'OCEANS AND LAKES'

INTERUNIVERSITY MASTER OF SCIENCE IN MARINE AND LACUSTRINE SCIENCE AND MANAGEMENT

Modeling Plastic Removal and Bycatch of Air-Bubble Clean-up Mechanism

(The content of this master thesis is CONFIDENTIAL)

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September 2023

Master Thesis Submitted in Partial Fulfilment for Master's Degree in Marine and Lacustrine Science and Management

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Abstract

Technological innovations to mitigate plastic pollution in water bodies, called plastic clean-up technologies, have increased in recent years. One of the devices used in European rivers, ports, and harbors is an air-bubbling curtain system (commonly used to block the passage of jellyfish, oil spills, etc). However, the knowledge of their environmental impact is limited, particularly about bycatch or the unintentional collection of non-plastic materials such as reed (i.e., vegetation material). The goal of this work was to determine the effects of (1) plastic litter type, (2) water flow, and (3) plastic litter load on items caught and bycatch of the air bubble curtain mechanism. To do so we did series of flume experiment with an air bubbling prototype and used Bayesian Belief Network (BBN) model. The structure of the BBN was simplified based on natural riverine environment and the observations in the experiment. We also asked for expert knowledge in developing the model which consist of the nexus of flow velocity, plastic object, plastic load, biota, and biota load to plastic caught and bycatch. The model simulation showed that plastic caught in the air bubble has the probability of changing depending on the plastic object due to characteristics of plastic objects that affect their transport and deposition, favouring floating plastics such as bottles. The plastic items do not affect the amount of bycatch due to the minimal interaction of plastics and reeds. We also observed that the probability of more plastic being caught, and the amount of bycatch increase with flow velocity. The amount of plastic loaded only had a negligible effect on the amount of plastic caught and did not affect bycatch. Overall, the study suggests that the air-bubbling mechanism is more likely to collect bycatch than plastic. The plastic caught-to-bycatch ratio is 1:3 at low flow and 3:4 at high flow. Our study is innovative and provides new insights in the growing holistic understanding of the impacts of plastic clean-up technologies to effectively maximize their potential as a complementary tool amongst other measures to mitigate plastic pollution.

List of Abbreviations

ATR-FTIR	Attenuated Total Reflectance- Fourier Transform Infrared
BBN	Bayesian Belief Network
CIWM	Chartered Institution of Wastes Management
cm	centimeter
CPT	Conditional probability table
CPUE	Catch-per-unit-effort
CSF	Corey shape factor
$g\ cm^{-3}$	gram per cubic centimeter
m	meter
$m\ s^{-1}$	meter per second
PVC	Polyvinyl chloride
SUP	Single-use plastic
UNEP	United Nations Environment Programme

Chapter 1: Introduction

The use of plastic over time has led to a trade-off between its usefulness in various industries and pollution, now referred to as a global threat to ecosystems and human health (Thompson et al., 2009; Geyer et al., 2017; Waring et al., 2018; & Welden, 2020). The usage of plastic goods may vary in duration depending on the product type, design, manufacture, and purpose (Geyer, 2020b; Geyer et al., 2017). On the one hand, durable plastics are intended to last for a few decades, such as those used in construction, industrial machinery, and transportation (Chen et al., 2021; (Geyer, 2020a). On the other hand, single-use plastics (SUP) are only used for a short time (i.e., ranging from hours to weeks), such as disposable packaging, cutlery, or bottles (X. Chen & Yan, 2020; Chen et al., 2021). In recent years, plastic use shifted from more durable plastics to SUP (Chen et al., 2021), coinciding with increasing production (Zhu & Wang, 2020). Given the continuously high demand for plastic, its annual global production in 2021 reached 390.7 million metric tons (Plastics Europe, 2022). Mass production resulted in a sizable amount of plastic waste beyond management capacity (Geyer, 2020b). Plastic waste can come from the material outflow in production (pre-consumer waste) and the consumption and displacement (post-consumer waste) of plastic (Geyer et al., 2017). A global estimate of 7 billion tons of plastic waste was generated out of 9.2 billion tons produced from 1950 to 2017 (UNEP, 2021), often post-consumer waste, including packaging and food service waste (Lebreton & Andrady, 2019). Most plastic waste is non-biodegradable and accumulates in the environment, which can lead to pollution (Zhu & Wang, 2020).

Plastic pollution is a complex global issue defined as discarded plastic wastes that are inadequately managed and accumulated in the environment, which might cause adverse effects on the biota, ecosystem, and society (Welden, 2020; Windsor et al., 2019; CIWM & WasteAid UK, 2018). Large plastic debris, such as fishing nets, ropes, and plastic bags (Law, 2017), can cause entanglement of fauna, leading to impaired mobility, lacerations, infections, and potential mortality (Welden, 2020; Dolman & Moore, 2017). So far, approximately 350 species have been documented victims of plastic entanglement (Kühn & Van Franeker, 2020), such as marine mammals, turtles, and seabirds (Welden, 2020). Besides entanglement, another direct impact of plastic pollution is its ingestion, with a severity that varies from gastrointestinal blockages, reduced feeding, change in the gut microbiota, and less reproductive output (Gall & Thompson, 2015; Windsor et al., 2019). Based on a recent report, 1565 terrestrial, freshwater, and marine species are affected by the ingestion of plastics (Santos et al., 2021). Aside from aquatic fauna, plastics may also pose ecotoxicological hazards to the ecosystem (Khan et al., 2022). A recent ecotoxicological risk assessment of plastic pollution says that the risk from plastic pollution is small (Everaert et al., 2020). However, an understanding of implications such as vector effects, leachate-related toxicity, and bioaccumulation, to name a few, is yet to be known entirely (Khan et al., 2022; Carbery et al., 2018). Also, effects at a population level are expected to be more severe than effects at the individual level (Everaert et al., 2022). Furthermore, plastic debris can provide a novel substrate for the organisms and transport them to other habitats, with the danger of introducing and colonizing species that can alter local biodiversity patterns and may result in competition with the existing community assemblage (Welden, 2020).

Societal impacts of plastic pollution go hand-and-hand with ecosystem services affected by plastic pollution, and areas like coastal communities are the most vulnerable (Naeem et al., 2016). Reduction of productivity and fish stock due to plastic entanglement (fishing caused by ghost fishing gears; Azevedo-Santos et al., 2022; DEBRIS, 2020) and ingestion has consequences on fisheries and livelihood (Beaumont et al., 2019). Moreover, plastic pollution can cause delays in shipping vessels, damage to equipment, and loss of vessels and goods. In the Asia-Pacific region, the damage to fishing and shipping vessels was estimated at US$1.26 billion (Welden, 2020). Furthermore, economic consequences from the reduced aesthetic value of touristic places, such as beaches and lakes, can result in losses (Welden, 2020; Windsor et al., 2019) for example, the value of tourism loss in South Korea was estimated to be US$29–37 million (Welden, 2020). These global and frequently reported impacts of plastic pollution have a medium to a high degree of irreversibility (Beaumont et al., 2019) and made plastic pollution an urgent political agenda (Getor et al., 2020; MacLeod et al., 2021).

Among the environments affected by plastic pollution, studies in inland water bodies are relatively new compared to the marine environment (Kasavan et al., 2021). River systems are conduits of plastic pollution to other environments, such as terrestrial and marine habitats (Horton & Dixon, 2018), and might also act as sinks of plastic debris (van Emmerik et al., 2022). The problem of plastic pollution spreads across the world's rivers (Beaumont et al., 2019). Numerous factors, such as location, seasonality, and river discharge, can often influence river pollution (van Calcar & van Emmerik, 2019). Plastic waste enters the rivers through direct deposition or indirectly by wind transport and surface runoff from rain or flood events (van Calcar & van Emmerik, 2019). Both sources highly correlate with population density, urbanization, and waste management (Best, 2019; Schmidt et al., 2017). Once in the river, the movement of plastics is a trade-off between horizontal and vertical transport (van Emmerik, Tramoy, et al., 2019; van Emmerik & Schwarz, 2020). Horizontal transport is affected by the river's flow velocities, which influence the distance and speed at which plastic travels (van Emmerik & Schwarz, 2020). Parts of the river with higher flow velocity tend to have a higher concentration of floating plastics (van Emmerik et al., 2019; van Emmerik & Schwarz, 2020). In contrast, vertical transport refers to plastic movement from the surface to the bottom or vice versa (van Emmerik & Schwarz, 2020). This type of movement is highly driven by turbulence in the water (Kukulka et al., 2012). The other factors known to influence the movement of riverine plastics include intrinsic plastic properties such as density and size-to-mass ratio (van Emmerik & Schwarz, 2020), as well as biofouling and the presence of vegetation that deters the transport of plastic debris and increases retention and accumulation in the river system (van Emmerik et al., 2019). The plastic properties and the river's hydrology affect plastic transport and accumulation, which might form hotspot areas (van Emmerik & Schwarz, 2020). If not removed, plastic accumulated in the river systems will slowly and continuously degrade into smaller particles (van Emmerik & Schwarz, 2020).

Given the complexity of plastic pollution, collaboration between sustainable prevention and mitigation efforts is required to mitigate the issue (Bellou et al., 2021). Currently, solutions to prevent plastics from entering the environment exist at various levels, such as local, national, and regional (Abbott & Sumaila, 2019; Knoblauch & Mederake, 2021). However, there is no established threshold for plastic pollution emissions (Borrelle et al., 2020), so downstream solutions are still needed (Sherlock et al., 2023). According to Borrelle et al. (2020), a technological revolution is needed in environmental recovery to eliminate plastic pollution, such as plastic remediation technologies (Schmaltz et al., 2020; Leone et al., 2023; Moulaert et al., 2021). A recent global review of plastic remediation technologies by Leone et al. (2023) identified 124 remediation technologies, including prevention technologies aiming to reduce plastic litter's entrance into the environment and clean-up technologies aiming at removing legacy plastic litter. The trend of developing and deploying clean-up technology is increasing globally (Leone et al., 2023), and most of the technologies are in their pilot phase (Schmaltz et al., 2020), while some are still in the design phase (Helinski et al., 2021). The design of clean-up technologies depends on the target environment where the system will be installed or deployed (Moulaert et al., 2021; Helinski et al., 2021). Plastic clean-up technologies deployed in the environment were mainly placed in inland waterways like rivers (Leone et al., 2023; Moulaert et al., 2021). A report says that plastic clean-up devices (CLEAN TRASH) contributed to an average reduction of 43.5% of macroplastics emitted from rivers near the Saronikos Gulf (Gkanasos et al., 2021). Thus, contributing to the improvement of environmental recovery of plastic-polluted areas, raising public awareness, and aiding in data collection for policies on plastic (Leone et al., 2023; Sherlock et al., 2023). With the availability of these technologies, Helinski et al. (2021) developed a guide to aid water and waste managers in deciding when to adopt a clean-up technology and selecting clean-up technology. There are multiple examples of clean-up technologies used in Netherlands, USA, Australia and other countries, such as the air-bubble curtain, booms, conveyor belt, vacuum and others (Helinski et al., 2021; Schmaltz et al., 2020; Leone et al., 2023).

This study focused on the plastic removal and bycatch of air bubbles as a plastic clean-up mechanism, anchored on the concern of limited and unverified public knowledge on the impact of plastic clean-up technologies. This study defines bycatch as the unintentional collection of non-plastic matter in the air-bubbling system. For instance, a report said that most material collected by a passive clean-up device was >99% reeds (Maris et al., 2022). The air bubbling mechanism is one of the low-cost plastic clean-up technologies and reported to be highly efficient. However, it’s also used to deflect biota such as jellyfish (Lo, 1996), smolts (Leander et al., 2021) and organic debris (CanadianPond.ca, n.d.) which could lead to bycatch. The air-bubbling clean-up mechanism is made of a perforated pipe diagonally placed in the riverbed, an air supply, and a catchment system. The compressor system pumps air into the perforated tube and creates bubbles that continuously form a curtain-like barrier (Zhang et al., 2022; Spaargaren, 2018) and are used to deflect the jellyfish, algae, planktons, and organic debris in aquaculture farms, beaches, marinas and desalination plant (CanadianPond.ca, n.d.). In principle, the air-bubble barrier creates vertical flow in the water and increases the upward entrainment of the surrounding water (CanadianPond.ca, n.d.; Spaargaren, 2018). The vertical flow from air bubble barriers will crossflow with the horizontal flow of a river or inland waterways, leading the plastic debris to the catchment system that ideally collects the plastic debris (Zhang et al., 2022; Spaargaren, 2018). Most of the plastic caught is floating because the horizontal flow of the water is strongest on the surface and gradually declines with depth (Spaargaren, 2018). Some of the companies that used this technology are Bubble Tubing® and The Great Bubble Barrier®, which claims that the efficiency of the technology is 86% of the tracers based on pilot testing in river Ijssel (*The Great Bubble Barrier* ®, n.d.). The air bubble deployed in Amsterdam collects around 85 kg of plastic monthly (*The Great Bubble Barrier* ®, n.d.). Using the air bubbles does not obstruct the navigation of boats and is hypothesized to allow fish migration (*The Great Bubble Barrier*®, n.d.). The air bubbling system can also be used in removing microplastics (< 5 mm from Thompson et al., 2004) with experimental efficiency ranges from 0-100% and is affected by flow conditions, bubble configuration, plastic properties, and placement of the catchment device (Zhang et al., 2022). The use of technologies to remove legacy plastics is foreseen to increase in the coming years since the concentration of plastic litter in the environment is still high (Sherlock et al., 2023). Therefore, the environmental impacts, such as potential bycatch, of these technologies should be known and quantified (Moulaert et al., 2021; Leone et al., 2023). A recent study with Seabin observed that organic matter, such as macrophyte material, was entangled in the collected plastic litter (Sherlock et al., 2023). Some companies surveyed do not provide information on the possible impacts of clean-up systems; however, they acknowledge that organic materials were also removed in the process of clean-up (Brouwer et al., 2023), validating concerns about the potential negative impacts of clean-up technology (Falk-Andersson et al., 2020; Leone et al., 2022). Helinski et al. (2021) and Sherlock et al. (2023) developed protocols for using plastic clean-up technologies. Harmonizing the existing protocols in plastic clean-up technology with model predictions can help improve the decision-making process to optimize the use of clean-up technologies.

Modelling techniques can assist authorities in ecosystem management (Death et al., 2015), such as rivers facing plastic pollution. One increasingly known modelling method is Bayesian Belief Network (BBN; Barton et al., 2020), a probabilistic dependency model (Krieg, 2001). Bayesian Belief Network models are helpful in the diagnosis, prediction, and modelling of ecosystems (Norys Software Corporation, n.d.), especially in environmental management, such as river systems (Barton et al., 2020). The use of BBN to support the valorisation of plastic clean-up technology with consideration of its environmental impact, such as bycatch, is seen as ideal due to its advantages (Leone et al., 2022). One advantage is the ability to give probabilistic predictions on all variables (Leone et al., 2022). Another advantage of BBN is the inclusion of uncertainty in its predictions and its ability to integrate continuous and discrete data from vast sources such as literature, experts, field data, and laboratory experiments (Leone et al., 2022). Finally, it uses straightforward software that can be easily used (Parkyn et al., 2003), increasing accessibility to multiple stakeholders.

By developing a BBN model, this research project aims to investigate the trade-off between the percentage of plastic caught and bycatch of an air-bubbling plastic clean-up mechanism under a series of different mesocosm conditions. This study answers research questions on the effect of (i) water flow velocity, (ii) plastic object, (iii) plastic load to plastic caught, and bycatch of air bubbling mechanism. Furthermore, this study's insights aim to provide some initial knowledge on the potential environmental impacts of plastic clean-up technologies based on the bycatch collection.

Chapter 2: Materials and Methods

2.1. Experimental Design

2.1.1. Experimental Set-up

2.1.1.1. Flume Set-up

We performed a mesocosm experiment at the Department of Civil Engineering Laboratory of the University of Ghent Ardoyen Campus. The mesocosm (Figure 1) consisted of an artificial wave flume of 30 m in length, 1 m in width, and 1.2 m high. The floor of the flume and most of the walls are made of reinforced concrete, while one side of the walls is partly made of glass. Freshwater at around 15 °C was used for the experiments, and its depth was maintained at approximately 25 cm. The water inlet of the flume (Figure 2a) was controlled by a wheel-type system managing the water flow at the desired velocity. Immediately after the inlet, a honeycomb-shaped screen was deployed to reduce the turbulent discharge of the water inlet and create a more laminar flow in the flume. From the honeycomb screen, an unobstructed 10 m testing space was allocated. Within the testing space, the side adjacent to the honeycomb screen serves as loading area of the sample. Near the middle part of the testing space, the water flow was measured with a Valeport 802 electromagnetic current flow sensor (Figure 2b). The probe was lowered to 12.5 cm from the water surface five minutes after the flume was switched on and before the tests when measuring the flow velocity. The other side towards the end of the testing space, the air bubble system prototype was installed (Figure 1). After the air-bubble system, a custom-built screen made of 1 x 1 m wooden frame, a metal screen as the base and covered by 400 µm meshed net was installed at an angle of 30 degrees (Figure 2c). This screen collected all samples that were not caught by the prototype without disrupting the flow of the water.

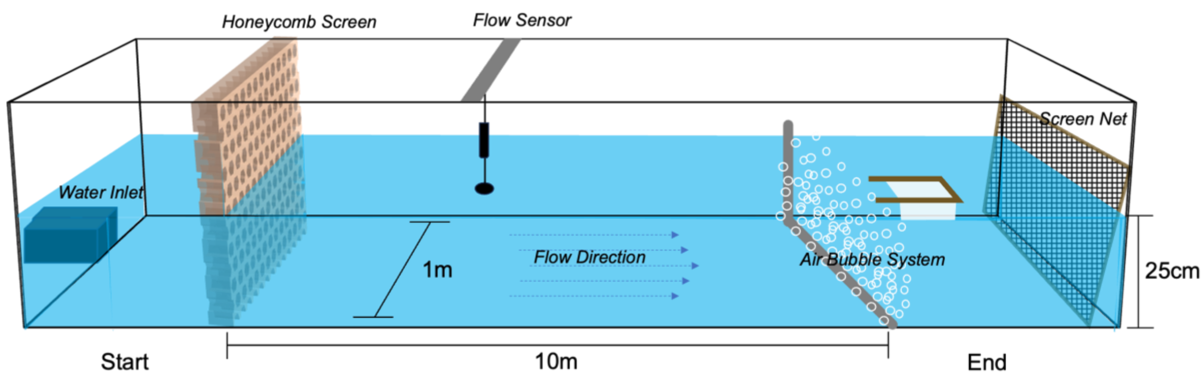


Figure 1. Schematic representation of the flume set-up (not to scale) used in the mesocosm experimentation.

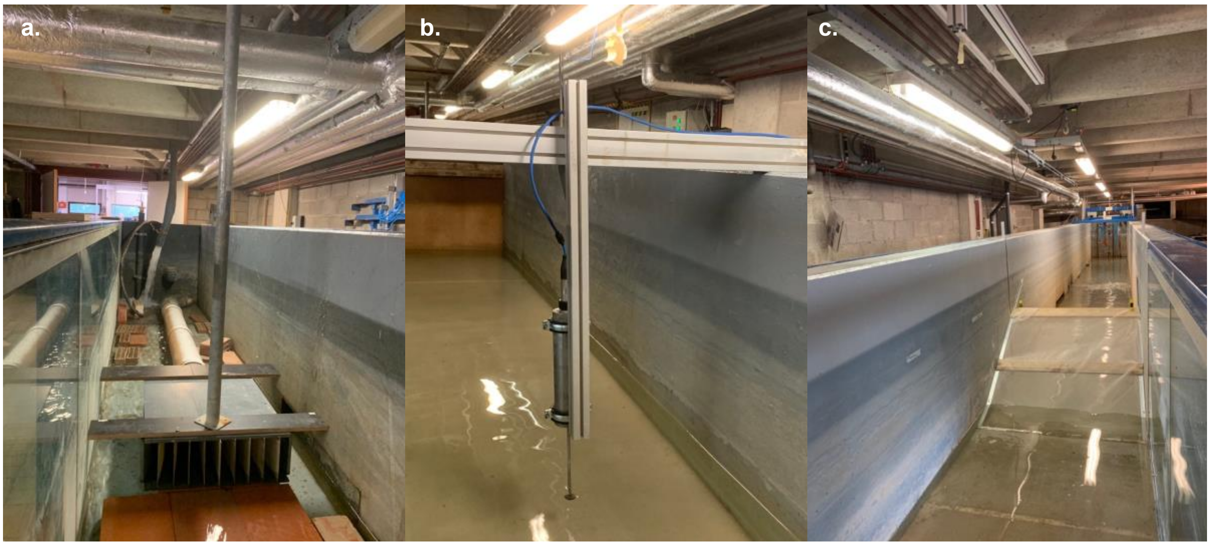


*Figure 2. Some components of the artificial flume setup. (**a**) Inlet of water in the flume. (**b**) Valeport 802 electromagnetic current flow sensor. (**c**) Installed screen near the end of the flume to trap samples that escape the catcher.*

2.1.1.2. Plastic Clean-up Mechanism

To mimic a generic air-bubbling curtain system, broadly based on the Bubble Tubing® and The Great Bubble Barrier®, we have created a prototype to be used in the experiment (Figure 3). This prototype consisted of a 302 cm L-shaped PVC pipe. The arm of the pipe was 190 cm drilled with a total of 110 holes (diameter = 1 mm) double lined at 1 cm between each hole. We connected the tube to an air compressor in which the airflow was kept at approximately 4 bars, supplying stable air as a bubble curtain. The tube was temporarily installed at the bottom with a 30 degrees angle covering the whole width of the flume. The position was maintained by attaching a 2 kg weight to the end of the PVC tube in the area with no holes, and the vertical part was attached to the wall of the flume (Figure 3). We placed the catchment system on the surface of the water at around 10 m from the start of the testing space depending on the flow. The catchment system was positioned at 9.33 m for low flow, and 9.75 m for high flow. The configuration was based on the result of the detection limits. These positions were marked to ensure that the placement of the catchment system is correct every test according to flow and for ease of instalment. The structure of the catchment system consisted of a wooden frame of 46.5 x 25.5 cm with an opening of approximately 15 cm in which a plastic container of 27 x 19 cm was used as a collecting chamber. The front side wall of the plastic container was removed while the other sides and bottom were replaced with a 400 μm-meshed net. This modification of the plastic container allowed the water to flow without letting the samples escape. Styrofoam was placed under the wooden frame, reinforcing the catchment system's buoyancy. The Styrofoam boards were rigid and did not release particles that could interfere with the experiments, which was assessed because of the different colors compared to the used plastic samples. Finally, we used ropes to hold the position of the catchment system, with one end tied to the left side of the wooden frame and the other end tied on the wall of the flume.

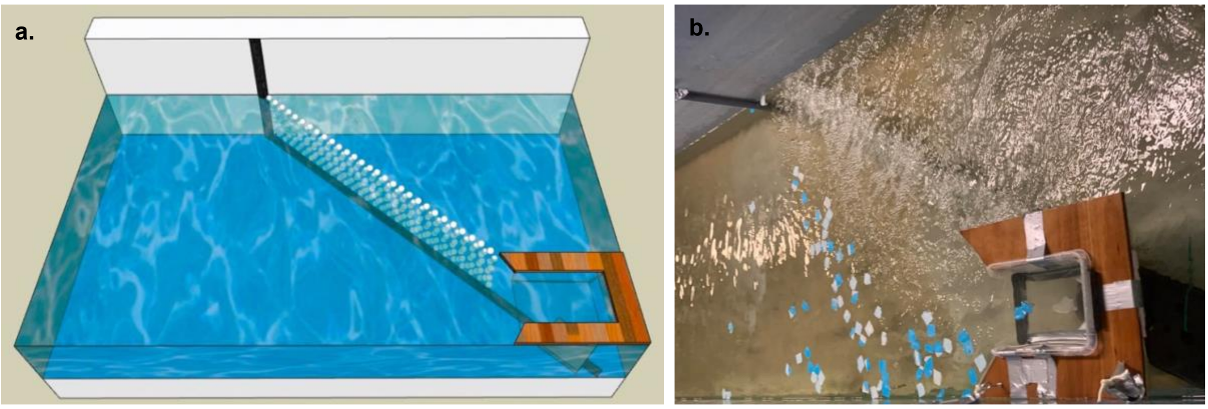


*Figure 3. (**a**) Schematic representation of the air-bubbling curtain system prototype, showing the perforated tube releasing air bubbles and the catchment system on the surface (drawing not to scale and the compressor air supply is not shown; generated using SketchUp). (**b**) Photo of the operational air-bubble prototype used in one of the tests with films.*

2.1.1.3. Loading Plank

The loading of samples was facilitated by two 84.5 x 31 cm metal planks with a series of holes and a 400 μm meshed screen net (Figure 4). The metal planks were layered in between the net and screwed together. Ropes were tied on both sides of the plank to hold the device while lowering the samples in the flume. Markings for samples were written on the plank to ensure uniform arrangement for all the tests.

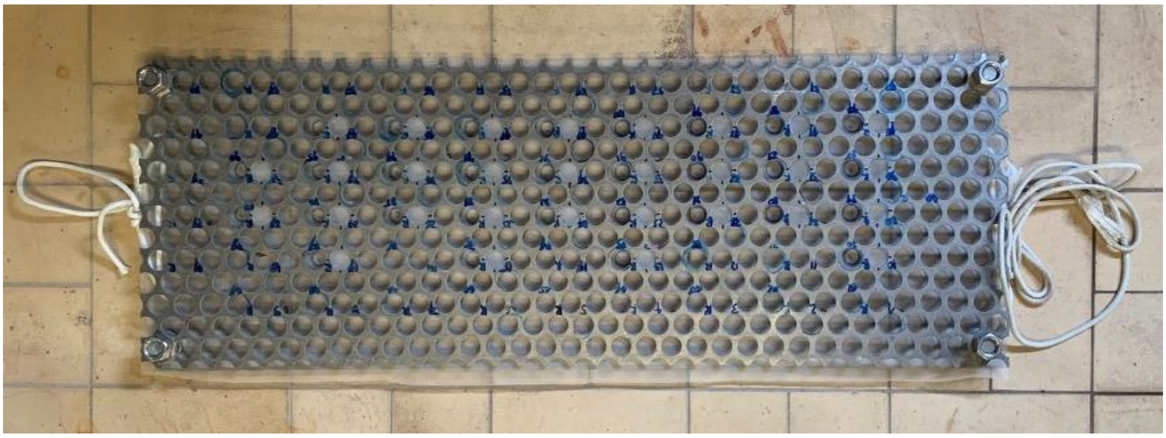


Figure 4. Image of the customed made loading plank, to insert plastic debris and reeds into the mesocosm setting.

2.1.1.4. Plastic and Non-Plastic Samples

In this study, we used three plastic samples to simulate three types of floating debris commonly observed in rivers, plastic films, foams, and plastic bottles (Al-Zawaidah et al., 2021). An important criterion in the selection of plastic samples was the ability to flow continuously toward the determined endpoint with minimal occurrence of entrapment on the walls of flume. This was necessary to test the suitability of the samples for the set-up and statistical analysis. The plastic films were cut into an average of 2.96 x 3.25 cm rectangles from plastic bags. The foam is irregularly-shape with average dimensions of 3.29 cm length, 1.40 cm height, and 1.18 cm width. The plastic-bottle-shaped vial has average dimensions of 3 cm length and 1 cm diameter. Since the samples were irregularly shape, we used the Corey shape factor as a non-dimensional descriptor of the relative flatness of the samples. The Corey Shape factor was calculated using 20 pieces of each sample following the method described by Núñez et al. (2023). The polymer type of all plastic samples was identified using Attenuated Total Reflectance-Fourier Transform Infrared (ATR-FTIR) spectroscopy (Table 1) as a reference of its density based on Hidalgo-Ruz et al. (2012). In order to test for the potential bycatch, we used dried reed collected in Oostende and Lienkebeek last December 2022 and January 2023, respectively, which was wetted before each test. The reed had an average length of 3.64 cm and a diameter of 0.46 cm.

Table 1. Specification of all samples.

Sample	Actual Photo	Item Mean Dimensions (cm) (n=20)	Mean Dry Weight (g)(n=20)	Corey Shape Factor	Polymer type (for plastic)	Density (g cm^{-3})
Bottles		Length = 3.20 (±0.01) Diameter = 1.14 (±0.01)	1.6021 (±0.366)	0.436	Polypropylene	0.9-0.91 (Hidalgo-Ruz et al., 2012)
Films		Length = 2.96 (±0.22) Width = 3.25 (±0.25)	0.0453 (±0.004)	0.002	Polyethylene	0.91-0.97 (Hidalgo-Ruz et al., 2012)
Foam		Length= 3.29 (±0.33), Height = 1.40 (±0.18) Width= 1.18 (±0.12)	0.1098 (±0.012)	0.381	Polyethylene	0.91-0.97 (Hidalgo-Ruz et al., 2012)

Reed		Length = 3.64 (±0.12) Diameter = 0.46 (±0.05)	0.1411 (±0.031)	0.328	NA	0.583 (Malheiro et al., 2021)

2.1.1.5. Experiment Calibration and Detection Limits

Before performing the experiments in which collected plastic and reeds were assessed, we performed tests to verify the flume and the air bubble prototype's detection limits. These tests allowed us to retrieve information on each experiment's run time, understand how many plastic and biota items would reach the end of the flume at different flow velocities, and test the clean-up mechanism. Normally, the transport of samples at high flow is faster, hence requiring no test for the purpose of deciding the duration of a single experiment. Accordingly, the transport of plastic films, foam, plastic bottles, and reeds to reach the 10 m identified endpoint was timed and recorded at low flow velocity. Each test used 30 samples to determine the total transport time based on the last sample that reached an identified endpoint (10 m). The mean of the total transport time per sample type was calculated to determine the time required to run one experiment (Table 6). The time for the experiments was standardized to four minutes.

In addition, we also tested the suitability of plastic samples for the experiment based on its ability to reach the identified endpoint (10 m) of the flume without the air bubbling system at low and high flow. For this test, we used varying numbers of sample loads, such as 15, 30, and 100, replicated three times. After loading the plastic sample in the flume, we counted and recorded the number of samples that reached the endpoint within four minutes. The detection limit of the flume is based on the recorded number after each test (Table 7) and is expressed in percentages following the formula:

$$Flume\ Detection\ limit\ (\%) = \left(\frac{sample\ at\ endpoint}{sample\ load}\right)100$$

The detection limit of the air bubbles was also tested using various plastic samples in both low and high flow. Each set of tests is replicated thrice for films, bottles, and foams. All tests were equally timed for four minutes. After each test, plastic samples caught in the catchment container of the air-bubble system were counted. The detection limit is based on the number of plastics in the catchment system (Table 8) and is expressed in percentages following the formula:

$$Air\ Bubble\ Detection\ limit\ (\%) = \left(\frac{sample\ in\ the\ catchment\ container}{sample\ load}\right)100$$

2.1.1.6. Experimental Protocol

The flow of the flume was stabilized before running experiments by waiting at least five minutes before running measurements of flow velocity and test. The Valeport 802 electromagnetic current flow sensor (Figure 2b) was lowered to 12.5 cm then measurements of flow velocity per second were sent to a computer continuously. One-hundred flow velocity measurements were randomly selected and averaged to determine the flow velocity of water in the flume. The average velocity of each flow was 0.14 (± 0.012) m s^{-1} for low and 0.29 (± 0.007) m s^{-1} for high. Two sets of experiments, with predetermined low and high flow, were carried out to test different plastic samples and load classes. The low-load class consisted of 0, 15, and 30 samples. The high-load class had 60, 80, and 100 samples. Before running the actual test, calibration for quality control was done. To run a calibration test, 20 wooded beads are loaded in the flume. After four minutes of the test, all wooden beads in the catchment container were counted. This process was replicated three times. Each test was standardized to four minutes, decided earlier by the series of detection experiments (cfr. Experiment Calibration and Detection Limits). The timer started after the loading of the samples in the flume, as soon as the samples were in the water. After four minutes, the plastics and reeds caught were counted and divided into categories based on where they were found in respect to the prototype and flume. Five categories have been used: (1) samples in the container; (2) in front of the container; (3) did not reach the catcher; (4) under the catchment structure, and (5) escaped (Table 2). All plastic items and reeds were counted and removed from the flume after each experiment.

Table 2. Characterization of samples' position after each test with respect to the flume and the catchment system.

Category	Definition
In the container	All samples inside the catchment chamber/container after the test
In front of the container	All samples in front of the catchment chamber/container after the test
Did not reach the catcher	All samples that did not reach the catchment chamber/container after the test
Under the catchment structure	All samples that were under and on sides of the catchment system's frame after the test
Escaped	All samples that passed through the air bubbles but were not caught after the test

2.2. Data Analysis

The study used the following statistical tool for the data analysis. The recorded data on flow velocity was used to test for its significant difference using the Wilcoxon Test. The low and high flow was significantly different (α=0.05) according to the test with $p < 0.01$, calculated using R software (version 2022.02.0; R Core Team, 2021). The calculation for the percentage of plastic caught was done using the formula:

$$Plastic\ Caught\ (\%) = \left(\frac{plastic\ in\ the\ \ container}{plastic\ load}\right)100$$

While to calculate the percentage of bycatch, we used the formula:

$$Bycatch\ (\%) = \left(\frac{reeds\ in\ the\ \ container}{reeds\ load}\right)100$$

The result was used in the conditional probability table for the model.

2.3. Model Development

2.3.1. Bayesian Belief Network Model

The structure of a BBN has two components, a causal network, and the conditional probability table (CPT) that give value to the relationships in the network (Forio et al., 2015). The causal network is a directed acyclic graph consisting of boxes called nodes representing variables and arrows representing the causal relationships (Krieg, 2001). Each node manifests a set of states and probabilities are used to determine the likelihood of a particular state happening (Forio et al., 2020). The CPT contains the probability for every possible combination of states, quantifying the strength of relationships of variables (nodes) in the network using the Bayes theorem (Forio et al., 2020; *Norys Software Corporation*, n.d.). The output of a BBN model is a probability distribution on the state of response variable (Van Echelpoel et al., 2015)

2.3.2. Network Development

The BBN model was developed aiming to understand the trade-off of plastic caught and bycatch of air-bubble mechanism. To do so, the model integrated information obtained from the mesocosm experiments (cfr. experimental design), literature findings, and expert knowledge. According to Leone et al. (2021), environmental conditions, potential bycatch characteristics, plastic debris properties, and clean-up technology mechanisms might lead to bycatch. Environmental condition in the rivers, such as water flow, is an essential vector in the mechanism of air-bubbling systems. In natural conditions, flow velocity acts in the vertical transport of plastic debris, with high flow velocity carrying more plastic debris than low flow velocity (van Emmerik et al., 2019; van Emmerik & Schwarz, 2020). The complexity of how these factors might lead to bycatch was simplified in a mesocosm. The mesocosm experiment tested plastic removal efficiency and bycatch in low and high flow velocity, types of plastic (bottles, films and foams), plastic load (low and high), biota (reeds), and biota load (low and high), which are all the identified nodes in the BBN model. Experts in plastic cleanup technology/plastic pollution and BBN models helped in the causal network arrangement that best represents the relationship of the variables in the mesocosm. Netica (version 6.09, 64 Bit for MS Windows 7 to 10), a BBN software by Norys Software Corp©, was used to develop the BBN model.

The BBN model output (Figure 5) showed the cause-and-effect relationship hypothesis of variables influencing the trade-off of plastic removal and bycatch in the river mesocosm. On the one hand, “PlasticCaught” is connected to the independent variables, plastic load, plastic object, and flow velocity. On the other hand, “Bycatch” is caused by independent variables such as biota load, biota object, flow velocity, and plastic object. The magnitude of plastic removal and bycatch is quantified in percentage relative to the plastic and biota load, respectively. Plastic caught and bycatch has five states based on the percentage of collected samples, 0%, 1-25%, 26-50%, 51-75%, and 76-100%.

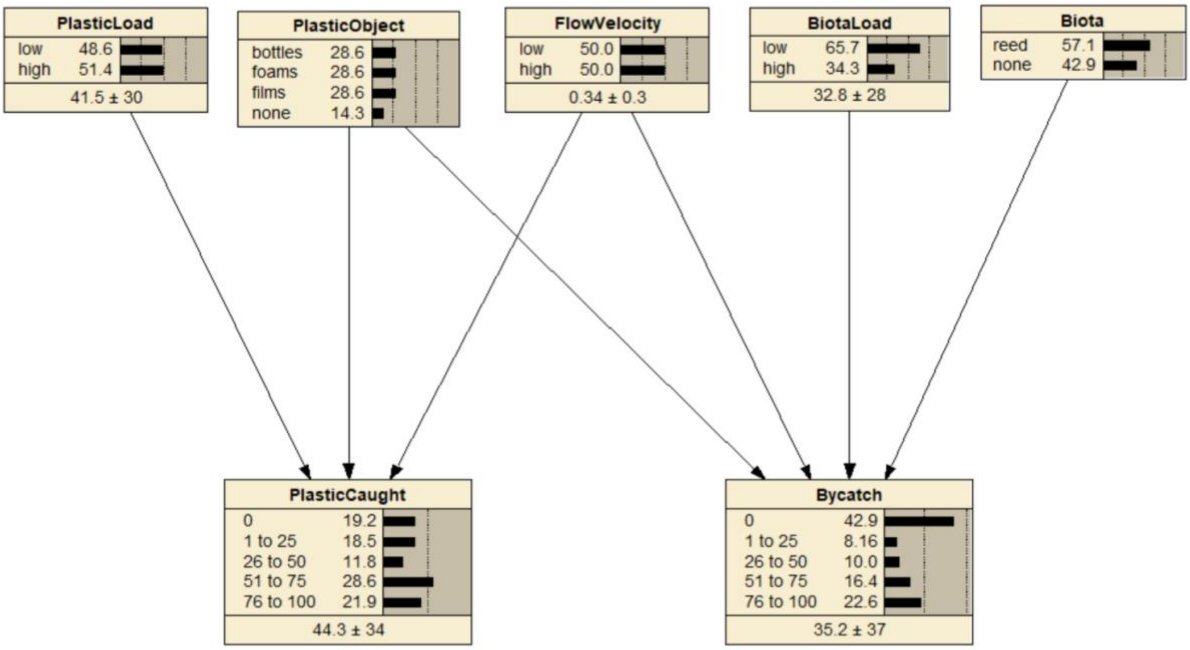


Figure 5. Result of BBN model. Each box is a node or variable that plays a role in the plastic caught or bycatch. The arrows represent the dependency relationship of causal nodes to the affected node.

2.3.3. Conditional Probability Table

A series of tests were run in the flume to generate data for the conditional probability table run the BBN model. An MS Excel spreadsheet with seven columns representing the seven nodes was created and imported on Netica as a .csv file. The node “FlowVelocity” was based on the average of the probe measurements taken in the flume and divided into high and low flows. Both “PlasticLoad” and “BiotaLoad” represent the number of samples per test with state variables high (31-100) and low (0-30). The variable “PlasticObject” described the type of plastic items: films, bottles, foams, and none (no sample). The “Biota” node represents states with the reed and none (without reeds). Finally, the nodes “PlasticCaught” and “Bycatch” respectively refer to plastic and reeds samples inside the catchment container after the tests. In the model, these states of catch efficiency and bycatch were quantified ranges (0-25%, 26-50%, 51-75%, 76-100%) based on the percentage of plastic caught and bycatch.

2.3.4. Scenario Simulations

Scenario simulations implemented using the model determined the effect of the different plastic objects, flow velocity, plastic load and flume scenarios on plastic caught and bycatch. The simulations with the different plastic objects (Table 3) gave insights into the interaction of each plastic object with the air bubble. At the same time, the simulations with the flume scenario (Table 4) revealed information on the influence variables to plastic caught and bycatch.

Table 3. A detailed description of the model simulation per plastic object at low and high settings.

Scenario	Description	Settings in the BBN model
All Bottles	Plastic caught and bycatch of air-bubbling system targeting only bottles	Flow velocity: low=50%, high=50%
		Plastic object: bottles-100%, film=0%, foam=0%, none-0%
		Plastic load: low=50%, high=50%
		Biota load: low=50%, high=50%
		Biota: reed= 100%, none=0%
All Film	Plastic caught and bycatch of air-bubbling system targeting only films	Flow velocity: low=50%, high=50%
		Plastic object: bottles-0%, film=100%, foam=0%, none-0%
		Plastic Load: low=50%, high=50%
		Biota load: low=50%, high=50%
		Biota: reed= 100%, none=0%
All Foam	Plastic caught and bycatch of air-bubbling system targeting only foams	Flow velocity: low=50%, high=50%
		Plastic object: bottles-0%, film=0%, foam=100%, none-0%

		Plastic Load: low=50%, high=50%
		Biota load: low=50%, high=50%
		Biota reed= 100%, none=0%
Low Flow velocity	Plastic caught and bycatch of air-bubbling system at low flow.	Flow velocity: low=100%, high=50%
		Plastic object: film= 33.3%, bottles =33.3% foam=33.3%, none-0%
		Plastic Load: low=50%, high=50%
		Biota load: low=50%, high=50%
		Biota: reed= 100%, none=0%
High Flow velocity	Plastic caught and bycatch of air-bubbling system at high flow.	Flow velocity: low = 0%, high = 100%
		Plastic object film= 33.3%, bottles =33.3% foam=33.3%, none-0%
		Plastic Load low=50%, high=50%
		Biota load low=50%, high=50%
		Biota reed= 100%, none=0%
Low Load Class	Plastic caught and bycatch of air-bubbling system for low load class (0, 15, 30).	Flow velocity: low = 50%, high = 50%
		Plastic object film= 33.3%, bottles =33.3% foam=33.3%, none-0%
		Plastic Load low=100%, high=0%
		Biota load low=50%, high=50%
		Biota reed= 100%, none=0%
High Load Class	Plastic caught and bycatch of air-bubbling system for high load class (30, 60, 100).	Flow velocity: low = 50%, high = 50%
		Plastic object film= 33.3%, bottles =33.3% foam=33.3%, none-0%
		Plastic Load low=0%, high=100%
		Biota load low=50%, high=50%
		Biota reed= 100%, none=0%

Table 4. A detailed description of the different flume scenario simulations using the BBN model.

Scenario	Description	Settings in the BBN model
A	Slow-flowing flume with low plastic pollution and low floating organic matter	Flow Velocity: low = 100%, high = 0%
		Plastic object: film = 33.3%, bottles = 33.3%, foam = 33.3%, none = 0%
		Plastic Load: Low = 100%, high = 0%
		Biota Load: low = 100, high = 0%
		Biota: reed = 100%, none = 0%
B		Flow Velocity: low = 100%, high = 0%

	Slow-flowing flume with high plastic pollution and low floating organic matter	Plastic object: film = 33.3%, bottles = 33.3%, foam = 33.3%, none = 0%
		Plastic Load: Low = 0%, high = 100%
		Biota Load: low = 100, high = 0%
		Biota: reed = 100%, none = 0%
C	Slow-flowing flumes with low plastic pollution and high-floating organic matter	Flow Velocity: low = 100%, high = 0%
		Plastic object: film = 33.3%, bottles = 33.3%, foam = 33.3%, none = 0%
		Plastic Load: Low = 100%, high = 0%
		Biota Load: low = 0, high = 100%
		Biota: reed = 100%, none = 0%
D	Slow-flowing flumes with high plastic pollution and high-floating organic matter	Flow Velocity: low = 100%, high = 0%
		Plastic object: film = 33.3%, bottles = 33.3%, foam = 33.3%, none = 0%
		Plastic Load: Low = 0%, high = 100%
		Biota Load: low = 0, high = 100%
		Biota: reed = 100%, none = 0%
E	Fast-flowing flume with low plastic pollution and low floating organic matter	Flow Velocity: low = 0%, high = 100%
		Plastic object: film = 33.3%, bottles = 33.3%, foam = 33.3%, none = 0%
		Plastic Load: Low = 100%, high = 0%
		Biota Load: low = 100, high = 0%
		Biota: reed = 100%, none = 0%
F	Fast-flowing flumes with high plastic pollution and low-floating organic matter	Flow Velocity: low = 0%, high = 100%
		Plastic object: film = 33.3%, bottles = 33.3%, foam = 33.3%, none = 0%
		Plastic Load: Low = 0%, high = 100%
		Biota Load: low = 100, high = 0%
		Biota: reed = 100%, none = 0%
G	Fast-flowing flumes with low plastic pollution and high-floating organic matter	Flow Velocity: low = 0%, high = 100%
		Plastic object: film = 33.3%, bottles = 33.3%, foam = 33.3%, none = 0%
		Plastic Load: Low = 100%, high = 0%
		Biota Load: low = 0, high = 100%
		Biota: reed = 100%, none = 0%
H	Fast-flowing flumes with high plastic pollution and high-floating organic matter	Flow Velocity: low = 0%, high = 100%
		Plastic object: film = 33.3%, bottles = 33.3%, foam = 33.3%, none = 0%
		Plastic Load: Low = 0%, high = 100%
		Biota Load:

		low = 0, high = 100%
		Biota: reed = 100%, none = 0%

2.3.5. Sensitivity Analysis

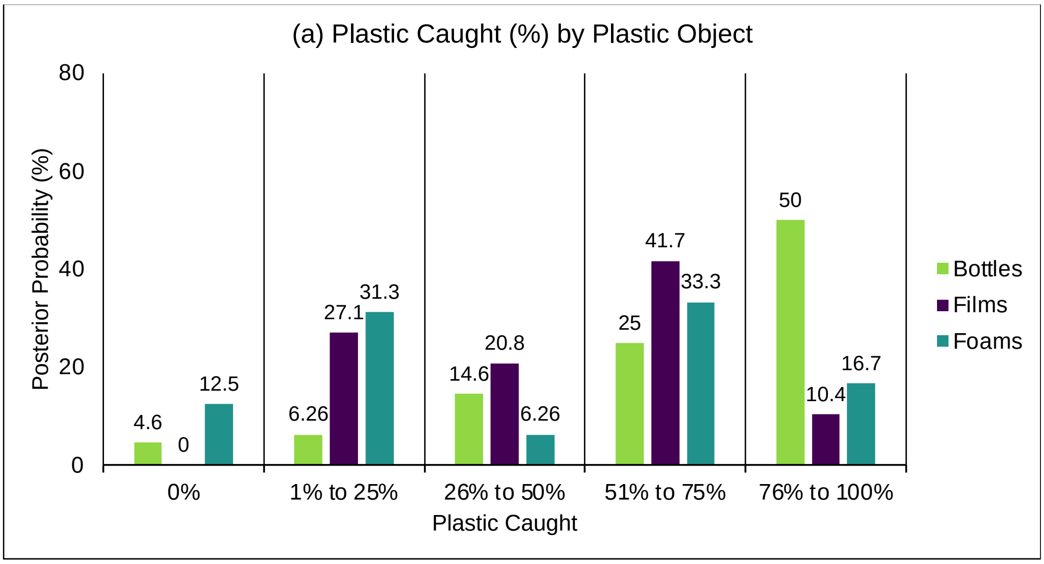
To understand how each node influence the response node plastic caught and bycatch we performed as sensitivity analysis. The sensitivity analysis represents the influence of other nodes in the model on the node of interest (Marcot, 2006; Sun & Müller, 2013). This function is included in the network analysis of Netica. The node of interest is selected first, then click on the sensitivity analysis on the network tab in Netica. For this study, the nodes of interest are the nodes “PlasticCaught" and "Bycatch." Using sensitivity analysis, the variables that influence plastic caught and bycatch are revealed according to their degree. Magnitude of influence is measured by the variance reduction (Forio et al., 2015). A strong influence on the target nodes is indicated by a higher variance reduction value (Forio et al., 2015).

Chapter 3: Results

3.1. Effects of Parameters on Plastic Caught and Bycatch

3.1.1. Influence of Plastic Objects on Plastic Caught and Bycatch Percentages

The probabilities of the amount of plastic caught and bycatch of bottles, films, and foams show that each plastic object affects the amount of plastic caught and bycatch differently. As shown in Figure 6a, 76% to 100% of the bottles have a 50% probability of being caught by the air bubble. Compared with films and foams catching 76% to 100% plastic is less likely with a probability of 16.7% and 10.4%, respectively. The films caught by the air bubble are most probably (41.7%) 51% to 75% of the films initially loaded. Similarly, the air bubble can also catch 51% to 75% of the foam, with a probability of 33.3%. The other probabilities per plastic object were also distributed to plastic caught less than 50%. Moreover, the air bubbling system may not catch foams and bottles with the probability of 12.5 % and 4.6%, respectively.



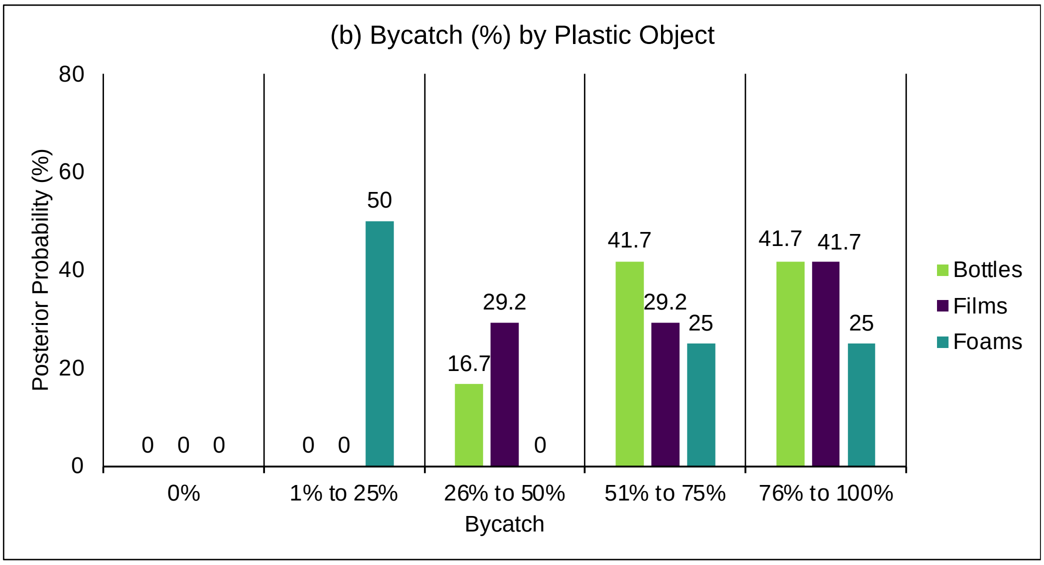


*Figure 6. (**a**) Distribution of posterior probabilities of bottles (green), foams (teal), and films (dark purple) on the range of plastic caught according to the BBN model. (**b**) Distribution of posterior probabilities of bottles (green), foams (teal), and films (dark purple) on the range of bycatch percentage according to the BBN model.*

Aside from plastic caught, the number of reeds collected by the air bubble was also modelled and treated as bycatch probabilities of each plastic object (Figure 6b). The probability of bycatch generated by bottles and films was mainly distributed to bycatch greater than 25%. As shown in Figure 6b, bycatch with bottles have a 41.7% probability to be 51% to 75% and 76% to 100% of reeds. Similarly, 76% to 100% of reeds caught with films also have a 41.7% probability of being bycatch. This bycatch probability of films decreased to 29.2% for catching fewer reeds (26% to 50% and 51% to 75%). The bycatch probability generated with the foams peaks differently than bottles and films. As shown in Figure 6b, 1% to 25% reed have the highest probability (50%) of bycatch generated with the foams. Moreover, the bycatch probability of foams having the same amount of bycatch (51 to 75% and 76 to 100% reeds) as bottles and films was lower (25%).

3.1.2. Influence of Flow Velocity on Plastic Caught and Bycatch

We tested two different flows to determine the influence of flow velocity on plastic caught and bycatch. These flows are categorized as low flow (0.14 ± 0.012) m s^{-1} and high flow (0.29 ± 0.007) m s^{-1}. The modeled probability distribution at each flow shows that flow velocity affects plastic caught and bycatch differently. As shown in Figure 7a, the plastic caught at high flow has a 59.7% probability of catching 51% to 75% plastic and a 37.5% probability of catching 76% to 100% plastic. The probabilities of low flow catching 51% to 75% and 76% to 100% were smaller by only 6.95% and 13.9%, respectively. The probability distribution of plastic caught at low flow is skewed to the right. Specifically, the highest probability (43.1%) of plastic caught is 1% to 25% at low flow. There is also an 11.1% probability that no plastic will be caught at low flow. Regarding the bycatch (Figure 7b), 76% to 100% reeds can be caught with a probability of 72.2% at high flow and 0% probability at low flow. A bycatch of 51% to 75% is most likely at low flow with a 41.7% probability, while at high flow, there is only a 22.2% probability. Moreover, there is also a 33.3% and 25% probability of catching 1% to 25% reeds and 26% to 50% reeds, respectively, at low flow, which was not the case at high flow.

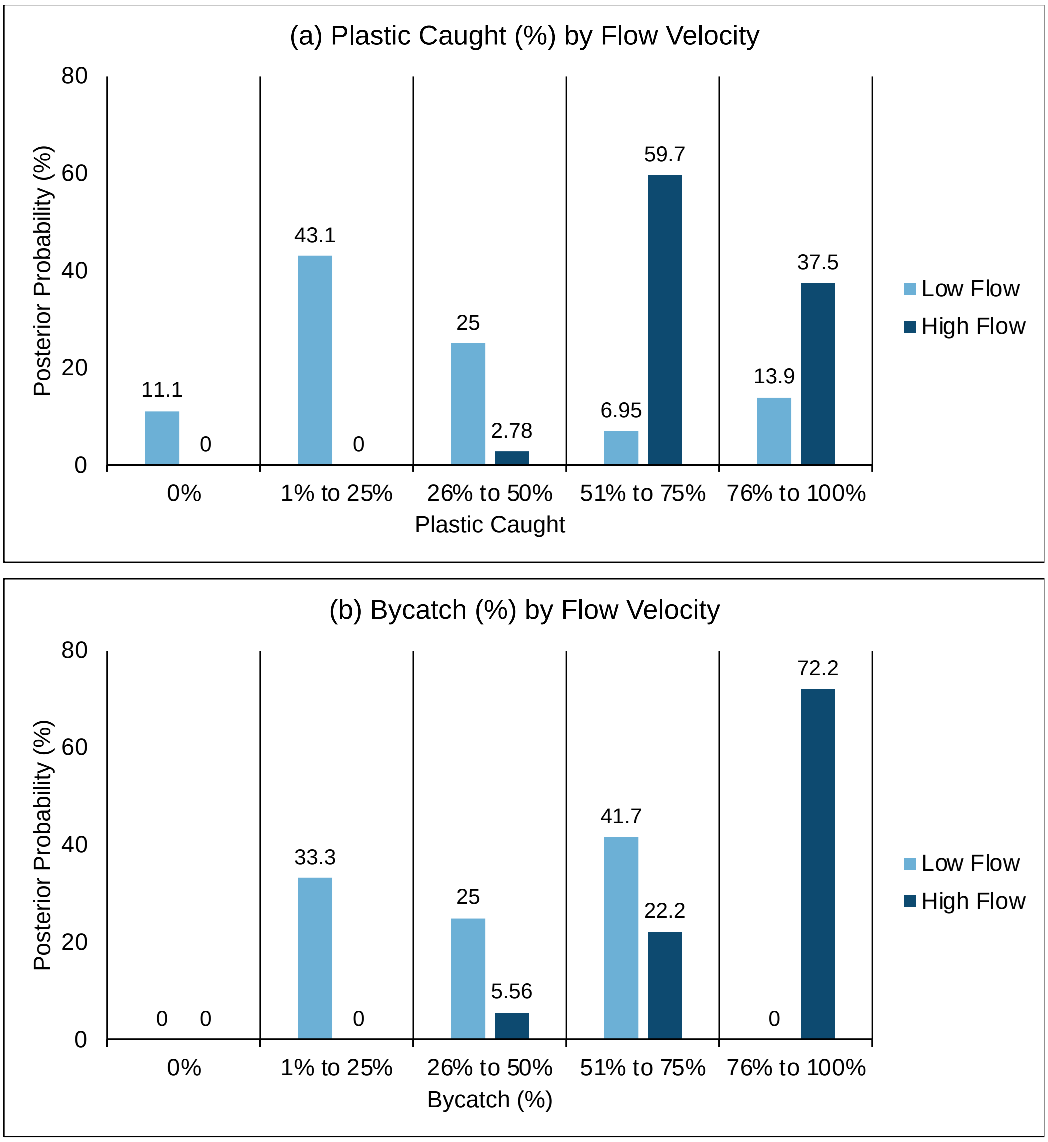
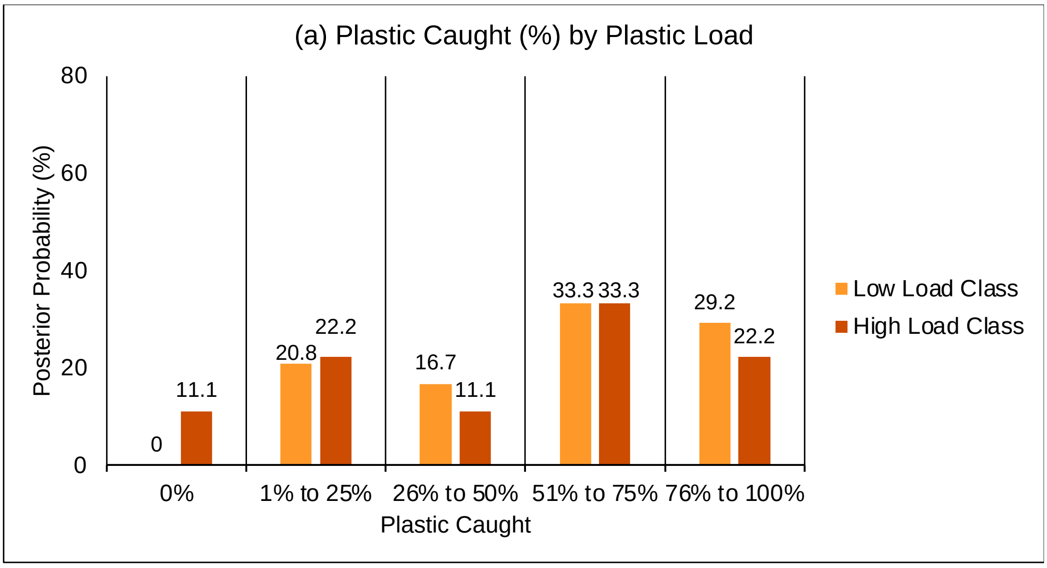


*Figure 7. (**a**) Distribution of posterior probabilities at low (aqua) and high (dark blue) flow on the range of plastic caught (%) according to the BBN model. (**b**) Distribution of posterior probabilities at low (aqua), and high (dark blue) flow on the range of bycatch (%) according to the BBN model. Low flow = 0.14 (± 0.012) m s^{-1}; high flow = 0.29 (± 0.007) m s^{-1}.*

3.1.3. Influence of Different Plastic Loads on Plastic Caught and Bycatch

Plastic load was categorized into low and high load classes. The low-load class consisted of 0, 15, and 30 samples, while the high-load class had 60, 80, and 100 samples.

The plastic caught and bycatch based on the plastic load showed fewer differences compared to the result of the plastic object and flow velocity (Figure 8). These slight differences in probability are shown in Figure 8a, catching 76% to 100% plastic with 29.2% probability for low load class and 22.2% probability for high load class; 1% to 25% plastic caught with 20.8% and 22.2% probability for low load class and high load class respectively; and 26% to 50% with 16.7% and 11.1% probability for low load class and high load class, respectively. Interestingly, the low-load and high-load classes have the same 33.3% probability of catching 51% to 75% plastic, while only high-load classes have an 11.1% probability of not catching plastic (0%). These slight differences in the plastic caught probability due to load classes were not seen in the bycatch probabilities. As shown in Figure 8b, the probabilities for low and high load classes were equal across the range bycatch percentage. The distribution of bycatch probabilities is skewed to the left, peaking with a 36.1% probability of catching 76% to 100% reeds. There is also a 31.9% probability of catching 51% to 75% for low and high-load classes, then a 16.7% and a 15.3% probability of catching 1% to 25% and 26% to 50% reeds, respectively.



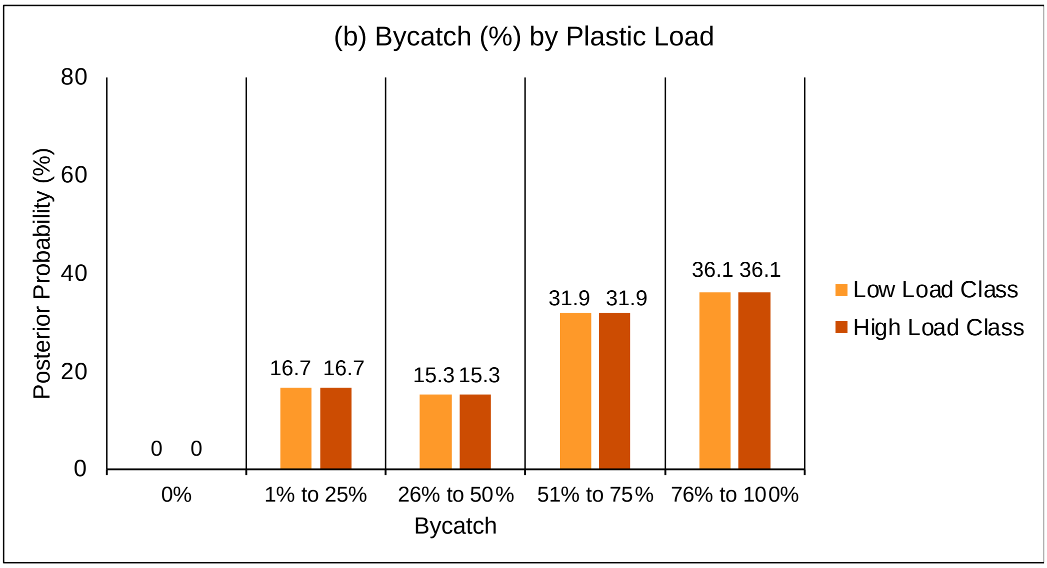
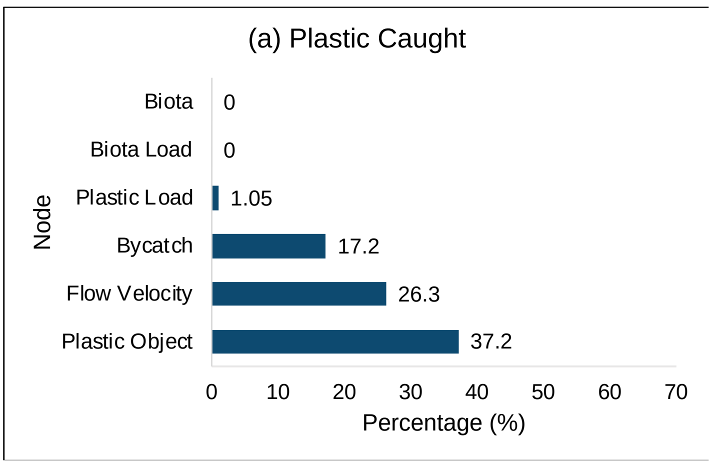


*Figure 8. (**a**) Distribution of posterior probabilities for low (light yellow) and high (orange) load class on the range of plastic caught (%) according to the BBN model. (**b**) Distribution of posterior probabilities for low (light yellow) and high (orange) load class on the range of bycatch (%) according to the BBN model. The low-load class is composed of 0, 15, and 30 samples. The high-load class is composed of 60, 80, and 100 samples.*

3.1.4. Sensitivity Analysis

The sensitivity analysis results depict the influence of all variables/nodes in the model (Figure 5) on plastic removal and bycatch. Figure 9a shows the variables that have a strong influence on plastic caught, which are plastic objects (37.2%), flow velocity (26.3%), and bycatch (17.2%). The plastic load has the slightest influence (1.05%) on plastic caught, while the nodes biota and biota load did not have influence. For bycatch (Figure 9b), biota (67.6%), flow velocity (10.30%), and plastic caught (10.30%) are the variables with the most decisive influence, while plastic objects (2.48%) and biota load (0.30%) had a weaker influence. These findings showing the strong influence of flow velocity and plastic objects are similar to the hypothesized effect of environmental conditions and plastic objects on plastic removal and bycatch.



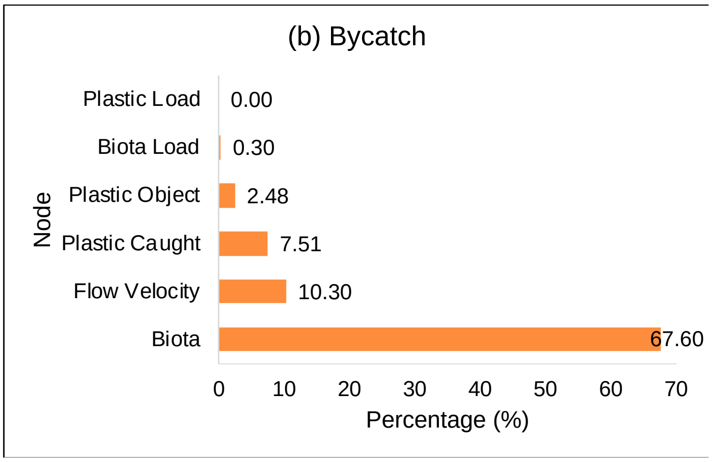
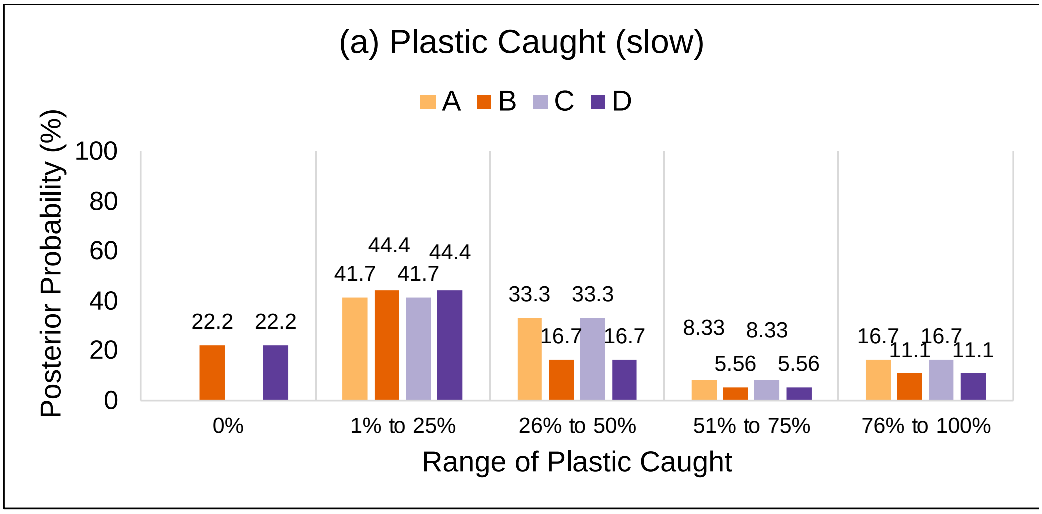
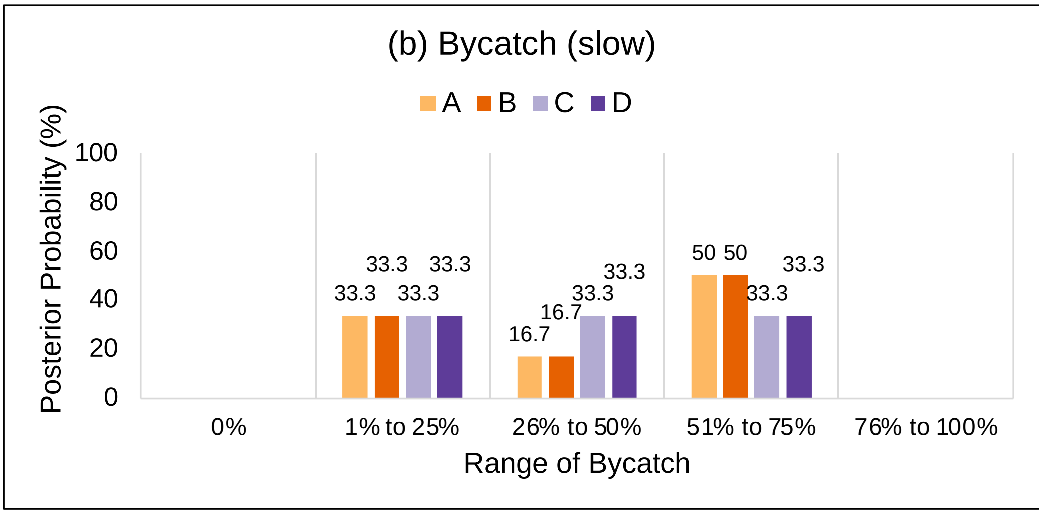


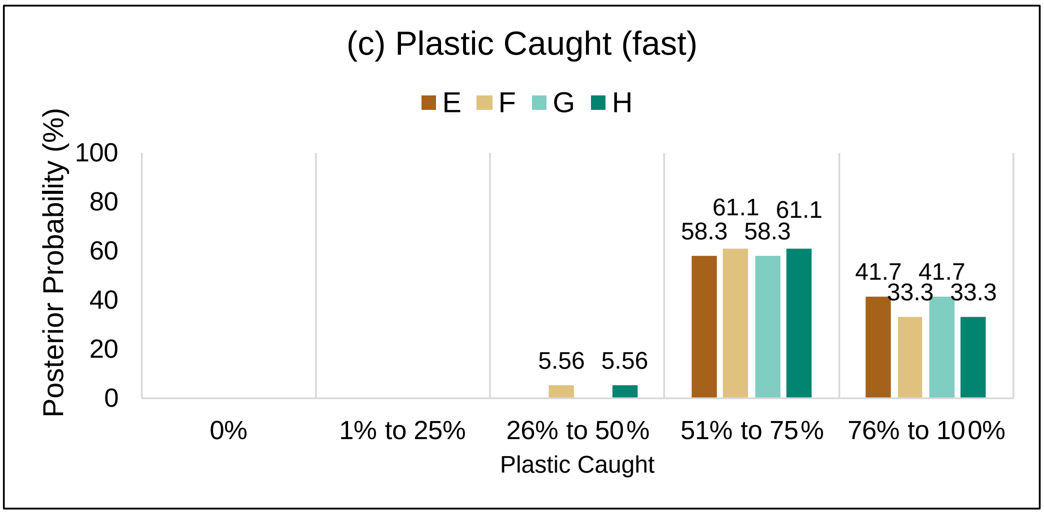
*Figure 9. Sensitivity analysis results from the BBN model, represented by the percentage of the variance of target variables (**a**) plastic caught and (**b**) bycatch.*

3.2. Modeled Flume Scenario

We simulated eight flume scenarios using the BBN model to predict the amount of plastic caught and bycatch using probabilities (Figure 10). These flume simulations were grouped into two, categorized as slow scenarios (A, B, C, D) and fast scenarios (E, F, G, H). At low flume velocity (scenarios A, B, C, and D) modeled result (Figure 10a) showed a wide distribution of the posterior probability of plastic caught ranging from 0% to 100%. The distribution of probabilities is identical for scenarios that have the same plastic load. Among the four scenarios, A and C have a low plastic load, while B and D have a high plastic load. The most probable plastic caught state for all four slow scenarios (Figure 10a) is 1% to 25% with 44.4% probability for B and D and 41.7% for A and C. The probability of catching 76% to 100% plastic were only 16.7% for scenarios A and C which decreases to only 11.1% for scenarios B and D. Moreover, scenarios B and D have a 22.2% posterior probability of not catching plastic (0%). Regarding bycatch (Figure 10b), the distribution of posterior probability is within 1% to 75% states for all four slow scenarios (A, B, C, D). Similar to the pattern of plastic caught, scenarios with identical reeds load have the same distribution of probabilities. For instance, scenario A and B has 50% probability of catching 51% to 75% reeds and a 33.3% probability of catching 1% to 25% reeds. While scenario C and D have a 33.3% probability of catching 1% to 25%, 26% to 50% and 51% to 75% reeds.


(a) Plastic Caught (slow)
A B C D
Posterior Probability (%)
100
80
60
40
20
0
22.2 22.2
41.7 44.4 41.7 44.4
33.3 16.7 33.3 16.7
8.33 5.56 8.33 5.56
16.7 11.1 16.7 11.1
0%
1% to 25%
26% to 50%
51% to 75%
76% to 100%
Range of Plastic Caught


(b) Bycatch (slow)
A B C D
Posterior Probability (%)
100
80
60
40
20
0
33.3 33.3 33.3 33.3
16.7 16.7 33.3 33.3
50 50 33.3 33.3
0%
1% to 25%
26% to 50%
51% to 75%
76% to 100%
Range of Bycatch


(c) Plastic Caught (fast)
E F G H
Posterior Probability (%)
100
80
60
40
20
0
5.56 5.56
58.3 61.1 58.3 61.1
41.7 33.3 41.7 33.3
0%
1% to 25%
26% to 50%
51% to 75%
76% to 100%
Plastic Caught

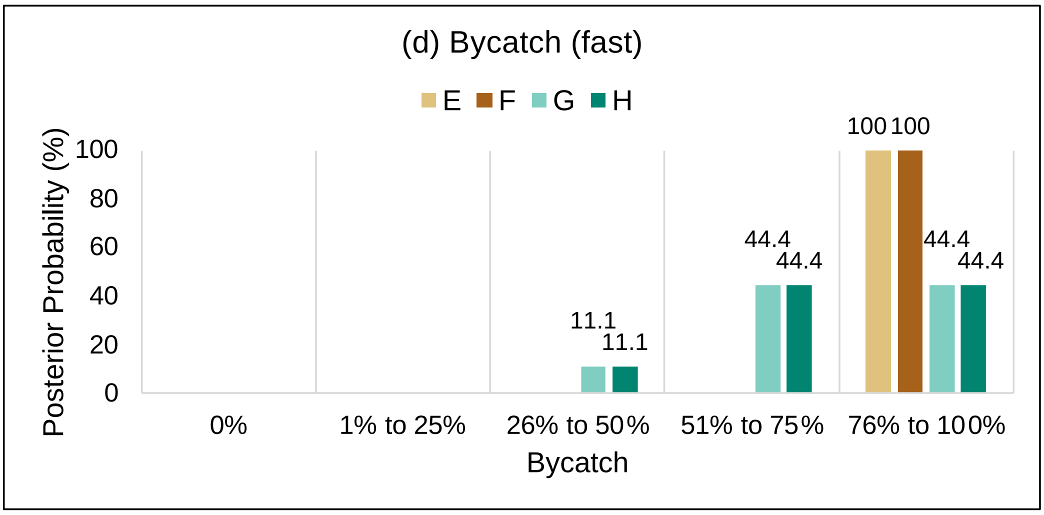


*Figure 10. The posterior probability of catch and bycatch of different river scenarios. (**a**) Distribution of plastic caught of slow flowing flume at scenarios A, B, C, and D. (**b**) Distribution of bycatch slow flowing flume at scenarios A, B, C, and D. (**c**) Distribution of plastic caught of slow flowing flume at scenarios E, F, G and H. (**d**) Distribution of bycatch slow flowing flume at scenarios E, F, G and H. A= Slow-flowing flume with low plastic pollution and low floating organic matter, B = Slow-flowing flume with high plastic pollution and low floating organic matter, C= Slow-flowing flumes with low plastic pollution and high-floating organic matter, D= Slow-flowing flumes with high plastic pollution and high-floating organic matter E= Fast-flowing flume with low plastic pollution and low floating organic matter, F= Fast-flowing flumes with high plastic pollution and low-floating organic matter, G= Fast-flowing flumes with low plastic pollution and high-floating organic matter, and H= Fast-flowing flumes with high plastic pollution and high-floating organic matter.*

Model simulation at high flume velocity is presented in four fast scenarios (E, F, G, H), as shown in Figure 10c-d. The result on plastic caught reveals the narrower distribution of posterior probabilities skewed to the right with values over 50%. The probabilities of the scenarios with similar plastic and reed load are also identical. In this group (Figure 10c), the probability of catching 51% to 75% plastic is higher for scenarios F and H (61.5%) than E and G (58.3%). However, catching 76% to 100% plastic the probability for scenarios F and H is less with only 33.3% than the 41.7% for scenarios E and G. Regarding bycatch simulations (Figure 10d), the low reed load scenarios E and F have a 100% probability of catching 76% to 100%, the chance of this happening to scenario G and H is only 44.4%. Moreover, there is another 44.4% probability for scenario G and H to have 51% to 75% bycatch and an even lower probability (11.1%) of 25% to 50% bycatch. A pattern of higher bycatch for low reeds load scenarios compared with high load scenarios was observed in slow and fast modeled simulations.

The summarized result between the trade-off of plastic caught and bycatch for all eight scenarios based on the most probable state is presented in Table 5. When films, foam, and bottles are combined, the plastic caught is less than the generated bycatch of the air-bubbling mechanism.

Table 5. Summarized result of the trade-off of plastic caught and bycatch of the eight simulations using the BBN model.

Scenario	Most Probable State of Plastic Caught	Most Probable State of Bycatch	Remarks
A	1% to 25%	51% to 75%	Plastic caught < bycatch
B	1% to 25%	51% to 75%	Plastic caught < bycatch
C	1% to 25%	1% to 25% and 51% to 75%	Plastic caught ≤ bycatch
D	1% to 25%	1% to 25% and 51% to 75%	Plastic caught ≤ bycatch
E	51% to 75%	76% to 100%	Plastic caught < bycatch
F	51% to 75%	76% to 100%	Plastic caught < bycatch
G	51% to 75%	51% to 75% and 76% to 100%	Plastic caught ≤ bycatch
H	51% to 75%	51% to 75% and 76% to 100%	Plastic caught ≤ bycatch

Chapter 4: Discussion

4.1. Factors Influencing the Plastic Caught and Bycatch of Air Bubble Mechanism

Our findings show that different plastic objects, flow velocities, and plastic loads are factors that might affect the percentage of plastic caught and bycatch in an air-bubble curtain type of system. In terms of plastic objects, bottles are modelled to be the most effectively caught plastic object by the air bubbling mechanism because of the higher probability (50%) of catching 76% to 100% of bottles (Figure 6) compared with films and foams. The first possible explanation relates to the transport mechanism of each plastic object. The transport of bottles was characterized by floating, with part of its body on the surface and the other part submerged. The bottles floated because they were made of polypropylene polymers, with a density lower than (0.90 g cm^{-3} - 0.91g cm^{-3}) the freshwater in the flume. The air-bubbling system easily caught bottles because they float on the water's surface, complementing the catchment system's floating position, as shown in the results (Figure 6a). The remaining probability of bottles caught was distributed to another percentage of plastic caught (0%, 1 to 25%, 26 to 50%, and 51 to 75%; Figure 6a) can be explained by the fact that bottles can hold water, which might decrease their ability to float. In some cases, if the bottles are entirely filled with water, they could settle on the flume floor and will not reach the catchment system (Table 2), especially at high flow. Bottles were also observed at times suspended between the water surface and the flume floor due to the crossflowing of rising air bubbles and horizontal flow of water in the flume, which frequently occurs at low flow resulting to increase in the plastics that are categorized as "under the catchment structure" and "escape" (Table 2). The films caught by the air bubble were modelled to be lower than bottles, with the most probability (41.7%) of catching 51% to 75%. This finding is potentially because the films were transported by suspension given the proximity of their density (0.91 g cm^{-3} - 0.97 g cm^{-3}) with fresh water (1.00 g cm^{-3} at 4 °C), large surface area to size ratio, thin walls, and flexibility. At times they can also float on the surface of the flume and be resuspended by the turbulence created by the air bubbles. The size, flexibility, and the 0.002 Corey shape factor of films enabled them to behave like fluid and sometimes flow under the catchment system or pass through the bubble curtain. Consequently, after each test, films typically have the highest number of plastics categorized as "under the catchment structure" and "escaped" (Table 2). Similar to films, the most probable (33.3%) number of foams caught is 51% to 75% (Figure 6a). However, the transport mechanism of foam was floating due to its low density (0.91 g cm^{-3} - 0.97g cm^{-3}), large surface area to size ratio, and thick wall with air spaces, which is unlike films. The tiny air pockets in the manufacturing of foam lower the density of the polyethylene (Al-Zawaidah et al., 2021; Andrady, 2015), explaining the difference in the transport mechanism of films and foam despite the same polymer, as well as their difference in size and shape. Most of the body of the foam was above the surface, causing frequent entrapment on the walls of the flume and sticking with other foams or reeds, possibly the reason for the different percentage of plastic caught between bottle and foams despite having similar transport mechanism. These observed transport mechanism of bottles, films, and foams is similar to the transport mechanisms of macroplastics in rivers described by Al-Zawaidah et al. (2021), who also mentioned the influence of polymer density and shape on the dynamics of plastic transport. We know that as density integrates with other characteristics such as shape, weight, and surface area to size ratio of each plastic object, this generates differences in their transport mechanism (Al-Zawaidah et al., 2021; He et al., 2020; Blondel & Buschman, 2022), as observed in the experiments. In addition, Andrady (2015) and Al-Zawaidah et al. (2021) noted physical condition as a factor in the transport of plastic; for example, the sinking of open bottles and floating of foams due to air pockets. In reality, the properties of plastic litter in the environment are continuous values (Kooi & Koelmans, 2019) due to their complex and diverse nature and the influence of fouling and weathering (Leone et al., 2022) and their effects to transport mechanism is yet to be understood in detail (Hurley et al., 2023).

Aside from the transport mechanism, deposition is another reason for the difference in plastic caught of the plastic object (Figure 6b). Deposition, in the context of the experiment, was the entrapment in the walls of the flume or the clogging in front of the catchment system of plastics and reeds. Deposited plastic can sometimes result in an accumulation of plastics and reeds into patches in the flume. The deposition was frequent in foams, reflected in the 12.5% probability of not catching plastic (Figure 6b). The air spaces in foams absorb water, strengthening adhesion to the other foam and reeds. Adhesion is further increased by the large surface area of foam, thereby creating small patches of foam, or combining with reeds in the flume. These patches may clog the entrance of the catchment system and entrap on the flume's wall, resulting in lower plastic caught in foam. The adhesive tendency of bottles and films was weak, so other factors, such as the flow dynamics, may cause their deposition. Plastic samples that were deposited were typically categorized as "in front of the container" and "did not reach the catcher" (Table 2), which were considered not caught.

In terms of bycatch, plastic objects do not have much influence on the bycatch, as confirmed by the sensitivity analysis. The interaction of plastic objects and reeds that leads to bycatch is minimal except for plastic objects which might agglomerate the reeds. For instance, clogging of foams in front of the catchment system might also trap reeds, resulting in a possible lower bycatch percentage. At the same time, films and bottles have fewer interactions because of the differences in transport mechanism and speed (Table 6). On rare occasions, we found reeds inside the bottle.

The influence of flow velocity on plastic caught and bycatch was also evident in the study. Plastic caught at low flow increased by around 50% compared to high flow based on the BBN model (Figure 7a). At the same time, the bycatch at high flow is also larger by 25% than at low flow (Figure 7b). The result is because flow velocity affects the transport and deposition of plastics and reeds, as observed in the experiments and also noted by Al-Zawaidah et al. (2021), van Emmerik et al. (2019) and Shumilova et al. (2019). Higher flow velocity carries more plastic objects (Williams & Simmons, 1997) and organic debris (Shumilova et al., 2019), hence the increase of plastic caught and bycatch (Figure 7). Similarly, clogging of plastics in front of the catchment system was unlikely to occur due to high advective force (Williams & Simmons, 1997). Moreover, it can also lessen the incidence of plastic and reeds sticking or deposited on the walls of the flume. On the contrary, deposition is frequent at low flow (Williams & Simmons, 1997), causing less interaction of plastic and reeds with the air-bubbling system, hence the low plastic caught and bycatch (Figure 7). Deposited plastics and reeds can also be remobilized depending on the flow velocity (Liro et al., 2020). However, remobilization of plastic remains to be understudied (Cozzolino et al., 2020). In addition, as the air bubbles reach the surface, it creates a current that cross flow with the horizontal flow of water in the flume. At low flow, the crossflow sometimes leads the plastic to the flume wall, resulting in the deposition of plastic, and since there is less horizontal flow, there is less chance of remobilization. While at high flow, the deposited plastics on the wall of the flume due to the crossflow were easily remobilized and led to the catchment container.

Findings on the plastic load suggest that it might only slightly affect the plastic caught. Consequently, the BBN model showed an equal posterior probability (33.3%) of catching 51% to 75% plastic, the most probable state for low and high-load classes (Figure 8a). The model also suggests that there is an 11.1% probability of not catching plastic with the high load because it may increase the deposition of plastic that will not reach and in front of the air bubbling system. In terms of bycatch, the plastic load does not affect the percentage of bycatch, given the identical distribution of bycatch probabilities for low and high load classes (Figure 8b). The finding can be explained by the fact that the air bubble mechanism is a passive system that mainly relies on the water flow to carry plastic and reeds, so the plastic and reeds load does not immediately translate to collection of the air-bubble. The framework developed by Helinski et al. (2021) noted the importance of environmental assessment to identify plastic hotspot areas in deciding whether to use plastic clean-up technology, given the installation and maintenance cost. Aside from the plastic load, it is also essential to understand the spatial and temporal dynamics of plastic debris in an area to strategically use the most efficient plastic clean-up technology (Sherlock et al., 2023). According to (Falk-Andersson et al., 2020), the closer a plastic clean-up system to the source of plastic pollution, the higher its efficiency will be. Furthermore, the sensitivity analysis also agrees with the findings that plastic load does not affect bycatch (Figure 9).

Finally, based on the modelled flume experiment, the sensitivity analysis identifies the nodes influencing the percentage of plastic caught and bycatch. The sensitivity analysis also determined the strength of influence that each node has on plastic removal and bycatch. A strong influence means a robust causal relationship on plastic caught and bycatch. We found that the percentage of plastic caught was influenced by the type of plastic objects, flow velocity, bycatch, and to a lesser extent, the plastic load (Figure 9). This means that depending on the type of plastic objects, such as bottles, foams, and films, the amount of plastic caught by the air bubble mechanism will vary (Figure 6a). Zhang et al. (2022) tested different plastic polymers and reported differences in the amount of plastic caught by air bubbles suggesting similar results as in the sensitivity analysis. Likewise, flow velocity is a known environmental factor that dictates the fate and transport of plastic in the riverine systems (Emmerik & Schwarz, 2020), with higher flow velocity carrying more plastic litter compared to lower flow, as observed in the experiments and also by van Emmerik et al. (2023), Roebroek et al. (2021), van Emmerik & Schwarz (2020), van Emmerik, Tramoy, et al. (2019). A second finding revealed that bycatch, which in the scope of this study consisted of reeds, was influenced, in the BBN model, mainly by the nodes biota, flow velocity, and percentage of plastic caught. In contrast, the nodes plastic object and biota load, representing the reed, had a minor influence (Figure 9b). These findings suggest the prominence of air-bubbling mechanisms in catching reeds. The river plastic monitoring in Belgium, also showed that most materials collected by the passive plastic clean-up technology installed are reeds (Maris et al., 2022). The sensitivity of bycatch to flow velocity is also similar to plastic caught, as seen in Figure 7, considering that it is one of the factors affecting the transport of reeds and other organic material (Wohl & Scott, 2016; de Brouwer et al., 2017; Nakamura et al., 2017 as cited by Shumilova et al., (2019)). To date, there is limited information on how environmental conditions might affect potential bycatch clean-up technologies (i.e., air-bubbling technology; (Moulaert et al., 2021). Environmental conditions that influence the transport of plastic debris rivers, such as flow velocity (van Emmerik & van Schwarz, 2020) and the presence of organic (van Emmerik et al., 2019), might also affect bycatch (Leone et al., 2022). Plastic debris targeted by air-bubbling systems might also impact the bycatch (Leone et al., 2022) however the effect is low. A remarkable finding of the sensitivity analysis is the causal relationship between the nodes bycatch and plastic caught to each other. The influence of bycatch on plastic caught is more decisive (17.2%) compared to the influence of plastic caught to bycatch (7.51%), which is possible because of the agglomeration of reeds and plastic samples that tend to float, which resulted in increased mobility and interaction with the air-bubble system. Moreover, the clean-up mechanism of the air-bubble prototype was non-discriminative of the materials collected. This result is like what has been seen in non-selective fishing gear. The relationship between catch and bycatch in fisheries suggests that increased catch is also increased bycatch (Davies et al., 2009).

4.2. Modeled Flume Scenarios

The eight modeled simulations showed the efficiency of air bubbles in removing the combined plastics and bycatch at different flume scenarios. Similar to what was noted in the previous section, flow velocity and the physical characteristics of plastics and reeds are essential in their transport and deposition, affecting the efficiency and bycatch of the air-bubbling system. The four low flow scenarios (A, B, C, D) is most likely to catch 1% to 25% of plastic load regardless of the load (Figure 10a). This finding can be attributed to a few reasons observed in the flume. Firstly, a large amount of plastic "did not reach the catcher" (approximately 14%) due to deposition caused by low flow and distance. The distance (10m) from the loading point of samples and the catcher potentially played an important role, causing plastic samples to be deposited in the side walls of the flume with not enough advective force to remobilize the plastics given the constant low flow. According to Falk-Andersson et al. (2020), the position of the plastic clean-up technologies is critical in increasing the efficiency of the clean-up technologies, with higher catch per unit effort (CPUE) when its closer to the source of plastic pollution. The second reason was plastic clogging in front of the catcher. The clogging can be explained by the deposition of agglomerated of plastic and reeds, the narrow space in front of the catchment system, and the continuously rising bubbles moving toward the flume's wall. As observed in the experiments, plastic deposition was prevalent at low flow, especially in foams. Another reason for clogging was the narrow space in front of the catchment system that created a choking point for plastic led by the crossflow of the water's horizontal flow and current created by the air bubbles. Liro et al. (2020) and

Williams & Simmons (1997) discussed that macroplastic deposition occurs due to local river conditions, such as low flow. The third reason for the low plastic caught might be explained by the plastic that escaped. Escaped plastics refer to the plastics that were categorized as “under the catchment structure” and “at the end of the flume” (Table 2). Based on the experiments, the average percentage of plastics “under the catchment structure” was 3.31% at high plastic load (scenarios B & D) and 15% at low plastic load (scenarios A & C), while the plastics “at the end of the flume” was 10.48% at high plastic load (scenarios B & D) and 21.67% at low plastic load (scenarios A & C). There was also an observed pattern that escaped plastics were mostly bottles and films. In contrast, the plastics that "did not reach" and "in front of the catcher" consisted mainly of foam, which can be attributed to the different transport mechanisms of macroplastics, as described in the previous section.

In the same way, the probability distribution of bycatch was affected by the reeds trapped in the flume's walls and the plastic clogging in front of the catchment system. On the one hand, the average percentage of reeds that “did not reach the catcher” was approximately 22%. On the other hand, reeds in front of the catcher ranged from 24.85% (A & B) to 47.17% (C & D) where most of the plastic especially foam are deposited. A study in the Saigon River in Vietnam found that plastic abundance correlates with the presence of organic matter such as water hyacinth (van Emmerik et al., 2019). The number of reeds that escaped the catcher was negligible, unlike plastics, since they were naturally floating during transport, complementing the mechanism of the air-bubbling system. Also, the straight shape of the flume is efficient for transporting organic matter, such as reeds, based on the natural cycle of floating matter (Shumilova et al., 2019).

The modeled trade-off between plastic caught and bycatch for high flow scenarios (E, F, G, H) had a probability distribution skewed towards >50% of the plastic and reeds load. The flow velocity strongly influences the probability distribution of plastic caught and bycatch, as confirmed in the sensitivity analysis. Williams & Simmons (1997) and van Emmerik et al. (2023) showed empirical evidence that high flow velocity carries more plastic debris and organic matter. For instance, flooding events characterized by high flow bring more plastics into rivers (Hurley et al., 2018; Al-Zawaidah et al., 2021). Consequently, the average percentage of not caught plastics, categorized as "did not reach," "in front of the catcher," "under the catchment structure," and "at the end of the flume," were all smaller (ranging from 0.75-7.78%; Table 9) suggesting better efficiency of the air bubble curtain at high flow. An exception on the not caught plastics was the 21.21% plastic "at the end of the flume" for the high plastic load (scenario F & H), potentially causing the 5.56% probability for 26% to 50% plastic caught. The average percentage of not caught reeds for bycatch was also relatively minor, ranging from 1.67% to 12.54% (Table 9). The higher average percentage of reeds " under the catchment structure " at 12.54% for the high load was an exception that potentially caused the 11.11% probability of 26-50% bycatch.

Generally, based on the probability distribution, the amount of plastic caught by the air bubbling mechanism, from the mesocosm experiments, is lower than that of the bycatch in most scenarios at low and high flow. A potential reason for the finding is the low percentage of escape reeds once they interact with the air bubble system, which was observed regardless of the flow velocity and number of reeds loaded since they are floating during transport and complements the air bubble mechanism. Hence, it could be a limiting factor in the use of air-bubbling mechanisms as plastic clean-up in areas where there is a lot of organic debris or in seasons when there is a high discharge of organic debris.

Plastic clean-up technologies are promising in removing plastic in the environment (Moulaert et al., 2021); based on the modeled simulations, plastic interaction with the catcher, such as an air-bubbling system, is critical for its efficiency. Falk-Andersson et al. (2020) also discussed plastic interaction with clean-up technology to improve efficiency. Plastics that, in the context of this study, were categorized as "did not reach the catcher" and "in front of the container" can be collectively classified as plastic that did not encounter the air-bubbling system. For passive clean-up technologies, such as the air-bubbling system that relies on the horizontal flow of the water to transport plastic, a higher flow velocity can increase its efficiency. Zhang et al. (2022) also noted flow velocity as a factor affecting the efficiency of the air-bubbling system assessed for microplastic removal. However, higher flow velocity also increases the probability of higher bycatch. Optimal use of an air-bubbling system means maximized plastic caught with the least negative environmental impacts, such as bycatch which was not the case for air bubbling mechanism based on the model simulations. The influence of plastic and biota loads had a weaker influence on the plastic caught and bycatch reeds, respectively, of the air bubbling mechanism. However, for the case of plastic load, the framework developed by Helinski et al. (2021) noted the importance of the amount of plastic litter as a criterion for the selection of plastic clean-up devices.

The BBN model revealed the trade-off of plastic caught and bycatch, proving its potential use in decision-making towards the optimal use of air bubbles and plastic clean-up technology in general. Natural fluvial systems and the transport of plastics vary with seasonality which could challenge remediation efforts (van Emmerik, Strady, et al., 2019) like air-bubbling systems. Hence, knowledge of the macroplastics budget of the riverine environment (Al-Zawaidah et al., 2021) and the spatiotemporal distribution of floating organic matter and biota is essential to optimize the use of the air-bubbling system.

4.3. Importance of Floating Organic Matter in the Riverine Environment

The mesocosm data and BBN model showed the inevitability of floating organic matter such as reeds as a bycatch of air bubbling mechanism. In the field performance of deployed clean-up technologies, Brouwer et al. (2023) and Sherlock et al. (2023) also stated the same narrative on organic matter and vegetation materials as bycatch. In rivers, there is a variety of floating particulate organic matter, such as wood, twigs, leaves, seeds, carcasses, or faeces (Shumilova et al., 2019). Inputs of organic matter in the rivers is through direct and episodic events, such as leaves senesce of leaves and landslides, respectively (Abelho, 2001; Reeves et al., 2003; Hart et al., 2013; Comiti et al., 2016; Shumilova et al., 2019) and the amount of floating organic matter correlates with the size of the catchment area (Shumilova et al., 2019). Floating organic matter is pivotal in maintaining the integrity of rivers, which are often neglected (Shumilova et al., 2019).

The roles of floating organic matter vary with seasonal natural cycles (Baldwin et al., 2014). The natural cycle of floating organic matter involves transport and deposition (Shumilova et al., 2019). While at transport, floating organic matter serves as a vector of dispersal for the attached organisms (Tenzer, 2003; Trottmann, 2004). When deposited, organic matter can serve as a geomorphic agent, especially for large wood that drives the development and character of floodplains and channel boundaries (Montgomery et al., 2003; Ravazzolo et al., 2015a; Gurnell, 2013; Zen et al., 2017). While smaller vegetative debris, like the reeds in this study, can help in soil development and fertilization (Mardhiah et al., 2015; Gurnell et al., 2018). Floating seeds and other plant propagules also act as geomorphic drivers when deposited, ensuing vegetation growth and potential landform building (Gurnell, 2014; Cunnings et al., 2016; Shumilova et al., 2019). Serving as habitat is another role of deposited organic matter (Harmon et al., 1986; Braccia & Batzer, 2001; as cited by (Shumilova et al., 2019)) for some organisms to be protected from desiccation, thermal stress, and predation (Loeser et al., 2006; Gabel et al., 2008; Harris et al., 2014; Czarnecka et al., 2014; Heerhartz et al., 2016; Brien et al. 2017 as cited by Shumilova et al., (2019)).

Regardless of the natural cycle of organic matter, it serves as a nutritional resource, especially during decomposing phase (Shumilova et al., 2019). For instance, crabs, birds, lizards, or rodents (Heerhartz et al., 2016) consumed the organic matter or its associated organism (Bowen et al., 1998; Haden et al., 1999; Hoffmann & Hering, 2000; Eggert & Wallace, 2007; Harris et al., 2014; Heehrhartz et al., 2016) as cited by (Shumilova et al., 2019)). In general, floating organic matter as a nutritional resource is more valuable in higher-order streams (Haden, 1997; Haden et al., 1999, as cited by (Shumilova et al., 2019)). In addition, floating organic matter is a biogeochemical component linked with carbon and nutrient cycling (Xiong & Nilsson, 1997; Krause et al., 2014; Shumilova et al., 2019). Such can contribute 30-60% of total organic carbon export at the catchment scale during extreme events (West et al., 2011). Floating organic matter also promoted biofilms which are areas for high chemical transformation with carbon, nitrate, and phosphate uptake (Baldwin et al., 2014; Shumilova et al., 2019)

Despite its importance, floating organic matter are negatively perceived and eradicated from inland water systems (Strayer & Findlay, 2010); and the natural cycle of floating organic matter has been modified due to anthropogenic activities such as dams (Shumilova et al., 2019). In the context of this study, removing organic matter due to air-bubbling systems and other plastic clean-up technologies is another potential impact that might affect the integrity of riverine ecosystems. The potential impact on the organic matter of plastic clean-up technologies is removal from the environment as bycatch, as shown in the study and other field assessments (Sherlock et al., 2023; Brouwer et al., 2023). How this will affect the integrity of the riverine system is unknown; however, returning the organic matter to the environment is possible after the segregation from the collected plastic litter.

4.4. Use of BBN as a Support Tool for Decision Making

This study developed a BBN model that estimates the probability of plastic removal and bycatch of air bubbling clean-up mechanism (Figure 5). The BBN model was fed with discrete and continuous data from mesocosm experiments tested in an artificial flume with different parameters influencing the plastic caught and bycatch. The nexus of nodes and arrows in the model is a simplification of the natural riverine environment, assuming a causal relationship of the five independent nodes (plastic load, plastic object, flow velocity, biota, and biota load) to plastic removal and bycatch. The simplified structure of the BBN model is essential in minimizing the uncertainties of the result (Forio et al., 2020; Chen & Pollino, 2012). Applying the BBN model can help determine the potential impact of a plastic clean-up mechanism, such as air bubbles, before its deployment. A model like BBN can be critical in ensuring a precautionary approach and maximizing the use of any plastic clean-up mechanism while minimizing other impacts, such as bycatch. Leone et al. (2022) proposed the use of BBN model as a support tool to inform decisions on utilizing plastic clean-up technologies in rivers and estuaries. Later, Forio et al. (2023) published that BBN is applicable in environmental management, describing its application in policy making and ecological risk assessment. Bayesian Belief Network models can also be easily adapted to regional situations to improve the accuracy of results (Landuyt et al., 2016), hence the adjustment based on the limitations of the data flume experiments. A limitation of the BBN model developed is its need for validation to verify the model output hindered by the lack of publicly available in-field data on the performance of air-bubbles clean-up technologies.

4.5. Prospective and Future Work

The study results are valuable insights into the data-poor and novel field of plastic clean-up technologies and their potential impacts. Using these results as a benchmark will further our understanding of the impacts of air bubbling and other plastic clean-up mechanisms. These include expanding the environmental factors affecting plastic removal and bycatch, such as wind, temperature, and tide. Another is testing for other plastic litter and biota such as eggs, seeds, plant propagules, and other organisms to gain more information on the mechanism's potential impact. It will also be interesting to understand how different configurations of the air bubble system would affect its impact on plastic caught and bycatch. We could also use data from in-field testing or actual data from the installed air bubble system for future work in scaling up the result. These prospective can be integrated into the BBN model we developed in this study, which successfully visualizes the trade-off between plastic removal and bycatch of air bubbling mechanism.

Chapter 5: Conclusion

The use of air-bubbling mechanisms, among other clean up technologies, to minimize plastic pollution across the aquatic environment is increasing. However, to date, a policy framework still needs to be developed to make informed decisions on their use. The first reports made about the unintentional bycatch are still limited so this study aims to provide the first information on the trade-off between plastic caught and bycatch of the air-bubbling system through BBN modeling fed with flume experiment data. With these, we know that depending on the type of plastic litter, plastic caught may vary due to its characteristics that affect the transport and deposition of plastics. Floating plastics, such as bottles, are caught most efficiently by the air-bubbling mechanism. On the contrary, easily deposited plastic, such as foams, lessens its interaction with air bubbles, resulting in low plastic caught. Suspended plastic, such as films, is more challenging to catch than floating plastic. The plastic object does not necessarily affect the amount of bycatch or the reeds collected. The agglomeration of plastics and reeds may result in deposition or clogging in front of the catchment container of the air bubble. Flow velocity is another factor affecting the plastic caught and bycatch. The BBN model showed that the percentage of plastic and reeds caught by an air-bubbling system would likely increase with high flow velocity. The plastic load has a negligible effect on the plastic caught and does not influence bycatch. Moreover, the BBN model was demonstrated to be an effective tool in visualizing the trade-off between the probability of plastic caught and bycatch with its ability to simulate scenarios that can aid in impact assessment and decision-making towards optimized use of the air-bubbling system to alleviate the problem of plastic pollution.

Appendix

Table 6. Transport time of tested items at low flow.

Sample	**Mean Transport Time** (seconds; n=30)
Films	91(± 11.1)
Bottles	198 (± 7.09)
Foams	106 (± 23.1)
Reeds	111 (± 8.92)

Table 7. The detection limit of the flume at low and high flow.

Sample	**Sample Load**	**Detection Limits**	
		low flow	**high flow**
bottles	15	85.33	100
	30	88.67	100.0
	100	91	100.0
films	15	98.67	100
	30	94.67	100
	100	95	100
foams	15	89.33	98.67
	30	87.33	92.67
	100	88.00	97
reeds	15	91.11	100
	30	96.57	100
	100	97	100

Table 8. The detection limit of air bubble prototype at low and high flow.

Sample	**Sample Load**	**Mean Detection Limit (%) (n=3)**	
		Low Flow	*High Flow*
Films	30	98.89	92.22
	100	62.33	79.33
Bottles	30	61.11	77.77
	100	93.33	77.67
Foams	30	74.44	93.33
	100	34.00	80.67

Table 9. Plastic and Reeds that are not caught at high flow.

Position After Test	**Plastic Load**		**Reeds Load**	
	High-Load Class	**Low-Load Class**	**High-Load Class**	**Low-Load Class**
Did not reach the catcher	2.93	1.97	6.42	4.17
In front of the container	7.34	4.17	4.88	5.56
Under the catchment structure	0.75	0.83	12.54	2.78
Escaped	21.21	7.78	4.00	1.67

Table 10. Plastic and Reeds that are not caught at low flow.

Position After Test	**Plastic Load**		**Reeds Load**	
	High-Load Class	**Low-Load Class**	**High-Load Class**	**Low-Load Class**
Did not reach the catcher	13.93	14.44	22.55	22.42
In front of the container	46.63	24.47	47.17	24.85
Under the catchment structure	3.31	15	1.2	10.3
Escaped	10.48	21.67	0.72	1.21

Acknowledgements

This thesis is only possible with the contribution of the people who shared their expertise. By enumeration, the researcher expresses sincere gratitude for all their contributions. To the supervisors from Flanders Marine Institute, MSc Giulia Leone, Dr. Ana Catarino, and Dr. Gert Everaert, for the privileged of working with them provided learnings and skills beyond expectation. To the promoter. Prof. Dr. Marleen De Troch for her valuable input and guidance. To the Department of Civil Engineering Laboratory of the University of Ghent Ardoyen Campus headed by Peter Troch and the technical staff for letting us use the flume facilities. To Marie Anne Eurie Forio for her expertise in BBN modeling. To the authors whose names appear in the bibliography. To the scholarship provider VLIR-UOS. Finally, to Oceans and Lakes and the Vrije Universiteit Brussel, the University of Ghent, and the University of Antwerp for training and education.

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