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An Overview to the Plastic Waste Estimation Models

AN OVERVIEW TO THE PLASTIC WASTE ESTIMATION MODELS

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Executive Summary

The purpose of this report is to assess methodologies for evaluating plastic waste flows and leakage into the environment, specifically focusing on plastic leakage into waterways and oceans. We conducted a literature review on current plastic waste evaluation methodologies and investigated 18 methodologies out of a range of models and tools. We used specific criteria to select the best platforms and available models. Our study focused on methodologies that assess at a geographical level rather than those focusing on the corporate level. We also considered the operability of the method, looking for those that are usable at various levels, not just in scientific research. Additionally, we evaluated the validity of the model based on its publication in high-ranking scientific journals or by well-known international institutes/organizations. We also took into account the completeness of the model, ensuring it covers a range of plastic sources and their leakage pathways.

The most relevant methodologies were chosen based on specific criteria and by reviewing the literature, resulting in the selection of eighteen methods. These include BC Guidance, BPW, GPAP NAM, ISWA PPC, Minderoo, UNEP&IUCN Guidance, Pathways, PLASTEAX, Plastic Drawdown, WFD, UN-Habitat WaCT, WWF M&E, OECD ENV-Linkages, GIS-Based Models, Machine Learning, NOAA Marine Debris, OSPAR, and CSIRO. Various aspects of these models, such as release date, author, complexity of data collection, and the availability of an online tool, were compared to provide a snapshot of their strengths and weaknesses. The study also provided input and output data for each model, along with quick information on the processing method and scale of operation. Finally, a table summarized the main points, the technical complexity of using each model, and the plastic waste breakdown for each one.

1. Introduction

Since the 1950s, over 8,000 million metric tons of plastics have been produced. Due to the widespread use of plastic products and inadequate waste management, plastic waste has entered the environment and can be found in almost all ecosystems, including remote locations such as mountain lakes and polar sea ice. The most notable example of extensive plastic pollution is found in the world's oceans (UNEP, 2020).

The use of plastics has significantly increased since the mid-20th century, with global production of plastic waste reaching over 400 million tonnes in 2023, leading to significant consequences for the environment. (Sarah Perreard et al., 2023; UNEP, 2022). The environmental impact of plastics spans their entire lifecycle. Plastics are produced, used, and eventually become waste, some of which is inadequately managed or littered, leading to plastic leakage into the environment. Approximately 25% of the world's plastic waste, which is about 82 million tonnes, is mismanaged or littered, meaning it is not securely stored in landfills, recycled, or incinerated. Of this mismanaged waste, around 19 million tonnes end up leaking into the environment, with 13 million tonnes entering terrestrial environments and 6 million tonnes reaching rivers or coastlines (OECD, 2022b).

As there is a growing global political push to tackle this issue, efforts have shifted to identifying the sources of plastic, particularly in quantifying the amount of mismanaged plastic waste (MPW) coming from land-based sources and rivers, which are significant contributors of plastic pollution in the ocean (Lechner et al., 2014; Meijer, van Emmerik, van der Ent, Schmidt, & Lebreton, 2021).

As noted at the fifth United Nations Environment Assembly Governments at UNEA 5.2 agreed to negotiate an internationally legally binding instrument by 2024 to end plastic pollution establish a science-policy panel on chemicals and waste and prevent pollution (UNEA, 2022). It is, however; currently, there is no standardized way to measure the extent of the plastic problem. Although there are various methods and tools to assess plastic pollution, it is challenging to measure how much plastic is entering the oceans and to make comparisons. Decision-makers need credible, meaningful, and legitimate data to estimate and analyze the current state of the issue, set measurable goals, implement effective actions, and track progress over time. Therefore, the purpose of this report is to review existing methodologies that assess plastic waste flows and leakage into the environment, with a specific focus on plastic leakage into waterways and oceans.

The detailed objectives of this study are:

- To identify methodologies and tools allowing the assessment of plastic flow and leakage within the waste management chain.
- To compare them and give the reader an overview of the features of each methodology.
- To provide the reader with the context of the application in which each methodology best fits and assess

2. Materials and Methodology

The primary methodology for this study involves conducting a thorough literature review of recent models used to estimate the generation and leakage of plastic waste into land and sea, as well as its movement into the aquatic environment. To accomplish this, a variety of innovative methods and guidelines have been selected, studied, and compared.

We used several criteria to select the best platforms and models available. The main focus of our study was on methodologies that assess at a **geographical level**, rather than those focusing on the corporate level. We also considered the **operability** of the method, looking for those that are usable at various levels, not just in scientific research. Additionally, we evaluated the **validity** of the model based on its publication in high-ranking scientific journals or by well-known international institutes/organizations. We also took into account the **completeness** of the model, ensuring it covers a range of plastic sources and their leakage pathways. This process was designed to assess the quality and robustness of the source data and the methodology behind its development.

The reviewed literature sources were compared to these criteria and comments have been added to give additional information on the data source. Each reference has been given a unique reference code in the EndNote in order to be easily identified within the model.

2.1. Waste Generation Modeling Terminology

When building plastic waste generation models, it is necessary to distinguish whether an estimate of the current or the future generation rate is made. The differences in the terminology regarding Baseline, prediction, forecasting, and projection are provided in the following sections. When creating models for plastic waste generation, it's important to differentiate between estimating the current or future generation rates. The following sections provide explanations of the terminology differences related to Baseline, Prediction, Forecasting, and Projection.

Baseline Analysis

The term "baseline analysis" refers to the process of identifying the type and quantity of waste generated in each waste class. This analysis can specifically focus on the main sources of waste, plastic waste generation, and how plastic waste ends up in the environment. When it comes to plastic waste generation, the baseline analysis can also identify the points where plastic waste is leaked and estimate the amount of plastic waste leaked at each source point. Depending on the scope of the study, the baseline analysis can quantify household waste generation, non-household waste generation, recovered waste quantities, and the amount of municipal solid waste (MSW) disposal.

Forecasting

Forecasting, specifically involves estimating future developments. In waste management, most forecasts focus on waste generation, while forecasts for waste composition and waste treatment are uncommon. When making a forecast, it's important to remember that predicting future developments based on current or historical data is always a challenging task.

Projection

Projections involve estimating future developments, but unlike forecasting, they assume that there will be changes in the boundary conditions such as legislative and technological progress. These conditions, which affect waste generation, cannot be forecasted. Therefore, projections often involve creating future scenarios based on specific boundary conditions chosen by the authors. These scenarios can be developed based on waste management objectives, but any deviations from the corresponding forecast should be minimal.

Impact Analysis

When discussing the generation of plastic waste, it is important to consider the outcomes of direct and indirect intervention in the medium to long term. Some current models for estimating plastic waste generation not only quantify the current rate of waste generation and predict future trends, but also analyze the effects of direct or indirect intervention through scenario analysis. These models estimate future trends in plastic waste generation by comparing the "business-as-usual" scenario with other defined scenarios such as formal/informal collection, sorting/recycling, incineration, etc. In this study, when we refer to impact analysis, we are analyzing the effects of interventions, whether they are direct or indirect.

3. Plastic Waste Generation Models

Table 1 represents a list of selected methodologies for estimating the plastic waste generation or leakage into the environment. This table demonstrates the name of methodology, its common short name, the year of the first release, the main author or group of authors, and also indicates whether it is supported by an online tool for users or not. It also gives the reader an overview of the model and its main application along with the time period it is defined for.

Table 1 Overview of analyzed plastic waste estimation methodologies

Model Name	Overview
Name: Basel Convention Practical guidance for the development of inventories of plastic waste **Short Name: BC Guidance** **Authors: Basel Convention** **Year of Release: 2022** **Online tool: No**	The Basel Convention has developed additional practical guidance for creating inventories of plastic waste. This guidance is intended to assist the Convention's parties in their annual reporting. The guidance outlines three practical methodologies for inventorying plastic waste. Two of these methodologies are used to estimate plastic waste generation (the product lifetime approach and survey approach), while the third focuses on mapping the flow of plastic waste (Material Flow Analysis).
Name: Breaking the Plastic Wave **Short Name: BPW** **Authors: Systemiq/ The Pew Charitable Trust** **Year of Release: 2020** **Online tool: No**	BPW is a modeling approach used to assess global plastic pollution and estimate the amount of plastic entering the oceans. The baseline is calculated for the year 2016, and the model predicts plastic flows and stocks, as well as their impact, by 2030 and 2040. The baseline covers three plastic categories and uses eight geographical archetypes (four income levels, distinguishing between urban and rural areas). The forecast includes six different scenarios (including a business-as-usual 2016 scenario) based on eight possible interventions.
Name: Global Plastic Action Partnership's National Analysis and Modelling tool **Short Name: GPAP NAM** **Authors: Systemiq** **Year of Release: 2022** **Online tool: Yes**	GPAP is an approach used to assess national plastic pollution and estimate the amount of plastic waste entering the oceans. It is based on the BPW methodology and allows users to customize the baseline. The model can predict plastic waste flows and stocks, as well as their impact, up to 2040. It includes preloaded data from Breaking the Plastic Waste (which maps countries to three income archetypes) and from PLASTEAX data for some countries. The model calculates 5 different scenarios (Business as Usual, Upstream, Downstream, System change, Custom scenario) by combining different levers from the following categories: Reduce & Substitute, Redesign, Collection & Sorting, Trade control, Recycle, Disposal, and Mismanaged..
Name: ISWA Plastic Pollution Calculator **Short Name:** ISWA PPC **Authors:** ISWA - International Solid Waste Associations/ University of Leeds **Year of Release:** 2019 **Online tool:** No	The ISWA models focus on the generation of plastic waste for specific items, and how this waste moves through the waste management system and ultimately ends up in the environment. It helps to quantify and prioritize different pathways through which plastic waste can leak into the environment. This tool uses data on solid waste management systems, as well as local socioeconomic, geographical, and meteorological factors.

Model Name	Overview
Name: Minderoo **Short Name: Minderoo** **Authors: Dominici Charles et al/ Minderoo Foundation** **Year of Release: 2021** **Online tool: No**	The Minderoo global single-use plastic tool was created to identify the primary producers of single-use plastic and the amount that ends up as waste. This tool can assess the production and trade of polymers as well as the generation of single-use plastic waste at the country level.
Name: National Guidance for Plastic Pollution Hot Spotting and Shaping Actions **Short Name: UNEP&IUCN Guidance** **Authors: UNEP/ IUCN/ Life Cycle Initiative/ EA – Environmental Action/ Quantis** **Year of Release: 2020** **Online tool: No**	The National Guidance for Plastic Pollution Hot Spotting and Shaping Action aims to help countries identify areas where plastic waste is leaking and prioritize effective interventions to reduce this leakage. It includes a country-level assessment of both micro- and macro-plastic leakage, which is specific to different sectors, types of plastic, and products. This assessment highlights the most problematic sectors, types of plastic, products in specific areas, and waste management practices that contribute the most to plastic leakage. Finally, it provides a list of possible strategies and actions to help reduce plastic waste entering the ocean and waterways.
Name: Breaking the Plastic Wave Plastic Pathways Tool **Short Name: Pathways** **Authors: The Pew Charitable Trusts/ Oxford University** **Year of Release: 2022** **Online tool: No**	The Pathways tool is a free software application and flexible modeling framework that analyzes the movement of plastic throughout the value chain to assess plastic leakage into the environment. It can be used at local, national, regional, or global scales and can simulate plastics flows by plastic category, polymer, or product type. Pathways enhances the "Breaking the Plastic Wave" model by increasing its flexibility and analytical capabilities, such as allowing users to redefine system flows and allowing material to flow between model archetypes.
Name: PLASTEAX **Short Name: PLASTEAX** **Authors: EA – Environmental Action** **Year of Release: 2021** **Online tool: No**	The PLASTEAX tool and methodology aim to establish a baseline for plastic packaging waste management and its leakage into oceans and waterways on a country-by-country basis. The results are specific to the type of polymer and product. As of July 2022, the PLASTEAX database contains baseline assessments for over 43 countries.

Model Name	Overview
Name: Plastic Drawdown **Short Name: Plastic Drawdown** **Authors: Common Seas** **Year of Release: 2019** **Online tool: No**	Plastic Drawdown evaluates the specific challenges of plastic pollution in different countries and recommends a set of policies and actions to reduce plastic pollution in rivers and oceans. It projects the impact of these measures up to 2030 and compares them to the Business-as-Usual scenario. The report offers suggestions for the most effective global measures and how they can be implemented..
Name: Waste Flow Diagram **Short Name: WFD** **Authors: GIZ/ The University of Leeds/ Eawag/ Wastewater** **Year of Release: 2020** **Online tool: Yes**	The Waste Flow Diagram (WFD) is a quick tool used to estimate the amount of municipal solid waste that is leaking into the environment and water from various sources. It uses a Material Flow Analysis (MFA) approach combined with systematic qualitative assessment based on observations, interviews, and data collection from waste management stations. The WFD presents the quantities of municipal solid waste streams within a waste management system in a standardized Waste Flow Diagram and Sankey diagram. This tool allows for the insertion of data based on different scenarios and facilitates comparison of different waste management assessments for planning purposes.
Name: Waste Wise Cities Tool **Short Name: UN-Habitat WaCT** **Authors: UN-Habitat** **Year of Release: 2021** **Online tool: Yes**	The main purpose of this methodology is to provide a comprehensive, step-by-step guide for collecting data on municipal solid waste (MSW) to assess the state of the waste management system. The Excel tool is designed to help centralize and visualize the collected data. Additionally, there is a specific analysis on marine litter.
Name: WWF Monitoring & Evaluation Framework **Short Name: WWF M&E** **Authors: WWF/ EA – Environmental Action** **Year of Release: 2022** **Online tool: No**	The framework is designed to evaluate the effects of direct and indirect measures at the city level, specifically in the context of WWF's Plastic Smart Cities target of achieving a 30% reduction in plastic pollution by 2030. While it doesn't conduct a baseline evaluation on its own, it still requires baseline data to be applied effectively. Therefore, the framework is intended to complement a more technical baseline assessment tool by adding an additional layer of analysis on the impact of measures.
Name: ENV-Linkages Plastic Leakage Model **Short Name: OECD ENV-Linkages** **Authors: OECD** **Year of Release: 2022** **Online tool: Yes**	The OECD ENV-Linkage introduces a new method for modeling and predicting plastic usage and waste by using the OECD ENV-Linkages computable general equilibrium model. This approach was utilized for the OECD Global Plastic Outlook (2022). The projections with ENV-Linkages differ from previous studies due to variations in methodology and data sources, including the projected drivers of future economic growth. This modeling approach offers the advantage of considering structural and technological changes, allowing for a more comprehensive analysis of economic variables, such as the growing importance of services in the economy.

Model Name	Overview
Name: GIS-Based Plastic Generation Modeling **Short Name: GIS-Based Model** **Authors: Asian Institute of Technology/ UNEP** **Year of Release: 2022** **Online tool: No**	In this type of modeling, the goal is to promote evidence-based policy-making by developing a method to identify how plastic waste enters the environment, where it comes from, and how much of it is present throughout the production and consumption process. To achieve this, we will address plastic waste by analyzing waste management practices and by studying how plastic waste moves through the environment. This involves: (i) conducting a material flow analysis to identify areas where plastic waste is most prevalent, and (ii) conducting a hydrological study to understand how plastic waste enters waterways (Tran-Thanh, Rinasti, Gunasekara, Chaksan, & Tsukiji, 2022).
Name: Machine Learning Modeling **Short Name: ANN Model** **Authors: Polytechnic Institute of Coimbra, Portugal** **Year of Release: 2019** **Online tool: No**	The AI-powered machine learning model develops a prediction model for estimating the volume of plastic waste based on historical data at different scales. These types of models can utilize techniques such as Artificial Neural Network (ANN), Random Forest (RF), or other machine learning methods to forecast future plastic waste generation using complex non-linear modeling. One of the strengths of this model is its ability to accurately capture nonlinear relationships within the data.
Name: NOAA Marine Debris Model **Short Name:** NOAA **Authors:** NOAA/ Florida State University **Year of Release:** 2023 **Online tool:** Yes	A team of scientists from Florida State University used data about the types, amounts, and sources of plastic marine debris. They combined this data with information about ocean currents, wind, and waves to create the Global Marine Debris Model. This model visualizes the movement of plastic debris in the ocean environment, showing potential movement throughout the ocean and identifying areas of concentration such as gyres and hot spots.
Name: Guideline for Monitoring Marine Litter on the Beaches in the OSPAR Maritime Area **Short Name:** OSPAR **Authors:** OSPAR Commission **Year of Release:** 2020 (Last Edition) **Online tool:** No	The primary goal of OSPAR beach litter monitoring is to gather data on the amount, types, location and changes over time of litter found on beaches in the OSPAR area. This information can help assess the impact of actions taken at both national and OSPAR levels to decrease marine litter pollution on a large scale, especially in the OSPAR Maritime Region.
Name: Modelling and monitoring marine litter movement, transport, and accumulation **Short Name:** CSIRO **Authors:** Commonwealth Scientific and Industrial Research Organization of Australia/ UNEP **Year of Release:** 2017 **Online tool:** No	This model uses numerical simulations to enhance our understanding of the distribution and pathways of microplastics in the marine environment. It specifically focuses on floating marine microplastics with a diameter of less than 5 mm. The model emphasizes the importance of accurately identifying the sources or entry points of marine plastic debris, including potential sources that have not been considered in previous studies, such as contributions from the atmosphere.

3.1. In-Depth Analysis of the Suggested Models

Table 2 represents the specifications of the studied methods in more detail. In this table, the other specifications of the suggested methodologies are presented which might be useful for planning and management.

In the second column after the name, the processing method associated with each methodology is presented. This column introduces the main methodology applied in the model as follows:

1- **Material Flow Analysis,** also known as substance flow analysis, is a method used to quantify the flows and stocks of materials or substances within a specific system**.**

2- **Statistical Analysis** is the process of collecting, exploring, and presenting large amounts of data to uncover underlying patterns and trends.

3- **Linear regression** is a statistical model that estimates the linear relationship between a single response variable and one or more explanatory variables.

4- **System analysis** is a process of collecting and interpreting facts, identifying problems, and decomposing a system into its components.

5- **GIS processing** involves the use of GIS tools to analyze geospatial data and reveal patterns, relationships, and insights. This includes conducting spatial analysis operations like buffering, overlaying, proximity analysis, spatial querying, and statistical analysis to extract valuable information from the data.(Anastasia Sarelli, 2023).

6- **Numerical modeling** is a widely used technique for addressing complex geological problems through computational simulation of geological scenarios. It involves the use of mathematical models to describe the physical conditions of geological scenarios using numbers and equations (Wikipedia, 2024).

7- **Machine Learning** is a field of study in artificial intelligence concerned with the development and study of statistical algorithms that can learn from data and generalize it to unseen data, and thus perform tasks without explicit instructions.

8- **Leakage Probability Analysis** Refers to the probability of spillage of unmanaged plastic waste that originates on land and reaches the ocean.

The next column represents the Assessment Type, indicating the type of evaluation in 4 categories (Baseline, Forecasting, Projection, Impact Analysis). A detailed definition is provided in section 2.1. The next column represents the scale in which the model is performed on a variety of urban, national, regional, and global levels. Input data refers to the input information that should be entered into the model and output data is the format of output layers or type of information that will be presented after processing by models. At the end of each model, its main reference is presented.

Table 2 Specifications of the analyzed methodologies

(Environmental Action, Cecilia Manzoni, Paola Paruta, & Julien Boucher, 2022; Intersessional Correspondence Group on Marine Litter, Barbara Wenneker, & Lex Oosterbaan, 2010)

Methodology Name	Processing Methods	Assessment Type	Scale	Input Data	Output Data	Reference
BC Guidance	Material flow analysis	Baseline Analysis	National	– The amount of plastic imported – The amount of plastic exported – The amount of plastic domestically produced	The weight of plastic (PE, PP, PS, PET, PVC, PUR, Others) by sectors for the desired timeframe and calculation of the generated plastic waste.	(Archana Pisharody & David Lerpiniere, 2021)
BPW	System Analysis/ Statistical Analysis/ etc	Baseline Analysis/ Projection/ Impact Analysis	Global/ National	Breaking the Plastic Wave uses archetypes based on income levels and rural/urban population splits to estimate waste generation and waste management practices globally. However, if you want to use the BPW at a national level, you will need to calculate the total waste input for that country and adjust the scenario assumptions accordingly.	Variable. The tool includes default data for all mass flows, costs, GHG emissions, and job impacts for eight geographic archetypes (high-income urban, rural, upper-middle-income urban, rural, etc.). However, any updates to this data or the creation of country-specific data overrides will take as much time as needed to ensure accuracy for the specific use case.	(Nordic Council of Ministers, 2020)
GPAP NAM	System Analysis/ Statistical Analysis/ etc	Baseline Analysis/ Projection/ Impact Analysis	National	It is designed to use data from external databases, such as PLASTEAX (EA – Environmental Action) data, or What a Waste (World Bank Group) combined with the results from the BPW report.	– Assessment of a business-as-usual, Upstream, Downstream, System changes, and Customized scenario. – Information about the key metrics of Plastic Pollution, Cost to government, Livelihoods supported, GHG emissions, Circularity score, and Source of plastics.	(UNEP, 2023)
ISWA PPC	Leakage Probability Analysis/ Material flow analysis	Baseline Analysis	Urban	– Population statistics – Per capita waste generation – Per capita waste composition – Formal/informal collection/ Recycling/ Landfilling – Energy recovery – Composting – Uncollected plastic waste	– Uncollected waste – Littered waste – Residual streams waiting for collection – Primary and secondary transportation – Residual streams – Informal sector – Disposal – Treatment	(International Solid Waste Associations & University of Leeds, 2019)

Methodology Name	Processing Methods	Assessment Type	Scale	Input Data	Output Data	Reference
Minderoo	Linear Regression	Baseline Analysis	Global National	– Identification of 1,200 production facilities globally that produce the five main polymers – Tracking of the trade of the polymers at global level – The proportion of polymers that have been converted into Single-Use-Plastics – The volume of SUPs traded in bulk	– Single-use plastic waste generation by country; by polymer type; by rigid or flexible format – An estimation of SUP waste in each country globally	(Dominic Charles & Laurent Kimman, 2021)
UNEP&IUCN Guidance	Canvas/ COMTRADE/ GIS Processing/ Statistical Analysis	Baseline Analysis	National	– Import and export of plastic by polymer – Production of plastic by polymer – Recycling of plastic by polymer – Share of MSW uncollected, incinerated, etc – Waste management data – Specific information for the textile, automotive, and fishing sector – Prioritization of proposed intervention and instruments	– Sector-, Polymer- and Product- specific information – Maps showing waste management and leakage at the sub-national level – Charts with a prioritization of intervention and instruments	(UNEP & IUCN, 2021)
Pathways	Statistical Analysis/ Plastic value chain analysis	Baseline Analysis/ Projection/ Impact Analysis	Global National Urban	– Key stocks and flows of macroplastics – Waste management costs – Revenue from recycling and incineration – Number of people employed throughout the plastics value chain – Key stocks and flows of microplastics	– Plastic flows, costs, jobs, and greenhouse gas emissions under business-as-usual and scenarios with customized interventions – Trade-offs among potentially competing policy objectives to identify optimal solutions	(Environmental Action et al., 2022)
PLASTEAX	MULTI–dimensional statistical analysis/ Interviews	Baseline Analysis	National	– Import and export of plastic by polymer – Production of plastic by polymer – Recycling of plastic by polymer – Share of MSW uncollected, incinerated, sent to sanitary landfill, improperly disposed of, collected for recycling by the informal sector	Packaging polymer- and product-specific information on: – Waste generated – Domestic recycling – Export of waste, Incinerated – Sent to Sanitary landfill – Improperly disposed, Uncollected – Mismanaged – Leaked to ocean and waterways	(Environmental Action et al., 2022)

Methodology Name	Processing Methods	Assessment Type	Scale	Input Data	Output Data	Reference
Plastic Drawdown	Statistical Analysis	Baseline Analysis/ Projection/ Impact Analysis	National	– Country-level waste and consumption data – Historical data on waste management and Consumption – Baseline transmission factors, representing the relative amount of plastic waste along each pathway – Timeframe and immediacy of each selected policy intervention	– Baseline assessment of the amount of plastic from different waste sources – Business-as-usual projection of annual plastic emissions – Modelling and visualization of the interventions that could have the greatest potential impact on reducing plastic waste leakage	(Royle et al., 2022)
WFD	Linear Regression	Baseline Analysis/ Link to SDG indicators	Urban	– Waste generation information – Waste treatment and disposal – Managed in controlled facilities – Plastic leakage potential levels per leakage influencer – Plastic pollution levels per fate	– A waste flow diagram per baseline or scenario and per material – A summary table including waste management flows for both plastics only and general MSW, – A summary table on sources, pathways, and fates of unmanaged plastic pollution	(GIZ, University of Leeds, Eawag-Sandec, & Wasteaware, 2020)
UN-Habitat WaCT	Linear Regression	Baseline Analysis	Urban	– Population statistics by income levels – Household waste composition – Data on municipal solid waste generation – Data from disposal facilities – Data from recovery facilities	– waste collection performance and waste generation factors – Summary table for household waste generation – Summary table for non-household waste generation – Summary table for recovered waste quantities – Summary table for MSW disposal – Flow diagram summarizing the data collected and relative flows in tones/day	(UN Habitat, 2021)

Methodology Name	Processing Methods	Assessment Type	Scale	Input Data	Output Data	Reference
WWF M&E	Statistical Analysis	Impact Analysis	Urban	– Plastic waste generation per capita – Uncollected plastic waste – Plastic waste properly and improperly disposed	– Actual plastic leakage to the environment – Actual reduction based on the implemented interventions – Potential leakage reduction, – Qualitative evaluation of the interventions in terms of reducing the overall plastic leakage in the city	(WWF, 2022)
OECD ENV-Linkages	Regression Analysis/ System Analysis	Projection	Regional	– Plastics production and consumption by economic sector – Regional flows of a range of plastic polymers and application	– Current rate of Plastics use, waste, and leakage – Rate of plastic leakage to aquatic environments – Projected growth of plastic use, waste, and leakage	(OECD, 2022b)
GIS-Based Models	GIS Processing By Fuzzy Overlay Analysis	Projection	Urban	– Plastic leakage density – Plastic leakage source hotspots – Leakage pathway accumulation	– Mapping of plastic leakage density – Identifying plastic leakage source hotspots – Identifying plastic leakage accumulation	(Tran-Thanh et al., 2022)
Machine Learning	Artificial Neural Network/ Random Forest/ etc	Projection	Urban National	– level of education of the population – The size and level of urbanization – Social aspects related to poverty and economic power – Factors intrinsic to the waste collection service	Estimation of the annual amount (kg/inhabitant/year) of separately collected household packaging waste at various scales	(Oliveira, Sousa, & Dias-Ferreira, 2019)

Methodology Name	Processing Methods	Assessment Type	Scale	Input Data	Output Data	Reference
NOAA Marine Debris Model	Numerical Modeling	Projection	Global	– Air pressure – Water density – Wind stress – Temperature – Salinity	– The transport of floating marine debris – The likely fate of debris from known point sources, population centers, or extreme events such as hurricanes and tsunamis, – Identify potential sources of debris	(NOAA, 2023)
OSPAR	Statistical Analysis	Baseline Analysis	Regional	The number of following items found in the sampling beach: Plastic/ Rubber/ Cloth/ Paper/ Wood/ Metal/ Glass/ Pottery/ Sanitary/ Medica/ Faeces/ Other	The methodology provides information on the quantities, trends, and sources of marine litter in the OSPAR region. This information can be utilized to focus on effective measures for mitigation and to assess the effectiveness of current legislation and regulations.	(Intersessional Correspondence Group on Marine Litter et al., 2010)
CSIRO	Numerical Modeling	Projection	Global	– Oceanic compartments – Fluxes, distribution and hotspots – Litter sources – Changes in debris with time – Sinks of debris	– Minimum travel time for particles from coastlines to the ocean – Relative density of plastic debris in surface trawl data around the globe	(Hardesty et al., 2017)

4. Application of the Suggested Models

Table 3 provides a summary of the recommended models categorized by their application in reducing plastic pollution. In contrast to the previous section, which presented the models based on their applications, here we begin by outlining the desired applications of the plastic pollution models and then introduce the most relevant models for each application. The potential applications include inventory and data collection, national and regional planning, global advocacy and investment, specific area assessment and management, monitoring and evaluation, regulation, and global monitoring. Additionally, the table includes the most relevant land uses and geographical coverage. A brief description of each application is presented as follows.

1) **Inventory and Data Collection:** This forms the foundation for all other activities. It involves gathering information on plastic pollution, including types, sources, quantities, and distribution in the environment. This data is crucial for informing effective strategies and monitoring progress.
2) **National and regional planning:** This involves establishing strategies and policies to address plastic pollution at the national or regional level. It considers factors like waste generation, collection systems, and infrastructure.
3) **Global advocacy and investment:** This refers to efforts to raise awareness and secure funding for tackling plastic pollution on a global scale. It involves mobilizing governments, industries, and NGOs.
4) **Specific area assessment and management:** This focuses on evaluating plastic pollution in a particular location, like a specific waterway or coastline. It involves data collection and analysis to inform targeted management plans.
5) **Monitoring and evaluation:** This refers to the ongoing process of tracking progress in reducing plastic pollution. It involves collecting data on waste generation, management practices, and environmental impact.
6) **Regulation:** This involves establishing laws and policies to control plastic production, use, and disposal. It aims to promote responsible plastic use and reduce plastic pollution.
7) **Global monitoring:** This refers to the systematic collection of data on plastic pollution on a global scale. It helps assess the overall extent of the problem and track progress over time.

Table 3 Summary of the Models Application

<table>
<tr><th colspan="13">Inventory and Data Collection</th></tr>
<tr><td>Model</td><td colspan="12">Basel Convention</td></tr>
<tr><td>Application</td><td colspan="12">Develop national inventories to track plastic waste generation and disposal patterns</td></tr>
<tr><th colspan="13">National and Regional Planning</th></tr>
<tr><td>Model</td><td colspan="4">Global Plastic Action Partnerships (GPAP)</td><td colspan="4">Breaking the Plastic Wave Pathways Tool</td><td colspan="4">National Guidance for Plastic Pollution</td></tr>
<tr><td>Application</td><td colspan="4">Assists countries in creating national action plans based on their plastic waste profiles</td><td colspan="4">Models the potential impact of plastic pollution reduction policies and interventions</td><td colspan="4">Identifies plastic pollution hotspots within a country to prioritize cleanup efforts and develop targeted action plans</td></tr>
<tr><th colspan="13">Global Advocacy and Investment</th></tr>
<tr><td>Model</td><td colspan="6">Minderoo</td><td colspan="6">Plastic Drawdown</td></tr>
<tr><td>Application</td><td colspan="6">Advocates for systemic changes to reduce plastic pollution globally</td><td colspan="6">Identifies and promotes solutions for reducing plastic use and improving plastic waste management across different sectors</td></tr>
<tr><th colspan="13">Specific Area Assessment and Management</th></tr>
<tr><td>Model</td><td colspan="4">ISWA Plastic Pollution Calculator</td><td colspan="4">GIS-based Plastic Generation Modelling</td><td colspan="4">Machine Learning Modelling</td></tr>
<tr><td>Application</td><td colspan="4">Estimates plastic pollution generation in a specific area to inform waste management strategies</td><td colspan="4">Develops spatial models to estimate plastic waste generation within a specific area</td><td colspan="4">Develops models to predict plastic waste accumulation in specific areas based on historical data and environmental factors</td></tr>
<tr><th colspan="13">Monitoring and Evaluation</th></tr>
<tr><td>Model</td><td colspan="3">WWF M&E</td><td colspan="3">OSPAR Guideline for Monitoring Marine Litter</td><td colspan="3">NOAA Marine Debris Model</td><td colspan="3">CSIRO Modelling and Monitoring</td></tr>
<tr><td>Application</td><td colspan="3">Design monitoring programs to track the effectiveness of plastic pollution reduction interventions within a specific project</td><td colspan="3">Conducts standardized monitoring of marine litter on beaches to track trends and inform regional management strategies</td><td colspan="3">Predicts the movement and accumulation of plastic debris in oceans, informing cleanup efforts and protecting marine ecosystems</td><td colspan="3">Monitors plastic movement, transport, and accumulation</td></tr>
<tr><th colspan="13">Regulation</th></tr>
<tr><td>Model</td><td colspan="12">Waste Framework Directive</td></tr>
<tr><td>Application</td><td colspan="12">Regulates plastic waste management practices within the EU to promote recycling and reduce plastic pollution</td></tr>
<tr><th colspan="13">Global Modelling</th></tr>
<tr><td>Model</td><td colspan="12">OECD ENV-LINKAGE</td></tr>
<tr><td>Application</td><td colspan="12">Models environmental pressures associated with human activities, including plastic pollution, at a global scale</td></tr>
</table>

Choosing the best model depends on the specific application. If the aim is to develop a national plan, the GPAP or Breaking the Plastic Wave Pathways Tool might be suitable. For local waste management strategies, the ISWA Calculator or GIS-based models could be helpful. In addition, some models can be adapted for different land uses depending on the project's design.

4.1. Time-Frame of the Forecasting Models

Table 4 provides the time frames for the application of different forecasting models. The forecasting methods are divided into four categories: long-term forecasting, medium-term forecasting, short-term forecasting, and flexible time frames. The rationale behind categorizing the models based on their time frame (short-term, medium-term, long-term forecasting) is provided as follows:

1. **Model Purpose and Design:** Each model is designed to address a specific aspect of plastic pollution and has a built-in timeframe for its forecasts or outputs.
    - Short-term models (e.g., ISWA Plastic Pollution Calculator) are typically designed for quick assessments or to inform immediate decisions. They focus on data collection and analysis for a short period, like a day or a week.
    - Medium-term models (e.g., Basel Convention) aim to track trends and project impacts over a time horizon of several years (2-10 years). They consider historical data and use it to make projections about future trends.
    - Long-term models (e.g., Breaking the Plastic Wave) focus on far-reaching goals and project potential scenarios over extended periods (10+ years). They often involve complex simulations and economic factors.
2. **Data Requirements:** The type of data a model uses influences its forecasting timeframe.
    - Short-term models often rely on readily available data from ongoing monitoring or on-site measurements.
    - Medium-term models might use historical data along with projections based on economic or demographic trends.
    - Long-term models incorporate complex datasets and require significant computational power to forecast over extended periods.
3. **Stakeholder Needs:** The stakeholders who use the models often have specific timeframes in mind.
    - Short-term models cater to entities needing immediate insights, like waste management companies for operational planning.
    - Medium-term models are valuable for policymakers who require projections to inform mid-term strategies.
    - Long-term models provide a vision for long-range planning and goal setting, as seen with initiatives like Breaking the Plastic Wave (2040 target).

According to the table, BPW and Minderoo utilize long-term forecasting, which looks ahead to 10 or more years. Basel Convention, ENV-Linkage & WWF M&E Framework fall under medium-term forecasting, covering a period of 2 to 10 years. ISWA, Pathway Tools, and NOAA forecast plastic generation within a period of less than 2 years. Other methods have a flexible time frame that depends on project design and national action plans. It's important to note that models not listed in this table are not time-constrained or are focused on real-time data from online databases.

Table 4 Time frame of the forecasting method of the models

Time frame	Models
Long-Term Forecasting (10+ years)	• Breaking the Plastic Wave (2040 Target) • Minderoo (Aligned with long-term goals)
Medium-Term Forecasting (2-10 years)	• Basel Convention (Recommended 5 to 10 years of data) • Env-Linkage Plastic Leakage Tool • WWF M&E Framework (Project-specific timeframe)
Short-Term Forecasting (Less than 2 years)	• ISWA Plastic Pollution Calculator (on-the-spot-assessment) • Breaking the Plastic Wave Pathway Tool (user-defined timeframe) • NOAA (Short to medium term)
Flexible Time Frame	• National Guidance for Plastic Pollution (Ongoing hotspot identification) • Plasteax (Focuses on up-to-date data) • Global Plastic Action Partnerships-GPAP (Depends on national action plan) • GIS-Based Plastic Generation Modeling • Machine Learning Modeling • CSIRP (Depends on project design)

4.2. The Target Audience of the Models

Table 5 shows the target audience recommended for each methodology introduced, based on the comprehensive literature review on all 18 introduced models. The users of each method vary based on the project's objective, complexity, user capacity, and time frame. Some models are designed for professionals in highly specialized organizations, some for academic and educational purposes, focusing on a narrow range of plastic materials, and others for use by municipalities, and national governments, and as a basis for policy and planning. We suggest target groups based on method complexity and accessibility for all.

Table 5 The Suggested Target Groups and Stakeholders for Applying Each Method

Stakeholders	Most Relevant Models
National Governments	Basel Convention, Global Plastic Action Partnerships (GPAP), National Guidance for Plastic Pollution, Breaking the Plastic Wave Pathways Tool, OECD ENV-Linkages plastic leakage model
International Organizations	Breaking the Plastic Wave, OECD ENV-Linkages plastic leakage model
Local Authorities	Global Plastic Action Partnerships (GPAP), ISWA Plastic Pollution Calculator, Waste Wise Cities
Waste Management Companies	Basel Convention, ISWA Plastic Pollution Calculator, Breaking the Plastic Wave Pathways Tool, National Guidance for Plastic Pollution, Waste Wise Cities
Environmental Agencies	Basel Convention, National Guidance for Plastic Pollution, OSPAR Guideline for Monitoring Marine Litter, CSIRO Modelling and Monitoring
Recycling Industries	Basel Convention, National Guidance for Plastic Pollution
Philanthropists & Investors	Minderoo
NGOs	Breaking the Plastic Wave, Global Plastic Action Partnerships (GPAP), Minderoo, National Guidance for Plastic Pollution, Breaking the Plastic Wave Pathways Tool, Plasteax, WWF Monitoring and Evaluation Framework, OSPAR Guideline for Monitoring Marine Litter, CSIRO Modelling and Monitoring
Researchers	Plasteax, OECD ENV-Linkages plastic leakage model, WWF Monitoring and Evaluation Framework, OSPAR Guideline for Monitoring Marine Litter, CSIRO Modelling and Monitoring (plastic transport), NOAA
Policymakers	Breaking the Plastic Wave, Breaking the Plastic Wave Pathways Tool, OECD ENV-Linkages plastic leakage model, National Guidance for Plastic Pollution, Waste Wise Cities, CSIRO Modelling and Monitoring (plastic transport)
Citizens	Waste Wise Cities
Community Groups	Global Plastic Action Partnerships (GPAP), Waste Wise Cities
Marine Conservation Organizations	OSPAR Guideline for Monitoring Marine Litter
Coastal Management Authorities	CSIRO Modelling and Monitoring (plastic transport)

4.3. Suggested Land Uses of the Models

Categorizing these models by specific land uses like densely populated areas, rural zones, or agricultural areas can be challenging, because many models focus on plastic pollution issues at a national or global scale, making it difficult to pinpoint a specific land use. Also, the model's applicability to a land use depends on the data it requires. For instance, a model designed for waste generation in urban areas might not be suitable for rural areas due to limited data availability. However, some models might be a better fit for certain land uses due to their focus:

- **Urban Areas:** Models like ISWA Plastic Pollution Calculator or Waste Wise Cities could be relevant for urban areas as they deal with on-the-spot assessment and waste management practices in cities.
- **Rural Areas & Agricultural Areas:** Global or national models like the Basel Convention or OECD ENV-Linkages might still be applicable for rural and agricultural areas, but their effectiveness would depend on the data availability for those specific regions.
- **Industrial Sites:** The Basel Convention, which tracks plastic waste generation across various sectors, could be relevant for industrial sites. Additionally, models focusing on plastic pollution pathways (e.g., CSIRO Modelling and Monitoring) could be useful for understanding plastic movement from industrial areas.
- **Wetlands & Coastal Areas:** OSPAR Guideline for Monitoring Marine Litter specifically targets coastal areas, while the NOAA Marine Debris Model focuses on plastic accumulation in the world's oceans.

Overall, while a definitive land-use categorization might not be possible for all models, understanding their purpose and data requirements can provide insights into their potential applicability to different land uses.

5. Conclusion

Table 6 summarizes the results of the plastic generation estimate methodologies benchmarking conducted in this study. 18 methodologies and/or tools for assessing plastic flows and leakage within the waste management chain have been reviewed. Tools and methodologies for assessing a specific product at the company level have not been included in the study.

As this table shows, the scale in which each methodology is performed is different. Some of them such as ISWA, WFD, WaCT, and WWF M&E just focus on urban scales, while others such as BPW, Minderoo, and Pathways target a wider national or regional scale. NOAA, OSPAR, and CSIRO are those that can perform analyses at a global scale.

To choose a methodology, it's important to first determine the type of waste that will be analyzed. Factors to consider include whether the plastic in general municipal waste is granular enough, and whether the assessment should focus specifically on the packaging sector or be divided into different product categories or polymers. Polymer-specific analysis can only be done with PLASTEAX, the ISWA Calculator, Pathways, or the national Guidance (UNEP & IUCN). Another consideration is whether industrial waste should be included in the analysis. Additionally, only Breaking the Plastic Wave, the National Guidance (UNEP & IUCN), Plastic Drawdown, and Pathways allow for the assessment of microplastics. Also, it is important to know the movement and transportation of marine debris through the oceanic circulations, and the types of analysis which is operated by NOAA, OSPAR, and CSIRO. Machine Learning modeling can perform for any type of waste as they are able to be customized for each type of waste and GIS-Based models are also best performed with municipal waste and packaging. OECD-Linkage best fits with all types of waste except microplastic and product-specific packaging.

All the methodologies, except for the WWF M&E Framework, allow for baseline assessment. Breaking the Plastic Wave, GPAP NAM tool, Plastic Drawdown, and Pathways include forecasting analysis and the ability to predict the impact of direct measures, such as policies or bans, over time. The WFD, ISWA PPC, and Pathways allow for fine-tuning parameters to compare different scenarios and compare the results if different actions were implemented. The WWF M&E Framework has been specifically developed to assess indirect measures through indicators such as waste generation reduction and the number of people affected by the interventions. NOAA, OSPAR, and CSIRO focus on predicting marine debris through oceanic flows. Machine Learning models are designed to predict the rate of plastic waste generation considering the past trends and OECD-Linkage is designed to reflect the various scenarios in 2040 in terms of waste generation. GIS-Based models predict the amount and the possible location of plastic hotspots in an urban area.

In this study, two additional indicators were defined to account for differences in methodologies and tools. These indicators are Data collection complexity and Technical (software) expertise. Each indicator was assigned a label (low, medium, high) to help users make a comprehensive preliminary assessment of the effort required to apply a method.

It's important to note that these methodologies can complement each other. For instance, the UN-Habitat WaCT can be used to enhance the data collection process of the WFD. Country baseline data from PLASTEAX (available at polymer and product-specific levels) can also be utilized to support secondary data collection in other tools, like the GPAP NAM or Pathways tools.

The WWF Monitoring and Evaluation (M&E) Framework necessitates the completion of a baseline assessment prior to being able to assess the effectiveness of interventions. In this scenario, a baseline tool at either the municipal or national level can be utilized, depending on the geographical scope of the interventions that the user wishes to evaluate.

The Machine Learning Model can utilize initial data from other models to track trends and predict future plastic waste generation. The GIS-based model can use data from WFD, UN-Habitat WaCT, and WWF M&E as a reference for site location and waste transfer analysis. NOAA, OSPAR, and CSIRO complement each other in predicting marine debris transmission in oceanic currents, and can also use each other's data and input information. In the last part of this table, the release date of each model is presented to give a reader a snapshot of the chronical sequence of the models and their progress during the time.

5.1. Step By Step Methodology Selection

Figure 1 illustrates the step-by-step procedure of the model development. As this figure shows the first step in developing any plastic estimation model is to define the geographical scale. We need to know whether the model is applicable at the international, national, or urban scale. Then based on the information presented in Table 6, the suitable model can be adopted.

The next step for developing a plastic waste estimation model is to determine what is the desirable waste category. Does it focus on municipal waste, industrial waste, microplastic, polymer-specific, product-specific, packaging and food waste, or other categories than plastic? The suitable template model for each of these selections is presented in Table 6.

Next, we need to define the type of assessment. This involves determining whether the model focuses solely on a baseline study, forecasts the future situation of plastic generation based on fixed variables, or predicts a longer-term future based on user-defined scenarios. Lastly, we need to determine whether the model analyzes the impacts of plastic pollution on the land and aquatic environment.

Step 4 involves determining the complexity of the data gathering and the required expertise for developing the model. It's essential to assess the available expertise and databases to decide whether the model will require extensive data gathering and be highly complex, moderately complex, or have the lowest level of complexity.

Finally, we need to determine the specific application of the model. In this stage, we define whether the model solely focuses on inventory and data collection, national and regional planning, global advocacy and investment, specific area assessment, and management, monitoring and evaluation, regulation, and global modeling.

The template for each of these categories has been summarizes in Table 6. The developers can get the benefit of the pre-designed models and templates based on the defined requirements, resources, and expertise.

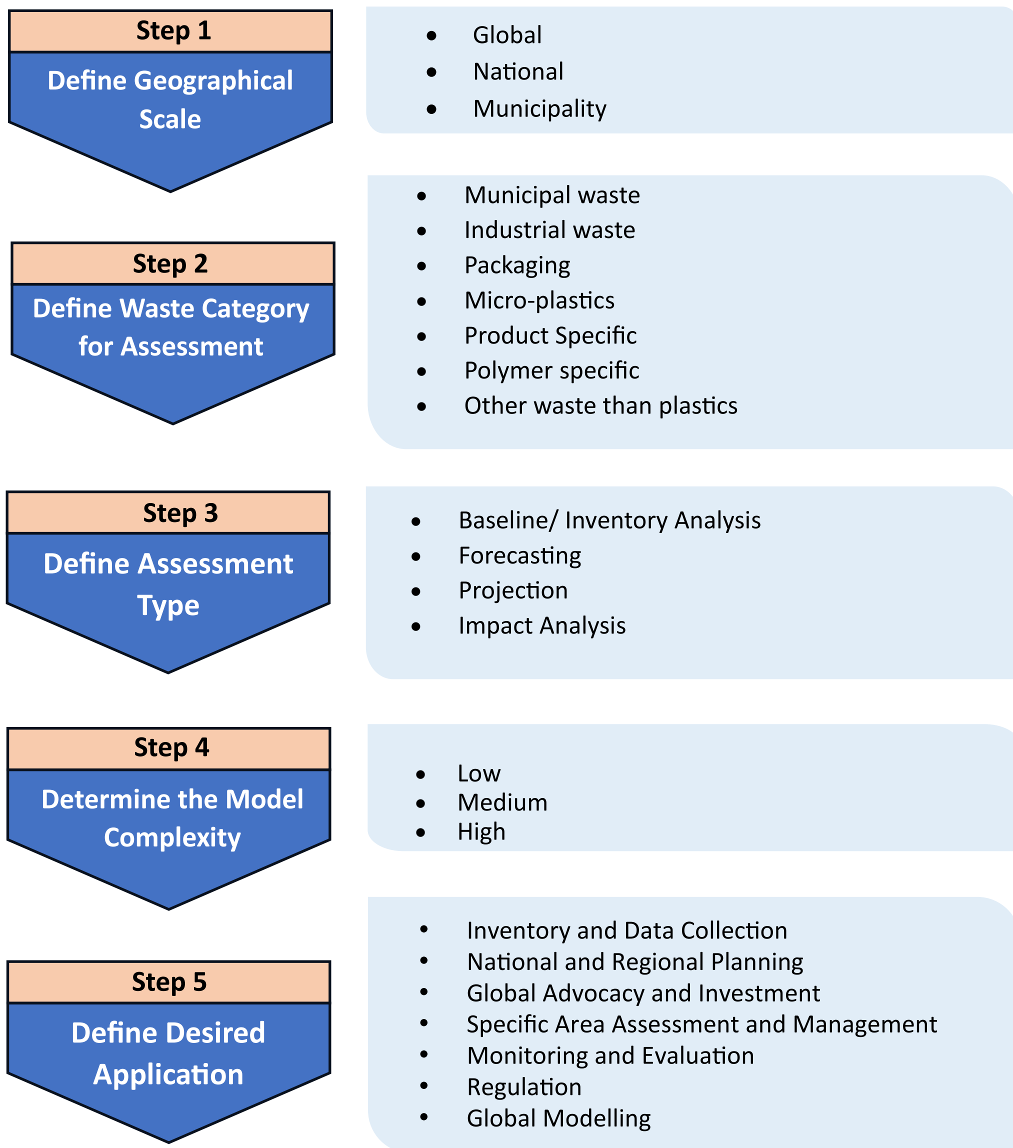


Figure 1 Step-by-step methodology selection

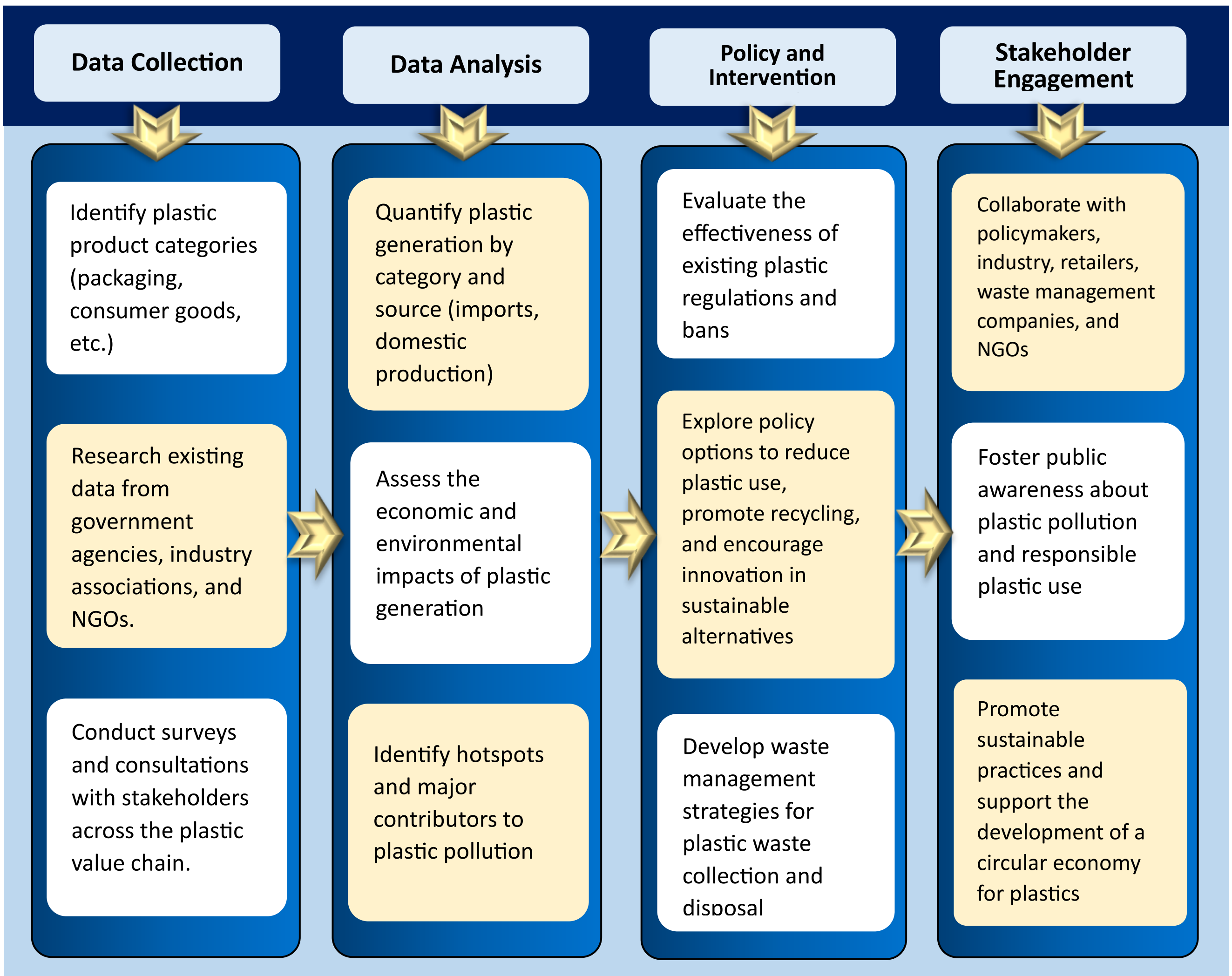
Table 6 A summary of the benchmarking of plastic generation estimate methodologies

		BC Guidance	BPW	GPAP NAM	ISWA PPC	Minderoo	UNEP&IUCN Guidance	Pathways	PLASTEAX	Plastic Drawdown	WFD	UN-Habitat WaCT	WWF M&E	OECD ENV-Linkages	GIS-Based Models	Machine Learning	NOAA	OSPAR	CSIRO
Geographical Coverage	Global		✓			✓		✓						✓			✓	✓	✓
	National	✓	✓	✓		✓	✓	✓	✓	✓				✓		✓		✓	
	Urban	✓			✓			✓			✓	✓	✓		✓	✓			
Waste Breakdown	Municipal Waste	✓	✓	✓	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓			
	Industrial Waste	✓					✓	✓		✓		✓	✓	✓		✓			
	Packaging	✓					✓	✓		✓		✓	✓		✓	✓			
	Microplastic	✓	✓	✓		✓	✓	✓	✓	✓			✓			✓			
	Product-Specific	✓	✓	✓	✓	✓	✓	✓	✓	✓				✓		✓			
	Polymer Specific	✓				✓	✓	✓	✓					✓		✓			
	Waste Other than Plastic				✓			✓			✓	✓		✓	✓	✓			
	Marine Debris																✓	✓	✓
Assessment Type	Baseline	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓			✓	✓	✓
	Forecast		✓	✓	✓			✓		✓		✓							
	Prediction														✓	✓	✓	✓	✓
	Impact Analysis		✓	✓				✓		✓			✓						
Technical Requirement	Data Collection Complexity	M	L	L	H	M	L	L	L	M	M	H	M	H	M	M	M	M	M
	Technical Expertise	L	H	L	M	L	M	M	H	L	L	L	L	M	M	H	H	H	H
Date	Release Year	2022	2020	2022	2019	2021	2020	2022	2021	2019	2020	2021	2022	2022	2022	2019	2023	2020	2017

L: Low, M: Medium, H: High

5.2. A Roadmap Toward Developing a Plastic Generation Estimation Model

Figure 2 illustrates a proposed roadmap to address plastic pollution at a national level. This roadmap involves collaboration among various stakeholders, including the government, businesses, and citizens. A national roadmap to evaluate plastic pollution generation is crucial for several reasons. First of all, it identifies the scope of the problem. Quantifying plastic pollution generation helps understand the severity of the issue and target areas for intervention. Secondly, it informs policymaking. Data-driven insights from the roadmap guide policymakers in developing effective regulations and strategies to curb plastic use. And lastly, it can assist in monitoring the progress. The roadmap establishes benchmarks to track progress over time and measure the effectiveness of implemented solutions.



Annex 1- Plastic Waste Leakage Sources

In 2019, macro-plastics (pieces larger than 5 mm) accounted for 88% of plastic leakage into the environment, totaling around 20 million metric tons and causing pollution in all ecosystems. Single-use products like bottles, caps, cigarettes, shopping bags, cups, and straws contribute significantly to the world's plastic pollution problem. (IUCN, 2024). In the marine environment, plastic pollution originates primarily from land runoff but includes paint shed from shipping, discarded fishing gear, and more.

The current use of plastics is not sustainable. In 2019, out of the 353 million metric tons of global plastic waste generated, only around 55 million metric tons were collected for recycling, and 22 million metric tons of that were disposed of. Secondary plastics made up just 6% of total plastic use in 2019. Additionally, 67 million metric tons of plastic waste and residues were incinerated in industrial facilities, and 174 million metric tons were disposed of in sanitary landfills. The amount of mismanaged and littered plastic waste is increasing, reaching 82 million metric tons per year. Mismanaged waste, inadequately disposed of, accounted for the largest leakage source at 82%, while other sources included abrasion and losses of microplastics (12%), littering (5%), and marine activities (1%) (OECD, 2022a). From production to disposal, plastics interact with the economy and the environment in complex ways, requiring understanding for effective policies.

Rivers are the main route through which plastics enter the ocean. This process can take years or even decades. In 2019, an estimated 6.1 million tons of plastic waste ended up in aquatic environments, with 1.7 million tons flowing into the ocean. This brings the total accumulated stock of plastics in aquatic environments in 2019 to 139 million tons. Although the estimated inflows are lower than in earlier studies that did not account for the residence time of leaked plastics in rivers, the amount is still alarming.

Overall, these quantified insights, along with a growing understanding of the environmental, health, and economic impacts, emphasize the necessity for a comprehensive policy package and international collaboration to promote greater circularity of plastics across the value chain. Figure 3 illustrates a schematic view of the main sources of plastic leakage into the aquatic environment.

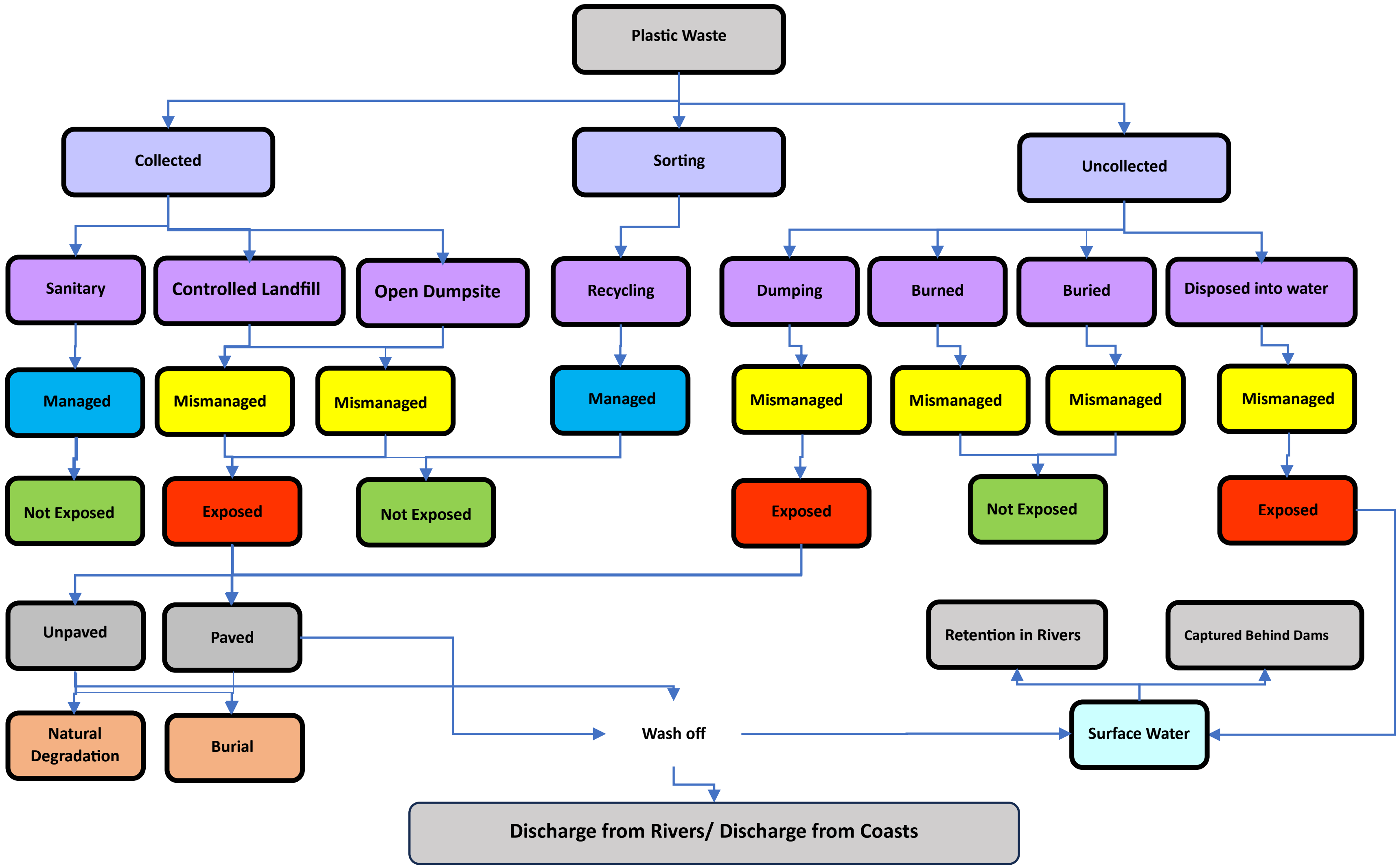


Figure 3 schematic view of the main sources of plastic leakage into the aquatic environment (Veiga et al., 2023)

Annex2- A Snapshot to Data Analysis Method

This annex provides some information on the data analysis method, which is phase 2 of developing a roadmap for plastic pollution estimation methodologies. As probably the main goal of estimating plastic generation at the national level is providing a baseline for policy-making and planning in the long and medium term, a combination of some methods could be beneficial. So, a list of suggested methods for analyzing data on plastic generation estimation is presented as follows:

1. **Rapid Assessment Methods:** Conduct waste characterization studies and stakeholder surveys to get a quick understanding of plastic use patterns, waste generation hotspots, and stakeholder perspectives. This provides valuable baseline data for policymakers.
2. **Material Flow Analysis (MFA):** This method offers a comprehensive picture of the plastic flow in Kenya's economy. It tracks plastic from production and consumption to waste generation and disposal. By understanding these flows, policymakers can identify areas for intervention and design targeted strategies to reduce plastic use, promote recycling, and improve waste management.
3. **Econometric Modeling:** This method can help assess the economic impacts of different policy options. For instance, you can model the potential effects of a plastic bag ban or a plastic tax on plastic consumption and waste generation. This helps policymakers design cost-effective policies that achieve environmental goals.

By combining these methods, a good understanding of plastic pollution could be obtained and inform effective short- and long-term policy decisions.

For the specific purpose of this report which is inventory and data collection for further policy-making and planning the Rapid Assessment Method is suggested for data analysis. The Rapid Assessment Method assists in assessing an inventory of plastic generation, consumption, and leakage at a national level and provides a quick insight into the country's baseline on plastic pollution. There are three phases for the rapid assessment method as listed below:

1. **Waste Characterization Studies:** Conduct rapid waste audits at key locations (beaches, dumpsites, landfills) to identify the composition and quantity of plastic waste. This provides a snapshot of plastic use patterns and leakage into the environment.
2. **Market Analysis:** Assess data on plastic imports and domestic production of plastic products. Industry reports and trade data can offer insights into plastic usage trends.
3. **Stakeholder Surveys:** Conduct surveys with policymakers, industry representatives, and retailers to estimate plastic consumption patterns and identify areas for intervention.

There are some mathematical formula for estimating plastic waste generation that can provide a very preliminary snapshot of the plastic inventory at the national level. While there's no universally accepted formula for rapid plastic pollution assessment, some methods utilize conversion factors to estimate plastic pollution generation based on data availability. Here's a general formula that can be adopted for the specific purpose of this report (Jambeck & Johnsen, 2015):

Estimated Plastic Pollution (EPP) = Plastic Consumption (PC) x Mismanaged Plastic Factor (MPF)

- **EPP:** Represents the amount of plastic entering the waste stream and potentially polluting the environment.
- **PC:** Represents the total plastic consumption within a specific region or timeframe. This data can be acquired from plastic production statistics or waste generation surveys.
- **MPF:** Represents the fraction of plastic mismanaged through littering, improper disposal, or inadequate waste collection. This factor can vary depending on waste management infrastructure and consumer behavior.

By incorporating local data on plastic consumption and mismanaged waste percentages, this formula can provide a preliminary assessment of plastic pollution generation. Remember, this is an estimate and may not account for complexities like plastic recycling rates or specific plastic types.

Another approach to estimating plastic pollution generation is through the Plastic in Leakage (PIL) formula:

PIL = (Plastic Production (PP) + Plastic Imports (PI)) - (Plastic Exports (PE) + Plastic Waste Recycled (PWR))

This formula considers the plastic entering a specific region and subtracts the amount that leaves through exports or recycling.

Here's a breakdown of the variables:

- **PIL:** Plastic Leakage (amount of plastic entering the waste stream and potentially polluting the environment)
- **PP:** Plastic Production within the region
- **PI:** Plastic Imports
- **PE:** Plastic Exports
- **PWR:** Plastic Waste Recycled

Both formulas are the simplest in terms of data collection and complexity based on the specific project needs. While they may not provide categorized information on the types of plastic waste, the size (micro or macro plastic), or the fate of plastic, they do offer an initial overview of mismanaged plastic waste that could end up in the oceans and waterways. Using these formulas, a baseline of plastic inventory can be established, which can then be used for future policy-making and national-level planning.

References

Anastasia Sarelli. (2023). GIS and its 5 most common processes. Retrieved from https://www.geo.university/pages/blog

Archana Pisharody, & David Lerpiniere. (2021). *Toolkit for developing an inventory of plastic waste using the Material flow analysis methodology*: Basel Convention,.

Dominic Charles, & Laurent Kimman. (2021). *The Plastic Waste Makers Index*: Minderoo Foundation.

Environmental Action, Cecilia Manzoni, Paola Paruta, & Julien Boucher. (2022). *Benchmark of Plastic Hotspotting Methodologies* (Phong Giang, Coralie Marszewski, & M. Koedel Eds.). Bonn and Eschborn, Germany: Internationale Zusammenarbeit (GIZ) GmbH.

GIZ, University of Leeds, Eawag-Sandec, & Wasteaware. (2020). *User Manual: Waste Flow Diagram (WFD): A rapid assessment tool for mapping waste flows and quantifying plastic leakage* (Z. I. Velis C.A. Research team: Cottom J., Zurbruegg C., Stretz J. and Blume S. Eschborn, Germany. Ed. Vol. Version 1.0).

Hardesty, B. D., Harari, J., Isobe, A., Lebreton, L., Maximenko, N., Potemra, J., . . . Wilcox, C. (2017). Using Numerical Model Simulations to Improve the Understanding of Micro-plastic Distribution and Pathways in the Marine Environment. *Frontiers in Marine Science, 4*. doi:10.3389/fmars.2017.00030

International Solid Waste Associations, & University of Leeds. (2019). *ISWA Combats Plastic Pollution*. Vienna, Austria: ISWA Marine Task Force.

Intersessional Correspondence Group on Marine Litter, Barbara Wenneker, & Lex Oosterbaan. (2010). *Guideline for Monitoring Marine Litter on the Beaches in the OSPAR Maritime Area*. London: OSPAR Commission.

IUCN. (2024). *Plastic pollution*. Gland, Switzerland -: International Union for Conservation of Nature.

Jambeck, J. R., & Johnsen, K. (2015). Citizen-Based Litter and Marine Debris Data Collection and Mapping. *Computing in Science & Engineering, 17*(4), 20-26. doi:10.1109/MCSE.2015.67

Lechner, A., Keckeis, H., Lumesberger-Loisl, F., Zens, B., Krusch, R., Tritthart, M., . . . Schludermann, E. (2014). The Danube so colourful: A potpourri of plastic litter outnumbers fish larvae in Europe's second largest river. *Environmental Pollution, 188*, 177-181. doi:https://doi.org/10.1016/j.envpol.2014.02.006

Meijer, L. J. J., van Emmerik, T., van der Ent, R., Schmidt, C., & Lebreton, L. (2021). More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. *Science Advances, 7*(18), eaaz5803. doi:doi:10.1126/sciadv.aaz5803

NOAA. (2023). *Modeling Oceanic Transport of Floating Marine Debris*. Maryland 20910: Silver Spring

Nordic Council of Ministers. (2020). *Toward Ending Plastic Pollution: 15 Global POlicy Interventions for Systems Change*.

OECD. (2022a). *Global Plastics Outlook ECONOMIC DRIVERS, ENVIRONMENTAL IMPACTS AND POLICY OPTIONS*. Paris: OECD Publishing, .

OECD. (2022b). *Modelling plastics in ENV-Linkages* (E. Lanzi Ed.): Organisation for Economic Co-operation and Development.

Oliveira, V., Sousa, V., & Dias-Ferreira, C. (2019). Artificial neural network modelling of the amount of separately-collected household packaging waste. *Journal of Cleaner Production, 210*, 401-409. doi:https://doi.org/10.1016/j.jclepro.2018.11.063

Royle, J., Jack, B., Parris, H., Elliott, T., Castillo, A. C., Kalawana, S., . . . Woodall, L. C. (2022). Plastic Drawdown: A rapid assessment tool for developing national responses to plastic pollution when data availability is limited, as demonstrated in the Maldives. *Global Environmental Change, 72*, 102442. doi:https://doi.org/10.1016/j.gloenvcha.2021.102442

Sarah Perreard, Dr Feiyi Li, Dr Julien Boucher, Adrienne Gaboury, Noémie Voirin, Martina Gallato, & Riccardo Puppi. (2023). *Plastic Overshoot Day*. Lausanne, Switzerland: Environmental Action,.

Tran-Thanh, D., Rinasti, A. N., Gunasekara, K., Chaksan, A., & Tsukiji, M. (2022). GIS and Remote Sensing-Based Approach for Monitoring and Assessment of Plastic Leakage and Pollution Reduction in the Lower Mekong River Basin. *Sustainability, 14*(13), 7879.

UN Habitat. (2021). *WASTE WISE CITIES TOOL: Step by Step Guide to Assess a City's Municipal Solid Waste Management Performance through SDG indicator 11.6.1 Monitoring*.

UNEA. (2022). Written statements from Member States and Stakeholders Retrieved from https://www.unep.org/environmentassembly/unea-5.2

UNEP. (2020). *Monitoring Plastics in Rivers and Lakes: Guidelines for the Harmonization of Methodologies* Nairobi: United Nations Environment Programme.

UNEP. (2022). Our planet is choking on plastic. Retrieved from https://www.unep.org/interactives/beat-plastic-pollution

UNEP. (2023). Global Partnership on Plastic Pollution and Marine Litter Digital Platform. *Plastic Pollution and Marine Litter.*

UNEP, & IUCN. (2021). *National Guidance for Plastic Pollution Hotspotting and Shaping Action*.

Veiga, J. M., van Veen, B., Buckman, L., van Gils, J., Wuriyandoko, D. T., van der Sluys, C., . . . Acharya, A. (2023). Assessing Plastic Waste Discharges into the Sea in Indonesia: An Integrated High-Resolution Modeling Approach That Accounts for Hydrology and Local Waste Handling Practices. *Water, 15*(6), 1143.

Wikipedia. (2024). Numerical modeling (geology). Retrieved from https://en.wikipedia.org/wiki/Numerical_modeling_(geology)

WWF. (2022). *PLASTIC SMART GUIDES FOR CITIES*.