected Characteristics

The participant information collected for this study included demographic details and familiarity with the context of the study. Specifically, data were gathered on age, gender, education level, occupation or study field, computer literacy, experience with data visualisation tools, familiarity with oceanic or environmental data and accessibility related factors, including colour vision deficiencies and dyslexia.

5.3.4 Sample Size

An initial target of at least thirty participants was established to ensure that the quantitative analysis would be statistically meaningful, given that the minimum recommended typically ranges from ten to twelve participants [78]. Before, two pilot tests were conducted to evaluate the experimental protocol, identify any necessary adjustments and refine the procedure before proceeding with further testing.

5.3.5 Ethical Considerations

All participants were required to read and accept the informed consent prior to participation in the study. Participation was entirely voluntary and participants were free to withdraw at any time without consequence or penalty. For questions involving sensitive or personal information, an option was provided for participants to decline to answer. All collected data were anonymised and

used solely for academic research purposes. Additionally, the use of mouse movement tracking was disclosed in advance and was enabled or disabled only with the participant's consent, with the participant observing the process and being fully informed of its implementation.

5.4 Test Design Methodology

This section provides an overview of the methodology employed in designing the testing phase and explains the rationale behind key decisions, including the study design, evaluation methods, variables considered and types of data collected.

5.4.1 Study Design

The study employed a one-group, single-session usability design, combining both formative and summative evaluation methods. The formative assessment focused on identifying usability issues through direct observation and participants' think-aloud comments during and at the conclusion of each session. The summative evaluation, in contrast, focused on performance metrics and standardised questionnaires. Each participant completed the same set of tasks in a single session lasting approximately twenty minutes.

5.4.2 Evaluation Methods

The evaluation methods employed to gather insights included a questionnaire completed by participants, combined with direct observation during sessions. Observations focused on participant hesitation, verbal comments, types of movements, facial expressions and other notable behavioural patterns. Think-aloud comments provided during task execution were particularly important for capturing user thought processes. Additionally, interaction data, including hotspot usage and mouse movements, were recorded to provide further information on participant behaviour.

Demographic information was collected alongside quantitative performance metrics such as task completion time, success rates and errors. Following the completion of the main tasks, standardised questionnaires were administered, specifically the System Usability Scale (SUS) [79], one of the most widely used instruments for evaluating usability [80] and the Perceived Readability Evaluation for Visualizations (PREVis) [81]. The SUS questionnaire is used to collect participants' opinions regarding the usability of the visualisations, while the PREVis instrument assesses whether users found the visualisations easy to interpret. Although PREVis is designed for static data visualisations, no validated standardised questionnaire specifically targeting animated visualisations was identified. Given that the prototype included both static and animated elements and considering the lack of a pre-existing foundation for designing a new questionnaire, this instrument was considered the most appropriate choice. Finally, additional feedback was gathered through open-ended post-test written questions and interviews with participants.

5.4.3 Variables

The study examined both independent and dependent variables. The independent variables included the visualisation prototype interface and participant characteristics, such as computer literacy, familiarity with data visualisation and other factors recorded in the pre-test questionnaire, presented in Appendix H.

The dependent variables included task completion time, task success, number of attempts per task, user errors, system errors, number of help requests and the scores obtained from the SUS and PREVis questionnaires.

5.4.4 Data Types

The collected data can be classified as either quantitative or qualitative. Quantitative data included task completion times, success rates, error counts and questionnaire scores. Qualitative data included participant comments, observations recorded by the moderator and responses to open-ended feedback questions.

5.5 Tasks

This section of the chapter describes the tasks selected to evaluate users' understanding of the prototype. It presents the rationale behind the design choices and provides a detailed description of each task performed.

5.5.1 Task Design

The tasks designed for this study were derived from those identified during the final selection phase (section 4.3.3), which were established in the requirements analysis phase (section 4.3) of this dissertation. These tasks formed the basis of the prototype's conceptualisation, ensuring that the evaluation would provide meaningful insights into the visualisation itself. Each task describes what needs to be accomplished rather than specifying how to accomplish it, representing real analytical challenges. Some tasks were considered more difficult than others. All participants performed the same set of tasks under identical conditions.

5.5.2 Task Descriptions

The following questions were presented to participants:

A - Which of the following regions shows the highest maximum value of coastal plastic emissions at the start of 2020, clearly exceeding 10,000 kg/person/day?

B - At the beginning of 2020, which region is most likely to contribute plastic waste to riverine pathways that lead to the ocean?

C - During the first 13 days of 2020, in which of the following African countries do plastics accumulated on beaches tend to move along the coast toward the south?

These questions were presented as multiple-choice items, with varying levels of difficulty in interpreting and comparing the options. The order of the questions was randomised for each participant.

The available options for each question were as follows:

A - South America, Asia, Oceania, Europe

B - Asia, Europe, South America, Africa

C - Egypt, Morocco, Senegal, South Africa

All answers were validated using the dataset and a script [82], yielding the results presented in Listing 5.1. The results also indicate the relative difficulty of each question, as reflected by the discrepancies among the available options.

Listing 5.1: Task Answer Results from Script Validation.

```
======================================================================
RUNNING ALL ANALYSES...
======================================================================

======================================================================
ANALYSIS 1: COASTAL EMISSIONS - MAX VALUE PER REGION
======================================================================

*Top coastal emissions (compared to threshold of 10,000)*
       Region    Max Value Above Threshold?
         Asia 64182.257812    Yes (>10,000)
       Africa 31508.607422    Yes (>10,000)
      Oceania  8612.388672    No (<=10,000)
South_america  8492.792969    No (<=10,000)
       Europe  1560.885742    No (<=10,000)
North_america   490.726898    No (<=10,000)
     Portugal   298.193115    No (<=10,000)

======================================================================
ANALYSIS 2: RIVERINE EMISSIONS - TOTAL PER REGION
======================================================================

*Total river plastic per region*
       Region  Total River Plastic
         Asia        825445.599452
       Africa         76240.877348
South_america         53794.057765
```

```
       Europe          5541.391646
      Oceania          3980.635494
North_america          2665.434001
     Portugal            70.140465

========================================================================
ANALYSIS 3: PREDOMINANT DIRECTION - BY AFRICAN COUNTRY (N, S, E, W, NE, NW, SE, SW)
========================================================================
Coastal Africa cells: 2485
Total initial particles: 2485

Predominant direction per country (single direction):

Algeria: NE
Angola: SE
Benin: SW
Cameroon: NW
Comoros: SW
Côte d'Ivoire: SE
Democratic Republic of the Congo: SW
Djibouti: SW
Egypt: NE
Equatorial Guinea: SE
Eritrea: NE
Gabon: NW
Ghana: NE
Guinea: NE
Guinea-Bissau: NW
Kenya: SW
Liberia: SE
Libya: NE
Madagascar: SW
Mauritania: NW
Morocco: NW
Mozambique: SW
Namibia: SW
Nigeria: SE
Republic of Cabo Verde: NW
Republic of the Congo: NW
Senegal: NW
Sierra Leone: SE
Somalia: W
Somaliland: NW
South Africa: SW
Sudan: NE
São Tomé and Principe: NE
Tanzania: NW
The Gambia: NW
Togo: SE
```

```
Tunisia: NE
Western Sahara: NW

========================================================================
ANALYSES COMPLETED
========================================================================
```

The results generated by the script indicate the correct answers for each question as follows:

A - Asia

B - Asia

C - South Africa

5.6 Test Moderator

In this study, the author of this dissertation also assumed the role of moderator during all usability testing sessions. The moderator was responsible for explaining the objectives of the study and the experimental procedure, ensuring adherence to the testing protocol, observing participant behaviour and taking detailed notes. Additional responsibilities included tracking task completion times for the three tasks, providing limited assistance (restricted to a maximum of two help requests per task) and offering clarification solely on interface-related issues, without interpreting the data or the visualisation for participants. The moderator also conducted the final debrief interview and distributed the participation reward. The complete moderator guide is provided in Appendix I.

Throughout all testing sessions, the moderator maintained a strong focus on the user-centred nature of the project and was attentive to potential usability challenges anticipated in advance. As the author responsible for the design and development of the prototype, the moderator possessed in-depth knowledge of the system itself, which facilitated accurate observation of participant interactions. Detailed notes were taken during each session and immediately afterwards to minimise reliance on memory alone. Particular attention was given not only to verbal feedback but also to non-verbal cues, including facial expressions and behavioural patterns.

All sessions were conducted as sit-by usability sessions [78], which supported close interaction between the moderator and participants and enabled the collection of rich qualitative data. The moderator did not intervene in task execution time and encouraged participants to independently explore the interface as much as possible. When signs of frustration emerged, the moderator initially allowed a brief period of observation to assess how participants responded to the difficulty. If participants were unable to progress and did not request assistance, they were reminded of the availability of help. Otherwise, no intervention was made. Minor adjustments to clarify ambiguities were made when necessary, requiring flexibility on the part of the moderator, which was managed in a consistent and controlled manner across sessions, as much as possible.

5.7 Apparatus

This section provides a detailed description of the environment in which participants conducted the testing phase. Considerations regarding the hardware and software used during the experiments are presented, along with a description of the experimental materials.

5.7.1 Hardware and Software

All sessions were performed using the author's personal desktop computer and a mouse. Participants had access to the visualisation prototype, which was opened in one browser tab and a Google Form [83] questionnaire in another. Mouse movements were tracked using the tool implemented in the script [84]. This tracking was activated and deactivated before and after the Task List, respectively, by the moderator. Timing began once the participant finished reading the question for the first time and ended when an answer was submitted and the participant advanced to the next question. If the participant returned to a previous question, the additional time was added to the previously recorded duration for that task. The moderator was also responsible for annotating all relevant observations during the experiment. Before each session, the prototype was reset to its initial state, the questionnaire was opened as a blank form and both the timing and tracking tools were cleared to ensure no data from previous sessions was retained.

5.7.2 Experimental Materials

The experimental materials used to conduct the study and collect data included an informed consent form, which participants were required to agree to before proceeding with the rest of the experiment. A pre-test questionnaire was administered to gather demographic information and assess participants' background knowledge relevant to the study. The tasks, along with the available answer options for each question, were provided to the participants. The post-test questionnaire included the SUS and the PREVis instruments, as well as additional open-ended questions to capture participants' opinions and feedback. The experiment materials also included the moderator guide and the observational record, where all session-related information was recorded.

5.8 Experiment Protocol

Each session followed a standardised protocol consisting of a welcome and introduction by the moderator, followed by the reading and completion of the informed consent form. Participants then completed a pre-test questionnaire. This was followed by a familiarisation phase with the prototype, lasting approximately two minutes, during which each participant could explore the interface at their own pace within this time limit. Participants subsequently completed the experimental tasks, with the opportunity to use a think-aloud approach, which was not explicitly mentioned to avoid influencing their natural interaction. After task completion, participants completed the post-test questionnaires, participated in a debriefing session and were invited to provide

final comments. At the conclusion of the session, the moderator thanked participants for their time and provided a small reward in recognition of their contribution. The complete moderator guide is provided in Appendix I.

5.9 Pilot Tests

A pilot study involving two participants was conducted to validate the experimental protocol, assess task clarity, estimate session duration and test the data collection instruments. It also provided an opportunity for the moderator to become more familiar with the tasks and procedures. The total session times for the pilot participants were ten minutes and thirty six seconds and fifteen minutes and thirty two seconds. To provide realistic time expectations for subsequent participants, an additional buffer was added and a total participation time of approximately twenty minutes was communicated.

Following the pilot study, minor adjustments were made to the protocol. These included specifying which applications were opened initially on the study's computer, adding a reminder for the moderator to distribute the reward at the end of the session and ensuring the mouse tracking tool was activated correctly. A note was added for the moderator to pause and explain the mouse tracking tool to the participant before enabling it. Additionally, the pre-task form was revised to include a mandatory pause before the tasks began, ensuring participants hear the facilitator's instructions before engaging with the tasks. This change was based on observations during the pilot study, where participants began reading the questions prematurely, potentially affecting timing and understanding. Implementing this pause helped to approximate realistic session times while minimising interference with the experimental results.

5.10 Summary

The characteristics presented in this chapter are essential for understanding the foundation of this study. By considering the rationale behind the decisions made to evaluate the prototype described in chapter 4, these characteristics provide the basis for collecting data, which will be analysed statistically in the following chapter to draw conclusions about the study.

Chapter 6

Results and Discussion

The following chapter presents the results of the experimental study and provides a detailed discussion of their significance.

6.1 Introduction

In this chapter, the statistical analysis of the results obtained from the experiment described in the previous chapter is presented and conclusions are drawn accordingly. The analysis begins with an outlier detection process and its discussion, followed by an overview of the study participants. Both quantitative and qualitative results are then examined in detail. Finally, a comprehensive discussion of the findings is provided to synthesise the collected data and evaluate the participants' perceptions and feedback regarding the developed prototype.

6.2 Outliers Identification

Considering that the study was conducted entirely in person and was continuously moderated, all participants were fully engaged throughout the experimental session. Participants did not complete the questionnaires without first understanding the objectives of the study and informed consent was obtained from all of them.

Despite this controlled setting, a systematic inspection for potential outlier values was carried out in order to ensure the robustness and validity of the results. Certain variables were more susceptible to the presence of outliers than others. Task completion time was not considered for outlier analysis as the moderator was able to directly observe participants' behaviour during the experiment. No instances of task skipping were recorded. Moreover, longer completion times are meaningful within the context of an exploratory usability study, as they may reflect genuine difficulties encountered by users.

The primary variables examined for potential outliers were SUS and PREVis scores. In these cases, outlier values could indicate participants who misunderstood the scales or questions or who did not engage attentively with the questionnaires. For example, by assigning identical ratings

to all items or by consistently rating all items to extreme values. Additionally, some negatively worded items in the PREVis questionnaire, particularly those involving double negations, may have introduced confusion for certain participants.

An inspection of the SUS boxplots revealed two potential outliers, corresponding to participants 8 and 29, as seen in Figure 6.1.

Figure 6.1: Boxplot of Overall SUS Score.

During the testing phase, these participants exhibited noticeable difficulties in understanding how to use the prototype. Therefore, although their SUS scores were lower than those of the remaining participants, they reflect genuine usability issues encountered by real users. For this reason, their responses were retained and not treated as outliers.

Regarding the PREVis results, particularly for the Layout scale, which includes negatively phrased items, the scores did not substantially deviate from those of the other categories, as shown in Figure 6.2.

While some lower PREVis scores were observed in the boxplots, these values are consistent with natural variability in user perceptions and interpretations of the visualisations. Removing such values would artificially reduce variability, which is an important aspect of visualisation research involving real users.

Finally, participant attentiveness was also assessed by examining whether any participant provided identical responses across all SUS and PREVis items. No such patterns were observed. Consequently, no responses were excluded from the analysis and no participant was ultimately classified as an outlier.

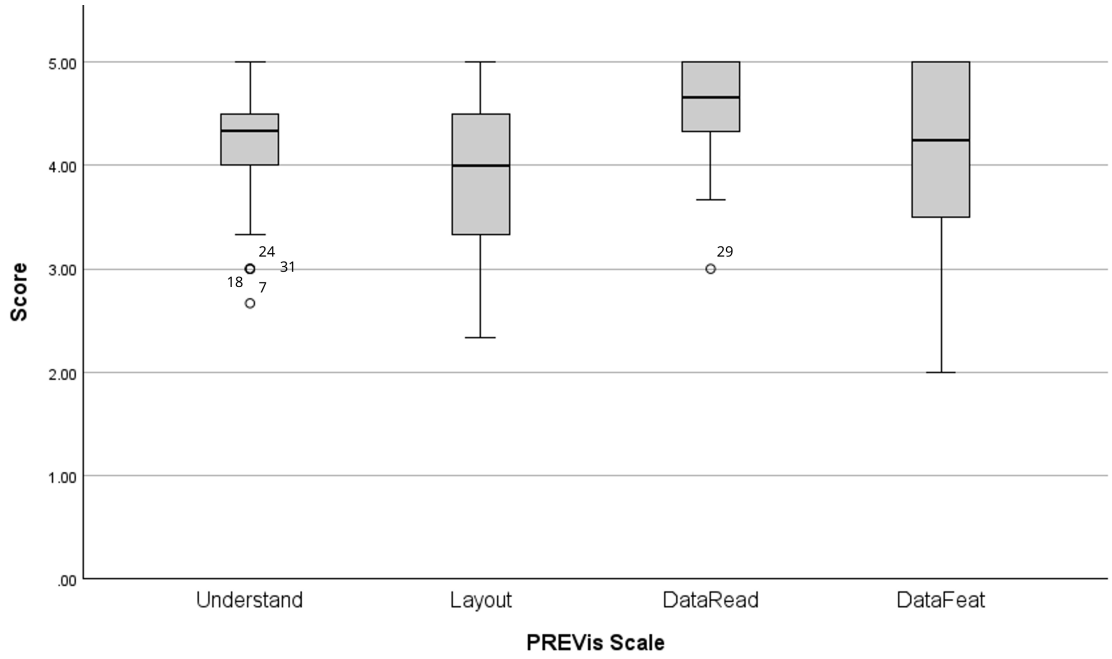


Figure 6.2: Boxplot of Score by each PREVis Scale.

6.3 Participant Overview

The study involved a total of 32 participants, of whom 22 identified as male (68,8%), 9 as female (28,1%) and 1 as non-binary (3,1%), as illustrated in Figure 6.3.

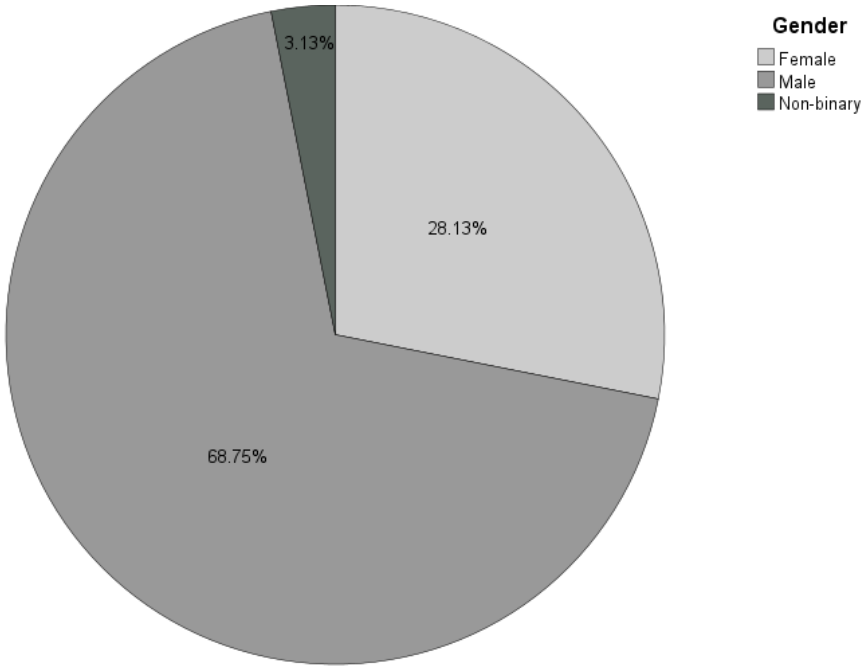


Figure 6.3: Pie Chart Count of Gender.

The age distribution of the participants is shown in the boxplot presented in Figure 6.4, with the majority of participants falling within the 20-24 age range.

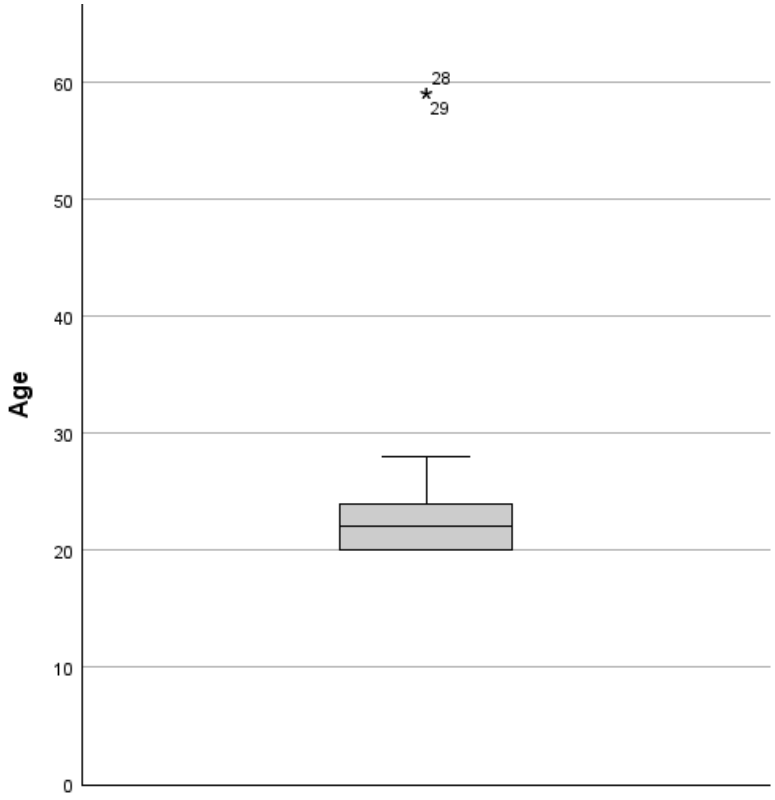


Figure 6.4: Boxplot of Age.

The educational background of the participants is illustrated in Figure 6.5. Most participants reported having completed secondary education, a bachelor's degree or a master's degree. Regarding occupation, the majority of participants either study or work in engineering, technology or computer-science related fields, as can be seen in the graph of the Figure 6.6.

Participants' prior familiarity with relevant tools and concepts is summarised in Figure 6.7. Scores range from 1, indicating no familiarity, to 5, indicating high familiarity. Overall, the results indicate high levels of computer literacy, which is consistent with the participants' reported fields of study or work. Participants reported moderate prior exposure to data visualisation tools, low prior experience with oceanic environmental data and regular use of interactive digital tools.

With respect to accessibility considerations, two participants reported having colour vision deficiencies and four participants reported dyslexia-related difficulties (Figure 6.8). All participants responded to this question and no missing values were recorded.

6.4 Quantitative Results (Summative)

This section presents the main summative results of the study, including task performance data collected during the testing phase, analysis of the mouse tracking tool and the statistical analy-

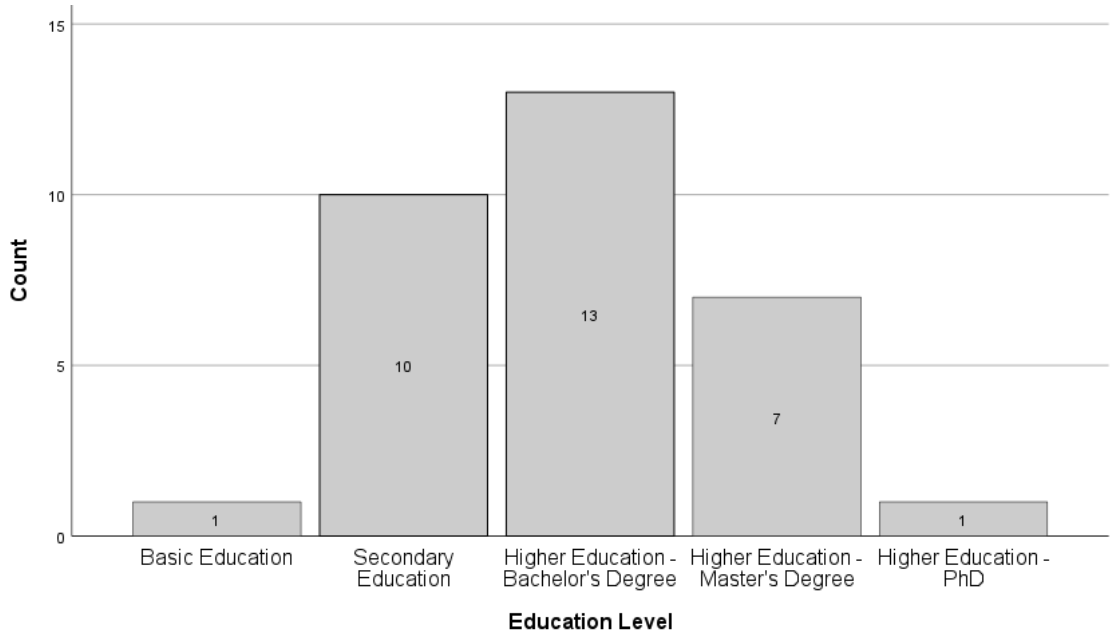


Figure 6.5: Bar Count of Education Level.

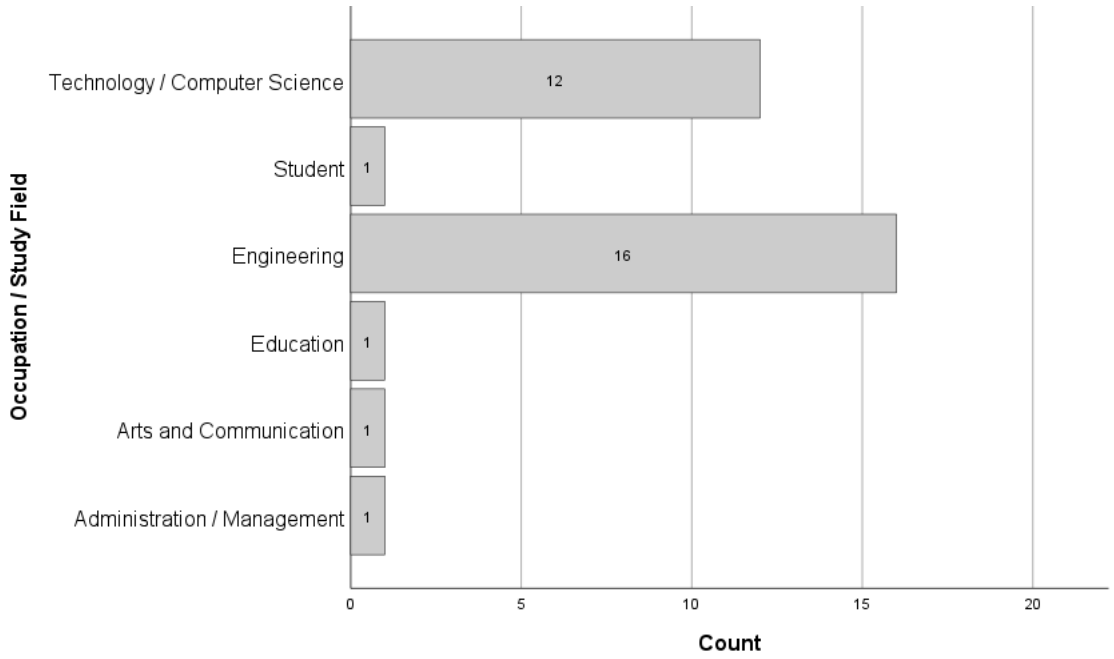


Figure 6.6: Bar Count of Occupation or Study Field.

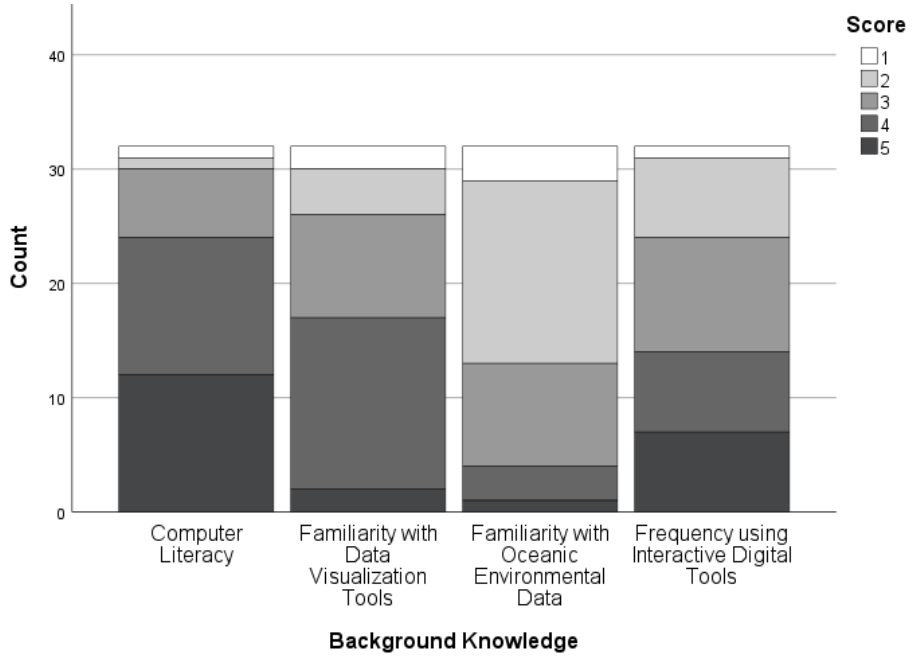


Figure 6.7: Stacked Bar Count of Background Knowledge by Score.

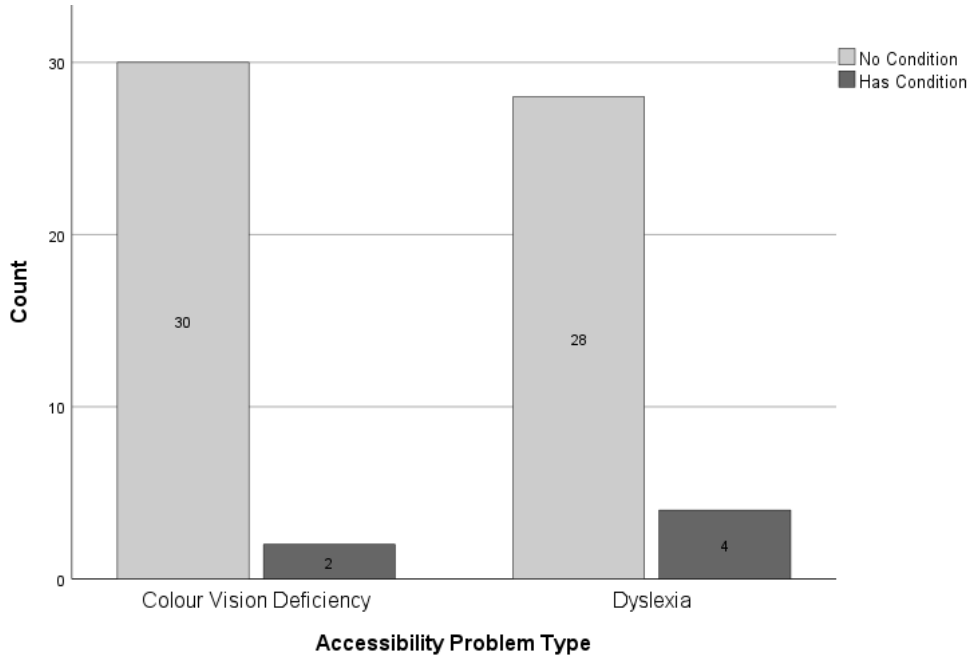


Figure 6.8: Bar Count of Accessibility Problem Type.

sis of the System Usability Scale (SUS) and Perceived Readability Evaluation for Visualizations (PREVis) questionnaires. These results are described and discussed in detail in the following subsections.

6.4.1 Task Performance

To evaluate task performance, a participant's response was considered successful if it matched the expected answer defined in Section 5.5.2. As shown in Table 6.1, Task A resulted in 21 correct and 11 incorrect responses, Task B in 28 correct and 4 incorrect responses and Task C in 30 correct and 2 incorrect responses.

Task	Result	Frequency	Percent	Cumulative Percent
A	Correct	21	65,6%	65,6%
	Incorrect	11	34,4%	100,0%
B	Correct	28	87,5%	87,5%
	Incorrect	4	12,5%	100,0%
C	Correct	30	93,8%	93,8%
	Incorrect	2	6,3%	100,0%

Table 6.1: Task accuracy results for Tasks A, B and C.

For each task, the distribution of the selected alternatives is presented below:

For Task A, the available options were South America, Asia, Oceania and Europe. Among the incorrect responses, most participants selected Europe, as illustrated in Figure 6.9. According to the script [82] results and within the available options, Europe corresponds to the region with the lowest coastal plastic emissions.

For Task B, the options were Asia, Europe, South America and Africa. The majority of participants selected the correct answer (Asia: 28 participants). Two participants selected Europe and two selected South America, as shown in Figure 6.10. Based on the script [82] results, these two regions correspond to the lowest plastic emission values among the available options.

For Task C, the options were Egypt, Morocco, Senegal and South Africa. Most participants answered correctly (South Africa: 30 participants). One participant selected Egypt and another selected Senegal, as illustrated in Figure 6.11. The incorrect options selected correspond to particle trajectories with northeast and northwest directions, respectively, as indicated by the script results.

Table 6.2 summarises the distribution of the number of incorrect tasks per participant.

The number of incorrect answers in the three tasks varied across the sample. Figure 6.12 shows the frequency of wrong responses. Only one participant answered all three tasks incorrectly, two participants had two incorrect answers, ten participants made a single error and nineteen participants (59,4%) answered all tasks correctly.

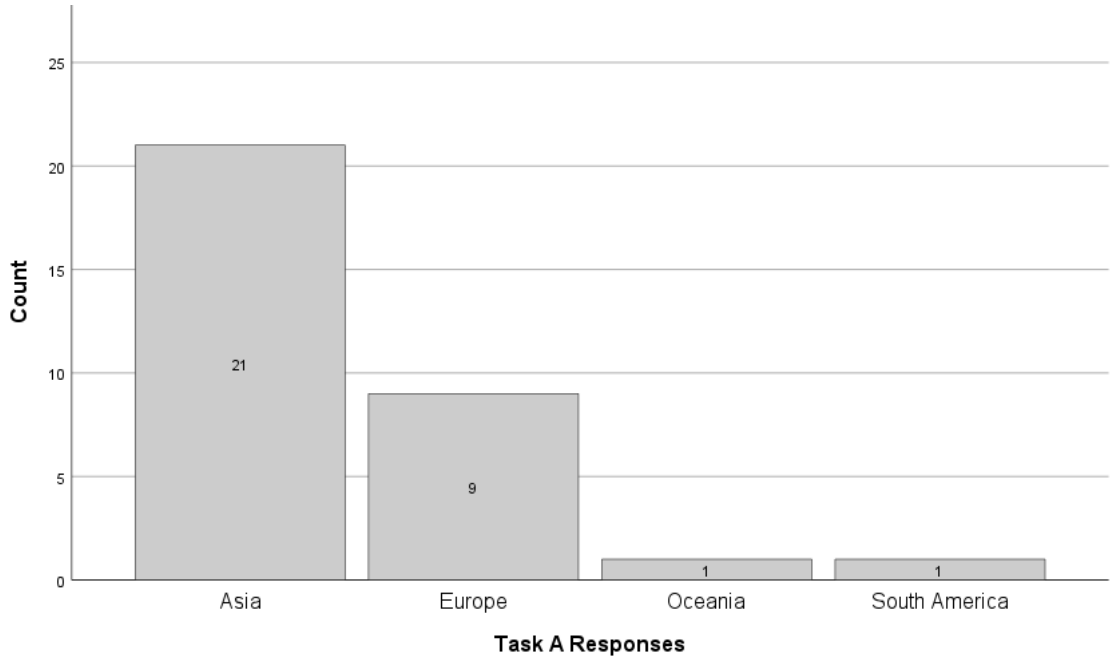


Figure 6.9: Bar Count of Responses for Task A.

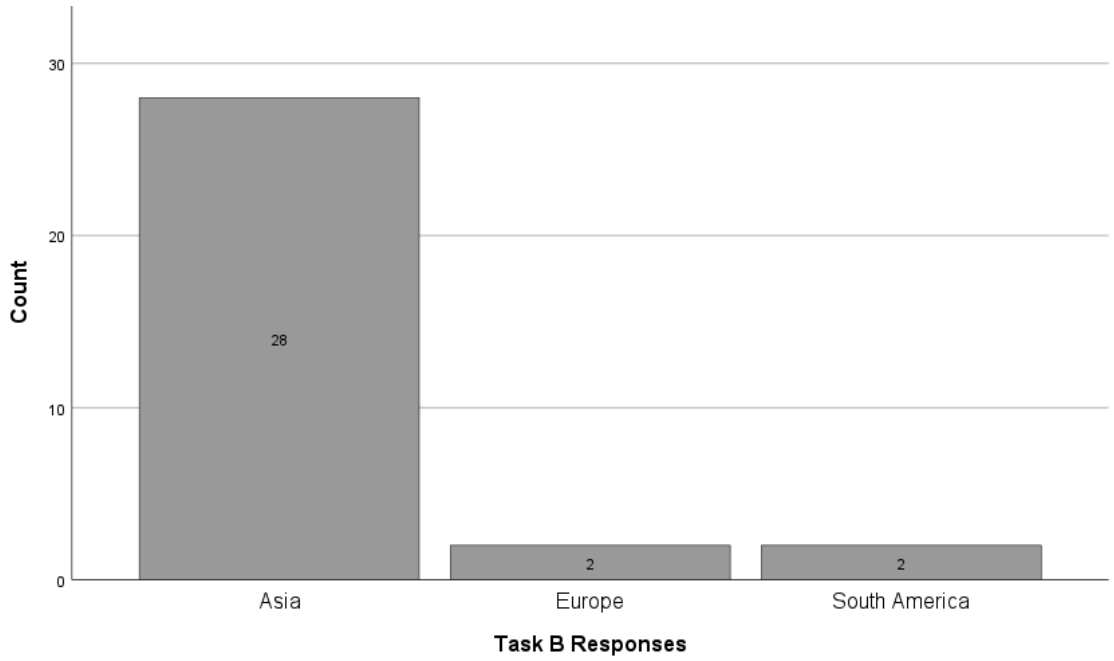


Figure 6.10: Bar Count of Responses for Task B.

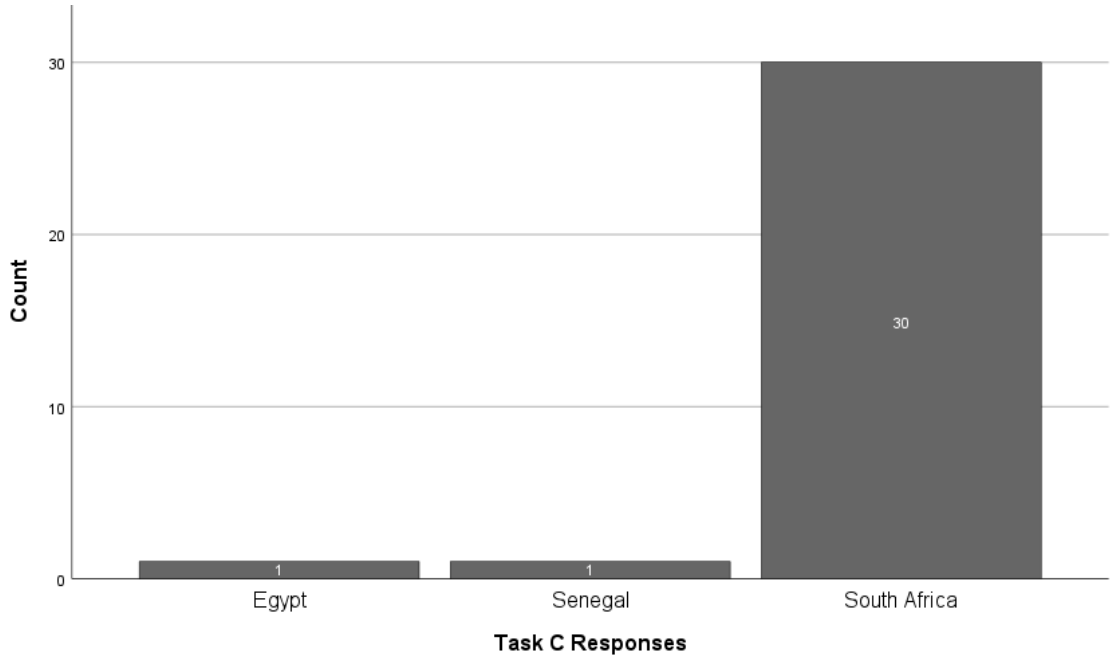


Figure 6.11: Bar Count of Responses for Task C.

Number of Wrong Tasks	Frequency	Percent	Cumulative Percent
0	19	59,4%	59,4%
1	10	31,3%	90,6%
2	2	6,3%	96,9%
3	1	3,1%	100,0%
Total	32	100,0%	–

Table 6.2: Distribution of the number of incorrect responses.

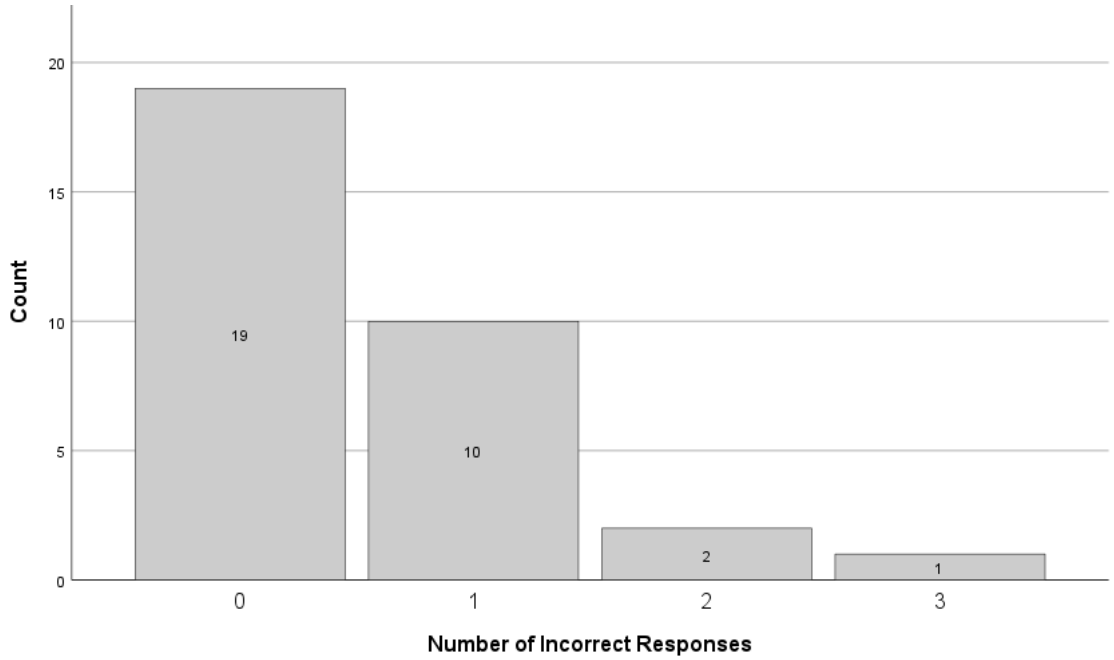


Figure 6.12: Frequency of Incorrect Responses per Participant.

For each task, the time taken by participants to provide an answer also varied. Table 6.3 presents descriptive statistics for task completion time. Task A required the longest average completion time (approximately 2 minutes and 15 seconds), while Task B was completed the fastest on average (approximately 1 minute and 41 seconds).

Task	Mean	Std. Deviation
A	2,2	0,95179
B	1,7	0,74890
C	1,8	0,71596

Table 6.3: Descriptive Statistics for Task Completion Times (in minutes).

Figure 6.13 presents boxplots of completion time per task, as well as a stacked histogram showing the frequency distribution of response times.

For Task A, four participants requested one help interaction and one participant requested two. For Task B, four participants requested one help interaction. Task C registered the highest number of help requests, with nine participants requesting assistance.

The most frequent help requests occurred during Task C and were related to locating the country of Senegal, despite the country being labelled on the map. Other help requests included clarifications regarding the difference between the accumulated and dynamic visualisation modes (without testing both visualisation modes), questions about whether the arrows in the legend represented the minimum and maximum values for that region or the minimum and mean values. This question could not be answered, as it would have influenced how participants interpreted the data. One participant also inquired whether individual particle values could be inspected and in this

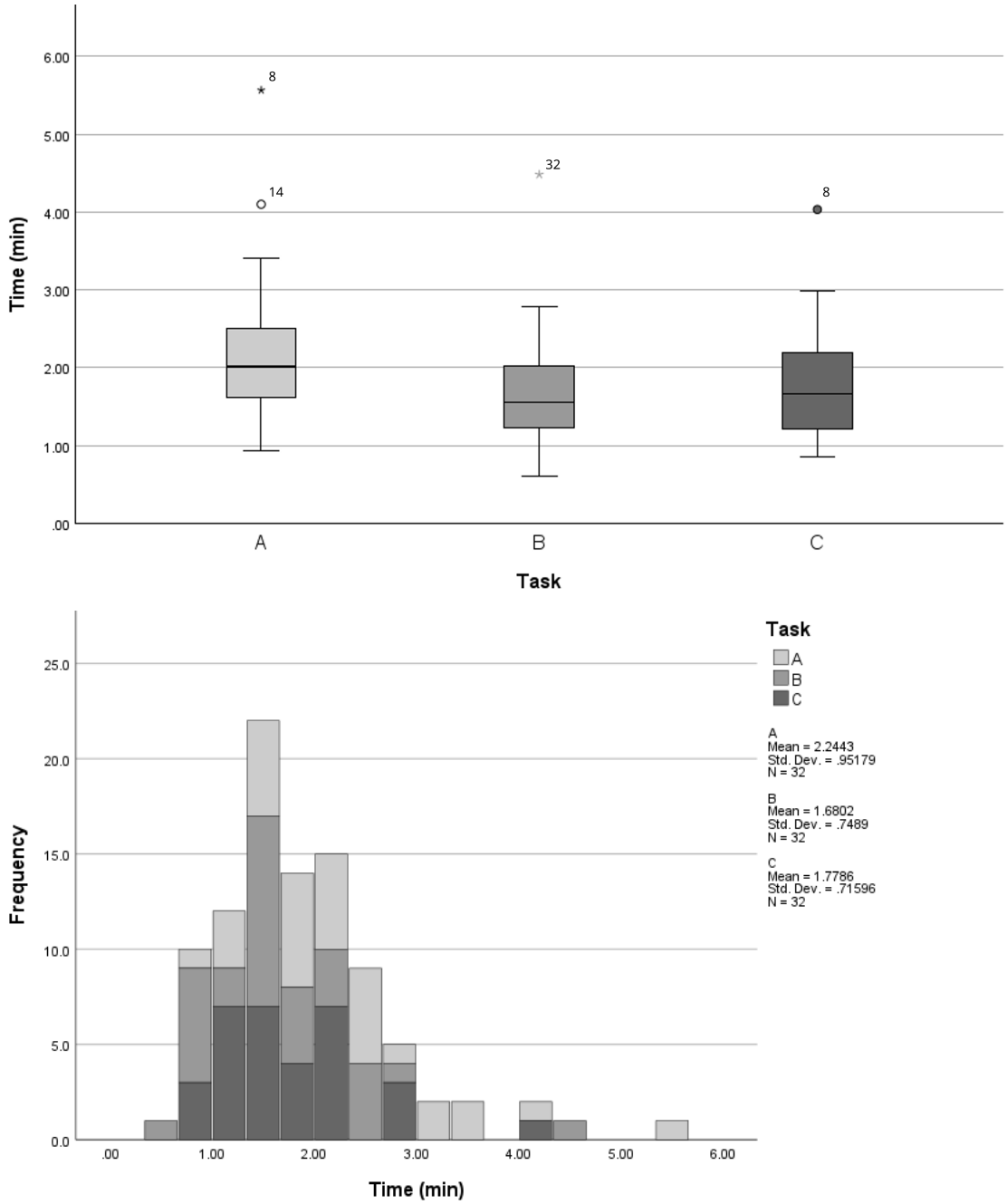


Figure 6.13: Completion Time Analysis per Task: (top) Boxplots and (bottom) Stacked Histogram of Response Time Frequencies.

case, guidance was provided to demonstrate the existing functionality of hovering over particles to access this information.

6.4.1.1 Domain Knowledge Influence in Task Performance

It was necessary to explore the relationship between participants' domain knowledge and their task performance. For this purpose, the variables considered were computer literacy, familiarity with data visualisation tools, familiarity with oceanic environmental data and frequency of use of interactive digital tools, alongside the total number of correct responses on the tasks.

A correlation analysis was conducted using the Spearman rank-order correlation coefficient, which measures monotonic relationships between variables (i.e., whether they increase or decrease together). Spearman's method uses ranks rather than raw values, making it suitable for ordinal data and eliminating the need for normal distribution assumptions. All domain knowledge variables were scored on a 1–5 scale, making them ordinal in nature.

The results of the analysis are presented in Table 6.4 and a heatmap in Figure 6.14 provides a visual interpretation of the correlations. Significant positive correlations were observed between Computer Literacy and Familiarity with Data Visualisation Tools (ρ = 0,622, p < 0,01) and between Computer Literacy and Frequency of Using Interactive Digital Tools (ρ = 0,446, p < 0,05). However, no significant correlations were found between Total Correct Responses and any of the other variables, as highlighted in the figure. These findings indicate that participants' prior domain knowledge did not have a significant impact on their task performance.

	Computer Literacy	Familiarity with Data Visualization Tools	Familiarity with Oceanic/Environmental Data	Frequency using Interactive Digital Tools	Total Correct Responses
Computer Literacy	1,000	0,622**	-0,021	0,446*	0,133
Familiarity with Data Visualization Tools	0,622**	1,000	-0,056	0,595**	0,028
Familiarity with Oceanic/Environmental Data	-0,021	-0,056	1,000	0,308	-0,001
Frequency using Interactive Digital Tools	0,446*	0,595**	0,308	1,000	0,045
Total Correct Responses	0,133	0,028	-0,001	0,045	1,000

Table 6.4: Spearman's ρ Correlations between Domain Knowledge Variables (N = 32).

* p < 0,05; ** p < 0,01

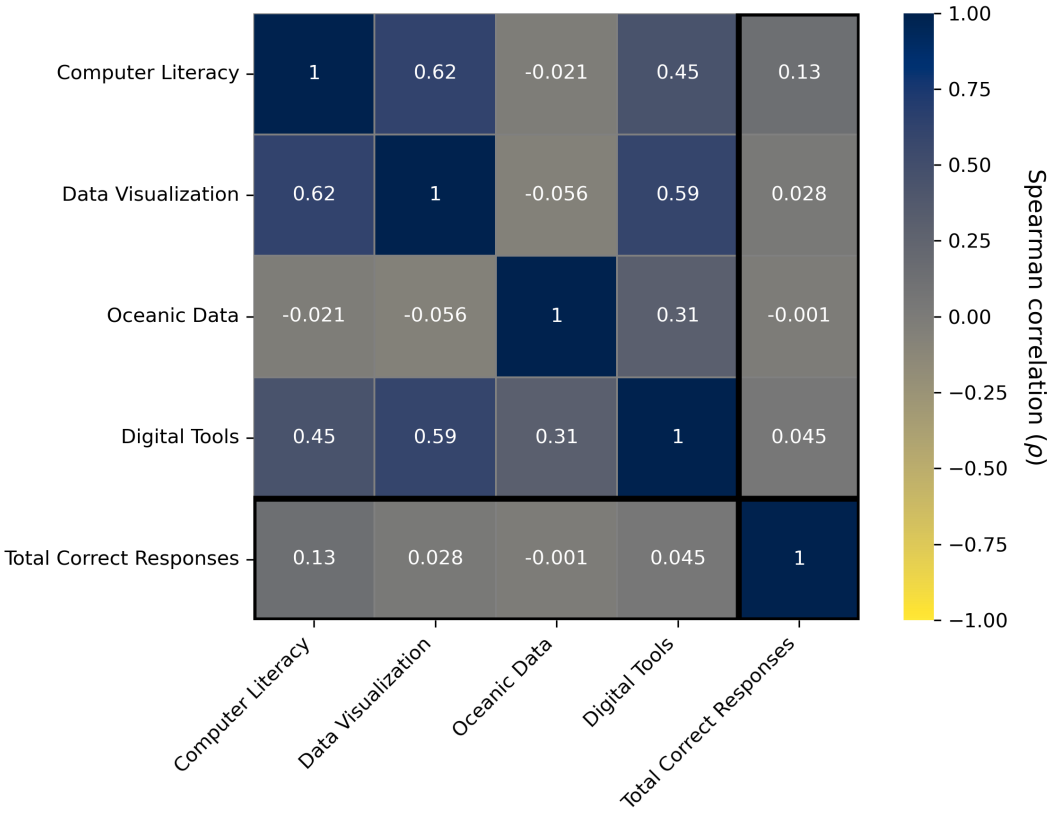


Figure 6.14: Heatmap of Spearman Correlations between Domain Knowledge Variables and Task Performance.

6.4.1.2 Time Spent Influence on Task Performance

Figure 6.15 presents task completion time (in minutes) plotted against task accuracy for each task. The boxplot analysis indicates that task correctness is not strongly associated with differences in median completion time, as the medians for correct and incorrect responses are similar across all tasks. This suggests that, on average, participants spent a comparable amount of time on tasks regardless of whether their answers were correct or incorrect.

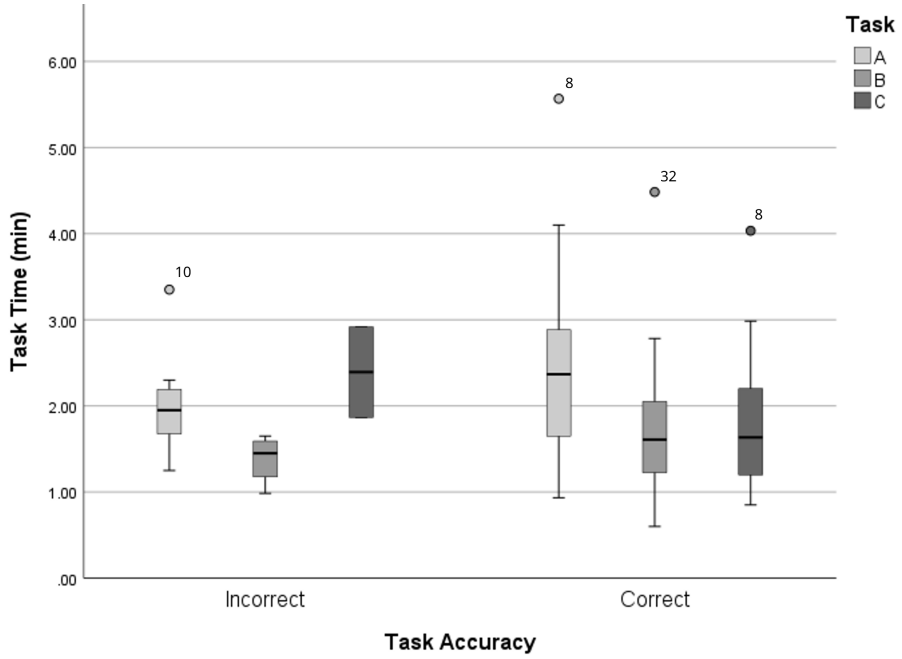


Figure 6.15: Task Completion Time by Accuracy for Each Task.

However, differences emerge in the variability of task completion times. For Tasks A and B, incorrect responses exhibit a smaller interquartile range compared to correct responses, indicating that participants who answered incorrectly tended to complete these tasks within a more consistent and narrower time window. In contrast, correct responses display greater variability in completion time, suggesting a wider range of strategies or levels of effort among participants who arrived at the correct solution.

Task C deviates from this pattern, as the interquartile ranges for correct and incorrect responses are similar. This indicates that, for Task C, the variability in task completion time is largely independent of task correctness.

6.4.1.3 Number of Help Requests Influence on Task Performance

Spearman's rank-order correlations were conducted to examine the relationship between the number of helps used and task accuracy for each task. This non-parametric measure was selected because the variables were not normally distributed and task accuracy was measured on a binary

scale, making Spearman's correlation more appropriate than Pearson's correlation. The results are presented in Table 6.5 and visualised in Figure 6.16.

	TASK A Number of Helps	TASK B Number of Helps	TASK C Number of Helps	TASK A Correct	TASK B Correct	TASK C Correct
TASK A Number of Helps	1,000	0,089	0,101	0,311	0,162	0,111
TASK B Number of Helps	0,089	1,000	0,184	-0,124	-0,143	0,098
TASK C Number of Helps	0,101	0,184	1,000	-0,279	-0,184	0,162
TASK A Correct	0,311	-0,124	-0,279	1,000	0,323	0,085
TASK B Correct	0,162	-0,143	-0,184	0,323	1,000	0,293
TASK C Correct	0,111	0,098	0,162	0,085	0,293	1,000

Table 6.5: Spearman's ρ Correlations between Number of Help Requests and Task Accuracy (N = 32).

For Task A, a small positive correlation was observed between the number of helps and accuracy, although this relationship was not statistically significant (ρ = 0,31, p = 0,083). For Task B, the correlation was weak and negative (ρ = -0,14, p = 0,435) and for Task C, it was small to moderate and negative (ρ = -0,28, p = 0,122). Overall, no statistically significant associations were found between the number of help requests used and task accuracy.

6.4.2 Mouse Tracking Analysis

A mouse tracking tool was running in the background of the map web page while participants completed the questionnaire tasks, as described in Section 5.7.1. The script of the mouse tracking tool recorded interactions of the participants with the interface, capturing cursor positions over time (cursor samples), clicks on interactive elements, scroll events and hover durations over page elements.

Another script [85] processed the session data from all 32 participants and generated summary metrics of user behaviour. It aggregates cursor movements, clicks and hover durations across all participants. The output of this script is presented in Listing 6.1.

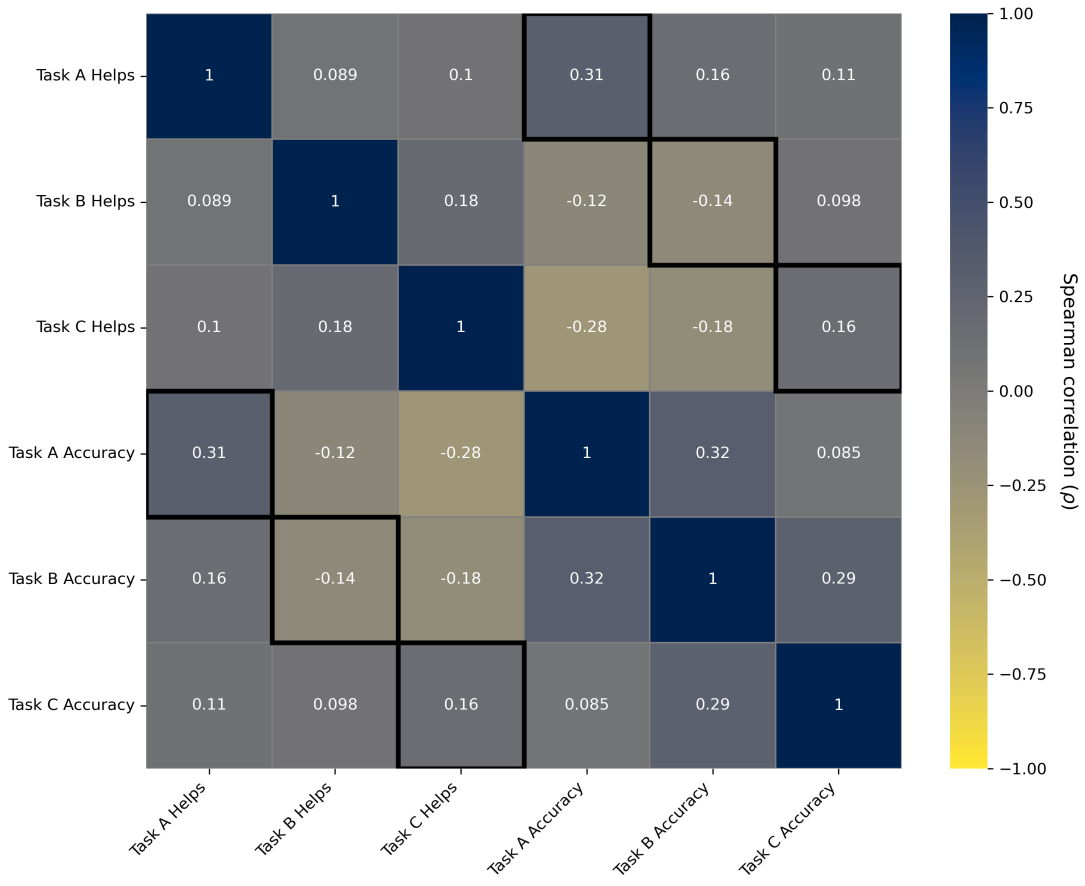


Figure 6.16: Heatmap of Spearman Correlations between Number of Help Requests and Task Performances.

Listing 6.1: Mouse Tracking Analysis Results.

```
Loaded 32 participant sessions

=== ANALYSIS COMPLETE ===
Participants analysed: 32
Total cursor points: 160823

Top 5 clicked elements:
          Element  Clicks
1   #regionSelect     878
6            #map     636
0  #datasetSelect     261
4           input     132
5        #playBtn      78

Top 5 high-hesitation elements:
                            Element  HoverPerClick
2                  #loadingOverlay     757.978400
5                         #sidebar      85.601775
15                  #viewModeForm      50.928500
11  div.info.legend.leaflet-control      35.088033
7                           strong      29.914700
```

Figure 6.17 illustrates the aggregated cursor data as a heatmap. The heatmap represents a grid of the screen, where each square is colored according to the number of cursor samples recorded. Lighter colours indicate fewer cursor samples, whereas darker colours indicate more. As observed in the figure, the left side and the bottom of the screen recorded the highest number of cursor samples.

The mouse tracking results show that the five most frequently clicked elements were the button to select regions, the map (presumably for zooming via double-click), the button to choose datasets, the radio buttons for selecting visualisation modes (particles, heatmap or vectors, referenced in the script as "input") and the play button of the animation controls. Figure 6.18 presents a heatmap of click events, where darker colours correspond to higher click frequencies in the areas identified by the script analysis.

Additionally, interface areas associated with greater hesitation were identified by calculating the Hover Per Click (HPC) metric, which measures the average time users spent hovering over an element before clicking. This metric is computed by dividing the total hover duration over each element by the number of clicks on that element plus one, as formalised in Equation 6.1.

$$HPC_e = \frac{H_e}{C_e + 1} \tag{6.1}$$

In this equation, HPC_e represents the Hover Per Click for element e, H_e is the total hover duration on element e and C_e is the total number of clicks on that element (the addition of 1 in

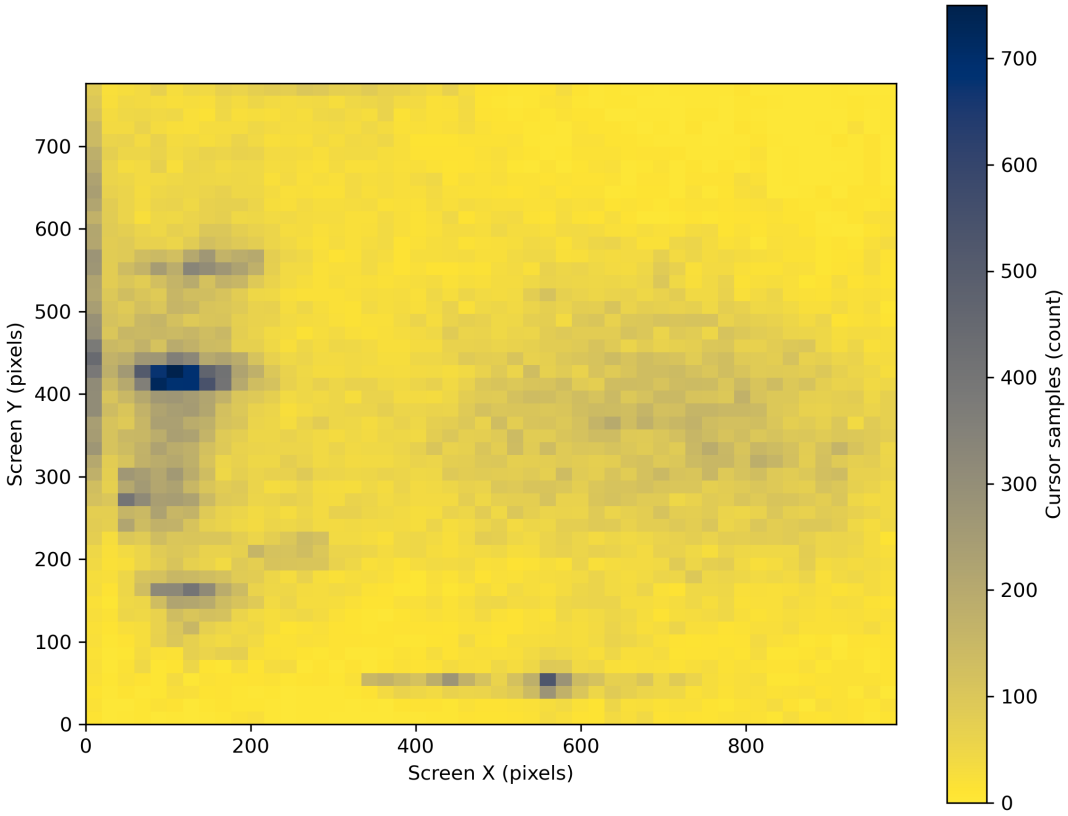


Figure 6.17: Aggregated Mouse Cursor Heatmap.

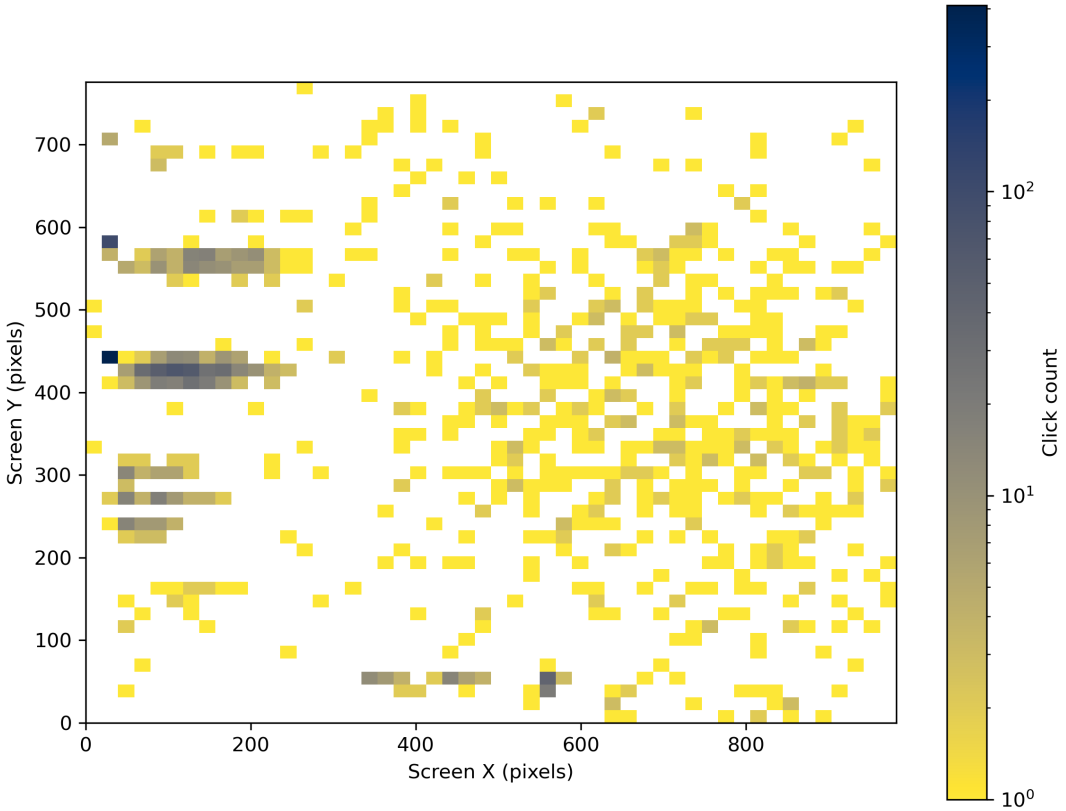


Figure 6.18: Heatmap of Click Events for All Participants.

the denominator ensures that the metric is well-defined even for elements that were never clicked, preventing division by zero).

This metric highlights interface elements where participants spent a disproportionately long time making decisions. The top five elements by this metric were the loading overlay message, the sidebar menu, the view mode radio buttons, the map legend and the headings of the buttons (referred to as "strong" in the mouse tracking results). This is further illustrated by the heatmap presented in Figure 6.19, where darker colours indicate areas of greater user hesitation.

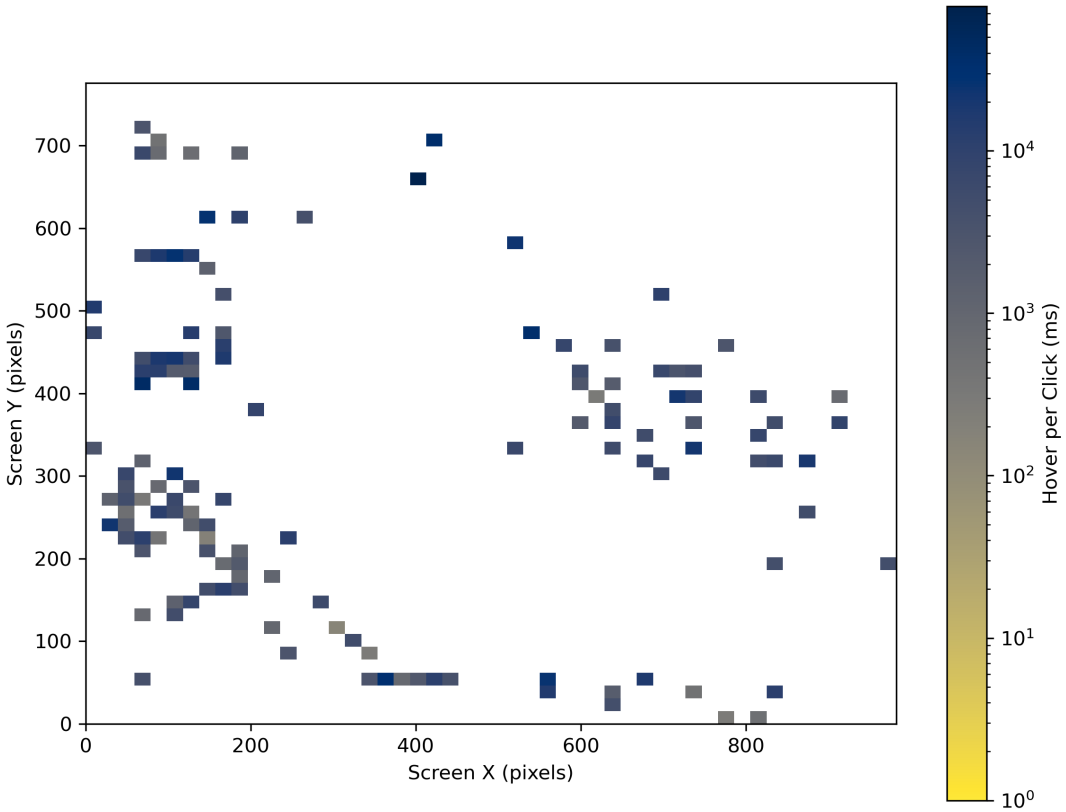


Figure 6.19: Heatmap of User Hesitation.

6.4.3 Accessibility Challenges

This section presents the participants' self-reported difficulties related to colour perception and reading or comprehension while interacting with the prototype. These results provide insight into potential accessibility barriers that may affect the interpretability of the visualisations.

Regarding colour perception, most participants reported no colour-related accessibility issues when using the prototype. Specifically, 26 participants (81.25%) indicated that they did not experience any difficulties related to colour perception. However, a small subset of participants reported issues that may impact accessibility. Three participants (9.38%) reported difficulty distinguishing some of the colours displayed on the map, while another three participants indicated that certain

colours were too similar to one another. Figure 6.20 presents a bar chart illustrating the frequency of reported colour-related difficulties.

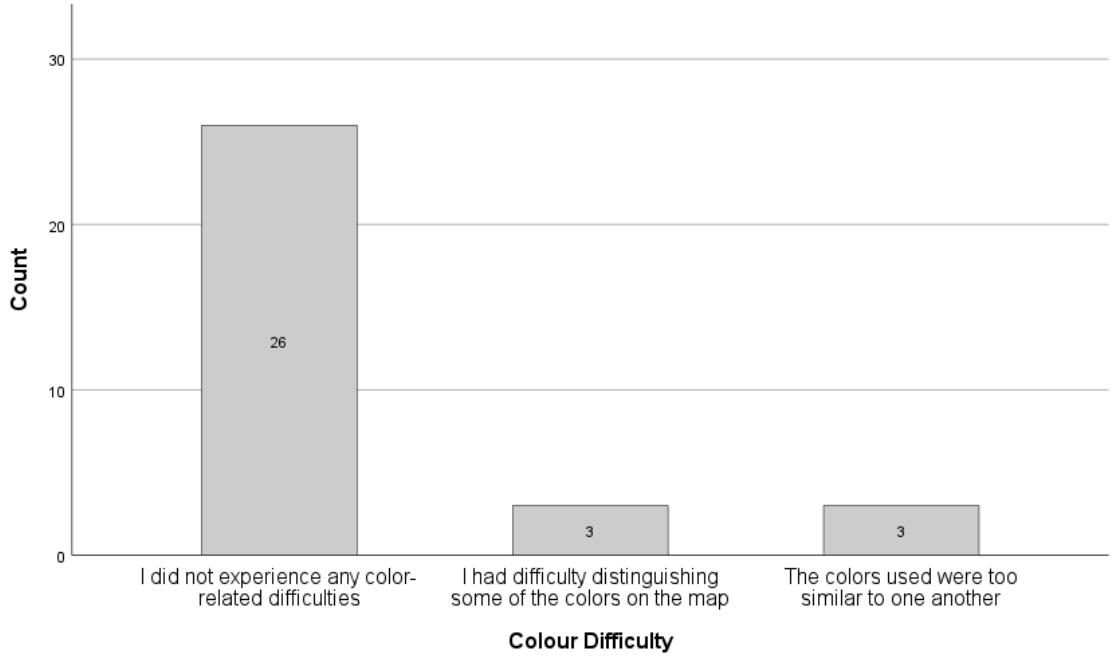


Figure 6.20: Reported Colour Perception Difficulties Among Participants.

With respect to reading and comprehension, a multiple-response question was used, allowing participants to report more than one difficulty or to provide additional comments. As a result, the total number of reported issues exceeds the number of participants. A total of 18 participants (56.3%) reported that they did not experience any reading or comprehension difficulties while using the prototype. Among those who did report issues, the most frequently cited difficulty was processing visual and textual information simultaneously, reported by 7 participants. Responses categorised as "Other" included comments that were not directly related to accessibility concerns, such as issues associated with system errors (e.g., decimal separators) or difficulties locating geographic boundaries.

Figure 6.21 presents a bar chart illustrating the frequency of reported reading and comprehension difficulties. Since multiple responses were allowed, the total count shown in the chart exceeds the total number of participants.

A crosstabulation analysis was conducted to examine the relationship between self-reported colour blindness and experienced colour-related difficulties, as presented in Table 6.6. Among participants without colour blindness (n = 30), the majority (83.3%) reported no colour-related difficulties. Nevertheless, 16.7% of this group indicated experiencing some degree of difficulty, including challenges in distinguishing colours or perceiving colours as too similar.

In contrast, among participants who reported colour blindness (n = 2), 50% indicated difficulty distinguishing colours, while the remaining 50% reported no colour-related difficulties. Although

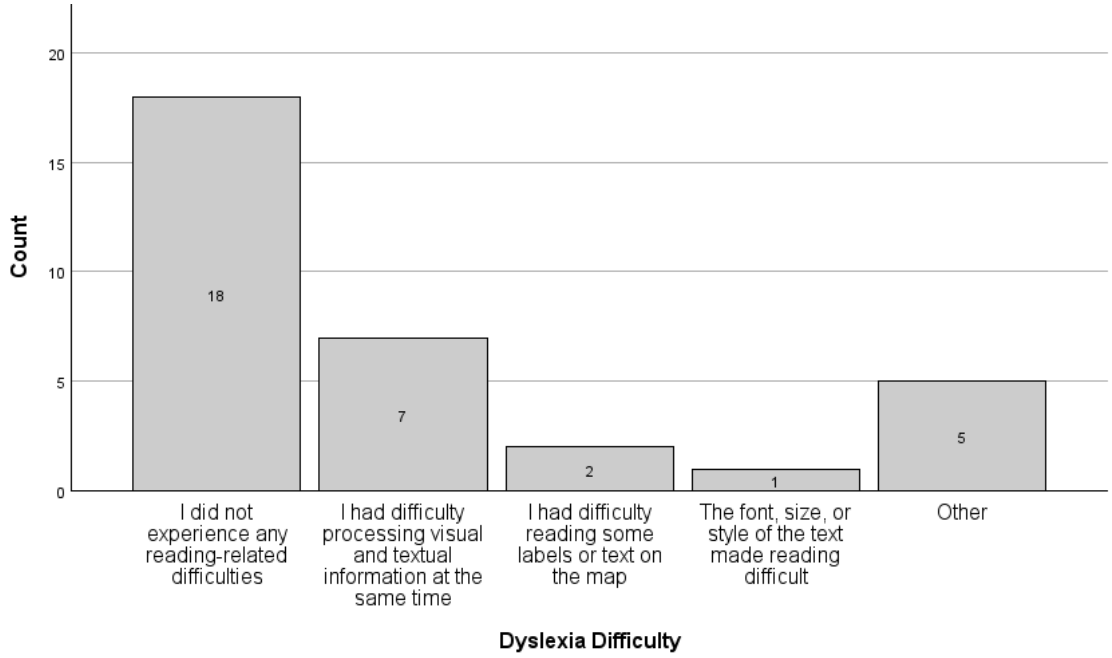


Figure 6.21: Reported Reading and Comprehension Difficulties Among Participants.

	No colour-related difficulties	Difficulty distinguishing colors	Colors too similar	Total
No color blindness (n = 30)	25 (83,3%)	2 (6,7%)	3 (10,0%)	30 (100%)
Color blindness (n = 2)	1 (50,0%)	1 (50,0%)	0 (0,0%)	2 (100%)
Total	26 (81,3%)	3 (9,4%)	3 (9,4%)	32 (100%)

Table 6.6: Cross-tabulation of Self-Reported Colour Blindness and Experienced Colour-Related Difficulties (N = 32).

the number of colour-blind participants was small, this finding suggests a higher proportion of reported colour-related issues within this group.

A second cross-tabulation analysis was performed to investigate the relationship between self-reported dyslexia and experienced reading or comprehension difficulties, as shown in Table 6.7. Among participants without dyslexia (n = 28), 60.7% reported no reading-related difficulties, whereas 39.3% reported at least one accessibility issue. The most frequently reported difficulty within this group was processing visual and textual information simultaneously (17.9%).

Dyslexia Difficulty	No dyslexia (n = 28)	Dyslexia (n = 4)	Total
No reading-related difficulties	17 (60,7%)	1 (25,0%)	18 (56,3%)
Difficulty locating countries/borders	1 (3,6%)	0 (0,0%)	1 (3,1%)
Difficulty processing visual and textual information	5 (17,9%)	1 (25,0%)	6 (18,8%)
Difficulty reading labels or text	1 (3,6%)	0 (0,0%)	1 (3,1%)
Reading + processing difficulties	0 (0,0%)	1 (25,0%)	1 (3,1%)
Difficulty differentiating data types	1 (3,6%)	0 (0,0%)	1 (3,1%)
Confusion about legend arrows	1 (3,6%)	0 (0,0%)	1 (3,1%)
Difficulty identifying dates	1 (3,6%)	0 (0,0%)	1 (3,1%)
Legend formatting inconsistencies	0 (0,0%)	1 (25,0%)	1 (3,1%)
Font, size or style made reading difficult	1 (3,6%)	0 (0,0%)	1 (3,1%)

Table 6.7: Transposed Cross-Tabulation of Dyslexia Status and Reported Reading-Related Difficulties (N = 32).

In contrast, among participants who reported dyslexia (n = 4), only 25% indicated no reading-related difficulties, while 75% reported one or more issues. Reported difficulties in this group included challenges related to visual–textual integration, reading labels and interpreting numerical formatting. Although the number of participants with dyslexia was limited, these results indicate a higher prevalence and greater diversity of reading and comprehension difficulties among participants with dyslexia.

6.4.4 System Usability Scale (SUS)

As previously mentioned in Section 5.4.2, the System Usability Scale (SUS) questionnaire was administered to all study participants. The SUS consists of 10 items, each rated on a 5-point Likert scale. Table 6.8 presents the minimum, maximum, median, mean and standard deviation for each item.

Figure 6.22 displays the distribution of scores for all SUS items. As observed, participants generally scored higher on the odd-numbered items than on the even-numbered items. Since the odd-numbered items are positively phrased and the even-numbered items are negatively phrased, this pattern indicates an overall positive perception of the system's usability.

To calculate the overall SUS score, responses to odd-numbered items were scored as the item response minus 1, whilst responses to even-numbered items were scored as 5 minus the item response. The sum of these scores was then multiplied by 2,5 to obtain the final SUS score, as shown in Equation 6.2.

SUS Question Number	Mean	Median	Std. Deviation	Minimum	Maximum
SUS1	3,5938	4	0,87471	1	5
SUS2	1,5000	1	0,80322	1	4
SUS3	4,0938	4	0,89296	2	5
SUS4	2,1250	2	1,21150	1	5
SUS5	4,2500	4	0,76200	2	5
SUS6	1,3750	1	0,60907	1	3
SUS7	4,2188	4,5	1,03906	1	5
SUS8	1,5000	1	0,91581	1	4
SUS9	3,8750	4	0,79312	2	5
SUS10	1,2813	1	0,52267	1	3

Table 6.8: Descriptive Statistics for SUS items 1–10.

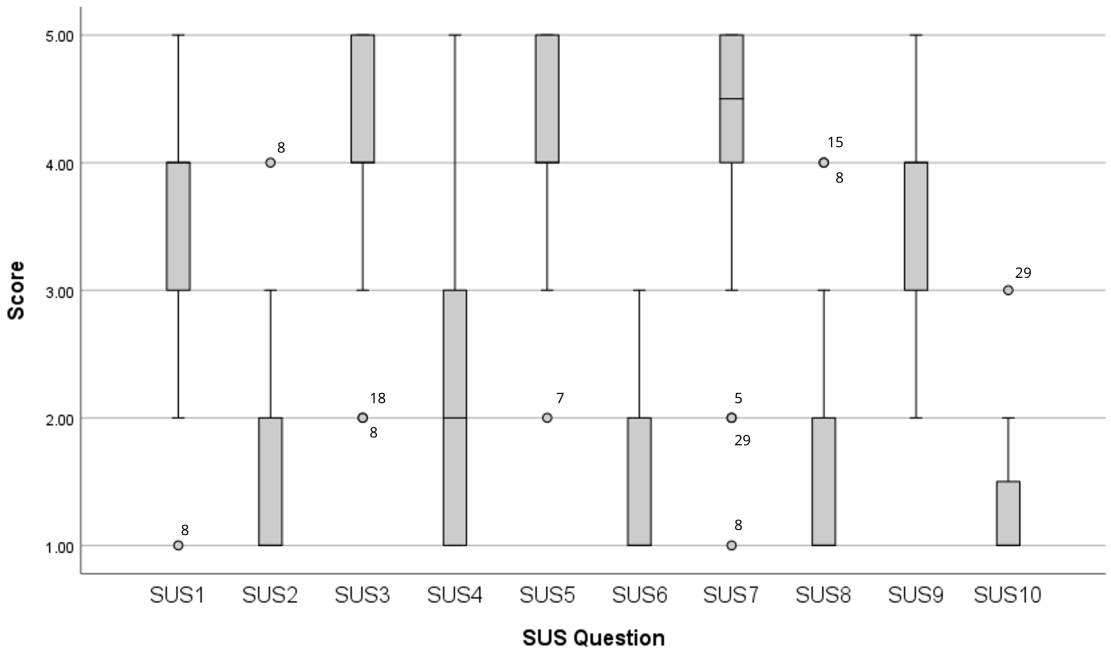


Figure 6.22: SUS Scores per Question.

$$\text{SUS} = 2.5 \times \left(\sum_{i=1,3,5,7,9} (Q_i - 1) + \sum_{i=2,4,6,8,10} (5 - Q_i) \right) \tag{6.2}$$

In this equation, Q_i represents the participant's response to the i-th item on a 5-point Likert scale, where 1 indicates "strongly disagree" and 5 indicates "strongly agree". Table 6.9 and the boxplot in Figure 6.1 present descriptive statistics for the overall SUS scores. The mean SUS score was 80,63, which corresponds to a "good" rating according to the standard SUS subjective scale [86].

Variable	Mean	Median	Std. Deviation	Minimum	Maximum
SUS	80,6250	87,5000	14,49416	35,00	95,00

Table 6.9: Descriptive Statistics for SUS Overall Score.

6.4.4.1 Task Performance Influence on SUS Scores

Spearman's rank-order correlation was conducted to examine the relationship between perceived usability, as measured by the System Usability Scale (SUS) and task accuracy. Spearman's correlation is appropriate for assessing monotonic relationships and does not assume linearity or normality, making it suitable for the ordinal nature of SUS scores.

A moderate positive correlation was observed between SUS scores and task accuracy (ρ = 0,33), suggesting that higher perceived usability tended to be associated with greater task accuracy. However, this relationship did not reach statistical significance (ρ = 0,065).

6.4.5 Perceived Readability Evaluation for Visualizations (PREVis)

PREVis is an 11 item instrument designed to assess the perceived readability of visualisations. Initial descriptive statistics were computed for the PREVis questionnaire, as seen in Table 6.10. Figure 6.23 presents the frequency distribution of scores across all PREVis questionnaire items.

PREVis Question Number	Minimum	Maximum	Mean	Std. Deviation
PREVis1	2	5	4,2188	0,90641
PREVis2	2	5	4,0000	0,84242
PREVis3	2	5	4,1250	0,65991
PREVis4	2	5	4,4375	0,75935
PREVis5	1	5	3,3437	1,28539
PREVis6	1	5	4,1250	1,07012
PREVis7	3	5	4,6250	0,60907
PREVis8	1	5	4,5937	0,87471
PREVis9	3	5	4,4688	0,67127
PREVis10	1	5	4,2813	0,88843
PREVis11	1	5	3,9063	1,05828

Table 6.10: Descriptive Statistics for PREVis Questionnaire Items.

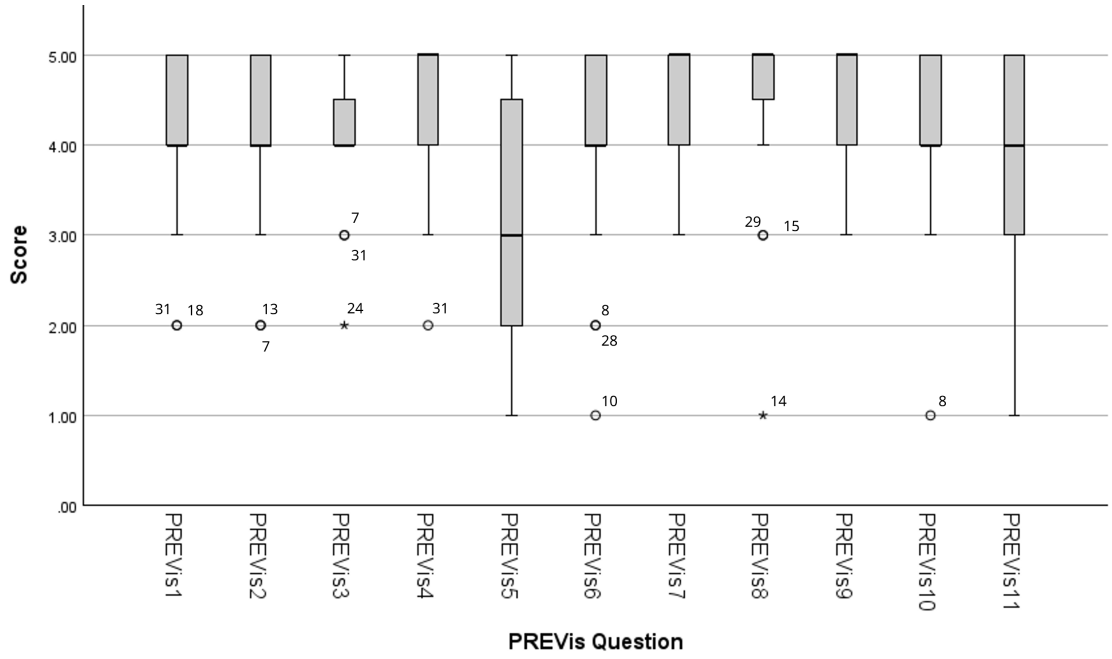


Figure 6.23: PREVis Scores per Question.

The overall PREVis score is organized into four scales: Understand, which evaluates the intelligibility of the visual encodings, Layout, which assesses the visual clarity and organisation of the layout, DataRead, which measures how easily users feel they can read individual data points and values and DataFeat, which evaluates how easily users perceive higher-level data patterns such as trends, clusters, extrems, outliers or ranges. The 11 items were subsequently aggregated into the four PREVis scales. The Understand score was computed as the mean of the first three items, Layout as the mean of the following three items, DataRead as the mean of the next three items and DataFeat as the mean of the final two items. These computations are formally defined in Equation 6.3, where R_i denotes the participant's response to the i-th PREVis item on a 5-point Likert scale.

$$\begin{aligned} \text{Understand} &= \frac{R_1 + R_2 + R_3}{3} \\ \text{Layout} &= \frac{R_4 + R_5 + R_6}{3} \\ \text{DataRead} &= \frac{R_7 + R_8 + R_9}{3} \\ \text{DataFeat} &= \frac{R_{10} + R_{11}}{2} \end{aligned} \tag{6.3}$$

Based on this aggregation, Table 6.11 presents the statistics for each PREVis scale. Figure 6.2 presents the score distribution and mean values for each PREVis scale. Mean values close to or above 4 across all scales indicate generally positive results regarding the perceived readability of the visualisation.

PREVis Variable	Mean	Median	Std. Deviation	Minimum	Maximum
Understand	4,1146	4,3333	0,57803	2,67	5,00
Layout	3,9688	4,0000	0,75424	2,33	5,00
DataRead	4,5625	4,6667	0,48959	3,00	5,00
DataFeat	4,0938	4,2500	0,84660	2,00	5,00

Table 6.11: Descriptive Statistics for PREVis Scales.

6.4.5.1 Task Performance Influence on PREVis Scores

To examine the relationship between task performance and PREVis scores, Spearman's rank-order correlation coefficient (ρ) was used. This non-parametric method was chosen because PREVis scale scores are measured on ordinal Likert-type scales and task accuracy does not meet the assumptions of normality required for parametric correlation analyses. Spearman's correlation assesses monotonic relationships without assuming linearity, making it appropriate for the characteristics of the data in this study.

The correlation results between PREVis scales and overall task accuracy are presented in Table 6.12. As indicated, none of the PREVis dimensions demonstrated a statistically significant correlation with task accuracy, although moderate to strong correlations were observed among the PREVis subscales themselves.

	Understand	Layout	DataRead	DataFeat	Total Correct
Understand	1,000	0,571**	0,184	0,341	0,020
Layout	0,571**	1,000	0,367*	0,469**	0,130
DataRead	0,184	0,367*	1,000	0,646**	0,109
DataFeat	0,341	0,469**	0,646**	1,000	0,126
Total Correct	0,020	0,130	0,109	0,126	1,000

Table 6.12: Spearman's ρ correlations between pre-visualization measures and total correct responses (N = 32).

* $p < 0{,}05$; ** $p < 0{,}01$ (2-tailed)

6.4.6 Observed System Errors

Four system errors were observed during the evaluation. The first was identified by a participant and concerned the minimap interaction. The minimap included a built-in control to collapse it and when this control was used, the minimap minimised as expected. However, when attempting to reopen it, the clickable area of the control was very small, making it difficult for some users to interact with it. Although several participants were able to use this functionality without issues, it was classified as a system error because the interaction did not respond consistently across users.

The second system error is related to the language selection feature available in the side menu, which allowed users to switch between English and Portuguese. One participant observed that, after changing the interface language to Portuguese, most textual elements were translated correctly,

but the country labels displayed on the map remained in English. A post-test investigation revealed that these labels were rendered as part of a map layer provided by a third-party tile service, which does not support the Portuguese language. Addressing this issue would therefore require the adoption of an alternative map label solution.

The third issue concerned inconsistencies in the numerical formatting used in the legend. Specifically, some values used decimal points while others used commas as decimal separators. This inconsistency was noticed by several participants. Although users who raised this issue were able to understand the intended values after clarification, it was considered a system error originating from the interface rather than from user misunderstanding. Consequently, these interactions were not recorded as user help requests.

The most frequent system error occurred when selecting datasets with a large number of particles, particularly for regions with high data density. In these cases, the system displayed a loading message, but after a prolonged loading period, the browser prompted a warning indicating that the page was unresponsive and asking whether the user wished to wait or exit. This issue affected four participants during Task A. For one of these users, the prototype had to be reloaded to restore normal functionality, making this the only instance in which a participant required two attempts to complete a task. During Task B, this issue affected one participant and no occurrences were observed during Task C.

No additional system errors were observed or reported by participants throughout the duration of the experiment.

6.5 Qualitative Results (Formative)

This section presents the formative results of the study, including the usability issues identified, participant feedback collected during the testing phase and the behaviours observed by the moderator throughout the sessions. These aspects are examined in detail in the following subsections.

6.5.1 Participant Feedback

Participant feedback was collected through two complementary methods: open-ended questions included at the end of the questionnaire and additional comments gathered during the final stage of the testing session, when the moderator invited participants to share any further observations.

Most Confusing Aspects of the Prototype When asked about the most confusing aspects of the prototype, participants' responses consistently focused on five main topics: the map legend, the visualisation modes, the colour schemes, general interface issues and additional suggestions. One participant specifically expressed uncertainty about whether their interpretation of the visualisation accurately reflected the underlying data values.

The map legend was the most frequently cited source of confusion, mentioned by a total of 13 participants. Two participants identified the legend as confusing without providing further detail. Two others indicated difficulty understanding the meaning of the arrows in the legend,

noting that it was unclear whether these represented minimum and maximum values or mean values and that the absence of numerical labels on the arrows further complicated interpretation. Additionally, four participants reported confusion arising from the fact that legend values changed depending on the selected region and dataset. These participants noted that they initially associated specific colours with particular value ranges and that the subsequent changes in those ranges across regions made interpretation difficult. Three participants also referred to a previously identified system issue (Section 6.4.6) concerning inconsistent use of decimal separators, where commas and points were used interchangeably. One participant expressed a desire for more numerical values to be explicitly displayed, despite the availability of individual particle values through interaction. Another participant suggested making the legend more interactive, for example, by allowing users to adjust values using a slider or otherwise clarifying the legend's functionality. Finally, two participants reported that they did not perceive any confusing aspects.

Regarding the visualisation modes, two participants reported confusion related to the vector representation, particularly concerning its meaning and the low visual salience of the vectors. Two additional participants indicated a need for clearer explanations of the purpose, importance and differences between the available visualisation modes, with particular uncertainty surrounding the heatmap and vector views. Two participants also reported difficulty distinguishing between the accumulated and dynamic animation modes, while one participant expressed dissatisfaction with the reduction in visible particle density when zooming in.

With respect to the colour schemes, three participants reported difficulty distinguishing between colour levels due to their similarity. One participant specifically identified the green colour scheme as problematic, stating that they were unable to differentiate the two middle colour levels. Additionally, three participants reported confusion arising from the mapping of lighter colours to higher levels of plastic aggregation and darker colours to lower levels, as this contradicted their expectations.

Several general interface-related issues were also identified. Two participants reported that the dataset descriptions were too similar, making it difficult to select the appropriate dataset. One participant found the representation of open-sea fishing-related plastic emissions in units of fishing hours confusing. Two participants reported difficulty visualising data for specific countries that were not included in the region selection dropdown. One participant also indicated trouble discovering how to access the side menu, as it was activated through a hover interaction that was not immediately apparent.

Additional suggestions included a request from one participant to visualise data from additional years and a suggestion from another participant to enable comparison between two regions simultaneously.

Most Liked Aspects of the Prototype When asked what they liked most about the prototype, participants highlighted ease of use, the visualisation modes, the topic of the data, the world map-based representation and the colour schemes. Only one participant stated that there was no aspect of the prototype they particularly liked, all other participants identified at least one positive feature.

Ease of use was the most frequently mentioned aspect, reported by 17 participants. Participants described the prototype as intuitive, easy to learn and usable without prior instruction. They emphasised that the interaction flow generally behaved as expected and that the dynamic and interactive nature of the visualisation enhanced usability. Specific interface elements, such as the simplicity of the design and the organisation of the side menu, were also positively noted.

The visualisation modes were also well received. Three participants appreciated the availability of multiple visualisation modes in general. Two participants identified the heatmap as their preferred mode, two favoured the vector representation and four highlighted the particle animation as particularly engaging. One participant noted that the combination of visualisation modes provided all the necessary information to effectively use the prototype.

The topic of the visualisation was highlighted by four participants, who emphasised the relevance and importance of ocean plastic pollution. These participants appreciated the ability to identify regions with higher ecological vulnerability and greater exposure to pollution-related impacts.

Regarding the world map-based visualisation, one participant noted that the use of a map was a positive choice, another highlighted the usefulness of country labels and borders and a third appreciated the interactivity of the map itself. Finally, two participants expressed satisfaction with the colour schemes used in the prototype.

Suggested Improvements When asked what they would improve in the prototype, participants suggested changes related to visualisation options, visualisation modes, interface design, colour schemes and the map legend. Three participants indicated that they would not change anything.

In terms of visualisation options, four participants suggested adding a global view to facilitate comparison and making legend value ranges easier to interpret, even if this resulted in reduced detail. Two participants expressed a preference for selecting individual countries rather than regions, while two others suggested enabling simultaneous comparison between two continental regions. Additionally, two participants indicated a desire to explore data across a broader temporal range, such as additional months or years.

With regard to visualisation modes, one participant stated that they would change the dynamic animation, although no further details were provided. Two participants suggested that the vector visualisation mode was difficult to interpret and required improvement.

Several interface-related improvements were also suggested. One participant noted that informational messages displayed at the bottom of the screen in the heatmap and vector modes were too subtle and often went unnoticed. Another participant suggested replacing the hover-based side menu with a button-controlled mechanism, allowing users to explicitly show or hide the menu. One participant recommended improving the minimap interaction, citing difficulty reopening it once minimised and expressing a preference for zoom functionality within the minimap. Two participants suggested adding more labels or legends to interface elements, such as particle values, even though this information was already available through interaction.

Colour-related suggestions were provided by six participants, who expressed a preference for alternative colour schemes. One participant suggested using four clearly distinct colours instead of gradients, while another noted that the green and purple schemes contained overly similar colour levels. Two participants suggested adding more colour scheme options and two others recommended reversing the colour mapping so that lighter colours would represent lower levels of plastic concentration.

Beyond these specific suggestions, three participants expressed a desire for more comprehensive guidance on how to use the prototype. Suggestions included interactive information buttons, clearer explanations of the differences between accumulated and dynamic visualisations and the addition of a full tutorial.

Final Participant Comments Finally, participants were invited to provide any additional comments. Most chose not to respond. One participant noted that some of the questionnaire tasks could be answered using general knowledge. Two participants expressed appreciation for the relevance of the research topic. Another participant commented positively on the responsiveness of the prototype, the intuitiveness of the menu and the effectiveness of presenting the information through a map-based visualisation.

6.5.2 Observed Behaviors

One of the primary objectives of the moderator during the testing phase was to collect qualitative insights based on participants' observed behaviour while interacting with the prototype. These observations were derived from participants' facial expressions, spontaneous verbal remarks and, in two cases, the use of a think-aloud protocol. Because the study was conducted in person and fully moderated, it was possible to closely monitor interaction patterns such as hesitation, pauses, corrective actions, repeated interactions, expressions of frustration (e.g., sighing or frowning) and moments of apparent confidence.

The observations focused on several aspects of the prototype, including dataset selection, interaction with the map interface, use of visualisation modes (particles, heatmap, vectors and trajectories), interpretation of the legend, use of bottom controls, interaction with the side menu, colour perception, accessibility concerns, participant characteristics and perceptions of the thematic focus of the visualisation.

Dataset selection was the first interaction step for most participants. The majority selected the correct dataset, although at least four participants chose an incorrect option. Several participants who ultimately selected the correct dataset needed to reread the task description multiple times and adjusted their selections accordingly. Participants who selected an incorrect dataset appeared to struggle with the terminology used to describe the datasets, which they perceived as similar. For example, some participants associated beaches exclusively with coastal regions and therefore did not clearly distinguish between dataset categories. This uncertainty was reflected in non-verbal behaviour such as head shaking and prolonged hesitation. One participant also showed visible signs of effort and impatience early in the session, including frequent sighing and verbal remarks

indicating reluctance to read longer textual descriptions. Another participant initially failed to understand why fishing-related data appeared outside the selected region (e.g., fishing activity near Africa when Europe was selected), revealing confusion regarding how datasets were spatially represented.

Several interaction patterns were observed in relation to the map interface. Only two participants independently discovered the individual particle value labels available in the particle view. Many participants struggled to locate Senegal during the relevant task, leading to extensive exploratory navigation, repeated zooming and panning and, in some cases, explicit requests for assistance. This behaviour is consistent with the help requests reported earlier. One participant noticed that country labels did not change language when switching the interface language, despite other textual elements updating accordingly. Another participant spent a considerable amount of time interacting with the minimap, attempting to understand its functionality beyond its intended use as a spatial reference. One participant, despite selecting the correct dataset and recognising that legend values varied by region, still answered incorrectly. In the post-test discussion, this participant explained that comparing regions of different sizes based on particle density or heatmap area was confusing and reduced confidence in their answer. This participant also expressed dissatisfaction with the reduced visibility of particles when zooming into smaller regions.

The heatmap view was the most frequently used visualisation mode for 13 participants. Two participants explicitly stated that it was their preferred mode. However, for at least one participant, the preference for the heatmap appeared to stem from difficulties encountered in the particle view, particularly when zooming caused particles to appear sparse or less visible. Notably, several participants who relied primarily on the heatmap view produced incorrect answers. In post-test discussions, some of these participants indicated that they interpreted the size or spatial extent of heatmap shapes as directly representing higher values, suggesting a potential misinterpretation of the encoding.

Participants exhibited some difficulty interpreting the vector and trajectory visualisations. Several participants relied heavily on zooming to attempt to understand vector behaviour, particularly in Task C. Some participants were uncertain about the directionality of the vectors and required time to realise that trajectories originated near the coast. In one case, the participant misunderstood the vectors as a three-dimensional representation or interpreted line length as indicating magnitude rather than direction. Others did not clearly distinguish between dynamic and accumulated animation modes, expressing uncertainty about their purpose and differences. Some participants played animations repeatedly, even when not required for the task, suggesting reliance on motion to support interpretation. In three cases, participants abandoned attempts to interpret vector directions altogether and ultimately, some did not answer the task correctly, indicating that the vector representation posed a challenge for some users.

Legend interpretation varied widely among participants. Some participants did not consult the legend at all, while others examined it in detail. Several participants initially focused on colour associations without noticing that numerical ranges changed across regions. Others realised this only midway through the session and adjusted their interpretations accordingly. One participant

attempted to interact with the legend, such as clicking on colour segments, apparently expecting filtering behaviour. Others focused on the arrow indicators but were unsure whether these represented minimum and maximum values or other statistical measures. Participants frequently reported that the changing scale across regions increased cognitive load and made comparisons more difficult.

The bottom controls were frequently overlooked or misunderstood. Several participants did not notice the play button or failed to understand the meaning of the progress bar and temporal indicators.

The side menu also presented usability challenges. Many participants did not immediately realise that it was revealed through hovering and one participant attempted to use browser navigation buttons to return to an initial state. Several participants explicitly stated that they disliked the hover-based interaction and would have preferred a fixed or collapsible menu.

Participants expressed mixed preferences regarding colour schemes. Some preferred the purple scheme, while others found the green scheme difficult to distinguish. One participant explicitly commented that the blue colour scheme was the most accessible, while the green scheme was the least effective. Several participants found it counterintuitive that lighter colours represented higher plastic concentrations, even when they understood that this choice was motivated by dark-mode design considerations.

Participants who reported dyslexia generally did not experience difficulties with isolated labels or numbers but noted that longer blocks of text would have been more challenging.

Participants varied in their interaction styles. Some explored the prototype extensively before answering questions, while others aimed to minimise interaction. Several participants adapted their strategy after noticing performance limitations, such as avoiding vector visualisations due to longer loading times and switching to particle views when directionality was not required. These adaptive behaviours often correlated with higher task accuracy.

Overall, participants responded positively to the thematic focus of the visualisation. Several highlighted the relevance of plastic pollution data, particularly for environmental or engineering contexts. Participants expressed interest in seeing longer temporal spans, river-based data or the ability to compare multiple regions simultaneously. Some explicitly stated that the visualisation was understandable even without prior domain knowledge, reinforcing its accessibility for non-expert audiences.

6.6 Discussion

This section discusses the findings of the evaluation study by synthesising quantitative results, qualitative feedback and observed interaction behaviour. The aim is to interpret how users engaged with the prototype, how effectively the visualisations supported accurate data interpretation and where usability and accessibility challenges emerged. This section identifies key strengths and limitations of the prototype and derives design implications for interactive visualisations of complex environmental data.

6.6.1 Task Performance and Data Interpretation

Task performance analysis revealed differences in difficulty across the three tasks. Task A emerged as the most challenging, with the lowest accuracy rate, the longest average completion time and multiple system performance issues due to high data density. This task required participants to compare regions of different sizes and interpret relative magnitudes using region-specific legends, increasing cognitive demands. In contrast, Task C achieved higher accuracy, although it generated the highest number of help requests, primarily related to geographic orientation and interpretation of vector trajectories.

Errors were rarely attributable to navigation difficulties or lack of engagement. Instead, both quantitative results and qualitative observations indicate that misinterpretations often stemmed from ambiguities in visual encodings, particularly the legend and the representation of aggregated values. For example, some participants incorrectly inferred higher values from larger heatmap areas or particle density, while others struggled to interpret vector directionality or trajectory origins. These findings suggest that task difficulty was driven more by representational complexity than by interface mechanics.

One of the key findings of the study is the lack of a significant relationship between participants' prior domain knowledge and task performance. Although strong correlations were observed among background variables such as computer literacy, familiarity with data visualisation tools and frequency of using interactive digital tools, none of these variables were significantly associated with the number of correct task responses. This indicates that participants' success was not dependent on prior expertise in data visualisation or oceanic environmental data.

This result supports the effectiveness of the prototype in communicating complex environmental data to non-expert users. Despite reporting low familiarity with ocean-related datasets, participants were generally able to interpret the visualisations and answer the tasks correctly. This finding aligns with the study's goal of designing an accessible visualisation tool suitable for broad audiences, including users without specialised domain knowledge.

6.6.2 Usability and User Acceptance

The results indicate that the developed prototype achieved a generally high level of usability. The mean System Usability Scale (SUS) score of 80,6 places the system within the "good" usability range, suggesting that participants perceived the interface as intuitive, coherent and easy to use. This overall positive perception is reinforced by the high task success rates, particularly for Tasks B and C and by the relatively low frequency of help requests across tasks. Taken together, these findings suggest that most participants were able to understand how to interact with the system and accomplish the required tasks without extensive guidance.

Importantly, lower SUS scores were not treated as statistical outliers, as they corresponded to participants who were observed to experience genuine interaction difficulties. Retaining these responses provides a more realistic representation of real-world usage and highlights that, while usability was generally strong, certain aspects of the interface still posed challenges for some

users. This variability is expected in exploratory usability studies and underscores the importance of complementing summative usability metrics with qualitative and behavioural evidence.

6.6.3 Perceived Readability

The PREVis results indicate high perceived readability across all four dimensions, with mean values close to or above 4. These results suggest that participants generally felt confident in their ability to read, understand and extract information from the visualisations. Strong correlations among the PREVis subscales further indicate internal consistency in participants' subjective evaluations of readability.

However, no significant correlations were found between PREVis scores and task accuracy. This discrepancy highlights an important distinction between perceived readability and actual interpretative correctness. Participants may feel that a visualisation is clear and readable while still misunderstanding specific encodings or drawing incorrect conclusions. This effect was particularly evident in the heatmap and legend interpretations, where some participants expressed confidence despite making incorrect assumptions about value mappings or comparative scales, particularly when visualisations are intended to support decision-making rather than exploration alone.

6.6.4 The Legend

The map legend emerged as the most problematic element, mentioned by 13 participants as confusing. This finding is consistent across participant feedback, qualitative observations and mouse tracking data (high hesitation area), providing strong evidence that legend design represents a critical usability barrier.

Several specific issues contributed to confusion, including difficulty interpreting the arrow indicators. The dynamic legend that adjusts ranges by region and dataset created cognitive load for cross-regional comparisons. Four participants noted they initially associated colours with specific values and found it disorienting when these changed between regions. Inconsistent decimal separators (commas vs. points) further reduced confidence in displayed data. This illustrates the broader visualisation design challenge of balancing technical accuracy with user comprehension. Adaptive scales maximise colour discrimination and are common best practice, but from a usability perspective, they complicate comparative tasks when users aren't aware that scales are changing.

6.6.5 Visualisation Mode and Interface Design

The prototype offered four visualisation modes (particle animation, heatmap and vector field), with varied user preferences and success rates.

Particle animation was described as engaging and intuitive. The dynamic nature facilitated pattern recognition, though only two participants independently discovered the hover functionality.

Additionally, confusion between accumulated and dynamic animation modes indicated the need for more explicit labelling of their different purposes.

Heatmap was frequently used (13 participants relied on it primarily). However, several participants who used it heavily provided incorrect answers. Post-test discussions revealed a critical misinterpretation: some interpreted spatial extent as magnitude rather than recognising colour intensity and density as the primary encoding. This highlights the challenge of multi-encoding visualisations where users may apply inappropriate mental models.

Vector visualisation proved problematic. Participants reported difficulty understanding the vector's purpose and directionality. Many zoomed extensively trying to interpret vectors, with one user confusing line length with magnitude. Low visual salience combined with insufficient explanatory information led three to abandon vector interpretation entirely. Despite the high accuracy observed for Task C, qualitative observations showed some struggled with vectors and relied on animation visualisation.

Bottom controls (play button, progress bar, temporal indicators) were similarly underutilised and identified as high-hesitation areas. Many participants didn't engage with these elements.

The minimap presented mixed results. While some found it useful, others struggled with its interaction, particularly reopening after minimising. One participant extensively explored it, expecting more features like zoom control.

6.6.6 Interaction Behaviour

Mouse tracking analysis provided additional insight into participants' interaction behaviour and cognitive load. Aggregated cursor heatmaps and Hover Per Click metrics revealed high levels of activity and hesitation around the legend, the sidebar menu, visualisation mode controls and loading overlays. These areas correspond closely with elements that participants identified as confusing or demanding during post-test feedback and observation.

High hesitation around the legend suggests that it played a central role in users' decision-making processes rather than serving as a passive reference. Similarly, prolonged hover times over visualisation mode controls and the sidebar indicate uncertainty regarding the purpose and effects of different interaction options. The frequent overlooking of bottom controls and reliance on repeated animation playback further suggest that motion was used as a compensatory strategy to support interpretation when static cues were insufficient. Together, these behaviours indicate points of increased cognitive load that warrant design refinement.

6.6.7 Accessibility

Accessibility-related findings reveal that potential barriers were not limited to participants with formally reported impairments. Although most participants reported no colour-related difficulties, a proportion experienced challenges distinguishing colour levels or interpreting similar hues, including participants without colour vision deficiencies. This suggests that colour encoding choices may impact a broader user population than anticipated.

Participants with dyslexia reported a higher frequency and diversity of reading and comprehension difficulties, particularly when visual and textual information had to be processed simultaneously. Nevertheless, even participants without dyslexia reported similar challenges, indicating that cognitive load and information density affected usability more generally. These results highlight the importance of inclusive design practices, such as increased colour contrast, clearer legend explanations, redundant encodings and reduced reliance on simultaneous visual–textual processing. This reinforces the value of accessibility-oriented design not only as an inclusive practice but as a means of improving overall usability.

6.6.8 Technical Performance

The most impactful system issue was browser unresponsiveness when loading high-density particle datasets, affecting five participants and requiring one to reload the prototype entirely. This highlights the challenge of balancing data richness against computational limitations in web-based visualisation.

The minimap control issue (extremely small clickable reopening area) and inconsistent decimal separators, while less impactful, affected user experience and confidence. These issues underscore the importance of thorough testing.

System errors affecting five participants represent a confounding factor that may have influenced perceptions, though high SUS scores despite these issues suggest that participants did not allow these issues to dominate their overall evaluation.

6.6.9 Contributions and Significance

This study provides evidence that interactive web-based visualisations can effectively communicate complex ocean plastic pollution data to non-expert audiences. The lack of correlation between domain knowledge and task performance supports the prototype's potential for diverse stakeholders, including policymakers, educators and the general public. Importantly, the inclusion of datasets related to fishing activity adds an additional socio-economic dimension to the visualisation, allowing users to contextualise plastic pollution not only as an environmental issue but also in relation to human economic practices.

This research contributes methodologically by demonstrating the value of combining multiple evaluations (performance metrics, questionnaires, mouse tracking, qualitative observation) and an in-person moderated format to create a comprehensive understanding of visualisation usability. The finding that subjective measures and objective performance don't always align reinforces the importance of multi-method evaluation.

Theoretically, it advances understanding of how non-experts interact with complex environmental visualisations. The identification of specific interpretation errors (e.g., heatmap spatial extent misreading) provides insights into user mental models and highlights the importance of aligning visual encodings with expectations.

Practically, the validated prototype and specific design recommendations inform future ocean plastic visualisation development. The study addresses the critical societal challenge of communicating environmental information effectively to diverse stakeholders, advancing on the ability to make ocean plastic pollution data accessible, accurate and engaging for policy, education and public awareness purposes.

6.7 Summary

This chapter examined the results of the prototype evaluation through a combined quantitative and qualitative analysis. Overall, the findings show that the system was usable and accessible to non-expert users, while also highlighting specific challenges in visual interpretation and interaction design. Key issues related to legend comprehension, visual encoding and system performance were identified. Together, these results provide a clear foundation for the conclusions and directions for future work discussed in the next chapter.

Chapter 7

Conclusions

This section of the conclusions synthesises the key outcomes of the dissertation. It begins by addressing the research questions formulated in Chapter 1, followed by a discussion of the study's limitations. The section then presents final remarks on the overall work and outlines directions for future research and subsequent iterations.

7.1 Addressing Research Questions

This section presents the study's findings in relation to the research questions, summarising the key insights and outcomes for each.

RQ1 - What visual information techniques are currently used in this context and are there comparable approaches in other domains?

The analysis of the state of the art identified a set of visualisation techniques commonly used to represent plastic dispersion, transport and accumulation processes. For the visualization of plastic dispersion and trajectories, these techniques include vector fields (typically represented through arrows indicating current speed and direction), streamlines (which provide a continuous and smooth representation of flow structure), particle systems (where particles are advected over time and display attributes such as velocity, lifespan and direction) and trajectory maps (which show cumulative particle paths over seasonal or annual periods, allowing the identification of accumulation zones and transport connectivity).

To represent the spatial distribution and accumulation of plastics, the literature frequently uses heatmaps (using continuous colour gradients to reveal spatial patterns and highlight concentration hotspots), as well as density maps (that indicate regions of particle aggregation). Additional approaches include source-to-sink pathway visualisations (which connect plastic input locations to final accumulation areas) and Priority Area Maps (which emphasise zones of ecological or economic relevance).

For spatiotemporal and dynamic analysis, the state of the art highlights the use of animated visualisations, coordinated multiple views (that support the simultaneous analysis of different variables or time frames) and real-time or interactive visual systems. Integrated and interactive visualisation approaches often combine multiple visual modalities, enabling users to explore data through interactions such as zooming, filtering and variable selection.

Comparable visualisation techniques are widely used in related domains, including oil spill visualisation, pelagic egg and larvae drift studies and weather and atmospheric phenomena visualisation, where similar challenges related to spatiotemporal dynamics and flow representation are addressed.

RQ2 - What techniques and methods are employed to create both macro and micro visualisations?

The state of the art indicates that micro-level visualisations are often implemented using three-dimensional representations. These include 3D surface visualisations incorporating bathymetry or sea surface features, volume rendering techniques (that allow the simultaneous visualisation of plastic distributions and oceanographic variables) and vertical profile visualisations (that support the analysis of particle sinking and vertical transport). Although these approaches provide detailed insights into vertical and subsurface dynamics, such micro-level three-dimensional visualisations were not developed within the scope of this dissertation.

Macro-level visualisations, by contrast, focus on the representation of large-scale spatial and temporal patterns. The state of the art introduces visualisation techniques such as particle system views, heatmaps and vector-based representations, which were also adopted in the developed prototype. These visualisations were generated using a Lagrangian particle tracking approach implemented with OpenDrift and were evaluated through user testing. This approach supports the exploration of dispersion patterns, accumulation areas and transport behaviour across broader geographic regions and time spans.

RQ3 - What tasks are considered essential in the process of visualising plastic data over time?

The essential tasks involved in visualising plastic data over time are those identified and structured in Tables 4.1 through 4.3 and primarily reflect how users interact with the visualisation to extract information. These tasks include identifying areas with higher or lower concentrations of plastics, understanding the direction and behaviour of plastic trajectories, comparing concentration levels across different regions and interpreting temporal changes in dispersion patterns.

Additional essential tasks involve interacting with the visualisation controls to explore the data, such as navigating through time, interpreting visual encodings and comparing different spatial views. The results of the usability study indicate that these tasks are fundamental to enabling users to explore and understand plastic data, highlighting the importance of interaction design and clear visual representations in supporting temporal and spatial analysis.

RQ4 - How can environmental and weather factors be visually represented to enhance scenario simulations?

In the developed prototype, environmental and weather-related factors, including wind, wave and ocean current data, were integrated into the creation of particle trajectories, which were then animated to represent plastic dispersion over time. This approach allows the influence of environmental conditions to be perceived directly through particle movement, rather than through separate visual layers.

While additional factors could be incorporated to further enhance scenario simulations, such as biochemical data related to plastic degradation or vertical sinking processes, these were not included in the current prototype. The integration of such data could enable additional visual encodings, for example, through changes in particle colour representation or behaviour over time and represents a potential direction for future work. An initial concept explored in the low-fidelity prototype involved allowing users to modify wind and wave velocities to observe their effects on dispersion, however, this interaction was not implemented in the final prototype, as the use of real environmental data from January 2020 made such modifications less appropriate. Furthermore, the results suggest that increasing visual and interaction complexity does not necessarily improve user understanding and that visualising real data provides different and more meaningful insights than visualising synthetic or randomly generated scenarios.

7.2 Limitations

This dissertation presents several limitations related to the scope of the study, the evaluation methodology and the technical implementation of the proposed visualisation system. These limitations should be considered when interpreting the results and identifying opportunities for future improvements.

One limitation concerns the evaluation process, particularly the sample size and diversity of participants involved in the usability study. Although the results provided useful insights into user interaction and interpretation, a larger and more diverse participant group could lead to more robust conclusions. In particular, additional testing with users from different backgrounds, languages and levels of expertise, as well as users with accessibility needs or visual impairments, would allow for a more comprehensive assessment of the system's usability and inclusiveness.

The experimental design also presents limitations related to the evaluation protocol. The absence of initial exploratory interviews or direct comparisons with existing visualisation systems limits the ability to contextualise user feedback and benchmark the proposed approach against alternative solutions. Additionally, the number of testing cycles was limited and improvements identified during the study were not followed by repeated testing iterations. Further evaluation cycles would be required to assess the impact of interface refinements and design changes. Some task questions could also be answered using general knowledge rather than by interacting with the prototype, which may reduce the reliability of the results in assessing participants' effective use of the visualisation. Providing an explicit option for participants to indicate uncertainty (e.g., "I do not know") could help reduce random responses and potential false positives in the collected data.

From a data and modelling perspective, the prototype focuses on surface-level plastic dispersion and does not incorporate biochemical degradation processes or vertical particle movement within the water column. The integration of biochemical components affecting particle degradation, as well as vertical transport and sinking behaviour, would enable a more complete representation of plastic dynamics. In addition, the simulations were limited to a relatively short temporal window and extending the duration to include more days or longer seasonal periods could provide additional insights into accumulation and transport patterns.

Technical limitations are also present in the current implementation of the system. The prototype relies on precomputed simulation data rather than real-time model generation and browser-based performance constraints affected responsiveness and scalability. Greater computational resources could support real-time simulation capabilities, improved browser performance and more responsive interaction. Furthermore, three-dimensional visualisation techniques, although identified in the state of the art, were not implemented in the prototype, limiting the analysis to two-dimensional representations.

Finally, several interface-related limitations were identified. The system currently supports the visualisation of one geographic region at a time, which restricts comparative analysis across multiple regions or global views. Expanding the system to allow simultaneous comparison of multiple regions or global-scale visualisation would enhance exploratory capabilities. Additionally, terminology used in the interface, such as "vectors", "particles" and "heatmaps" may not be intuitive for non-expert users. Adopting more descriptive terms (e.g., "flux" or "density") and ensuring consistent translation across supported languages, including translating map labels when the Portuguese language is selected, would further improve accessibility and usability.

7.3 Final Remarks

This dissertation focused on the exploration of visual data analysis techniques to support the understanding and interpretation of maritime plastic pollution events. Motivated by the growing environmental impact of plastic pollution and the increasing availability of complex simulation and observational data, the work aimed to investigate how visualisation can assist in making such data more accessible, interpretable and useful for analysis.

The research began with a systematic literature review conducted in accordance with PRISMA guidelines, which provided an overview of existing research related to plastic transport, numerical modelling and environmental data visualisation. This review highlighted both the techniques commonly employed in related domains and several gaps, particularly regarding the consistent application of visualisation methods to plastic data and the limited emphasis on usability and user-centred evaluation. Building on these findings, the state of the art chapter contextualised the problem by examining the physical processes influencing plastic transport, the modelling approaches used to simulate these processes and the visualisation techniques applied to oceanographic and environmental data.

Based on the insights gathered from the literature and state of the art, a user-centred approach was adopted for the design and development of an interactive visualisation prototype. The proposed solution aimed to support exploratory analysis through multiple visualisation modes, enabling users to examine plastic dispersion at a macro level. Particular attention was given to interaction design, visual encodings and accessibility considerations, to support users with different backgrounds and levels of domain knowledge.

An experimental study was conducted to evaluate the usability and interpretability of the developed prototype. Quantitative and qualitative results indicated that participants were generally able to perform key analytical tasks, such as identifying spatial patterns, interpreting temporal changes and understanding particle movement. At the same time, the evaluation revealed challenges related to colour perception, legend interpretation and the complexity of animated visualisations, emphasising the importance of careful design choices when presenting dynamic and dense visual content.

Overall, this dissertation highlights the role of visualisation as a complementary tool in the study of plastic pollution. Rather than aiming to improve or validate transport models themselves, the work contributes by examining how simulation results can be visually communicated and explored in a more accessible and user-oriented manner. By addressing both design and evaluation aspects, this research provides insights into the strengths and limitations of current visualisation approaches and identifies considerations that may inform future developments in this area.

An important aspect of the proposed visualisation approach is its applicability to users without specialised domain expertise. By prioritising visual clarity, accessibility and simple interaction mechanisms, the system supports exploratory analysis of complex spatiotemporal data without requiring detailed knowledge of plastic transport or oceanographic modelling. In addition to environmental information, the visualisation provides contextual insights related to human activities, particularly fishing, by enabling the exploration of plastic dispersion in relation to specific geographic areas. In this way, the approach may support communication between scientific data and broader policy-related discussions, serving as a complementary tool for stakeholders and decision-makers in the context of marine environmental management.

In conclusion, while limited in scope, this work contributes to the broader field of environmental data visualisation by demonstrating how interactive visual tools can support the exploration and understanding of complex marine pollution data. By improving the accessibility and interpretability of plastic dispersion information, such approaches may assist researchers and other stakeholders in gaining clearer insights into marine pollution phenomena, supporting ongoing efforts toward ocean protection and sustainability.

7.4 Future Work

Future work may build upon the findings and limitations identified in this dissertation through a series of iterative improvements to both the visualisation prototype and the evaluation methodology.

A first step would involve addressing several technical and interface-related issues identified during the usability study. These include resolving system errors observed during interaction, extending the temporal range of the simulations to include additional days and improving the consistency of language localisation by ensuring that country labels and interface elements are correctly displayed in Portuguese when that language is selected. Additionally, the interface terminology could be revised to adopt more intuitive and descriptive terms, such as using "density" instead of "heatmap" and "flux" instead of "vectors", along with their appropriate Portuguese translations. Expanding the visualisation to support global views or the simultaneous comparison of multiple regions would further enhance exploratory analysis capabilities.

Following these improvements, a second iteration of the prototype could be evaluated through an additional cycle of user testing. This new evaluation round would reassess usability after the implemented changes and include an extended questionnaire section to gather user feedback on potential future features. These features could include the integration of biochemical components into the trajectory models to represent particle degradation over time, the incorporation of vertical particle movement within the water column, the development of three-dimensional visualisations and the ability to compare different simulation models, such as PlasticParcels and OpenDrift. Providing users with the opportunity to express whether such additions would be useful or desirable would help prioritise future development efforts based on user needs.

Improvements to the evaluation methodology would also be an important focus of future work. Increasing the sample size and participant diversity would strengthen the reliability of the results, while targeted accessibility testing with users experiencing visual or cognitive impairments would support a more inclusive design process. Additional testing with users speaking different languages would further validate the effectiveness of localisation features. The design of evaluation tasks could also be refined to reduce reliance on common knowledge and better assess visualisation comprehension. Introducing an explicit option for participants to indicate uncertainty (e.g., "I do not know how to answer this question") could help reduce random responses and false positives, leading to more accurate statistical interpretations of user performance.

In parallel, future research could investigate the feasibility of generating simulations in real time by leveraging increased computational resources. Exploring whether additional computational power could support real-time trajectory generation and improve browser responsiveness would inform the potential scalability of the system and guide decisions for subsequent prototype iterations.

After completing the second round of testing, a new analysis of the results and conclusions could be conducted to assess the impact of the implemented changes. The insights gained from this evaluation would then inform a subsequent iteration of the prototype, following an iterative and user-centred design process. This cyclical approach, as illustrated in Figure 4.1, would allow the system to be incrementally refined over multiple development and evaluation cycles, ensuring that user feedback remains central to the evolution of the prototype and that usability and interpretability are continuously improved.

References

[1] Homin Kye et al. “Microplastics in water systems: A review of their impacts on the environment and their potential hazards”. English. In: *Heliyon* 9.3 (Mar. 2023). Publisher: Elsevier. ISSN: 2405-8440. DOI: 10.1016/j.heliyon.2023.e14359. URL: https://www.cell.com/heliyon/abstract/S2405-8440(23)01566-9.

[2] Merlin N. Issac and Balasubramanian Kandasubramanian. “Effect of microplastics in water and aquatic systems”. en. In: *Environmental Science and Pollution Research* 28.16 (Apr. 2021), pp. 19544–19562. ISSN: 1614-7499. DOI: 10.1007/s11356-021-13184-2. URL: https://doi.org/10.1007/s11356-021-13184-2.

[3] Nicholas Chartres et al. “Effects of Microplastic Exposure on Human Digestive, Reproductive, and Respiratory Health: A Rapid Systematic Review”. eng. In: *Environmental Science & Technology* 58.52 (Dec. 2024), pp. 22843–22864. ISSN: 1520-5851. DOI: 10.1021/acs.est.3c09524.

[4] Matthew J. Page et al. “PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews”. en. In: *BMJ* 372 (Mar. 2021). Publisher: British Medical Journal Publishing Group Section: Research Methods & Reporting, n160. ISSN: 1756-1833. DOI: 10.1136/bmj.n160.

[5] *Google Scholar*. URL: https://scholar.google.com/.

[6] *IEEE Xplore*. URL: https://ieeexplore.ieee.org/.

[7] *SCOPUS*. URL: https://www.scopus.com/.

[8] *ScienceDirect*. URL: https://www.sciencedirect.com/.

[9] *Clarivate Web of Science*. URL: https://www.webofscience.com/.

[10] *ACM Digital Library*. URL: https://dl.acm.org/.

[11] *Zotero*. URL: https://www.zotero.org/.

[12] Nicole L. Allison et al. “Modelled and observed plastic pollution on remote Scottish beaches: The importance of local marine sources”. In: *Marine Pollution Bulletin* 194 (2023), p. 115341. ISSN: 0025-326X. DOI: https://doi.org/10.1016/j.marpolbul.2023.115341. URL: https://www.sciencedirect.com/science/article/pii/S0025326X23007750.

[13] Caiyuan Cai, Liangsheng Zhu, and Bo Hong. “A review of methods for modeling microplastic transport in the marine environments”. In: *Marine Pollution Bulletin* 193 (2023), p. 115136. ISSN: 0025-326X. DOI: https://doi.org/10.1016/j.marpolbul.2023.115136. URL: https://www.sciencedirect.com/science/article/pii/S0025326X23005684.

[14] Jikke van Wijnen, Ad M. J. Ragas, and Carolien Kroeze. "Modelling global river export of microplastics to the marine environment: Sources and future trends". In: *Science of The Total Environment* 673 (2019), pp. 392–401. ISSN: 0048-9697. DOI: https://doi.org/10.1016/j.scitotenv.2019.04.078. URL: https://www.sciencedirect.com/science/article/pii/S0048969719315980.

[15] Claudio Cardoso and Rui M. A. Caldeira. "Modeling the Exposure of the Macaronesia Islands (NE Atlantic) to Marine Plastic Pollution". English. In: *FRONTIERS IN MARINE SCIENCE* 8 (Apr. 2021). Num Pages: 24 Place: Lausanne Publisher: Frontiers Media Sa Web of Science ID: WOS:000651375500001, p. 653502. ISSN: 2296-7745. DOI: 10.3389/fmars.2021.653502. URL: https://www.frontiersin.org/journals/marine-science/articles/10.3389/fmars.2021.653502/full.

[16] Maes Christophe et al. "Disentangling the physical dispersion of floating debris and plastics in the Indonesian Seas". In: *OCEANS 2021: San Diego – Porto*. ISSN: 0197-7385. Sept. 2021, pp. 1–9. DOI: 10.23919/OCEANS44145.2021.9705696. URL: https://ieeexplore.ieee.org/document/9705696/.

[17] Tonia Astrid Capuano et al. "Oceanic realistic application of a microplastic biofouling model to the river discharge case". In: *Environmental Pollution* 359 (2024), p. 124501. ISSN: 0269-7491. DOI: https://doi.org/10.1016/j.envpol.2024.124501. URL: https://www.sciencedirect.com/science/article/pii/S0269749124012156.

[18] Kunihiro Aoki and Ryo Furue. "A model for the size distribution of marine microplastics: A statistical mechanics approach". en. In: *PLOS ONE* 16.11 (Nov. 2021). Publisher: Public Library of Science, e0259781. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0259781. URL: https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0259781.

[19] Isabel Jalón-Rojas, Xiao Hua Wang, and Erick Fredj. "A 3D numerical model to Track Marine Plastic Debris (TrackMPD): Sensitivity of microplastic trajectories and fates to particle dynamical properties and physical processes". In: *Marine Pollution Bulletin* 141 (2019), pp. 256–272. ISSN: 0025-326X. DOI: https://doi.org/10.1016/j.marpolbul.2019.02.052. URL: https://www.sciencedirect.com/science/article/pii/S0025326X19301523.

[20] Matthieu George, Frédéric Nallet, and Pascale Fabre. "A threshold model of plastic waste fragmentation: New insights into the distribution of microplastics in the ocean and its evolution over time". In: *Marine Pollution Bulletin* 199 (2024), p. 116012. ISSN: 0025-326X. DOI: https://doi.org/10.1016/j.marpolbul.2023.116012. URL: https://www.sciencedirect.com/science/article/pii/S0025326X23014479.

[21] Nikolaos Simantiris, Markos Avlonitis, and Alexander Theocharis. "Simulation of the transport of marine microplastic particles in the Ionian Archipelago (NE Ionian Sea) using a Lagrangian model and the control mechanisms affecting their transport". In: *Journal of Hazardous Materials* 437 (2022), p. 129349. ISSN: 0304-3894. DOI: https://doi.org/10.1016/j.jhazmat.2022.129349. URL: https://www.sciencedirect.com/science/article/pii/S0304389422011426.

[22] Federica Guerrini, Lorenzo Mari, and Renato Casagrandi. "Microplastic as a vector of chemical contamination in the marine environment: A coupled Lagrangian-Eulerian approach". In: *Global Oceans 2020: Singapore – U.S. Gulf Coast*. ISSN: 0197-7385. Oct. 2020, pp. 1–7. DOI: 10.1109/IEEECONF38699.2020.9389405. URL: https://ieeexplore.ieee.org/document/9389405/.

[23] Alastor M. Coleby and Eric P. M. Grist. “Prioritized area mapping for multiple stakeholders through geospatial modelling: A focus on marine plastics pollution in Hong Kong”. In: *Ocean & Coastal Management* 171 (2019), pp. 131–141. ISSN: 0964-5691. DOI: https://doi.org/10.1016/j.ocecoaman.2018.12.021. URL: https://www.sciencedirect.com/science/article/pii/S096456911830440X.

[24] N.H. Jones et al. “Engaging communities in Sulawesi Island, Indonesia: A collaborative approach to modelling marine plastic debris through open science and online visualization”. In: *Cambridge Prisms: Plastics* 2 (2024). DOI: 10.1017/plc.2024.15.

[25] Kyle B. Mitchell et al. “Modelling marine microplastics accumulation zones through freshwater discharge sources: Simulated release from the Onkaparinga River and Torrens River, South Australia”. In: *Marine Pollution Bulletin* 194 (2023), p. 115334. ISSN: 0025-326X. DOI: https://doi.org/10.1016/j.marpolbul.2023.115334. URL: https://www.sciencedirect.com/science/article/pii/S0025326X23007683.

[26] Federica Guerrini, Lorenzo Mari, and Renato Casagrandi. “The dynamics of microplastics and associated contaminants: Data-driven Lagrangian and Eulerian modelling approaches in the Mediterranean Sea”. English. In: *SCIENCE OF THE TOTAL ENVIRONMENT* 777 (July 2021). Num Pages: 10 Place: Amsterdam Publisher: Elsevier Web of Science ID: WOS:000669366700012, p. 145944. ISSN: 0048-9697, 1879-1026. DOI: 10.1016/j.scitotenv.2021.145944. URL: https://linkinghub.elsevier.com/retrieve/pii/S0048969721010111.

[27] K.G. Preetha et al. “An interactive visualization tool for the exploration and analysis of multivariate ocean data”. In: *Indonesian Journal of Electrical Engineering and Computer Science* 36.2 (2024), pp. 1329–1337. DOI: 10.11591/ijeecs.v36.i2.pp1329-1337.

[28] Shuai Liu et al. “A framework for interactive visual analysis of heterogeneous marine data in an integrated problem solving environment”. In: *Computers & Geosciences* 104 (July 2017), pp. 20–28. ISSN: 0098-3004. DOI: 10.1016/j.cageo.2017.03.021. URL: https://www.sciencedirect.com/science/article/pii/S0098300417303758.

[29] Cui Xie et al. “A survey on visual analysis of ocean data”. In: *Visual Informatics* 3.3 (Sept. 2019), pp. 113–128. ISSN: 2468-502X. DOI: 10.1016/j.visinf.2019.08.001. URL: https://www.sciencedirect.com/science/article/pii/S2468502X19300440.

[30] Chen Guo et al. “Research on Visualization Technology of Ocean Situation Based on OSG”. In: *2022 IEEE International Conference on Electrical Engineering, Big Data and Algorithms (EEBDA)*. Feb. 2022, pp. 1305–1308. DOI: 10.1109/EEBDA53927.2022.9744935. URL: https://ieeexplore.ieee.org/document/9744935/.

[31] Weijie Li et al. “A Spherical Volume-Rendering Method of Ocean Scalar Data Based on Adaptive Ray Casting”. en. In: *ISPRS International Journal of Geo-Information* 12.4 (Apr. 2023). Number: 4 Publisher: Multidisciplinary Digital Publishing Institute, p. 153. ISSN: 2220-9964. DOI: 10.3390/ijgi12040153. URL: https://www.mdpi.com/2220-9964/12/4/153.

[32] Rufu Qin et al. “Web-based 3D visualization framework for time-varying and large-volume oceanic forecasting data using open-source technologies”. In: *Environmental Modelling & Software* 135 (2021), p. 104908. ISSN: 1364-8152. DOI: https://doi.org/10.1016/j.envsoft.2020.104908. URL: https://www.sciencedirect.com/science/article/pii/S1364815220309658.

[33] J. Yu, R. Qin, and Z. Xu. "The Implementation of a WebGPU-Based Volume Rendering Framework for Interactive Visualization of Ocean Scalar Data". In: *Applied Sciences (Switzerland)* 15.5 (2025). DOI: 10.3390/app15052782.

[34] P. F. J. Lermusiaux et al. "Plastic Pollution in the Coastal Oceans: Characterization and Modeling". In: *OCEANS 2019 MTS/IEEE SEATTLE*. ISSN: 0197-7385. Oct. 2019, pp. 1–10. DOI: 10.23919/OCEANS40490.2019.8962786. URL: https://ieeexplore.ieee.org/document/8962786/.

[35] Xu Shenghua et al. "DYNAMIC VISUALIZATION OF SPATIO-TEMPORAL PROCESS MODEL BASED ON NetCDF AND OPTIMAL INTERPOLATION FOR MARINE ENVIRONMENT". en. In: *Environmental Engineering and Management Journal* 19.11 (2020), pp. 1957–1967. ISSN: 1582-9596, 1843-3707. DOI: 10.30638/eemj.2020.185. URL: http://www.eemj.icpm.tuiasi.ro/pdfs/vol19/no11/3_335_Shenghu_19.pdf.

[36] Demetrius Lacet et al. "Multiplatform Ecosystem for Visualizing Ocean Dynamic Formations with Virtual Choreographies: Oil Spill Case". In: *2025 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. Mar. 2025, pp. 438–446. DOI: 10.1109/VRW66409.2025.00097. URL: https://ieeexplore.ieee.org/document/10972696/.

[37] Haowen Xu et al. "An overview of visualization and visual analytics applications in water resources management". In: *Environmental Modelling & Software* 153 (July 2022), p. 105396. ISSN: 1364-8152. DOI: 10.1016/j.envsoft.2022.105396. URL: https://www.sciencedirect.com/science/article/pii/S1364815222001025.

[38] Xu Han et al. "Design and Implementation of Smart Ocean Visualization System Based on Extended Reality Technology". In: *Journal of Web Engineering* 20.2 (Mar. 2021). Conference Name: Journal of Web Engineering, pp. 557–574. ISSN: 1544-5976. DOI: 10.13052/jwe1540-9589.20215. URL: https://ieeexplore.ieee.org/abstract/document/10247324.

[39] Yang Ouyang et al. "OceanVive: An Immersive Visualization System for Communicating Complex Oceanic Phenomena". In: *2025 IEEE Visualization and Visual Analytics (VIS)*. July 2025. DOI: 10.48550/arXiv.2507.17218.

[40] Xueguang Xie et al. "Dynamic ocean inverse modeling based on differentiable rendering". In: *Computational Visual Media* 10.2 (Apr. 2024), pp. 279–294. ISSN: 2096-0662. DOI: 10.1007/s41095-023-0338-4. URL: https://ieeexplore.ieee.org/document/10897648/.

[41] David C. Christie. "Efficient estimation of directional wave buoy spectra using a reformulated Maximum Shannon Entropy Method: Analysis and comparisons for coastal wave datasets". In: *Applied Ocean Research* 142 (2024), p. 103830. ISSN: 0141-1187. DOI: https://doi.org/10.1016/j.apor.2023.103830. URL: https://www.sciencedirect.com/science/article/pii/S0141118723003711.

[42] C. Kehl et al. "Efficiently simulating Lagrangian particles in large-scale ocean flows — Data structures and their impact on geophysical applications". In: *Computers and Geosciences* 175 (2023). DOI: 10.1016/j.cageo.2023.105322.

[43] Jiayue Hui et al. "Numerical Tracking of Floating Marine Plastic in the Sea of Japan Using Time-backward Probabilistic Method". In: *OCEANS 2021: San Diego – Porto*. ISSN: 0197-7385. Sept. 2021, pp. 1–4. DOI: 10.23919/OCEANS44145.2021.9706064. URL: https://ieeexplore.ieee.org/document/9706064/.

[44] Yunfan Kang et al. “Scalable Multi-resolution Spatial Visualization for Anthropogenic Litter Data”. In: *Proceedings of the 27th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems*. SIGSPATIAL ’19. event-place: Chicago, IL, USA. New York, NY, USA: Association for Computing Machinery, 2019, pp. 560–563. ISBN: 978-1-4503-6909-1. DOI: 10.1145/3347146.3359074. URL: https://doi.org/10.1145/3347146.3359074.

[45] Kabir Suara et al. “Material and debris transport patterns in Moreton Bay, Australia: The influence of Lagrangian coherent structures”. In: *Science of The Total Environment* 721 (2020), p. 137715. ISSN: 0048-9697. DOI: https://doi.org/10.1016/j.scitotenv.2020.137715. URL: https://www.sciencedirect.com/science/article/pii/S0048969720312262.

[46] Eloah Rosas et al. “Pathways and Hot Spots of Floating and Submerged Microplastics in Atlantic Iberian Marine Waters: A Modelling Approach”. English. In: *JOURNAL OF MARINE SCIENCE AND ENGINEERING* 10.11 (Nov. 2022). Num Pages: 13 Place: Basel Publisher: MDPI Web of Science ID: WOS:000883910600001, p. 1640. ISSN: 2077-1312. DOI: 10.3390/jmse10111640. URL: https://www.mdpi.com/2077-1312/10/11/1640.

[47] Gerald Schernewski et al. “Emission, Transport, and Deposition of visible Plastics in an Estuary and the Baltic Sea-a Monitoring and Modeling Approach”. English. In: *ENVIRONMENTAL MANAGEMENT* 68.6 (Dec. 2021). Num Pages: 22 Place: New York Publisher: Springer Web of Science ID: WOS:000694792100001, pp. 860–881. ISSN: 0364-152X, 1432-1009. DOI: 10.1007/s00267-021-01534-2. URL: https://link.springer.com/article/10.1007/s00267-021-01534-2.

[48] Vardis M. Tsontos, Flynn Platt, and Joe T. Roberts. “COVERAGE Data Viewer: A Generalized Web-Based Tool for Integrated Visualization of Oceanographic Satellite and In-Situ Data”. In: *OCEANS 2023 - MTS/IEEE U.S. Gulf Coast*. ISSN: 0197-7385. Sept. 2023, pp. 1–8. DOI: 10.23919/OCEANS52994.2023.10337364. URL: https://ieeexplore.ieee.org/document/10337364.

[49] Qingtong Shi et al. “Particle System-Based Multi-Hierarchy Dynamic Visualization of Ocean Current Data”. en. In: *ISPRS International Journal of Geo-Information* 10.10 (Oct. 2021). Number: 10 Publisher: Multidisciplinary Digital Publishing Institute, p. 667. ISSN: 2220-9964. DOI: 10.3390/ijgi10100667. URL: https://www.mdpi.com/2220-9964/10/10/667.

[50] Claire Dufau et al. “Satellite Solutions for Tracking Litter & Plastic Pollution in the Ocean”. In: *OCEANS 2019 - Marseille*. June 2019, pp. 1–5. DOI: 10.1109/OCEANSE.2019.8867370. URL: https://ieeexplore.ieee.org/document/8867370.

[51] Lei Wang. “The Development of Hainan Provincial Digital Ocean Environment Parameters Three-dimensional Visualization System”. en. In: *Procedia Computer Science* 154 (2019), pp. 556–560. ISSN: 18770509. DOI: 10.1016/j.procs.2019.06.088. URL: https://linkinghub.elsevier.com/retrieve/pii/S1877050919308579.

[52] Kai Wang et al. “Maritime Traffic Data Visualization: A Brief Review”. In: *2019 IEEE 4th International Conference on Big Data Analytics (ICBDA)*. Mar. 2019, pp. 67–72. DOI: 10.1109/ICBDA.2019.8713227. URL: https://ieeexplore.ieee.org/document/8713227.

[53] John D. Gould and Clayton Lewis. "Designing for usability: key principles and what designers think". In: *Commun. ACM* 28.3 (Mar. 1985), pp. 300–311. ISSN: 0001-0782. DOI: 10.1145/3166.3170. URL: https://dl.acm.org/doi/10.1145/3166.3170.

[54] *PlasticAdrift Website*. URL: https://plasticadrift.org/.

[55] *Copernicus MyOcean Pro Viewer*. URL: https://data.marine.copernicus.eu/viewer/expert/.

[56] Jennifer Preece, Yvonne Rogers, and Helen Sharp. *Interaction Design: Beyond Human-Computer Interaction*. New York, NY: John Wiley & Sons, Inc., 2002. ISBN: 0-471-49278-7.

[57] *Figma*. URL: https://www.figma.com/.

[58] *Live Server Extension for Visual Studio Code*. URL: https://github.com/ritwickdey/vscode-live-server.

[59] *Visual Studio Code*. URL: https://code.visualstudio.com/.

[60] *Leaflet*. URL: https://leafletjs.com/.

[61] *PlasticParcels*. URL: https://plastic.parcels-code.org/en/latest/.

[62] *OpenDrift*. URL: https://opendrift.github.io/.

[63] Michael C. Denes and Erik van Sebille. "plasticparcels: A python package for marine plastic dispersal simulations and parameterisation development using parcels". en. In: *Journal of Open Source Software* 9.102 (Oct. 2024), p. 7094. ISSN: 2475-9066. DOI: 10.21105/joss.07094. URL: https://joss.theoj.org/papers/10.21105/joss.07094.

[64] *Copernicus Marine Service*. URL: https://marine.copernicus.eu/.

[65] *CMEMS GLO PUM 001-030 Documentation*. URL: https://documentation.marine.copernicus.eu/PUM/CMEMS-GLO-PUM-001-030.pdf.

[66] *CMEMS GLO PUM 001-029 Documentation*. URL: https://documentation.marine.copernicus.eu/PUM/CMEMS-GLO-PUM-001-029.pdf.

[67] *ERA5: Data Documentation*. URL: https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation.

[68] *European Centre for Medium-Range Weather Forecasts (ECMWF) Data*. URL: https://cds.climate.copernicus.eu/.

[69] Jenna R. Jambeck et al. "Plastic waste inputs from land into the ocean". In: *Science* 347.6223 (Feb. 2015). Publisher: American Association for the Advancement of Science, pp. 768–771. DOI: 10.1126/science.1260352. URL: https://www.science.org/doi/10.1126/science.1260352.

[70] Lourens J.J. Meijer et al. "More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean". In: *Science Advances* 7.18 (2021), pp. 1–13. ISSN: 2375-2548. DOI: 10.1126/sciadv.aaz5803. URL: https://www.science.org/doi/10.1126/sciadv.aaz5803.

[71] David A. Kroodsma et al. "Tracking the global footprint of fisheries". In: *Science* 359.6378 (2018), pp. 904–908. DOI: 10.1126/science.aao5646. URL: https://www.science.org/doi/10.1126/science.aao5646.

[72] Mikael L. A. Kaandorp et al. "Global mass of buoyant marine plastics dominated by large long-lived debris". en. In: *Nat. Geosci.* 16.8 (Aug. 2023). Publisher: Nature Publishing Group, pp. 689–694. ISSN: 1752-0908. DOI: 10.1038/s41561-023-01216-0. URL: https://www.nature.com/articles/s41561-023-01216-0.

[73] *PlasticParcels Release Maps Script*. URL: https://github.com/Parcels-code/plasticparcels/blob/main/plasticparcels/scripts/create_release_maps.py.

[74] *PlasticParcels Example Initialisation Maps*. URL: https://plastic.parcels-code.org/en/latest/examples/example_initialisation_maps.html.

[75] *GlobeGL*. URL: https://globe.gl/.

[76] Fabio Crameri, Grace E. Shephard, and Philip J. Heron. "The misuse of colour in science communication". en. In: *Nat Commun* 11.1 (Oct. 2020). Publisher: Nature Publishing Group, p. 5444. ISSN: 2041-1723. DOI: 10.1038/s41467-020-19160-7. URL: https://www.nature.com/articles/s41467-020-19160-7.

[77] *Batlow Colour Maps*. URL: https://www.fabiocrameri.ch/batlow/.

[78] Jeffrey Rubin. *Handbook of usability testing: how to plan, design, and conduct effective tests*. Indianapolis, Ind: Wiley Pub, 2008. ISBN: 978-0-470-18548-3.

[79] John Brooke. "SUS: A Quick and Dirty Usability Scale". In: *Usability Evaluation in Industry*. Ed. by Patrick W. Jordan et al. London: Taylor & Francis, Jan. 1996, pp. 189–194.

[80] Antonio Piedra et al. "Evaluation of Usability, User Experience and Accessibility of Applications: a Tertiary Review". In: *2024 IEEE VII Congreso Internacional en Inteligencia Ambiental, Ingeniería de Software y Salud Electrónica y Móvil (AmITIC)*. Sept. 2024, pp. 1–8. DOI: 10.1109/AmITIC62658.2024.10747604. URL: https://ieeexplore.ieee.org/document/10747604.

[81] Anne-Flore Cabouat et al. "PREVis: Perceived Readability Evaluation for Visualizations". In: *IEEE Transactions on Visualization and Computer Graphics* 31.1 (Jan. 2025), pp. 1083–1093. ISSN: 1941-0506. DOI: 10.1109/TVCG.2024.3456318. URL: https://ieeexplore.ieee.org/abstract/document/10681245.

[82] *Tasks Script*. URL: https://gitlab.up.pt/up201806629/feup_thesis/-/blob/main/src/data/tasks.py.

[83] *Google Form*. URL: https://docs.google.com/forms/.

[84] *Mouse Tracker Script*. URL: https://gitlab.up.pt/up201806629/feup_thesis/-/blob/main/src/js/mouseTracker.js.

[85] *Mouse Tracker Statistics Script*. URL: https://gitlab.up.pt/up201806629/feup_thesis/-/tree/main/docs/mouseTracker/statistics.py.

[86] Admin. "Determining What Individual SUS Scores Mean: Adding an Adjective Rating Scale - JUX". en. In: *JUX - The Journal of User Experience* (May 2009). URL: https://uxpajournal.org/determining-what-individual-sus-scores-mean-adding-an-adjective-rating-scale/.

Appendix A

Quality Assessment - Problem

Reference	Title	Problem
[12]	Modelled and observed plastic pollution on remote Scottish beaches: The importance of local marine sources	Accumulation of plastic waste in the ocean and along coasts, lack of understanding of its abundance/distribution and the need to identify areas of high/low concentration (hotspots/-coldspots)
[13]	A review of methods for modelling microplastic transport in the marine environments	Modelling microplastic transport and destination lacks systematic evaluation of modelling methods
[14]	Modelling global river export of microplastics to the marine environment: Sources and future trends	Modelling origin and destination of marine debris, especially plastic pollution
[15]	Modeling the Exposure of the Macaronesia Islands (NE Atlantic) to Marine Plastic Pollution	Increase in marine plastic pollution (no control and uncertain sources)
[16]	Disentangling the physical dispersion of floating debris and plastics in the Indonesian Seas	Pathways and connectivity of floating plastic debris flow as well as analysis of the influence of wind and tides on its dispersion and accumulation
[17]	Oceanic realistic application of a microplastic biofouling model to the river discharge case	Understand the dynamic impact of algal concentration and the seasonal variability of biofouling on the transport of microplastics

Continued on next page

Reference	Title	Problem
[18]	A model for the size distribution of marine microplastics: A statistical mechanics approach	Size distribution of microplastics on the sea surface shows gradual increase followed by a rapid decrease for the smallest fragments, which existing fragmentation models do not fully explain
[19]	A 3D numerical model to Track Marine Plastic Debris (TrackMPD): Sensitivity of microplastic trajectories and fates to particle dynamical properties and physical processes	Modelling the 3D transport and destination of marine microplastics
[20]	A threshold model of plastic waste fragmentation: New insights into the distribution of microplastics in the ocean and its evolution over time	Fragmentation pattern of marine plastic debris and predict its size distribution over time
[21]	Simulation of the transport of marine microplastic particles in the Ionian Archipelago (NE Ionian Sea) using a Lagrangian model and the control mechanisms affecting their transport	Microplastic dispersion to identify the forces controlling their movement
[22]	Microplastic as a vector of chemical contamination in the marine environment: A coupled Lagrangian-Eulerian approach	Microplastics act as vectors for primary pollutants and the need to improve understanding of basin-scale effects and mass transfer to deeper layers
[23]	Prioritized area mapping for multiple stakeholders through geospatial modelling: A focus on marine plastics pollution in Hong Kong	Uncertainties in the sources, transport and deposition of plastic pollution around Hong Kong need to be mapped and communicated to stakeholders
[24]	Engaging communities in Sulawesi Island, Indonesia: A collaborative approach to modelling marine plastic debris through open science and online visualization	Plastic marine debris in Indonesia influenced by poor local waste management, non-domestic sources and seasonal ocean circulation patterns

Continued on next page

Reference	Title	Problem
[25]	Modelling marine microplastics accumulation zones through freshwater discharge sources: Simulated release from the Onkaparinga River and Torrens River, South Australia	Mapping sources, transport and deposition of plastic pollution
[26]	The dynamics of microplastics and associated contaminants: Data-driven Lagrangian and Eulerian modelling approaches in the Mediterranean Sea	Integration of microplastic particle tracking with PROP (Persistent Organic Pollutants) advection-diffusion in numerical simulations
[27]	An interactive visualization tool for the exploration and analysis of multivariate ocean data	Capture of interactions between multiple parameters in the visualisation of ocean data
[28]	A framework for interactive visual analysis of heterogeneous marine data in an integrated problem solving environment	There is a need for effective visualisation to understand ocean processes and for a global virtual terrain environment
[29]	A survey on visual analysis of ocean data	Ocean data's complexity and dynamics complicate automated analysis and visualisation
[30]	Research on Visualization Technology of Ocean Situation Based on OSG	Limitations on the spatial analysis and GIS processing capabilities for ocean data
[31]	A Spherical Volume-Rendering Method of Ocean Scalar Data Based on Adaptive Ray Casting	Lack of effective fusion with seafloor terrain and local feature extraction
[32]	Web-based 3D visualization framework for time-varying and large-volume oceanic forecasting data using open-source technologies	Ocean simulation results are time-varying, multivariable, multidimensional and large in volume, posing critical challenges for effective understanding and use by oceanographers and stakeholders
[33]	The Implementation of a WebGPU-Based Volume Rendering Framework for Interactive Visualization of Ocean Scalar Data	Traditional methods for visualising ocean scalar fields in 3D digital environments are imprecise and inefficient

Continued on next page

Reference	Title	Problem
[34]	Plastic Pollution in the Coastal Oceans: Characterization and Modeling	Characterise and model the transport of plastics (macro and micro) in coastal oceans
[35]	Dynamic Visualization of Spatio-Temporal Process Model Based on NetCDF and Optimal Interpolation for Marine Environment	Dynamic visualisation and analysing complex three-dimensional spatiotemporal processes in the marine environment
[36]	Multiplatform Ecosystem for Visualizing Ocean Dynamic Formations with Virtual Choreographies: Oil Spill Case	Visualisation of complex phenomena in a way that separates spatiotemporal patterns from rendering multi-platform visualisation
[37]	An overview of visualization and visual analytics applications in water resources management	Water science still faces challenges in exploratory analysis, support for complex decision-making and the systematic adoption of advanced visual computing techniques
[38]	Design and Implementation of Smart Ocean Visualization System Based on Extended Reality Technology	Lack of solutions to integrate/manage ocean information and insufficient development of systems/apps especially for marine data visualisation and tourism
[39]	OceanVive: An Immersive Visualization System for Communicating Complex Oceanic Phenomena	Communicating the complexity of oceanic phenomena to users with varying expertise
[40]	Dynamic ocean inverse modeling based on differentiable rendering	Dynamic reconstruction of the ocean
[41]	Efficient estimation of directional wave buoy spectra using a reformulated Maximum Shannon Entropy Method: Analysis and comparisons for coastal wave datasets	Wave spectrum measurements
[42]	Efficiently simulating Lagrangian particles in large-scale ocean flows — Data structures and their impact on geophysical applications	Improve performance of Lagrangian simulations and identify performance bottlenecks in the Parcels framework by exploring parallelism
[43]	Numerical Tracking of Floating Marine Plastic in the Sea of Japan Using Time-backward Probabilistic Method	Location and timing of the origin of floating marine plastic in the Sea of Japan based on observations

Continued on next page

Reference	Title	Problem
[44]	Scalable Multi-resolution Spatial Visualization for Anthropogenic Litter Data	Existing software does not scale to process, query and visualise large volumes of anthropogenic debris data and there is a need for interactive visualisation for scientists and environmental organisations
[45]	Material and debris transport patterns in Moreton Bay, Australia: The influence of Lagrangian coherent structures	Limited scalability of existing software to visualise large volumes of waste data and the challenges posed by marine data of multiple origins, formats and dimensions
[46]	Pathways and Hot Spots of Floating and Submerged Microplastics in Atlantic Iberian Marine Waters: A Modelling Approach	Limited understanding of the transport pathways and accumulation zones of microplastics in the ocean around the Iberian Peninsula
[47]	Emission, Transport, and Deposition of visible Plastics in an Estuary and the Baltic Sea-a Monitoring and Modeling Approach	Limited understanding of the emissions, transport, deposition and retention of visible plastics
[48]	COVERAGE Data Viewer: A Generalized Web-Based Tool for Integrated Visualization of Oceanographic Satellite and In-Situ Data	Increase in oceanographic observations requires better tools for data integration and synthesis, but the diversity of data types makes it difficult to develop a unified, interactive and user-friendly web visualisation tool
[49]	Particle System-Based Multi-Hierarchy Dynamic Visualization of Ocean Current Data	Existing methods for visualising ocean currents in 3D environments face issues (seed point distribution, abrupt density changes when scaling and cluttered or confusing visualisation)
[50]	Satellite Solutions for Tracking Litter & Plastic Pollution in the Ocean	Ocean plastic pollution

Continued on next page

Reference	Title	Problem
[51]	The Development of Hainan Provincial Digital Ocean Environment Parameters Three-dimensional Visualization System	Scarce number of studies focused on digital ocean environments at the provincial or municipal level and effective 3D integration and visualisation of marine environmental parameters based on basic geographic data and remote sensing images at this scale are needed
[52]	Maritime Traffic Data Visualization: A Brief Review	Massive traffic data

Table A.1: Problem per Article.

Appendix B

Quality Assessment - Approach

Reference	Title	Approach
[12]	Modelled and observed plastic pollution on remote Scottish beaches: The importance of local marine sources	Validate an existing particle tracking model with beach cleanup data to understand litter sources and identify hotspots/coldspots on the west coast of Scotland
[13]	A review of methods for modeling microplastic transport in the marine environments	Comprehensive review of numerical modelling methods for microplastics transportation, influencing factors and parameterisation schemes
[14]	Modelling global river export of microplastics to the marine environment: Sources and future trends	Lagrangian Coherent Structures (LCS) technique to understand the fate of floating material and employ geostatistical interpolation to map plastic pollution distribution and uncertainty, creating Priority Area Maps (PAM)
[15]	Modeling the Exposure of the Macaronesia Islands (NE Atlantic) to Marine Plastic Pollution	Characterisation of potential sources and trajectories of plastic particles reaching the Macaronesia archipelagos, combining modelled datasets of ocean currents, winds and waves with a Lagrangian tool to track virtual particles

Continued on next page

Reference	Title	Approach
[16]	Disentangling the physical dispersion of floating debris and plastics in the Indonesian Seas	Impact of wind and tides on the dispersion and beaching of surface-floating particles using a Lagrangian framework, simulating dispersion using ocean and particle tracking models (HYCOM and Parcels) during monsoons
[17]	Oceanic realistic application of a microplastic biofouling model to the river discharge case	Implement a one-dimensional biofouling model within a three-dimensional regional microplastic tracking setup to evaluate seasonal variability and impact
[18]	A model for the size distribution of marine microplastics: A statistical mechanics approach	New model for the distribution of marine microplastic sizes, inspired by statistical mechanics ideas, focused on fragmentation and assuming that greater energy is required to produce smaller pieces
[19]	A 3D numerical model to Track Marine Plastic Debris (TrackMPD): Sensitivity of microplastic trajectories and fates to particle dynamical properties and physical processes	New 3D Lagrangian tracking modelling framework (TrackMPD) that incorporates physical processes and particle properties, with sensitivity analysis
[20]	A threshold model of plastic waste fragmentation: New insights into the distribution of microplastics in the ocean and its evolution over time	"sugar lump" model based on physical principles to simulate plastic fragmentation, comparing the results with standard models and field data
[21]	Simulation of the transport of marine microplastic particles in the Ionian Archipelago (NE Ionian Sea) using a Lagrangian model and the control mechanisms affecting their transport	Investigate microplastic dispersion in the Ionian Archipelago using a common estuarine approach (comparing transport to sea and eddy diffusivity) and a Lagrangian particle tracking model (TrackMPD)

Continued on next page

Reference	Title	Approach
[22]	Microplastic as a vector of chemical contamination in the marine environment: A coupled Lagrangian-Eulerian approach	Coupled Lagrangian-Eulerian modelling approach to simulate microplastic and associated chemical pollutant dynamics, formalising the problem into sub-problems of transport, advection-diffusion and pollutant exchange
[23]	Prioritized area mapping for multiple stakeholders through geospatial modelling: A focus on marine plastics pollution in Hong Kong	Geostatistical interpolation to create maps characterising the spatial distribution of plastic pollution, port traffic intensity and ecological insecurity, along with associated uncertainty maps and combine them into Priority Area Maps (PAM)
[24]	Engaging communities in Sulawesi Island, Indonesia: A collaborative approach to modelling marine plastic debris through open science and online visualization	Model and visualise the dispersion of marine plastic debris using a community-focused approach
[25]	Modelling marine microplastics accumulation zones through freshwater discharge sources: Simulated release from the Onkaparinga River and Torrens River, South Australia	Geospatial approach using geostatistical interpolation to characterise marine plastic pollution and associated uncertainties, generating maps, identifying priority areas
[26]	The dynamics of microplastics and associated contaminants: Data-driven Lagrangian and Eulerian modelling approaches in the Mediterranean Sea	Use coupled Lagrangian-Eulerian modelling approaches to describe microplastic and pollutant dynamics, comparing them with simpler Eulerian models
[27]	An interactive visualization tool for the exploration and analysis of multivariate ocean data	Visual overlays of multivariate ocean data and develop an interactive, adaptive, multi-scale and multivariate visualisation system
[28]	A framework for interactive visual analysis of heterogeneous marine data in an integrated problem solving environment	Integrated marine visualisation framework to process, analyse and visualise multi-dimensional marine data

Continued on next page

Reference	Title	Approach
[29]	A survey on visual analysis of ocean data	Overview and survey of interactive visual analysis techniques
[30]	Research on Visualization Technology of Ocean Situation Based on OSG	Ocean situation visualisation based on OSG, proposing a new multi-hierarchical dynamic flow field visualisation method based on a particle system
[31]	A Spherical Volume-Rendering Method of Ocean Scalar Data Based on Adaptive Ray Casting	The study proposes a spherical volume rendering method based on adaptive ray casting to enhance scalar field visualisation and extract local features in a 3D Earth digital environment
[32]	Web-based 3D visualization framework for time-varying and large-volume oceanic forecasting data using open-source technologies	Effective and efficient visualisation structure for the use of ocean forecasting services
[33]	The Implementation of a WebGPU-Based Volume Rendering Framework for Interactive Visualization of Ocean Scalar Data	Visualisation framework for large-scale 3D scalar ocean data on regular and irregular grids. Spherical volume rendering method based on adaptive ray casting to enhance 3D visualisation and extract local structural features in a spherical environment
[34]	Plastic Pollution in the Coastal Oceans: Characterization and Modeling	New partial differential equations (PDE) methodology to characterise and model plastic transport in 4D, coupling an ocean dynamics solver with an advection solver
[35]	Dynamic Visualization of Spatio-Temporal Process Model Based on NetCDF and Optimal Interpolation for Marine Environment	Dynamic construction and visualisation of a marine spatiotemporal process model based on the Network Common Data Form (NetCDF) and optimal interpolation

Continued on next page

Reference	Title	Approach
[36]	Multiplatform Ecosystem for Visualizing Ocean Dynamic Formations with Virtual Choreographies: Oil Spill Case	Virtual choreographies to structure and store spatiotemporal patterns of oil spills, allowing exploration on multiple platforms through a visualisation ecosystem
[37]	An overview of visualization and visual analytics applications in water resources management	Comprehensive review of recent applications of visual computing (visualisation and visual analytics) in water resource management
[38]	Design and Implementation of Smart Ocean Visualization System Based on Extended Reality Technology	Intelligent ocean visualisation application based on extended reality (XR) technology to collect, manage and visualise data and provide virtual tourism services
[39]	OceanVive: An Immersive Visualization System for Communicating Complex Oceanic Phenomena	Immersive and interactive visualisation combining shared displays and personal devices
[40]	Dynamic ocean inverse modeling based on differentiable rendering	Dynamic inverse ocean modeling based on differentiable rendering
[41]	Efficient estimation of directional wave buoy spectra using a reformulated Maximum Shannon Entropy Method: Analysis and comparisons for coastal wave datasets	Estimate directional wave spectra from wave buoys using a reformulated Shannon Maximum Entropy Method (MEM-II), comparing it with alternatives for real data
[42]	Efficiently simulating Lagrangian particles in large-scale ocean flows — Data structures and their impact on geophysical applications	Discuss implications and performance improvements in the Python Parcels framework by deriving detailed performance metrics and comparing data structures
[43]	Numerical Tracking of Floating Marine Plastic in the Sea of Japan Using Time-backward Probabilistic Method	Numerical backtracking using a probabilistic method
[44]	Scalable Multi-resolution Spatial Visualization for Anthropogenic Litter Data	CleanUpOurWorld - spatial research database and visualisation system to collect, process, query and visualise human litter data

Continued on next page

Reference	Title	Approach
[45]	Material and debris transport patterns in Moreton Bay, Australia: The influence of Lagrangian coherent structures	Lagrangian Coherent Structures (LCS) to understand the fate of debris, develop a scalable spatial database (CleanUpOurWorld) for litter data and create integrated web visualisation frameworks for complex marine data
[46]	Pathways and Hot Spots of Floating and Submerged Microplastics in Atlantic Iberian Marine Waters: A Modelling Approach	Numerical modelling approach, combining a global ocean reanalysis model with a Lagrangian particle tracking model to investigate the pathways and accumulation patterns of floating and submerged microplastics originating from southwestern Iberia
[47]	Emission, Transport, and Deposition of visible Plastics in an Estuary and the Baltic Sea-a Monitoring and Modeling Approach	Linking existing knowledge, field monitoring and numerical modelling to analyse emissions, transport and deposition of visible plastics in the Warnow Estuary and the Baltic Sea
[48]	COVERAGE Data Viewer: A Generalized Web-Based Tool for Integrated Visualization of Oceanographic Satellite and In-Situ Data	Develop the COVERAGE Data Viewer (browser-based visualisation application and associated backend service)
[49]	Particle System-Based Multi-Hierarchy Dynamic Visualization of Ocean Current Data	New approach for multi-hierarchical dynamic flow field visualisation based on a particle system
[50]	Satellite Solutions for Tracking Litter & Plastic Pollution in the Ocean	solution by integrating satellite tracking (ARGOS and GPS) with a drift modelling service based on surface currents derived from Earth Observation satellites, complemented by the deployment of in-situ tracked buoys
[51]	The Development of Hainan Provincial Digital Ocean Environment Parameters Three-dimensional Visualization System	3D visualisation system of the ocean environment at a provincial level based on a digital Earth sphere model

Continued on next page

Reference	Title	Approach
[52]	Maritime Traffic Data Visualization: A Brief Review	Review of maritime traffic data visualisation techniques, focusing on spatiotemporal trajectories and vessel traffic density

Table B.1: Approach per Article.

Appendix C

Quality Assessment - Method/Experimentation

Reference	Title	Method/Experimentation
[12]	Modelled and observed plastic pollution on remote Scottish beaches: The importance of local marine sources	Field collection of visible macroplastic litter on beaches, analysing load (by count and weight) and composition in urban and remote sites and used data analysis in R
[13]	A review of methods for modeling microplastic transport in the marine environments	Literature review using scientific databases to classify modelling approaches, summarise parameterisation schemes for micorplastic behaviour and review influencing factors
[14]	Modelling global river export of microplastics to the marine environment: Sources and future trends	LCS technique using finite-time Lyapunov exponent (FTLE) in Moreton Bay and used geostatistical interpolation to create regional characterisation and uncertainty maps for plastic debris, shipping intensity and ecological insecurity in Hong Kong, defining PAMs

Continued on next page

Reference	Title	Method/Experimentation
[15]	Modeling the Exposure of the Macaronesia Islands (NE Atlantic) to Marine Plastic Pollution	OceanParcels Lagrangian framework to simulate virtual particle transport over 10 years, driven by ocean current, wind and Stokes drift reanalysis, complemented by observed drifter trajectories and connectivity evaluation to marine and land-based litter sources
[16]	Disentangling the physical dispersion of floating debris and plastics in the Indonesian Seas	Lagrangian framework to analyze wind and tidal impact. Simulated plastic dispersion for 3 months during monsoon seasons using HYCOM and Parcels models, analyzing spatial and temporal particle distribution
[17]	Oceanic realistic application of a microplastic biofouling model to the river discharge case	Integrating 1D biofouling model into a realistic 3D regional setup of a semi-enclosed basin, releasing virtual particles at a river mouth. Assessed the impact of algae concentration on horizontal/vertical behavior and seasonal variability of biofilm thickness for different polymers
[18]	A model for the size distribution of marine microplastics: A statistical mechanics approach	Models fragmentation of an idealized plastic sheet assuming break energy is proportional to the new surface area created and follows an exponential probability distribution, deriving a size spectrum formula that is then fitted to observational data
[19]	A 3D numerical model to Track Marine Plastic Debris (TrackMPD): Sensitivity of microplastic trajectories and fates to particle dynamical properties and physical processes	TrackMPD model simulates advection, dispersion, windage, sinking, settling, beaching and washing-off in 3D for MPD with variable dynamic properties, applying sensitivity analysis across 44 scenarios

Continued on next page

Reference	Title	Method/Experimentation
[20]	A threshold model of plastic waste fragmentation: New insights into the distribution of microplastics in the ocean and its evolution over time	Iterative model ("sugar cube model") based on a critical size below which fragmentation is inhibited, focusing on film-type objects and compared it with a standard model and observed field data
[21]	Simulation of the transport of marine microplastic particles in the Ionian Archipelago (NE Ionian Sea) using a Lagrangian model and the control mechanisms affecting their transport	TrackMPD model, adapted to the study area, to simulate particle behavior from different release sites and examined dispersion by comparing seaward transport and eddy diffusivity
[22]	Microplastic as a vector of chemical contamination in the marine environment: A coupled Lagrangian-Eulerian approach	Lagrangian simulation of microplastic transportation, Eulerian modelling of pollutant advection-diffusion and simultaneous simulation of pollutant exchange at the particle–seawater interface, over 2 years in the Mediterranean, compared with an Eulerian-only simulation
[23]	Prioritized area mapping for multiple stakeholders through geospatial modelling: A focus on marine plastics pollution in Hong Kong	Geostatistical interpolation to generate regional characterization maps and uncertainty maps for hypothetical plastics, ports, ecological based on collected spatial data
[24]	Engaging communities in Sulawesi Island, Indonesia: A collaborative approach to modelling marine plastic debris through open science and online visualization	Oceanographic (HYCOM) and particle-tracking models (Parcels) to simulate seasonal plastic debris dispersion from river sources. Interactive web application for visualization and outreach activities (beach cleanup, plogging)
[25]	Modelling marine microplastics accumulation zones through freshwater discharge sources: Simulated release from the Onkaparinga River and Torrens River, South Australia	Geostatistical interpolation to create regional characterization and uncertainty maps for plastic waste, port traffic intensity and ecological insecurity

Continued on next page

Reference	Title	Method/Experimentation
[26]	The dynamics of microplastics and associated contaminants: Data-driven Lagrangian and Eulerian modelling approaches in the Mediterranean Sea	Lagrangian tracking for floating microplastics (2D surface) with data-informed inputs and removal mechanisms (beaching, sinking) and used an Eulerian model for advection-diffusion of surface PROPs. Simulation for 2 years in the Mediterranean
[27]	An interactive visualization tool for the exploration and analysis of multivariate ocean data	Layered framework architecture (data, management, rendering, visualization) with data preprocessing, format conversion, cleaning, filtering, integration and interpolation. Uses multivariate analysis, 3D rendering
[28]	A framework for interactive visual analysis of heterogeneous marine data in an integrated problem solving environment	Method for processing and integrating heterogeneous data. Explores GPU-based visualization methods, including global terrain rendering with ETOPO1 and modified ray-casting for irregular Argo data. Implements the framework with a render engine, interface and visual analysis modules
[29]	A survey on visual analysis of ocean data	Reviews existing studies focusing on interactive visualization techniques and tools, categorizing them into four aspects: visualization of environmental elements/multivariate analysis, phenomenon identification/tracking, pattern/correlation discovery and exploration of datasets/uncertainties. It discusses related techniques for data preprocessing and manipulation

Continued on next page

Reference	Title	Method/Experimentation
[30]	Research on Visualization Technology of Ocean Situation Based on OSG	Particle system for dynamic multi-hierarchy ocean current visualization. Comparison of spherical uniform sampling algorithms for starting points . Adaptive visible density adjustment algorithm and dynamic pattern . Achieves a GPU-based parallel prototype with viewport coherence
[31]	A Spherical Volume-Rendering Method of Ocean Scalar Data Based on Adaptive Ray Casting	Optimizing spherical proxy geometry for terrain fusion, developing adaptive step sampling algorithm for efficiency and using nonlinear color mapping and transparency transfer functions for enhanced visualization and feature extraction, all evaluated experimentally
[32]	Web-based 3D visualization framework for time-varying and large-volume oceanic forecasting data using open-source technologies	No specific method or experimentation - focus on the need for visualization frameworks and graphic representations
[33]	The Implementation of a WebGPU-Based Volume Rendering Framework for Interactive Visualization of Ocean Scalar Data	WebGPU-based volume rendering method. Builds minimal bounding volume as proxy geometry, applies depth texture for terrain fusion, proposes adaptive step-sampling algorithm based on depth distribution/data change rate to improve efficiency and applies nonlinear color mapping/transparency transfer functions based on dataset asymmetry for enhancement and feature extraction. Tests frame rate with different datasets and sampling density factors and compares adaptive vs. equidistant sampling algorithms

Continued on next page

Reference	Title	Method/Experimentation
[34]	Plastic Pollution in the Coastal Oceans: Characterization and Modeling	PDE methodology for 4D plastic transportation. Solvers for ocean dynamics and Lagrangian transportation. Plastic destination from 4 sources. Transportation and accumulation patterns, comparing results with/without settling. Global estimates and identifies attractive LCSs
[35]	Dynamic Visualization of Spatio-Temporal Process Model Based on NetCDF and Optimal Interpolation for Marine Environment	Optimal interpolation to multidimensional NetCDF-stored data to eliminate temporal gaps, enabling dynamic 3D visual expression and analysis of marine environmental data
[36]	Multiplatform Ecosystem for Visualizing Ocean Dynamic Formations with Virtual Choreographies: Oil Spill Case	Virtual choreographies convert satellite data into sequential narratives. Two platforms to execute the same choreography using a particle-based approach and textured filling for visualization
[37]	An overview of visualization and visual analytics applications in water resources management	Revised method with visualization and visual analysis techniques, including different chart types, advanced visual representations (like TimeEdgeTrees and flow graphs), data transformation/representation techniques (statistical, ML, dimensionality reduction), user interaction techniques and visual analysis workflows for tasks like data discovery/management, model interpretation and exploratory analysis
[38]	Design and Implementation of Smart Ocean Visualization System Based on Extended Reality Technology	Python crawler technology to collect oceanic big data, building the system on the Unity platform (using C# programming) and AR Foundation for AR animation, providing real-time data query and virtual tourism services via mobile/computer terminals

Continued on next page

Reference	Title	Method/Experimentation
[39]	OceanVive: An Immersive Visualization System for Communicating Complex Oceanic Phenomena	Observational study with 5 oceanographers (semi-structured interviews, in-depth discussions) to gather 5 design requirements. After the development of OceanVive expert evaluation
[40]	Dynamic ocean inverse modeling based on differentiable rendering	Dynamic ocean inverse modeling framework to adjust lighting parameters from images or wave parameters from geometry sequences
[41]	Efficient estimation of directional wave buoy spectra using a reformulated Maximum Shannon Entropy Method: Analysis and comparisons for coastal wave datasets	Reformulated iterative scheme for MEM-II. Calculation of directional spectra from directional moments measured by buoys. Comparison results with cos2s and MEM-I methods using data from six UK coastal buoys over a year. Analyze spectral width and influence of higher-order moments
[42]	Efficiently simulating Lagrangian particles in large-scale ocean flows — Data structures and their impact on geophysical applications	Parcels framework, discussing memory/time performance profiles and general performance characteristics. Comparison of performance of different data structures in a Galapagos scenario with detailed metrics
[43]	Numerical Tracking of Floating Marine Plastic in the Sea of Japan Using Time-backward Probabilistic Method	Backward-in-time probabilistic method to estimate a release hotspot. Temporal change of a value (SDN01) and compared estimated vs observed concentrations at the estimated location, repeating calculations after removing outliers
[44]	Scalable Multi-resolution Spatial Visualization for Anthropogenic Litter Data	CleanUpOurWorld collects diverse datasets, converts them into a common format, cleans, integrates and stores them in a spatial relational database using data aggregation techniques for multi-resolution visualization with interactive navigation and filtering

Continued on next page

Reference	Title	Method/Experimentation
[45]	Material and debris transport patterns in Moreton Bay, Australia: The influence of Lagrangian coherent structures	Applied LCS to Moreton Bay. CleanUpOurWorld collects/processes litter data into a scalable spatial database for multi-resolution visualization (continent to street). Integrated frameworks use GPU methods and modified ray-casting, web applications use WebGL technologies for 3D static/dynamic visualization of ocean forecast data
[46]	Pathways and Hot Spots of Floating and Submerged Microplastics in Atlantic Iberian Marine Waters: A Modelling Approach	Lagrangian OpenDrift framework, forced by GLORYS12V1 ocean reanalysis data, to simulate virtual particle transport at three depths over 11 years, analyzing residence time and domain boundary crossing
[47]	Emission, Transport, and Deposition of visible Plastics in an Estuary and the Baltic Sea-a Monitoring and Modeling Approach	Combination of urban emission calculations, plastic monitoring in river/estuary water, sediments and shorelines (using nets, visual screening and flood accumulation zone method) and 3D modeling simulations of transport and deposition in the Baltic Sea
[48]	COVERAGE Data Viewer: A Generalized Web-Based Tool for Integrated Visualization of Oceanographic Satellite and In-Situ Data	The Viewer offers interactive selection/queries, integrated search, support for high data volume/standard protocols, sub-setting/download, integration of analysis tools and uses a backend architecture using web services (images, data), databases (Postgres/GIS), GeoServer, SOLR and subsetting/decimator services

Continued on next page

Reference	Title	Method/Experimentation
[49]	Particle System-Based Multi-Hierarchy Dynamic Visualization of Ocean Current Data	Experimental method preparing current data, camera control to adaptively adjust particle density in the viewport and dynamic rendering that involves uniform placement of spherical "seeds" (using the Marsaglia method for efficiency). Design of dynamic symbols to represent flow and iterative particle tracking using numerical integration like Runge-Kutta 4
[50]	Satellite Solutions for Tracking Litter & Plastic Pollution in the Ocean	Transmitter devices that resemble marine debris, tracked via ARGOS and GPS and using the Mobidrift drift model, driven by environmental data including surface currents from CMEMS, to simulate marine debris pathways and identify hotspots
[51]	The Development of Hainan Provincial Digital Ocean Environment Parameters Three-dimensional Visualization System	System using key technologies for visualizing multidimensional marine environmental parameters, integrating high-precision DEM and satellite images to achieve 3D integration and visualization on a digital Earth sphere model for the South China Sea
[52]	Maritime Traffic Data Visualization: A Brief Review	Reviews literature, describes general big data visualization pipeline, including collection (Radar, AIS, video), quality enhancement (interpolation), trajectory simplification (Douglas-Peucker). Reviews density visualization methods (KDE-based, multivariate maps), fishing data visualization and ship safety domain (SSD)

Table C.1: Method/Experimentation per Article.

Appendix D

Quality Assessment - Dataset

Reference	Title	Dataset
[12]	Modelled and observed plastic pollution on remote Scottish beaches: The importance of local marine sources	Dataset collected from 49 sites on the west coast of Scotland
[13]	A review of methods for modeling microplastic transport in the marine environments	182 articles, using 29 model applications
[14]	Modelling global river export of microplastics to the marine environment: Sources and future trends	Validated hydrodynamic model for Moreton Bay and spatial datasets on plastic waste, maritime traffic intensity and marine protected areas in Hong Kong
[15]	Modeling the Exposure of the Macaronesia Islands (NE Atlantic) to Marine Plastic Pollution	Reanalyses from CMEMS (GLORYS12V1 and GLORYS2V4), wind data from ECMWF ERA-Interim, Stokes drift data from WW3, Global Drifter Program trajectories, Global Fishing Watch effort data and Gridded Population of the World population density data
[16]	Disentangling the physical dispersion of floating debris and plastics in the Indonesian Seas	Surface ocean current field data, virtual particle initial positions, wind and tidal data
[17]	Oceanic realistic application of a microplastic biofouling model to the river discharge case	Virtual particles

Continued on next page

Reference	Title	Dataset
[18]	A model for the size distribution of marine microplastics: A statistical mechanics approach	Observed size distributions of microplastics collected at sea surface in previous studies around Japan and in global accumulation zones
[19]	A 3D numerical model to Track Marine Plastic Debris (TrackMPD): Sensitivity of microplastic trajectories and fates to particle dynamical properties and physical processes	Several ocean models and observations
[20]	A threshold model of plastic waste fragmentation: New insights into the distribution of microplastics in the ocean and its evolution over time	Field data from various studies
[21]	Simulation of the transport of marine microplastic particles in the Ionian Archipelago (NE Ionian Sea) using a Lagrangian model and the control mechanisms affecting their transport	Particles released from different locations using velocity data for the TrackMPD model
[22]	Microplastic as a vector of chemical contamination in the marine environment: A coupled Lagrangian-Eulerian approach	Oceanographic data and simulation data for the Mediterranean. Uses phenanthrene as the target pollutant
[23]	Prioritized area mapping for multiple stakeholders through geospatial modelling: A focus on marine plastics pollution in Hong Kong	Collected from beach surveys from port traffic intensity and marine protected areas
[24]	Engaging communities in Sulawesi Island, Indonesia: A collaborative approach to modelling marine plastic debris through open science and online visualization	Existing hydrodynamic data for the period of 1 year from the HYCOM GOFS 3.1 Analysis model
[25]	Modelling marine microplastics accumulation zones through freshwater discharge sources: Simulated release from the Onkaparinga River and Torrens River, South Australia	Published data on plastic waste on beaches, port traffic intensity and marine protected areas in Hong Kong

Continued on next page

Reference	Title	Dataset
[26]	The dynamics of microplastics and associated contaminants: Data-driven Lagrangian and Eulerian modelling approaches in the Mediterranean Sea	Indicators for sources for the Mediterranean Sea
[27]	An interactive visualization tool for the exploration and analysis of multivariate ocean data	NetCDF, ASCII, model data in situ
[28]	A framework for interactive visual analysis of heterogeneous marine data in an integrated problem solving environment	Argo and SST data and the global topography dataset ETOPO1
[29]	A survey on visual analysis of ocean data	Collected from numerical simulations or observations
[30]	Research on Visualization Technology of Ocean Situation Based on OSG	Global ocean current data provided by the South China Sea Marine Forecasting Center
[31]	A Spherical Volume-Rendering Method of Ocean Scalar Data Based on Adaptive Ray Casting	Experimental datasets included scalar ocean field data from ROMS and HYCOM models, as well as the global seafloor terrain dataset GEBCO_2022
[32]	Web-based 3D visualization framework for time-varying and large-volume oceanic forecasting data using open-source technologies	Volume ocean simulation results
[33]	The Implementation of a WebGPU-Based Volume Rendering Framework for Interactive Visualization of Ocean Scalar Data	Simulation results of environmental ocean parameters on regular horizontal/irregular vertical grids. Ocean acoustic field data on irregular cylindrical grids
[34]	Plastic Pollution in the Coastal Oceans: Characterization and Modeling	Uses debris and plastic data from literature and local monitoring for assessment and ocean fields from models (HYCOM) and synoptic data (CTD, atmospheric data, buoys, SST, HF Radar)

Continued on next page

Reference	Title	Dataset
[35]	Dynamic Visualization of Spatio-Temporal Process Model Based on NetCDF and Optimal Interpolation for Marine Environment	Obtained via global optimal interpolation from AVHRR products
[36]	Multiplatform Ecosystem for Visualizing Ocean Dynamic Formations with Virtual Choreographies: Oil Spill Case	Satellite data represented by geolocated points and density data. Real case data from ILIAD Project partners used for tests
[37]	An overview of visualization and visual analytics applications in water resources management	Origins such as sensors, simulation models and databases
[38]	Design and Implementation of Smart Ocean Visualization System Based on Extended Reality Technology	Python crawler technology
[39]	OceanVive: An Immersive Visualization System for Communicating Complex Oceanic Phenomena	Ocean data collected from the Great Bay Area (China Seas) through *in situ* measurements and provided by domain experts, that covers five years (2019–2024)
[40]	Dynamic ocean inverse modeling based on differentiable rendering	Images and geometric sequences
[41]	Efficient estimation of directional wave buoy spectra using a reformulated Maximum Shannon Entropy Method: Analysis and comparisons for coastal wave datasets	Dataset with one year of spectral data at 30-minute intervals from six UK coastal buoys, totalling about 17,000 files/year/buoy
[42]	Efficiently simulating Lagrangian particles in large-scale ocean flows — Data structures and their impact on geophysical applications	Galapagos scenario for experimentation
[43]	Numerical Tracking of Floating Marine Plastic in the Sea of Japan Using Time-backward Probabilistic Method	Floating marine plastic data, measurement data with outliers and velocity fields from the Sea of Japan
[44]	Scalable Multi-resolution Spatial Visualization for Anthropogenic Litter Data	Uses thirty real datasets (420K points) collected from various organisations and crowdsourcing, in different formats (Shapefiles, KML, XLSX, CSV)

Continued on next page

Reference	Title	Dataset
[45]	Material and debris transport patterns in Moreton Bay, Australia: The influence of Lagrangian coherent structures	Moreton Bay data. CleanUpOurWorld uses 30 real datasets from various sources (420K points) and crowdsourcing. Integrated frameworks - Argo and SST
[46]	Pathways and Hot Spots of Floating and Submerged Microplastics in Atlantic Iberian Marine Waters: A Modelling Approach	Daily mean current data from the CMEMS GLORYS12V1 Global Physical Ocean Reanalysis, derived from the Mercator-Ocean system and combining multiple observation and modelling sources
[47]	Emission, Transport, and Deposition of visible Plastics in an Estuary and the Baltic Sea-a Monitoring and Modeling Approach	Field monitoring data collected in the Warnow River, estuary and Baltic Sea beaches, combined with literature data, urban statistics and hydrodynamic forcing data for model simulations
[48]	COVERAGE Data Viewer: A Generalized Web-Based Tool for Integrated Visualization of Oceanographic Satellite and In-Situ Data	Oceanographic observation data, diverse satellite and in situ data, NASA field campaign datasets (SPURS 1 & 2, S-MODE), animal telemetry and fishing data and satellite image layers of key ocean parameters
[49]	Particle System-Based Multi-Hierarchy Dynamic Visualization of Ocean Current Data	Global circulation and tidal current forecasts provided by the South China Marine Forecasting Centre of the State Oceanic Administration, originally in NetCDF and converted to compressed texture format for web use
[50]	Satellite Solutions for Tracking Litter & Plastic Pollution in the Ocean	Location and sensor data - transmitters. GPS positions of buoys - ARGOS. Drift model environmental data - CMEMS

Continued on next page

Reference	Title	Dataset
[51]	The Development of Hainan Provincial Digital Ocean Environment Parameters Three-dimensional Visualization System	Basic geographic data, remote sensing images, high-precision DEM and multidimensional ocean environmental parameters are used for the South China Sea
[52]	Maritime Traffic Data Visualization: A Brief Review	Data from AIS, raw radar/video data, fishing effort/catch data and radar-based ship position data

Table D.1: Dataset per Article.

Appendix E

Quality Assessment - Technologies

Reference	Title	Technologies
[12]	Modelled and observed plastic pollution on remote Scottish beaches: The importance of local marine sources	Particle tracking model and R for data analysis
[13]	A review of methods for modeling microplastic transport in the marine environments	Numerical modelling and Lagrangian particle-tracking models (LPTMs) like Ichthyop, TrackMPD, Parcels, Delft3D-PART, PPTM, Pol3DD, using parameterisation methods and seawater state equations (TEOS-10)
[14]	Modelling global river export of microplastics to the marine environment: Sources and future trends	Lagrangian Coherent Structures (LCS) technique, Finite-Time Lyapunov Exponent (FTLE), geostatistical interpolation and Priority Area Maps (PAM)
[15]	Modeling the Exposure of the Macaronesia Islands (NE Atlantic) to Marine Plastic Pollution	Open-source Lagrangian modelling framework OceanParcels, the underlying numerical models for ocean reanalysis (such as NEMO) and wave models (WW3) and data collection and reanalysis systems that provided forcing fields and observational data (such as the Global Drifter Program)
[16]	Disentangling the physical dispersion of floating debris and plastics in the Indonesian Seas	Lagrangian framework/simulations, ocean current analysis, particle tracking models (HYCOM, Parcels)

Continued on next page

Reference	Title	Technologies
[17]	Oceanic realistic application of a microplastic biofouling model to the river discharge case	1D biofouling model and regional 3D microplastics tracking
[18]	A model for the size distribution of marine microplastics: A statistical mechanics approach	Mathematical framework of statistical mechanics to derive model formulations and fitting methods like least squares to compare the theoretical model with observational data
[19]	A 3D numerical model to Track Marine Plastic Debris (TrackMPD): Sensitivity of microplastic trajectories and fates to particle dynamical properties and physical processes	The TrackMPD framework, based on PaTATO, developed in Matlab
[20]	A threshold model of plastic waste fragmentation: New insights into the distribution of microplastics in the ocean and its evolution over time	The sugar lump model and the standard model (both iterative) and power law analysis
[21]	Simulation of the transport of marine microplastic particles in the Ionian Archipelago (NE Ionian Sea) using a Lagrangian model and the control mechanisms affecting their transport	Lagrangian particle tracking model (TrackMPD) and transport comparison to the sea and eddy diffusivity
[22]	Microplastic as a vector of chemical contamination in the marine environment: A coupled Lagrangian-Eulerian approach	Lagrangian-Eulerian coupled approach, Python 3
[23]	Prioritized area mapping for multiple stakeholders through geospatial modelling: A focus on marine plastics pollution in Hong Kong	Geostatistical interpolation, mapping, Priority Area Mapping (PAM) approach, data visualisation
[24]	Engaging communities in Sulawesi Island, Indonesia: A collaborative approach to modelling marine plastic debris through open science and online visualization	HYCOM ocean models and Parcels, R with R Shiny and the Leaflet library for the web visualisation app and online platforms like GitHub and YouTube for open dissemination

Continued on next page

Reference	Title	Technologies
[25]	Modelling marine microplastics accumulation zones through freshwater discharge sources: Simulated release from the Onkaparinga River and Torrens River, South Australia	Geospatial approach, geostatistical interpolation, mapping, Priority Area Maps (PAM), map layers
[26]	The dynamics of microplastics and associated contaminants: Data-driven Lagrangian and Eulerian modelling approaches in the Mediterranean Sea	Lagrangian modelling/particle tracking, Eulerian modelling/advection-diffusion, Lagrangian-Eulerian coupled approach, Python 3
[27]	An interactive visualization tool for the exploration and analysis of multivariate ocean data	Python (implementation), CPU/GPU rendering, 2D/3D rendering, Octree-based data representation, modified ray-casting algorithm, Kriging interpolation
[28]	A framework for interactive visual analysis of heterogeneous marine data in an integrated problem solving environment	Integrated visualisation framework, GPU-based visualisation, OpenGL, C++, Python, SWIG
[29]	A survey on visual analysis of ocean data	Interactive visual analysis, scientific visualisation, traditional tools (MATLAB, GIS), data preprocessing (aggregation, abstraction, clustering), direct/geometric/texture-based visualisation, multivariate analysis techniques, phenomenon detection algorithms, spatio-temporal pattern exploration, uncertainty visualisation
[30]	Research on Visualization Technology of Ocean Situation Based on OSG	OSG, particle system, spherical uniform distribution algorithms (Marsaglia's polar method), visible density adaptive adjustment algorithm, dynamic streamlet generation, GPU parallelism
[31]	A Spherical Volume-Rendering Method of Ocean Scalar Data Based on Adaptive Ray Casting	GPU-based ray casting for volume rendering, GIS software like QGIS for data preparation and the Cesium platform for 3D visualisation

Continued on next page

Reference	Title	Technologies
[32]	Web-based 3D visualization framework for time-varying and large-volume oceanic forecasting data using open-source technologies	Ocean forecast systems, graphical representations, data visualisation structures, 2D/3D visualisation, numerical modelling methods
[33]	The Implementation of a WebGPU-Based Volume Rendering Framework for Interactive Visualization of Ocean Scalar Data	Visualization structure, WebGPU-based volume rendering, spherical volume rendering, adaptive ray casting, proxy geometry (spherical mosaic), depth texture, terrain fusion, spatial interpolation (trilinear), adaptive sampling step algorithm, nonlinear color mapping, transparency transfer function, statistical analysis (skewness), NetCDF format
[34]	Plastic Pollution in the Coastal Oceans: Characterization and Modeling	Partial Differential Equations (PDE) methodology, primitive equations solver, composition-based advection solver, Lagrangian analysis/transport, 3D modelling, HYCOM ocean model
[35]	Dynamic Visualization of Spatio-Temporal Process Model Based on NetCDF and Optimal Interpolation for Marine Environment	Network Common Data Form (NetCDF) and optimal interpolation technique, used for dynamic 3D marine data visualisation
[36]	Multiplatform Ecosystem for Visualizing Ocean Dynamic Formations with Virtual Choreographies: Oil Spill Case	Virtual choreographies, multi-platform visualisation ecosystem, Cesium Ion (JavaScript library), Cesium platform, particle-based approach, 3D visualisation, textured filling, Digital Ocean Twins (DTOs)

Continued on next page

Reference	Title	Technologies
[37]	An overview of visualization and visual analytics applications in water resources management	Web platforms, particle systems, visual computing, Geographic Information Systems (GIS), Machine Learning (ML), statistical models, web graphic libraries like WebGL, HTML5 Canvas and SVG, 3D web tiling services, online game engines, online platforms for data analysis/visualization, altimetry, XR and AI-based visual computing
[38]	Design and Implementation of Smart Ocean Visualization System Based on Extended Reality Technology	Extended Reality (XR) technology, Python crawler technology, Unity platform (Unity3D), programming in C#, AR Foundation plugin
[39]	OceanVive: An Immersive Visualization System for Communicating Complex Oceanic Phenomena	Unity
[40]	Dynamic ocean inverse modeling based on differentiable rendering	Differentiable rendering, dynamic ocean inverse modeling framework. Deep neural networks and differentiable physical fluid simulation
[41]	Efficient estimation of directional wave buoy spectra using a reformulated Maximum Shannon Entropy Method: Analysis and comparisons for coastal wave datasets	Maximum Entropy Methods of Shannon (MEM-II) and Burg (MEM-I), cos 2s scattering function and Matlab
[42]	Efficiently simulating Lagrangian particles in large-scale ocean flows — Data structures and their impact on geophysical applications	Parcels (Python framework), Python, ctypes, C-mode (jit), SciPy (library), data structures (AoS, Nodes, SoA)
[43]	Numerical Tracking of Floating Marine Plastic in the Sea of Japan Using Time-backward Probabilistic Method	Backwards-in-time probabilistic method, numerical tracking
[44]	Scalable Multi-resolution Spatial Visualization for Anthropogenic Litter Data	Scalable spatial research database, spatial database technology, data aggregation techniques, data cleaning/integration modules, web applications, GIS software

Continued on next page

Reference	Title	Technologies
[45]	Material and debris transport patterns in Moreton Bay, Australia: The influence of Lagrangian coherent structures	Lagrangian Coherent Structures (LCS), scalable spatial database, GPU-based integrated visualization frameworks (C++, OpenGL, Python), WebGL-based visualization technologies (Cesium, Plotly.js, heatmap, etc.), visual computing (graphics, ML/DL, GIS, XR, Unity3D)
[46]	Pathways and Hot Spots of Floating and Submerged Microplastics in Atlantic Iberian Marine Waters: A Modelling Approach	Open-source Lagrangian modelling framework OpenDrift and hydrodynamic forcing data from the Global Physical Ocean Reanalysis CMEMS GLORYS12V1
[47]	Emission, Transport, and Deposition of visible Plastics in an Estuary and the Baltic Sea-a Monitoring and Modeling Approach	Nets and sieves for sampling, near-infrared spectroscopy for polymer identification, coastal monitoring methods and coupled 3D hydrodynamic models (GETM, WAVEWATCH 3) with a microplastic transport module
[48]	COVERAGE Data Viewer: A Generalized Web-Based Tool for Integrated Visualization of Oceanographic Satellite and In-Situ Data	COVERAGE Data Viewer (browser-based app), data backend service, open-source software, JavaScript (frontend), JPL's Common Mapping Client (CMC), geospatial visualization, mapping, Internet, web architecture/services/analytics, Postgres/gis, GeoServer, SOLR, Dynamic Data Decimator, In-situ Subsetting Service (ISS)

Continued on next page

Reference	Title	Technologies
[49]	Particle System-Based Multi-Hierarchy Dynamic Visualization of Ocean Current Data	Particle systems, implementation in a 3D digital environment (prototype based on Cesium and WebGL), GPU acceleration, spherical uniform distribution algorithms for seed placement, an adaptive density adjustment algorithm based on viewport, dynamic "streamlet"-type symbol design and numerical integration methods for particle tracking
[50]	Satellite Solutions for Tracking Litter & Plastic Pollution in the Ocean	Satellites (ARGOS, Earth Observation), GPS-tracked transmitters (PTTs), the Mobidrift drift model, altimetry, in situ buoys/drifters and a web interface for visualisation and dissemination
[51]	The Development of Hainan Provincial Digital Ocean Environment Parameters Three-dimensional Visualization System	Digital Earth sphere model, 3D visualisation system, multidimensional visualisation of marine environmental parameters, high-precision DEM, satellite imagery, data display, multi-temporal comparison, spatial overlay analysis, statistics, data management
[52]	Maritime Traffic Data Visualization: A Brief Review	Data visualisation techniques, AIS data, radar, video surveillance, non-linear interpolation, Douglas-Peucker (DP) algorithm, KDE-based density maps, animation, infographics, space-time cube, ship safety domain (SSD) models

Table E.1: Technologies per Article.

Appendix F

Quality Assessment - Limitations

Reference	Title	Limitations
[12]	Modelled and observed plastic pollution on remote Scottish beaches: The importance of local marine sources	Only included visible and removable items, leaving out large ones and data collection was limited by shoreline accessibility
[13]	A review of methods for modeling microplastic transport in the marine environments	The review provides a representative cross-section and existing simulations are often limited by unrealistically few particles and simplified releases
[14]	Modelling global river export of microplastics to the marine environment: Sources and future trends	FTLE visualisation may have deficiencies where stable and unstable lines coincide and LCS analysis focuses on floating particles with different levels of wind submersion
[15]	Modeling the Exposure of the Macaronesia Islands (NE Atlantic) to Marine Plastic Pollution	Spatial and temporal resolution of forcing data not fully resolving coastal and sub-mesoscale dynamics, simplification of particles' physical properties and omission of processes such as weathering, fragmentation and biofouling, as well as simplification of the grounding mechanism
[16]	Disentangling the physical dispersion of floating debris and plastics in the Indonesian Seas	Some increase in grounding involves interannual variability, suggesting the need for longer periods. Focuses only on surface-floating particles

Continued on next page

Reference	Title	Limitations
[17]	Oceanic realistic application of a microplastic biofouling model to the river discharge case	Focuses only on the biofouling mechanism
[18]	A model for the size distribution of marine microplastics: A statistical mechanics approach	Model idealised nature, explicit omission of size-dependent removal processes (like biofouling and sinking), sampling errors in observations and the need to consider variability in sources and properties of original material for more realistic application
[19]	A 3D numerical model to Track Marine Plastic Debris (TrackMPD): Sensitivity of microplastic trajectories and fates to particle dynamical properties and physical processes	The relative influence of degradation is difficult to compare due to long timescales. The actual influence of biofouling rate cannot be fully assessed due to the lack of quantification
[20]	A threshold model of plastic waste fragmentation: New insights into the distribution of microplastics in the ocean and its evolution over time	Ignores delamination and assumes film-type objects, being a generalist model based on few assumptions
[21]	Simulation of the transport of marine microplastic particles in the Ionian Archipelago (NE Ionian Sea) using a Lagrangian model and the control mechanisms affecting their transport	The U/A comparison approach is not valid
[22]	Microplastic as a vector of chemical contamination in the marine environment: A coupled Lagrangian-Eulerian approach	Simplified dynamics, neglects processes such as fragmentation and pollutant removal (sedimentation) and models only surface dynamics
[23]	Prioritized area mapping for multiple stakeholders through geospatial modelling: A focus on marine plastics pollution in Hong Kong	Beach survey data, when considered in isolation, may offer only a limited understanding of uncertainties associated with plastic pollution

Continued on next page

Reference	Title	Limitations
[24]	Engaging communities in Sulawesi Island, Indonesia: A collaborative approach to modelling marine plastic debris through open science and online visualization	Intentionally simplified models (2D simulations without grounding or aggregation parameterisation) due to time constraints and need for clarity and a short timeline (12 weeks) that prevented long-term impact evaluation
[25]	Modelling marine microplastics accumulation zones through freshwater discharge sources: Simulated release from the Onkaparinga River and Torrens River, South Australia	Beach survey data, in isolation, offer only limited understanding of uncertainties associated with plastic pollution
[26]	The dynamics of microplastics and associated contaminants: Data-driven Lagrangian and Eulerian modelling approaches in the Mediterranean Sea	2D description (ignores verticality/mixing), model uses simplifications, ignores processes like fragmentation and pollutant removal (sedimentation), modelling only the surface may not be exhaustive
[27]	An interactive visualization tool for the exploration and analysis of multivariate ocean data	The complexity of ocean data represents a challenge
[28]	A framework for interactive visual analysis of heterogeneous marine data in an integrated problem solving environment	The Argo data structure is semi-structured and vertically irregular. Visualisation methods rely on pre-processed data
[29]	A survey on visual analysis of ocean data	Traditional tools lack integration and interactivity. Visual complexity in some methods. Human memory limitations do not understand snapshot series. Interactive animation of large spatio-temporal datasets may lead to information overload
[30]	Research on Visualization Technology of Ocean Situation Based on OSG	There is still room for improvement in technology. Different people have different visual perceptions of particle density

Continued on next page

Reference	Title	Limitations
[31]	A Spherical Volume-Rendering Method of Ocean Scalar Data Based on Adaptive Ray Casting	Less significant efficiency gains with uniformly distributed depth intervals and applicability mainly to small and medium scale coastal areas
[32]	Web-based 3D visualization framework for time-varying and large-volume oceanic forecasting data using open-source technologies	The complex nature and large volume of ocean simulation results present challenges for understanding and effective use
[33]	The Implementation of a WebGPU-Based Volume Rendering Framework for Interactive Visualization of Ocean Scalar Data	The method focuses mainly on nearshore scalar ocean fields. Efficiency improvement may not be apparent for datasets with uniform depth intervals. The method is limited to small and medium scale coastal area visualisation
[34]	Plastic Pollution in the Coastal Oceans: Characterization and Modeling	Ideally should include fragmentation and degradation for major plastic classes, but the excerpt description focuses on transport and comparison with/without settling
[35]	Dynamic Visualization of Spatio-Temporal Process Model Based on NetCDF and Optimal Interpolation for Marine Environment	Not mentioned
[36]	Multiplatform Ecosystem for Visualizing Ocean Dynamic Formations with Virtual Choreographies: Oil Spill Case	The API used in the first web platform could not incorporate changes based on ocean characteristics (currents)
[37]	An overview of visualization and visual analytics applications in water resources management	Irregular distribution of seed points or abrupt changes in density in flow field visualizations, the complexity of interpreting advanced visualizations for non-specialists, challenges in managing and cleaning large datasets, the "black-box" nature of some ML models and the need to adapt techniques to handle spatial/temporal data variability

Continued on next page

Reference	Title	Limitations
[38]	Design and Implementation of Smart Ocean Visualization System Based on Extended Reality Technology	Not mentioned
[39]	OceanVive: An Immersive Visualization System for Communicating Complex Oceanic Phenomena	Steep learning curve for novice users due to its complexity, reliance on traditional desktop-based interaction limits its adaptability and the lack of integration with VR/AR headsets constrains the immersive potential. Also, the absence of a user study with a diverse participant pool
[40]	Dynamic ocean inverse modeling based on differentiable rendering	Not mentioned
[41]	Efficient estimation of directional wave buoy spectra using a reformulated Maximum Shannon Entropy Method: Analysis and comparisons for coastal wave datasets	Unimodal scattering functions do not fix higher-order moments. Practical implications of benchmark results for real data were unclear before this study. The method depends on directional moments as input
[42]	Efficiently simulating Lagrangian particles in large-scale ocean flows — Data structures and their impact on geophysical applications	Not mentioned
[43]	Numerical Tracking of Floating Marine Plastic in the Sea of Japan Using Time-backward Probabilistic Method	Observed fluctuations led to different estimation locations. Precise localisation requires outlier elimination
[44]	Scalable Multi-resolution Spatial Visualization for Anthropogenic Litter Data	Street level shows individual points, other levels are aggregated, limiting large-scale detailed visualisation

Continued on next page

Reference	Title	Limitations
[45]	Material and debris transport patterns in Moreton Bay, Australia: The influence of Lagrangian coherent structures	The LCS approach has shortcomings where stable/unstable lines coincide. CleanUpOurWorld visualises aggregated data (except at street level). Integrated frameworks have limitations with irregular data and advanced functionalities. Challenges in handling large and heterogeneous marine data for scalable and interactive visualisation
[46]	Pathways and Hot Spots of Floating and Submerged Microplastics in Atlantic Iberian Marine Waters: A Modelling Approach	Omission of complex vertical movements like sinking and biofouling due to lack of robust parameterisations, simplifications in particle properties and a resolution that may not fully capture coastal and sub-mesoscale dynamics, leading to possible discrepancies with field data
[47]	Emission, Transport, and Deposition of visible Plastics in an Estuary and the Baltic Sea-a Monitoring and Modeling Approach	Omission of complex vertical movements and simplifications in particle properties, model resolution not resolving the estuary, uncertainties in emission calculations and monitoring methods and lack of reliable data on plastic retention in rivers and estuaries
[48]	COVERAGE Data Viewer: A Generalized Web-Based Tool for Integrated Visualization of Oceanographic Satellite and In-Situ Data	Not mentioned
[49]	Particle System-Based Multi-Hierarchy Dynamic Visualization of Ocean Current Data	Rendering efficiency (FPS) tends to decrease as the camera zooms out from the globe, since more particles are generated and require more computation

Continued on next page

Reference	Title	Limitations
[50]	Satellite Solutions for Tracking Litter & Plastic Pollution in the Ocean	Need for in situ buoys to describe chaotic movement, the size and weight of some transmitters, the need to adapt lighter trackers, challenges in user adoption and interpretation and the spatial and temporal variability in current estimation errors
[51]	The Development of Hainan Provincial Digital Ocean Environment Parameters Three-dimensional Visualization System	Not mentioned
[52]	Maritime Traffic Data Visualization: A Brief Review	Raw traffic data are often degraded, large volumes lead to high computational costs, visual presentation of a single attribute is limited, integrating influencing factors for SSD is difficult

Table F.1: Limitations per Article.

Appendix G

Quality Assessment - Validation

Reference	Title	Validation
[12]	Modelled and observed plastic pollution on remote Scottish beaches: The importance of local marine sources	Validated the particle tracking model's predictions using the beach cleanup dataset collected
[13]	A review of methods for modeling microplastic transport in the marine environments	Discusses model validation methods using conventional observational data and ecological data
[14]	Modelling global river export of microplastics to the marine environment: Sources and future trends	Used a validated hydrodynamic model and compared results with beach cleanup data for marine debris analysis
[15]	Modeling the Exposure of the Macaronesia Islands (NE Atlantic) to Marine Plastic Pollution	Comparison of transport patterns and timescales from model results with GDP observational drifter trajectories, showing good agreement, especially for mixed particles and on consistency with previous field study findings on marine debris accumulation on archipelago beaches
[16]	Disentangling the physical dispersion of floating debris and plastics in the Indonesian Seas	Results are compared for the wet and dry seasons
[17]	Oceanic realistic application of a microplastic biofouling model to the river discharge case	Not mentioned

Continued on next page

Reference	Title	Validation
[18]	A model for the size distribution of marine microplastics: A statistical mechanics approach	Good fit to observed size distributions of micro and mesoplastics in various regions, including reproducing the cubic power law for larger sizes and by an observed correlation between the model parameter and expected wave energy levels in potential source regions
[19]	A 3D numerical model to Track Marine Plastic Debris (TrackMPD): Sensitivity of microplastic trajectories and fates to particle dynamical properties and physical processes	Sensitivity analysis assesses the relative importance of processes/behaviours by comparing particle trajectories and destinations across scenarios with a control scenario
[20]	A threshold model of plastic waste fragmentation: New insights into the distribution of microplastics in the ocean and its evolution over time	Compared the size distribution predicted by the model with available field data, showing the model predicts a fragment accumulation in a given size range consistent with observations
[21]	Simulation of the transport of marine microplastic particles in the Ionian Archipelago (NE Ionian Sea) using a Lagrangian model and the control mechanisms affecting their transport	Not mentioned
[22]	Microplastic as a vector of chemical contamination in the marine environment: A coupled Lagrangian-Eulerian approach	Comparison of results from the coupled model with a fully Eulerian simulation without particles
[23]	Prioritized area mapping for multiple stakeholders through geospatial modelling: A focus on marine plastics pollution in Hong Kong	The approach is demonstrated by producing map layers and associated uncertainty maps representing the perspective of different stakeholders

Continued on next page

Reference	Title	Validation
[24]	Engaging communities in Sulawesi Island, Indonesia: A collaborative approach to modelling marine plastic debris through open science and online visualization	Comparing modeling results with previous studies highlighting the influence of the monsoon regime, collecting positive feedback from participants in workshops and outreach activities and evidence of continued engagement with the online tools developed beyond the initial funding period
[25]	Modelling marine microplastics accumulation zones through freshwater discharge sources: Simulated release from the Onkaparinga River and Torrens River, South Australia	The approach is demonstrated through the production of map layers and associated uncertainty maps representing the perspective of different stakeholders
[26]	The dynamics of microplastics and associated contaminants: Data-driven Lagrangian and Eulerian modelling approaches in the Mediterranean Sea	Comparability between Lagrangian and Eulerian modules was maintained. Results support the use of data-informed clues for sources. Partitioning by source region provides insight into connectivity. Compared coupled model results with simulation without particles
[27]	An interactive visualization tool for the exploration and analysis of multivariate ocean data	Visualization results are presented and interpreted, demonstrating the framework's effectiveness and efficiency
[28]	A framework for interactive visual analysis of heterogeneous marine data in an integrated problem solving environment	The framework's effectiveness and efficiency are demonstrated through its implementation and application to SST and Argo data
[29]	A survey on visual analysis of ocean data	The research presents several techniques and tools often supporting interactive analysis and statistical methods
[30]	Research on Visualization Technology of Ocean Situation Based on OSG	Viability and effectiveness are verified through experiments. Results are compared with traditional methods. Density adjustment strategy and rendering efficiency are tested

Continued on next page

Reference	Title	Validation
[31]	A Spherical Volume-Rendering Method of Ocean Scalar Data Based on Adaptive Ray Casting	Comparison of fusion effect and visualization quality with traditional methods, demonstrating capabilities for local feature extraction and assessing rendering efficiency using FPS metrics in comparative tests
[32]	Web-based 3D visualization framework for time-varying and large-volume oceanic forecasting data using open-source technologies	Not mentioned
[33]	The Implementation of a WebGPU-Based Volume Rendering Framework for Interactive Visualization of Ocean Scalar Data	Viability and effectiveness are verified by presenting visual effects and conducting comparative analyses of framework efficiency (frame rate) with different datasets and by comparing the adaptive sampling algorithm with the equidistant one
[34]	Plastic Pollution in the Coastal Oceans: Characterization and Modeling	Comparison with synoptic data. Simulated transports and attractive regions are evaluated using debris/plastics data from the literature and monitoring
[35]	Dynamic Visualization of Spatio-Temporal Process Model Based on NetCDF and Optimal Interpolation for Marine Environment	Experimental results, which indicate the method expresses marine environmental data efficiently and intuitively, validating its effectiveness as a tool for expressing, analyzing and predicting complex phenomena
[36]	Multiplatform Ecosystem for Visualizing Ocean Dynamic Formations with Virtual Choreographies: Oil Spill Case	Proof of concept with two platforms running the same narrative. System successfully read the choreography. Further testing with real-world cases and user study planned

Continued on next page

Reference	Title	Validation
[37]	An overview of visualization and visual analytics applications in water resources management	The validation of the effectiveness of the methods is demonstrated through a review of successful research applications, the evaluation of the tools' ability to solve specific problems and in some cases through case studies or comparisons with observational data
[38]	Design and Implementation of Smart Ocean Visualization System Based on Extended Reality Technology	Viability is demonstrated through the development of the system and the execution of its functionalities
[39]	OceanVive: An Immersive Visualization System for Communicating Complex Oceanic Phenomena	Expert evaluation, focusing on tool perception, workflow adaptation and concerns about the immersive experience
[40]	Dynamic ocean inverse modeling based on differentiable rendering	Experimental results show that the framework is effective and usable for dynamic ocean reconstruction
[41]	Efficient estimation of directional wave buoy spectra using a reformulated Maximum Shannon Entropy Method: Analysis and comparisons for coastal wave datasets	The fidelity of MEM-II reconstruction is measured by the residual. Comparison of reconstruction methods with real data examines their effect on the outcome
[42]	Efficiently simulating Lagrangian particles in large-scale ocean flows — Data structures and their impact on geophysical applications	Performance comparison results using derived metrics
[43]	Numerical Tracking of Floating Marine Plastic in the Sea of Japan Using Time-backward Probabilistic Method	Comparison of estimated and observed concentrations at the estimated location
[44]	Scalable Multi-resolution Spatial Visualization for Anthropogenic Litter Data	Functionalities are demonstrated using real datasets
[45]	Material and debris transport patterns in Moreton Bay, Australia: The influence of Lagrangian coherent structures	Hydrodynamic model validated for LCS analysis. CleanUpOurWorld demonstrated with real datasets. Integrated framework and web applications demonstrated effectiveness and efficiency in marine data visualization

Continued on next page

Reference	Title	Validation
[46]	Pathways and Hot Spots of Floating and Submerged Microplastics in Atlantic Iberian Marine Waters: A Modelling Approach	Comparison of transport patterns and timescales from modeling results with observational drifter trajectories and consistency with findings from previous field studies identifying accumulation or low-microplastic areas in the region
[47]	Emission, Transport, and Deposition of visible Plastics in an Estuary and the Baltic Sea-a Monitoring and Modeling Approach	Comparison of emission calculations with estimated coastal accumulation in the estuary for indicator items and comparing the model's spatial patterns and concentrations with coastal monitoring data on Baltic Sea beaches, showing pattern consistency and some quantitative agreement despite uncertainties
[48]	COVERAGE Data Viewer: A Generalized Web-Based Tool for Integrated Visualization of Oceanographic Satellite and In-Situ Data	Illustrations of successful integration and visualization of diverse datasets demonstrate the tool's utility
[49]	Particle System-Based Multi-Hierarchy Dynamic Visualization of Ocean Current Data	The feasibility and effectiveness of the proposed method are validated through a series of experiments demonstrating the uniformity of seed placement, improved visual effect compared to traditional methods, smooth operation of adaptive density adjustment at different viewing distances and rendering efficiency
[50]	Satellite Solutions for Tracking Litter & Plastic Pollution in the Ocean	The CMEMS surface currents are validated by comparing them with the velocity of SVP drifters drogued at 15m and with other products such as OSCAR, demonstrating better consistency with the 15m drifters than with OSCAR

Continued on next page

Reference	Title	Validation
[51]	The Development of Hainan Provincial Digital Ocean Environment Parameters Three-dimensional Visualization System	Not mentioned
[52]	Maritime Traffic Data Visualization: A Brief Review	Review of research results demonstrates potential. SSD models empirically calibrated based on data. SSD models resemble traditional domains

Table G.1: Validation per Article.

Appendix H

Questionnaires

These include both questionnaires used to evaluate participants, provided in Portuguese and English.

Avaliação do Protótipo

Declaração de Consentimento
Está a ser convidado(a) a participar num estudo de usabilidade que analisa a forma como os utilizadores interagem com um protótipo de visualização de dados sobre plásticos nos oceanos. Antes de decidir participar, leia atentamente a informação abaixo. A sua participação é totalmente voluntária.

Objetivo do Estudo
O objetivo deste estudo é avaliar a forma como os utilizadores interagem com um protótipo de visualização de dados. Pretende-se compreender quão intuitiva é a interface, a facilidade com que os utilizadores completam tarefas e a clareza com que o sistema apresenta informação.
Este estudo avalia o software, não a sua capacidade enquanto utilizador(a). Não existem respostas certas ou erradas.

O que lhe será pedido
Se aceitar participar:

- Irá preencher um breve questionário inicial.
- Executará 3 tarefas utilizando o protótipo.
- Um facilitador observará a sua interação e tomará notas.
- Os seus movimentos e cliques de rato serão registados para analisar a forma como interage com a interface.
- No final, preencherá um pequeno questionário de avaliação.

A sessão terá a duração aproximada de 20 minutos.

Participação Voluntária
A participação é totalmente voluntária.
Pode recusar responder a qualquer pergunta ou desistir do estudo a qualquer momento, sem qualquer penalização ou consequência.

Confidencialidade
Todos os dados recolhidos serão anónimos.
Nenhuma informação que permita identificá-lo(a) será partilhada ou incluída em relatórios.
Os dados relativos aos movimentos do rato serão recolhidos de forma anónima e utilizados apenas para análise de usabilidade.
Toda a informação será armazenada em segurança e utilizada exclusivamente para fins de investigação.

* Indica uma pergunta obrigatória

Confirmo que li e compreendi a informação apresentada acima e aceito participar voluntariamente neste estudo *

- ◯ Sim
- ◯ Não

Questionário Pré-Teste

Idade *

A sua resposta

Género *

- ◯ Feminino
- ◯ Masculino
- ◯ Não-binário
- ◯ Outro
- ◯ Prefiro não responder

Nível de Escolaridade *

- ◯ Ensino Básico (1º, 2º ou 3º ciclo)
- ◯ Ensino Secundário
- ◯ Ensino Superior - Licenciatura
- ◯ Ensino Superior - Mestrado
- ◯ Ensino Superior - Doutoramento
- ◯ Outra: _____

Profissão ou Área de Estudos *

- ◯ Administração / Gestão
- ◯ Tecnologia / Informática
- ◯ Engenharia
- ◯ Saúde
- ◯ Educação
- ◯ Ciências Sociais
- ◯ Artes e Comunicação
- ◯ Comércio / Vendas
- ◯ Indústria / Construção
- ◯ Serviços
- ◯ Outra: _____

Literacia Informática *

	1	2	3	4	5	
Muito baixa	◯	◯	◯	◯	◯	Muito alta

Familiaridade com ferramentas de visualização de dados *

	1	2	3	4	5	
Nada familiar	○	○	○	○	○	Muito familiar

Familiaridade com dados oceânicos/ambientais *

	1	2	3	4	5	
Nenhuma	○	○	○	○	○	Muito elevada

Frequência de utilização de ferramentas digitais interativas *

	1	2	3	4	5	
Nunca	○	○	○	○	○	Muito frequente

Tem alguma forma de daltonismo (dificuldade na perceção de cores)? *

- ○ Sim
- ○ Não
- ○ Prefiro não responder

É disléxico(a) ou apresenta características de dislexia (dificuldade na leitura ou na interpretação de texto)? *

- ○ Sim
- ○ Não
- ○ Prefiro não responder

Antes de continuar

Por favor pare aqui.

Antes de iniciar as tarefas irá receber algumas instruções importantes sobre o que deverá fazer a seguir.

Quando lhe for indicado, poderá avançar para a próxima secção para iniciar as tarefas.

Tarefas

Leia cada tarefa antes de a executar no protótipo. Não existem respostas certas ou erradas — faça o melhor que puder.

Qual das seguintes regiões apresenta o valor máximo mais elevado de emissões costeiras de plástico no início de 2020, ultrapassando claramente os 10 000 kg/pessoa/dia? *

- ◯ Oceânia
- ◯ Ásia
- ◯ América do Sul
- ◯ Europa

No início de 2020, qual a região mais provável de contribuir com resíduos plásticos por vias fluviais que chegam ao oceano? *

- ◯ Ásia
- ◯ América do Sul
- ◯ África
- ◯ Europa

Durante os primeiros 13 dias de 2020, em qual destes países africanos se observa que os plásticos acumulados nas praias tendem a deslocar-se ao longo da costa em direção ao sul? *

- ◯ África do Sul
- ◯ Senegal
- ◯ Marrocos
- ◯ Egito

Acessibilidade

Sentiu alguma das seguintes dificuldades relacionadas com cores enquanto utilizava o protótipo? *

- ☐ Tive dificuldade em distinguir algumas cores no mapa
- ☐ As cores utilizadas pareciam demasiado semelhantes entre si
- ☐ Tive dificuldade em interpretar a legenda devido ao contraste ou escolha de cores
- ☐ Não senti dificuldades relacionadas com cores
- ☐ Outra: _____

Sentiu alguma das seguintes dificuldades relacionadas com leitura ou compreensão durante o uso do protótipo? *

- ☐ Tive dificuldade em ler alguns textos no mapa
- ☐ A fonte, tamanho ou estilo do texto dificultaram a leitura
- ☐ A disposição do texto tornou a informação confusa
- ☐ Tive dificuldade em acompanhar informação textual e visual em simultâneo
- ☐ Não senti dificuldades relacionadas com leitura
- ☐ Outra: _____

Questionário Pós-Teste

Por favor avalie a sua experiência com o sistema. Não existem respostas certas ou erradas

Escala de Usabilidade do Sistema (SUS) *

	1. Discordo totalmente	2.	3.	4.	5. Concordo totalmente
Penso que gostaria de utilizar este sistema com frequência	○	○	○	○	○
Achei o sistema desnecessariamente complexo	○	○	○	○	○
Considerei o sistema fácil de usar	○	○	○	○	○
Penso que precisaria do apoio de uma pessoa técnica para usar o sistema	○	○	○	○	○
Achei que as várias funcionalidades do sistema estavam bem integradas	○	○	○	○	○
Penso que existe demasiada inconsistência no sistema	○	○	○	○	○
Imagino que a maioria das pessoas aprenderia a usar o sistema rapidamente	○	○	○	○	○

Considerei o sistema demasiado complicado	○	○	○	○	○
Senti-me confiante ao usar o sistema	○	○	○	○	○
Precisei de aprender muitas coisas antes de conseguir utilizar o sistema	○	○	○	○	○

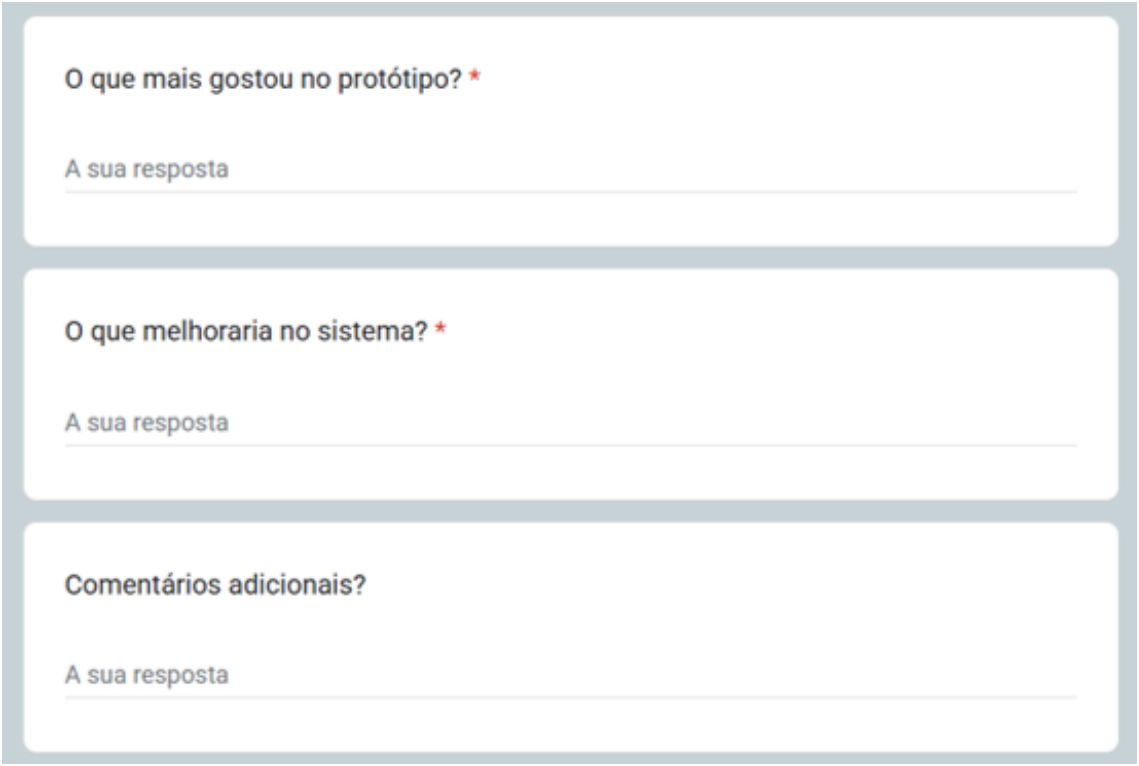
Avaliação de Legibilidade Percebida para Visualizações (PREVis) *

	1. Discordo totalmente	2.	3.	4.	5. Concordo totalmente
É óbvio para mim como ler esta visualização	○	○	○	○	○
Consigo compreender facilmente como os dados estão representados nesta visualização	○	○	○	○	○
Consigo compreender facilmente esta visualização	○	○	○	○	○
Não considero esta visualização confusa	○	○	○	○	○
Não considero esta visualização sobrecarregada	○	○	○	○	○
Não encontro partes distrativas nesta visualização	○	○	○	○	○

Consigo encontrar facilmente elementos específicos nesta visualização	○	○	○	○	○
Consigo identificar facilmente informação relevante nesta visualização	○	○	○	○	○
Consigo recuperar facilmente informação desta visualização	○	○	○	○	○
Consigo ver as características dos dados (por exemplo, mínimo, outlier ou tendência) nesta visualização	○	○	○	○	○
Consigo ver claramente as características dos dados (por exemplo, mínimo, outlier ou tendência) nesta visualização	○	○	○	○	○

Quais foram os aspetos que achou mais confusos? *

A sua resposta


O que mais gostou no protótipo? *
A sua resposta
O que melhoraria no sistema? *
A sua resposta
Comentários adicionais?
A sua resposta

Prototype Evaluation

Consent Form

You are being invited to participate in a usability study that examines how users interact with a prototype data visualization about plastic pollution in the oceans. Before deciding whether to participate, please read the information below carefully. Your participation is entirely voluntary.

Purpose of the Study

The purpose of this study is to evaluate how users interact with a data visualization prototype. The goal is to understand how intuitive the interface is, how easily users complete tasks, and how clearly the system presents information.
This study evaluates the software, not your abilities as a user. There are no right or wrong answers.

What You Will Be Asked to Do

If you agree to participate:

- You will complete a brief initial questionnaire.
- You will perform 3 tasks using the prototype.
- A facilitator will observe your interactions and take notes.
- Your mouse movements and clicks will be recorded to analyze how you interact with the interface.
- At the end, you will complete a short evaluation questionnaire.

The entire session will take approximately 20 minutes.

Voluntary Participation
Participation is entirely voluntary.
You may refuse to answer any question or withdraw from the study at any time, without any penalty or consequences.

Confidentiality
All data collected will remain anonymous.
No information that could identify you will be shared or included in any reports.
The data related to mouse movements will be collected anonymously and used solely for usability analysis.
All information will be securely stored and used exclusively for research purposes.

* Indica uma pergunta obrigatória

I confirm that I have read and understood the study information and I voluntarily agree to participate in this study *

- ◯ Yes
- ◯ No

Pre-Test Questionnaire

Age *

A sua resposta

Gender *

- ◯ Female
- ◯ Male
- ◯ Non-binary
- ◯ Other
- ◯ Prefer not to say

Education Level *

- ◯ Basic Education
- ◯ Secondary Education
- ◯ Higher Education - Bachelor's Degree
- ◯ Higher Education - Master's Degree
- ◯ Higher Education - PhD
- ◯ Outra: _____

Occupation or Study Field *

- ◯ Administration / Management
- ◯ Technology / Computer Science
- ◯ Engineering
- ◯ Health
- ◯ Education
- ◯ Social Sciences
- ◯ Arts and Communication
- ◯ Commerce / Sales
- ◯ Industry / Construction
- ◯ Services
- ◯ Outra: _____

Computer Literacy *

	1	2	3	4	5	
Very Low	◯	◯	◯	◯	◯	Very High

Familiarity with data visualization tools *

	1	2	3	4	5	
Not familiar	○	○	○	○	○	Very familiar

Familiarity with oceanic/environmental data *

	1	2	3	4	5	
None	○	○	○	○	○	Very High

Frequency of using interactive digital tools *

	1	2	3	4	5	
Never	○	○	○	○	○	Very often

Do you have any form of color blindness (difficulty perceiving colors)? *

- ○ Yes
- ○ No
- ○ Prefer not to say

Are you dyslexic or do you have characteristics of dyslexia (difficulty with reading or interpreting text)? *

- ○ Yes
- ○ No
- ○ Prefer not to say

Before continuing

Please stop here.

Before starting the tasks you will receive some important instructions about what to do next.

When prompted, you may proceed to the next section to begin the tasks.

Task List

Read each task carefully before performing it in the prototype. There are no right or wrong answers — just do your best.

Which of the following regions shows the highest maximum value of coastal plastic emissions at the start of 2020, clearly exceeding 10,000 kg/person/day? *

- ◯ Asia
- ◯ South America
- ◯ Oceania
- ◯ Europe

At the beginning of 2020, which region is most likely to contribute plastic waste to riverine pathways that lead to the ocean? *

- ◯ Europe
- ◯ Africa
- ◯ South America
- ◯ Asia

During the first 13 days of 2020, in which of the following African countries do plastics accumulated on beaches tend to move along the coast toward the south? *

- ◯ Senegal
- ◯ Egypt
- ◯ Morocco
- ◯ South Africa

Accessibility

Did you experience any of the following difficulties related to color perception while using the prototype? *

- ☐ I had difficulty distinguishing some of the colors on the map
- ☐ The colors used were too similar to one another
- ☐ The legend was hard to interpret due to low contrast or the choice of colors
- ☐ I did not experience any color-related difficulties
- ☐ Outra: _____

Did you experience any of the following reading or comprehension difficulties while using the prototype? *

- ☐ I had difficulty reading some labels or text on the map
- ☐ The font, size, or style of the text made reading difficult
- ☐ The layout made the information confusing or hard to follow
- ☐ I had difficulty processing visual and textual information at the same time
- ☐ I did not experience any reading-related difficulties
- ☐ Outra: _____

Post-Test Questionnaire

Please evaluate your experience with the system. There are no right or wrong answers

System Usability Scale (SUS) *

	1. Strongly Disagree	2.	3.	4.	5. Strongly Agree
I think that I would like to use this system frequently	○	○	○	○	○
I found the system unnecessarily complex	○	○	○	○	○
I thought the system was easy to use	○	○	○	○	○
I think that I would need the support of a technical person to use this system	○	○	○	○	○
I found the various functions in this system were well integrated	○	○	○	○	○
I felt there was too much inconsistency in the system	○	○	○	○	○
I would imagine that most people would learn to use this system very quickly	○	○	○	○	○

I found the system very cumbersome to use	○	○	○	○	○
I felt very confident using the system	○	○	○	○	○
I needed to learn a lot of things before I could get going with this system	○	○	○	○	○

Perceived Readability Evaluation for Visualizations (PREVis) *

	1. Strongly Disagree	2.	3.	4.	5. Strongly Agree
It is obvious for me how to read this visualization	○	○	○	○	○
I can easily understand how the data is represented in this visualization	○	○	○	○	○
I can easily understand this visualization	○	○	○	○	○
I don't find this visualization messy	○	○	○	○	○
I don't find this visualization crowded	○	○	○	○	○
I don't find distracting parts in this visualization	○	○	○	○	○

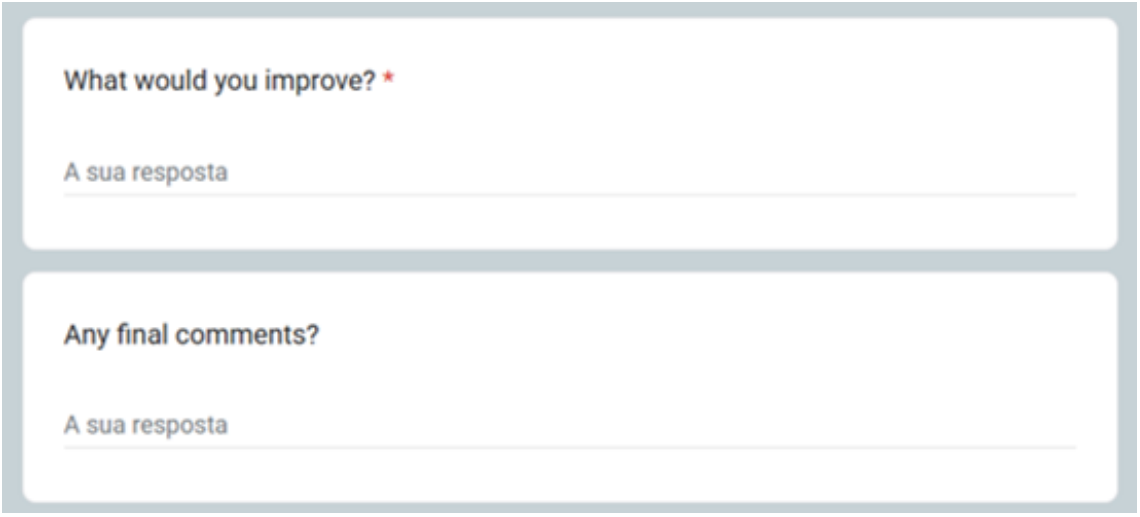
I can easily find specific elements in this visualization	○	○	○	○	○
I can easily identify relevant information in this visualization	○	○	○	○	○
I can easily retrieve information from this visualization	○	○	○	○	○
I find data features (for example, a minimum, or an outlier, or a trend) visible in this visualization	○	○	○	○	○
I can clearly see data features (for example, a minimum, or an outlier, or a trend) in this visualization	○	○	○	○	○

What aspects did you find most confusing? *

A sua resposta

What did you like most about the prototype? *

A sua resposta


What would you improve? *
A sua resposta
Any final comments?
A sua resposta

Appendix I

Moderator Guide

I.1 Before the Session

Prepare:

- Prototype open in initial state (no selections, clean interface)
- Google Form open (blank)
- Timer Ready
- Observation tables ready

Record BEFORE participant arrives:

- Participant ID
- Date and Time

I.2 Welcome Script

> Olá! Obrigada por participar.
>
> Este estudo faz parte da minha dissertação e o objetivo é perceber como as pessoas interagem com uma visualização de dados e como interpretam a informação apresentada.
>
> A visualização que vai usar representa dados sobre plásticos nos oceanos.
>
> Vamos testar o protótipo, não estamos a avaliar as suas capacidades. Tudo o que fizer (dúvidas, erros, hesitações) é útil para a investigação.
>
> A sessão dura cerca de 20 minutos.
>
> No computador já estão abertos dois separadores no navegador. Um contém o questionário e o outro o protótipo que vai usar mais tarde.

I.3 Questionnaire

> Por favor preencha o questionário.

Participant fills Google Form.

I.4 Familiarization Phase

> Antes de iniciar as tarefas, vou dar-lhe 1 a 2 minutos para explorar livremente o protótipo. Pode clicar, observar a visualização, passar o rato pelos elementos, o que quiser, apenas para se ambientar.
>
> Quando estiver preparado para passar para a próxima fase avise, por favor.

Observe natural exploration and take notes on:

- Hesitation
- Curiosity
- Confusion with controls
- Spontaneous comments

I.5 Task Instructions

> Vai realizar 3 tarefas. Cada tarefa tem um limite de 2 pedidos de ajuda. Pode pedir ajuda sobre o funcionamento da interface, por exemplo o que faz um botão, mas eu não posso explicar como interpretar os dados da visualização.
>
> Vou cronometrar o tempo, mas não se preocupe, não é uma prova, apenas uma medição.
>
> Antes de começarmos as tarefas vou ativar uma ferramenta que regista os movimentos do rato no ecrã, se me permitir. É apenas para efeitos da investigação e não altera o funcionamento do protótipo.

Start hotspot tool.

I.6 During Tasks

Take notes on:

- Completion Time
- Success / Failure

- User errors (wrong actions, misinterpretations)
- System errors (user does correct action, but system fails)
- Number of attempts
- Number of helps (0-2)
- Participant comments (think-aloud)

Observed Behaviours:

- Hesitation
- Backtracking
- Confusion with legend
- Misunderstanding of colours
- Searching for elements
- Apparent frustration/ease

Stop timing when the participant submits an answer.
Stop the hotspot tool.
Participant fills:

- SUS (10 items)
- PREVis (11 items)
- Open feedback

Record:

- Any verbal additional comments
- Any visible difficulties not captured before

I.7 Debrief Script

> Muito obrigado pela participação.
> Se tiver algum comentário final ou sugestão posso registar agora.
> Antes de acabar, só queria avisar que tenho uma pequena recompensa como agradecimento pelo tempo que dedicou ao estudo.

Record any final comments.

Participant Session Record

Participant:			**Date:**		
Task	**Completion Time**	**User Errors**	**System Errors**	**Number of Attempts**	**Number of Helps (0–2)**
Task A					
Task B					
Task C					

Participant:			**Date:**		
Task	**Completion Time**	**User Errors**	**System Errors**	**Number of Attempts**	**Number of Helps (0–2)**
Task A					
Task B					
Task C					

Participant:			**Date:**		
Task	**Completion Time**	**User Errors**	**System Errors**	**Number of Attempts**	**Number of Helps (0–2)**
Task A					
Task B					
Task C					

Participant:			**Date:**		
Task	**Completion Time**	**User Errors**	**System Errors**	**Number of Attempts**	**Number of Helps (0–2)**
Task A					
Task B					
Task C					