

MARINE LITTER IN PORT AREAS - DEVELOPING A PROPAGATION MODEL

ME2130 – RESEARCH ASSIGNMENT

by

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ABSTRACT

This research focuses on the marine litter propagation in port environments, where several aspects influence the marine litter movements. Many studies in literature confirm that the biggest part of solid litter on a global scale is transported via rivers, and originated from land bases sources. The items vary in many materials but plastics certainly account for the vast majority. Drifting towards the ocean, the marine litter flows through port areas, which are the main link with the inland waterways. As seaports are generally designed like tree structures with many branches, the marine litter gets divided when entering a port area. A part of the litter accumulates at the ends of these branches, and a part passes through the port area towards the open sea. Port authorities consider the implementation of both static and dynamic cleaning solutions that have recently been invented. When placing the static cleaning solutions at certain positions, it would be most efficient when the marine litter accumulation locations are known. Therefore, this research proposes a propagation model in order to simulate the marine litter movements inside port areas.

Given the complexity of the port environment and the the dynamic movements of marine litter, the propagation model incorporates a hydrodynamic model. A hydrodynamic model can be used to describe, define and simulate water movements in environments such as port areas, in order to achieve the most realistic results. A specific case study is performed in order to verify the application of the generic model, and hereby a hydrodynamic model of the case study environment is developed. The model is developed using the Delft3D hydrodynamic modeling software of Deltares, and it is imposed to boundary conditions in order to accurately describe the water flow. The main boundary conditions are the variable river flow rate and water levels, which are fluctuating due to the impact of changing tides. The developed model has been validated by comparing simulation results with real life measurements. The model output was hereby compared to data regarding the water level, obtained from Rijkswaterstaat, and measurements of both the water level and the flow velocity, obtained from the case study port authorities. From these comparisons it is concluded that the developed hydrodynamic model accurately describes the water flow in the port area.

A particle tracking tool is used to discharge separate particles and to track their path in time, in order to simulate the marine litter propagation within the port area. During the time of this research very few quantitative data regarding marine litter inside port areas was available. Therefore, a number of scenarios have been proposed in order to determine how the litter items behave under the influences of the different aspects. By distinguishing between litter items floating at- and drifting below the surface, and imposing several wind conditions, the impacts of these and other aspects are investigated. Overestimated discharge input values are chosen such that the discharged particles accumulate at several locations. From analyzing the simulation results of the different scenarios, it is concluded that the port structure affects the movements of marine litter, and that tidal ranges affect the marine litter inside port areas on a relatively short term. Furthermore the impact of wind conditions is a dominant factor for the movements of marine litter floating at the surface, and the river flow is dominant for litter items drifting below the surface level. A number of accumulation sites are found, but naturally they vary per scenario since the different aspects influence the marine litter.

This report displays the knowledge that has been acquired during a literature study, from which decisions for the modeling approach are made. It demonstrates the potential of hydrodynamic modeling and explains the process of developing a propagation model. Since researches regarding marine litter propagation in port environments are relatively young and few quantitative data is available to date, much potential in this topic exists. Therefore, the findings of this report can be taken further in the strive for creating a cleaner environment.

Lammerts (2016); Marine litter in port areas - Developing a propagation model.

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1

INTRODUCTION

Since the last century the increasing amount of marine litter is considered a global problem [1]. Marine litter consists of various items that have been deliberately discarded by humans, were unintentionally lost, or are transported by nature into the naval environment [2]. The materials vary from plastics to metals, wood, paper, glass, rope, rubber and even clothing. Estimating the total amount of marine litter that is present in the world, as well as the yearly increase has proved to be difficult to quantify [3]. Several studies have been performed to quantify this yearly accumulation rate. Plausible estimations based on comprehensive calculations vary from 6.4 million tonnes [1] to an enormous amount of 7 billion tonnes each year [4]. Although there is a big gap, both numbers are alarming since the actual accumulation rate will lie somewhere in between.



As can be seen in the pictures above, the presence of marine litter has various impacts on society. These impacts can be divided in environmental, public safety, social and economic categories [2]. Cleaning the coastlines from marine litter in the Netherlands and Belgium for example costs approximately 10,4 million euros each year [5]. Various research studies show that high buoyant litter items such as plastics have the highest presence in marine litter [6]. When comparing research results from the beginning of this century [7], with more recent findings an increase in the percentiles of plastic can be seen [8]. The percentage of plastics in marine litter contains a stunning number of up to 80% approximately [9]. Furthermore, according to a recent study approximately 10 million tonnes of plastic debris enters the ocean each year and this trend of plastic influx appears to be growing [10]. What may be even more alarming is that over the last 12 years no significant decrease in the overall quantity of marine litter can be seen in the North Sea, which presumably goes for everywhere else in the world as well [11], see figure 1.1.

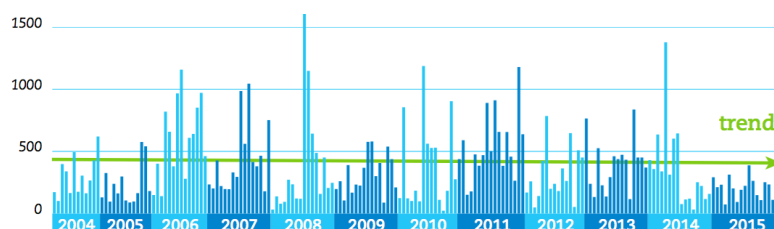


Figure 1.1: Average number of encountered litter items per survey [11]

Marine litter risks

Since the variety of marine litter chemical materials is enormous it is not only dangerous for living organisms, but can also be harmful for vessels [12]. Moreover, it is not only considered a problem in the oceans but also in inland waters and therefore as well in seaports all over the world. It has been determined that approximately 80% of solid litter found on beaches on a global scale was transported via the close-by rivers and originated from land bases sources [13]. As marine litter is transported by rivers from inland sources towards the ocean, it flows through port areas, which are the main link between the oceans and the inland waterways. If the port areas and the rivers should not be cleaned of marine litter, it would enter the open sea from where it either flows throughout the ocean or accumulates at coast lines [14], see figure 1.2.



Figure 1.2: Marine litter accumulation along coast line

Port Waste Catch Project

As seaports are generally designed like tree structures with many branches, the marine litter tends to get divided when entering a port area. It is expected that a part of the litter accumulates at the ends of these branches, a part enters and leaves the branches, and a part passes through the port area directly to the open sea [15]. Another part of the marine litter presumably originates from within the port area itself and then follows either of the previous mentioned paths. In the Netherlands a strong awareness exists that the amount of marine litter in the North Sea will increase if no actions are undertaken. The Port of Rotterdam (PoR) has the ambition to reduce the amount of marine litter in the sea and inland waterways in 2020. It wants to find solutions to remove roaming and floating waste items from the port area before it enters the open sea. In 2015, the project *Port Waste Catch* was initiated to develop techniques for a cleaner and more sustainable port area [16]. It has challenged market participants to invent an innovative way of removing marine litter that is roaming in the port area. A number of waste reduce systems were invented in cooperation with technologists, engineers, inventors and other companies, which could provide a solution for all steps in the chain of waste disposal. Some of these systems are static, thus can be implemented on fixed positions, and others are dynamic movers such as cleaning vessels.

Social relevance

In general port authorities use so-called sweeping vessels, that are specially designed for cleaning the water from marine litter [17]. Many types of vessels have been invented, and now more dynamic solutions are proposed as a result of the Port Waste Catch project. Due to the unpredictable propagating behavior of the marine litter, these vessels are being deployed when complaints regarding excessive amount of accumulated litter arise [18]. Naturally this is not very efficient and therefore a routing strategy for the sweeping vessels would be a better solution. Such a routing strategy can only be implemented when the propagation of marine litter inside the port area can be predicted. Furthermore, when placing the static cleaning solutions at certain positions it would be most efficient when the marine litter accumulation locations are known. Given these facts a high relevance exists in researches on strategies to clear the inland water and port areas from marine litter before it enters the open sea. The main challenge is to simulate how marine litter propagates in port areas over time and space, such that the accumulation locations could be predicted.

Research objective

Investigating how marine litter propagates within an entire port is a tremendous task. Therefore this research study will focus on the propagation of marine litter in a specific part of a port area, in order to determine where the cleaning solutions can be situated and deployed in the near future. With this focus, the following main research question was composed:

How could the propagation of marine litter, within port environments, be modeled?

In order to investigate this research question, a literature study needs to be performed to acquire background information regarding marine litter. A numerical model needs to be (re)developed to simulate the propagation of marine litter, and real world data is required to validate the model. The generic model should be tested on a specific case study in order to verify the specific application of the generic model. Therefore, answering the main research question can be achieved by answering the following sub questions:

1. What knowledge does exist in terms of the quantity, origins and consistency of marine litter?
2. Which aspects influence the movements of marine litter, and how should this be accounted for?
3. What can be learned from earlier performed studies regarding the movements of marine litter?
4. How is quantitative real world data regarding marine litter gathered, and what data is available?
5. Given the acquired knowledge on these four questions, which modeling technique is preferred?
6. How, and with which design tools, could the generic marine litter propagation model be developed?
7. Which port environment and what boundaries are a good representation for a specific case study?
8. What are the set-up and input values for this specific case of the developed model?
9. What is the output of the developed model, and how can this be validated?
10. Which scenarios can be simulated using the propagation model, and how do the results compare?

Report structure

This report consists of 6 chapters, including this first introduction chapter. The composed research questions are answered in different chapters, considering the observations learned from literature and the model development. Chapter 2 focuses on the first four research questions by conducting a literature study. By searching for key information in various resources, a large amount of literature is processed and structured according the different contents. With this acquired knowledge on background information, several modeling studies and quantitative data, the fifth research question is answered in chapter 3. This chapter elaborates on the preferred modeling technique and which tools are used to develop the numerical model, hence answering the sixth research question as well. In the first section of chapter 4 the generic propagation model is introduced. Thereafter a specific port is introduced as reference environment for the case study, capturing the seventh research question. Throughout this chapter the development process including the boundary conditions and input characteristics are explained, such that the eighth question is answered. Concluding the chapter the model output is presented in order to demonstrate the application of the model. In the last section the validation process is explained, hence answering the ninth research question as well. Then, chapter 5 elaborates on the different scenarios that are simulated, and how the different aspects that influence the marine litter are incorporated in these scenarios. Finally the results of the simulations are demonstrated and compared to each other, answering the tenth research question. Chapter 6 reflects on the research objective and summarizes how the research questions have been answered. Moreover, it discusses the generic capability of the developed model compared to the specific case study. Concluding this report, chapter 7 proposes a number of recommendations in order to suggest further research topics.

2

LITERATURE STUDY

In order to acquire more knowledge on the research objective a brief literature study was conducted. By searching for key information in various resources, a large amount of literature was processed and structured. This chapter elaborates on the approach and fulfillment of this study. First the research strategy is explained, search results are mentioned shortly and then the findings are explained according the different topics. Concluding this chapter the most relevant results are summarized and the relations between the different characteristics are visualized.

2.1. SEARCH APPROACH

As explained in the introducing chapter, the objective of this literature study is to investigate four different topics. The main thoughts of the different topics are summarized as in the following:

1. Sources and consistency of marine litter
2. Aspects influencing the dynamic movements of the marine litter transport
3. Propagation, spatial distribution or prediction studies regarding marine litter
4. Quantitative real world data of these topics

One of the challenges when searching for specific literature is to use proper *keywords*. Since the world wide web consists of billions pieces of literature, one could easily find a number of articles that are relevant to the searched topic. However, due to the high amount of literature it is possible that the use of synonyms could lead to other search results. Therefor, when focusing on the different search topics combined with the overall research objective, a number of important keywords were identified. Common synonyms for these keywords and related search terms relevant to the research objective were proposed and listed in table 2.1.

Table 2.1: Keywords and related search terms

Marine	Litter	Port	Spatial Distribution	Propagation	Prediction
Ocean	Pollution	Harbor	Accumulation	Transportation	Forecast
Naval	Debris	River	Congestion	Flow	Simulation
Sea	Waste	Coast	Abundance	Drift	Model

Various combinations of these keywords have been used as search terms in the following different resources:

- American Society of Civil Engineers
- 4TU Research data center
- CRCnetBASE
- Google Scholar
- Mendely
- Scopus
- TU Delft Repository
- Web of Science
- Institute of Electrical and Electronics Engineers
- Transportation Research International Documentation

Many results have been considered, but naturally not all of them were equally valuable or relevant for the research assignment. Some literature pieces were discarded almost immediately, others looked promising at first but turned out not to possess the required information, and some were partially containing relevant content. It should be mentioned that none of the results contained exactly the kind of information that was searched for. The different literature results were reviewed, documented and divided into the three relevant topics and the acquired information is explained in the following sections.

2.2. SOURCES AND CONSISTENCY OF MARINE LITTER

This section summarizes the most relevant information that was found in literature regarding marine litter. It captures important results from researches that were performed in order to acquire knowledge regarding the existing quantities, origins and consistency of marine litter. Researches from different locations and different scopes were studied in order to sketch a complete picture.

2.2.1. QUANTITY

An extensive report resulting from a study performed by UNEP Regional Seas Programme in cooperation with the IOC of UNESCO (2009), displays a broad perspective of estimates for the yearly accumulation of marine litter in the world [2]. One of the smallest plausible estimates results from a study performed by the National Academy of Sciences (1975), that based an annual influx of 6.4 million tonnes on comprehensive assessments [1]. The largest estimation regarding the global marine litter increase states an accumulation rate of 7 billion tonnes every year, coming from a fact sheet drafted by the Great Barrier Reef Marine Park Authority (GBRMPA, 2006) [4].

The UNEP/IOC report (2009) states that naturally the estimation from 1975 is now outdated, but also that the 7 billion tonnes estimate is very likely to be well overestimated. Analyzing multiple estimation studies regarding global plastic productions and marine litter accumulation, led them to believe that the global production rate of marine litter approximately varies between 10 and 70 million tonnes per year [2]. According to a more recent conducted study by several researchers of the National Research Council (2008), the accumulation rate of marine litter in the oceans is still difficult to quantify [3]. However they underline that marine litter is a global concern which is likely to increase in the 21st century. This is due to the persistent natures of plastics and other types of human based waste, the diversity and abundance of litter origins, and the capacity of tides and currents to transport marine litter over long distances.

The international Ocean Conservancy organization analyzed the amount of litter items that were collected by clean up volunteers from coastal areas all over the world. This has been done over a course of 25 years, just one day each year. The alarming numbers are illustrated in the figure on the right [19]. What may be even more alarming, as stated in the introducing chapter, a study in the North Sea showed that over the last 12 years no significant decrease in quantity can be seen [11].

Aside from the quantity, numerous research studies on the origins of marine litter have performed in different sections of the world. These findings are discussed in the coming section.



2.2.2. ORIGINS

According to Araújo and Costa (2007), approximately 80% of solid litter found on beaches on a global scale came from the close-by rivers [20]. The same conclusion was drawn by Moore et al. (2011) and several other studies [13]. Furthermore, an early study performed by Vauk and Schrey (1987), showed that a large amount of marine litter items originates from vessels themselves [21]. More *sea based origins* such as vessel traffic and fisheries have later been confirmed by Derraik (2002) [22]. Overall it has been found by Ryan et al. (2009) and Andrady (2011), that human based litter enters the marine environment from either *land located origins* or from sources at the open sea [23]. This is illustrated on the right in figure 2.1.

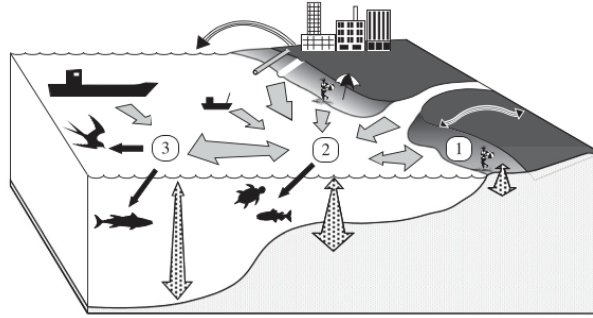


Figure 2.1: Main origins and flows of marine litter [24]

Furthermore, several researchers of the Dutch technology institute Deltares, including van der Wal et al. (2013), conducted a research that was commissioned by the Dutch Ministry of Infrastructure and Environment. The study focused on the contribution of marine litter from rivers towards the North Sea, it hereby analyzed the origins and transport processes of the litter items [14]. Their results comply with those of the previously mentioned studies and are summarized in figure 2.2. Very recently Stichting De Noordzee (2016), a Dutch organization striving to protect and create sustainability in the North Sea, investigated the presence of marine litter in the North Sea over 12 years. From a total of 184 surveys they found that 45% of all litter items can be deduced directly from the maritime industry, 13% certainly originated from land based sources, and the remaining 42% could either come from land- or sea bases sources [11].

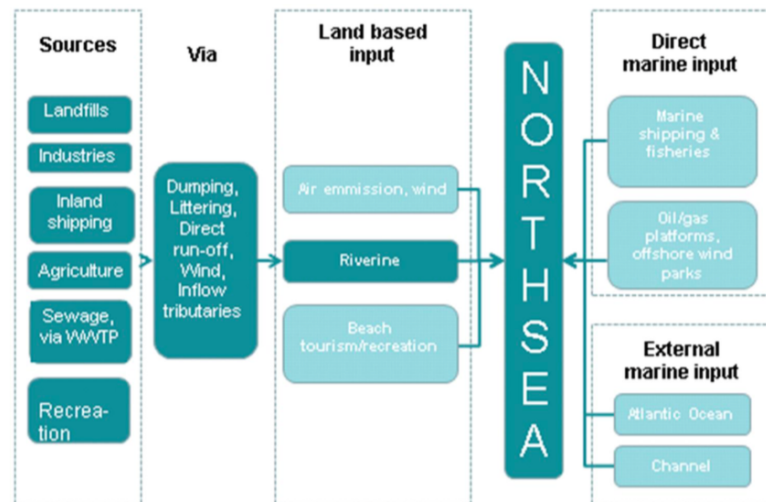


Figure 2.2: Main origins and flows of marine litter from rivers towards the ocean [14]

From these studies the hypothesis that large amounts of litter are transported from inland sources by rivers towards the open sea can be verified, and it can be concluded that this occurs everywhere in the world. Origins have been identified as inland sources on the one hand such as agriculture lands, industries and recreational areas. And on the other hand there are sea based origins such as vessel traffic, fisheries, and offshore platforms. Now that the origins of marine litter have been determined, the next step is to investigate the consistency of the litter items, this is done in the coming section.

2.2.3. CONSISTENCY

Balas et al. (2001) analyzed the spatial distribution of marine litter in rivers. The results regarding the different materials are visualized in figure 2.3. From this it can be seen that various materials are present in marine litter and that plastics represent an incredible large part of the total amount; approximately 50% in the beginning of this century. Rech et al. (2014) also conducted a marine litter composition research on several rivers in Chile. This research captures many different studies that have been performed throughout the recent years regarding specific focuses on marine litter in rivers. It should be noted that all these studies focus either on the quantities, consistencies and characteristics of the marine litter, rather than the propagation of it. From this research it had been found that *high buoyant litter items such as plastics* maintain the highest presence in marine litter [6]. This complies with the conclusion of the work of Thiel et al. (2013) who also conducted a marine litter consistency study [25].

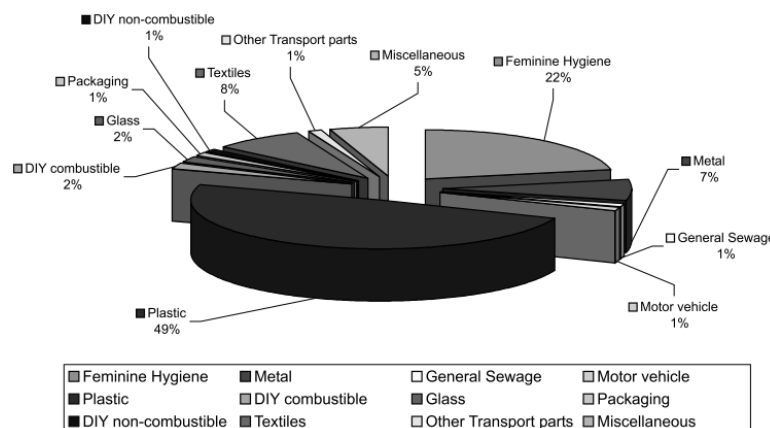


Figure 2.3: Consistency of different materials found in rivers (2001) [7]

PLASTICS

A study of Schulz et al. (2013) evaluated the consistency of marine litter across the North Sea. They showed that many global model studies regarding spatial distributions of marine litter have been performed over the years. These researches all focused on the open water area's in stead of inland rivers let alone port areas. The results regarding the consistency and abundance of plastic materials complied with the previously mentioned studies and show that the abundance of plastics is alarming [26]. An extensive research study on the accumulation and quantities of marine litter conducted by Barnes et al. (2009), focus on the percentage of plastic debris. It was stated that in general, plastics decide approximately 10% of by human discarded waste material. However, it had been found that the percentage of plastics in marine litter contains a stunning number of up to 80% approximately [9]. Various researches such as Thiel et al. (2011), confirm the abundance of plastic items in marine litter which accounts for 60-80% [8], see figure 2.4. An even higher percentile was reported by the Stichting De Noordzee (2016), over all 184 surveys conducted in 12 years they found that 90% of all encountered litter items is of plastic material [11]. Their findings are reported to the Rijkswaterstaat (Dutch Ministry of Infrastructure and the Environment) and online each year [27].

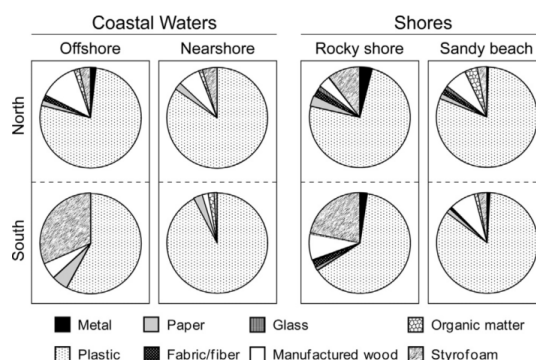


Figure 2.4: Consistency of different materials found in different waters (2011) [25]

THREATS

Leslie et al. (2011) reported the abundance of micro plastic litter in both offshore locations, see ports and beaches, as well as in the open North Sea water and its marine life [28]. Furthermore Langelaan et al. (2014), conducted a research specifically on the presence and effects of micro plastics in Dutch waters. They showed that approximately 38% of the European wasted (hence not recycled or used) plastics in 2012 was disposed of by humans, and how this affects the quality of the water thus threatens the health of the living organisms [29]. In addition to studies focusing on consistency of different materials, Turner and Solman (2016) performed an ingenious marine litter composition analysis, using a Niton field-portable-x-ray fluorescence (FP-XRF) spectrometer. Hereby they were able to determine the content of 17 different chemical elements in marine litter items of beached plastics, foams, ropes and painted items. The most important finding of this study contained the occurrence and elevated concentrations of hazardous elements in many samples and from all material categories considered. This emphasizes the risks that the occurrence of roaming marine litter inside port areas contain [12].

2.3. DYNAMIC MOVEMENTS OF MARINE LITTER

This section summarizes the most relevant information regarding the dynamic behavior of marine litter. It briefly captures featured findings from researches that were performed in order to acquire knowledge regarding several factors that influence the dynamic behavior and the different moving states of the marine litter.

2.3.1. INFLUENCING ASPECTS

An early research on the influences of *port geometries and tidal ranges* (the difference between the high tide and the low tide) conducted by numerical modeling and laboratory experiments, performed by Falconer and Jiang (1983), showed that tidal ranges and geometric characteristics of the environment do influence the dynamical behavior of the particle movements in water [30]. This has been confirmed later by a more recent study performed by Yin (2000) on the dynamical water movements in a basic harbor imitated environment [31]. Stoschek and Zimmermann (2006), performed a research where they investigated the effects of changing tides and variations in water flows and densities on the sedimentation process of litter material [32]. Figure 2.5 illustrates how the different effects combined lead to complicated simulations.

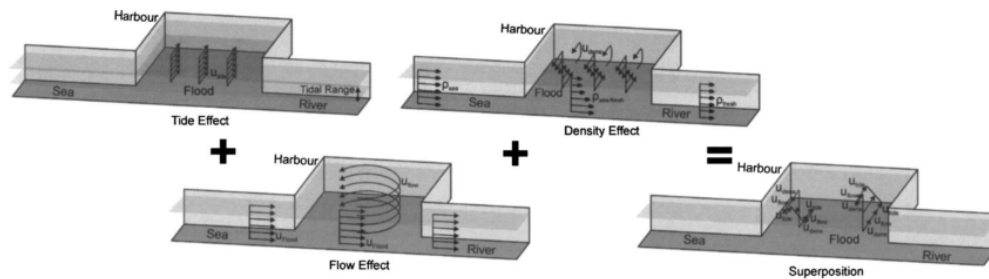


Figure 2.5: The effects of tides, different water densities and flows [32]

Browne et al. (2010) conducted a research on the spatial patterns of marine litter plastics and identified different factors that influence the dynamical transportation behavior of the litter. A distinction was made between litter related factors on the one hand, where they found the *shape, size and density* of the material as deciding factors. On the other hand they categorized external factors were *waves, wind and tide changes* influence the dynamical behavior of marine litter items [33]. Furthermore, from various researched such as conducted in the South East Pacific ocean by Astudillo (2009) and Hinojosa (2011), it was concluded that wind forces have a high influence on litter material with a higher *buoyancy* [34] [35]. Bilby and Heffner (2016), performed a research on factors influencing litter transportation of organic matter from land sights towards water streams. From their study it was concluded that wind forces also affect the river influx of litter [36]. Ryan et al. (2009) monitored the abundance of plastic items in marine litter. They hereby categorized these plastics in different size ranges according their diameter to analyze the buoyancy impact. So-called micro-debris (<5 mm), meso-debris (5-20 mm), macro-debris (>20 mm), and even mega-debris items (>100 mm) were distinguished [24]. A study on the floating characteristics of marine litter drifting at the surface, conducted by Martinez et al. (2009), found that *sea currents* also influence the routes and velocities of the marine litter items [37]. The same was concluded for *river currents* by Galgani et al. (2000) and other studies [38].

2.3.2. LOCATIONS AND MOVING STATES

Cleassens et al. (2011) conducted a research study regarding the occurrence and distribution of micro-plastic marine litter items along the Belgian coast. Different locations such as coastal port areas, beaches and sub-littoral areas were investigated and it was concluded that the highest concentrations of micro-plastics were found in coastal port areas. Within these areas, it seemed that so-called dead end port compartments contain the highest amount of micro-plastics, since they could get sucked into a vortex and then sink to the bottom instead of flowing out of the area [15]. Furthermore, it has been found by Andrady (2011) and other studies that the plastic items *mostly drift at sea level or flow just below the surface*, depending on their size, shape and density [23], this is illustrated in the figure underneath.

The same behavior has been confirmed for litter item flows in rivers by the research of Deltares. They also found that only a small fraction of the total amount of marine litter remains or is transported on the bottom of the river bed where the stream velocity is much lower. [14]. An interesting but rather unknown study that was conducted in the Dutch river the Maas performed by ISI, Royal HaskoningDHV and SK International (2013), showed that 98% of all litter items appeared to be flowing in the top meter water column and 95% in the top half meter water column [17]. This quantification is an important finding which can be used when modeling the marine litter propagation.



2.3.3. RECAPPING THE DECIDING ASPECTS

From the various studies it can be concluded that all aspects influence the dynamical behavior of marine litter in their own way. Since a part of the marine litter floats at sea level and a part drifts just beneath the surface, not all items are affected in the same manner. Common knowledge states that the size and shape, hence the volume, of a litter item together with its density determine the buoyancy. Moreover, since plastic items, which tend to drift and are easily picked up by streams, account for the vast majority (see section 2.2.3) it can be reasoned that both the river current and wind forces have a large influence and therefore neither one is to be neglected. Tidal ranges certainly influence the transportation of litter items on beaches and along coast lines, the influence in port areas however has not yet been determined from literature. The same goes for the impact of waves, moreover vessels in port areas do also generate waves in all directions, therefore it can be argued that the influence of waves can be neglected. Furthermore, naturally the design of the port structure determines the boundaries of the marine litter flow environment. These four different aspects that influence the marine litter movements are listed below. At the end of this chapter, figure 2.7 illustrates and summarizes these different aspects and the other findings of this literature study in order to determine how the marine litter propagation could best be modeled.

- Port structure characteristics; locations- and dimensions of port compartments
- River flow rate; water velocity in m/s
- Tidal ranges; water level differences due to tides in meters
- Wind conditions; wind force in m/s and source direction in degrees

2.4. EARLIER PERFORMED MODELING STUDIES

Many different simulation studies regarding marine litter have been performed over the years. Most of them focus on the spatial- (location) and consistency distributions of marine litter, and on drift simulations across the oceans. Also quite some studies developed forecasting models in order to predict the accumulation at coast lines, and only a few propagation studies have been found. This section captures many different researches that have been performed in order to display the most relevant observations, and to demonstrate the absence of port area studies.

2.4.1. SPATIAL DISTRIBUTION ANALYSES

Pham et al. (2014) presented distributions and densities of marine litter, gathered from surveys that were conducted between 1999 and 2011. In total, 32 different sites were analyzed, including continental shelves and slopes, submarine canyons, sea-mounts, banks, mounds, ocean ridges and deep basins. Unfortunately no port areas were included in the survey [39]. Another spatial distribution analysis conducted by Galgani et al. (2000), focused on the abundance of marine litter on continental shelves and slopes along European Seas. Over a course of 6 years, 27 oceanographic cruises were taken to enumerate and quantify different pieces and materials of the marine litter [38]. Several other spatial distribution studies have been performed (i.e. Dameron, 2007 and Hinojosa, 2011), but none of them apply specifically on port areas [40] [35].

2.4.2. PROPAGATION MODELS

Balas et al. (2001) proposed a statistical riverine litter propagation model in order to describe the propagation of marine litter in rivers. This model was developed based on the geographical river structure, stream velocity, litter probability statistics and the importance sampling Monte Carlo simulation technique, also called the random walking method [7]. Van Tol (2016), performed a master thesis on the development of an optimal routing method for cleaning vessels particular in the port of Rotterdam in the Netherlands. During this research he presented a marine litter prediction model which provides a simple estimation of the accumulation of marine litter in the port area. Remarkably this model only depends on the port structure and wind influences, whereas the river current and tide ranges have been neglected. The model assumes that the marine litter entering the port area flows into the several compartments, whereby the fractions of the total amount of litter depend on the width of the compartment and if the compartment is located rather upstream or downstream of the port entrance. Furthermore, it has been assumed that once the marine litter enters a compartment it does not flow back to the main waterway or into another compartment, hence presumed to accumulate at the dead-end. Since these neglects and assumptions have not been verified, this prediction method is rather exploring until it is validated, as stated by Van Tol. The input of the prediction model is based on data which was obtained from an agency that is involved in the cleaning operations in the PoR area. This data was converted into a probability density function, subjected to a Weibull distribution from which random numbers were generated to serve as influx quantities for the prediction model [18].

2.4.3. DRIFT SIMULATIONS

Potemra (2012) distinguished between different classifications of possible numerical models to simulate the marine litter flow. The so-called particular method can be used to assign parameters to several processes such as changing tides and internal current interactions. Applying this method can be done by for example with the so-called *horizontal parameterization*, where the equations of motion are solved on a rectilinear grid. Another method models the water environment as multiple layers of different densities, so-called layer coordinate models. It can be reasoned that this second method is the proper option when modeling litter in the ocean and the first method would be preferable when modeling less deep streams or rivers [41]. In earlier work Yoon et al. (2010) performed marine litter drift simulations using numerical prediction modeling techniques. This study underlines the significance of the buoyancy ratio when analyzing the dynamic behavior of marine litter. The research focused on marine litter transportation in the Japanese Sea in order to assess where it accumulates [42]. Another numerical study with a similar purpose was later conducted by Lebreton (2013) regarding the propagation of floating litter items in the ocean [43].

Kako et al. (2011) developed a forecasting model for marine litter accumulation at beaches. The study focuses on the area of the East China Sea, only taking into account the existence of marine litter rather than its origins [44]. Neumann et al. (2014) performed marine litter transport simulations using a Lagrangian transport modeling system. Over the course of nine years particles were released every 28 hours while drift simulations were carried out forward and backward in time, subjected to variable wind and current conditions. As a demonstration of their work figure 2.6 shows partial results from the simulations. A distinction of drifting behavior was made between items floating at sea level or just below the surface [45].

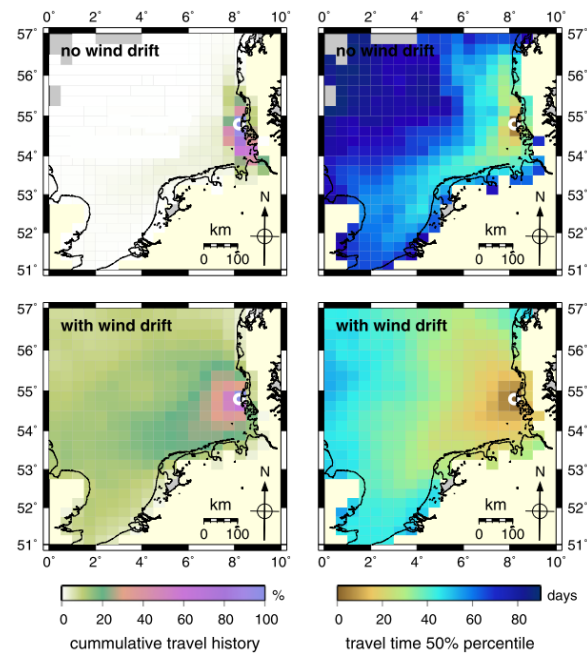


Figure 2.6: Simulations results using Lagrangian modeling [45]

2.4.4. HYDRODYNAMIC MODELS

Critchell et al. (2015) conducted a marine debris modeling study focusing on the shoreline environment along the Great Barrier Reef in Australia. According to them, numerical models as described in the previous section are used to simulate the open sea circulation, whereas hydrodynamic models are used to simulate water movements into higher detail. Therefore for their research they used a hydrodynamic model of the Great Barrier Reef to investigate the marine litter accumulations sites. This model incorporates both a hydrodynamic- and an advection-diffusion component of the interaction between the marine litter and the water. According to Critchell et al. the hydrodynamic component calculates the sea currents, sea-level values, tidal ranges and wind forces for each element for a certain time step. The advection-diffusion component on the other hand makes use of a Lagrangian schedule, hereby tracking the movement of released particles over each time step with respect to the sea currents, and then spreading them laterally based on a calculated value of the horizontal diffusion coefficient [46]. According to Lambrechts et al. (2008), the advantage of using the combination of a hydrodynamic model with the Lagrangian method is that it reaches much finer resolutions due to the more precise water movement predictions [47]. The modeling study of Critchell et al. showed that this combination successfully results in accurate predictions of the locations of marine litter accumulation sites, or so-called hot-spots.

Stuparu et al. (2015) developed a transport model for predicting the plastic spatial distribution in the North Sea in order to broaden the knowledge on accumulation sites [48]. The model was created using the Delft3D software developed by Deltares in Delft, the Netherlands. Deltares is a Dutch independent institute for applied research in the field of water and subsurface. As with Lagrangian modeling, this modeling environment releases particles representing the marine litter plastics and the software follows their tracks in three dimensions over time. This study distinguished three different states of the marine litter namely: floating-, suspended- and settling litter. The advantage of the Delft3D software is that it incorporates a hydrodynamic model such that it simulates the influences of tides, currents, winds, water densities, waves and a particle tracking model as well [49].

2.5. REAL WORLD QUANTITATIVE DATA

To achieve the main research objective as much data as possible is desired to verify the application of the simulation model. Preferably, this data contains the marine litter quantity, spatial distribution and accumulation locations from a certain port area. In theory this data could either be obtained from available resources such as the internet, companies that maybe posses relevant data, or possibly it can be obtained from port authorities directly.

Several studies have been conducted to acquire more knowledge on the origins and consistencies of marine litter as explained in section 2.2, and to propose spatial distributions as shown in section 2.4.1. When the hydrodynamic modeling software came to the mind of the author, the company Deltares was contacted with the intention to acquire more information regarding the potential of these existing techniques, and in the possession of real world data. It appeared that Deltares was interested in the author's research topic since they also conducted a small exploratory study regarding marine litter movements in the entire PoR area.

During a meeting with one of the experts of that particular project it became (even more) clear that conducting these kind of studies are highly complicated since very few real world data on specific port areas is known due to the lack of systems registering anything regarding marine litter. It should be noted that this has proved to be a reoccurring issue with many research studies, as can be seen in the following three relevant research quotes:

"Although several studies suggest the importance of rivers as a source of marine pollution by plastics and other litter ... there are very few studies that provide quantitative data about the amounts and types of anthropocentric litter in rivers. "

Rech et al. (2014); Rivers as a source of marine litter [6]

"The amount of available quantitative data for litter in Dutch rivers is limited and can mainly be found from sources that have not been scientifically validated. This means that research in this area depends strongly on estimations based on expert judgment and few available data sources. "

van der Wal et al. (2013); Contribution to plastic litter in the North Sea [14]

"The source regions chosen for simulations are close to possible input areas of marine litter into the North Sea and partly represent river- and port areas ... In the real-world North Sea system, marine litter from other sources may overlay this litter ... However, for realistic modeling of marine litter transport and distribution, one needs spatio-temporally resolved litter input profiles, which are not available. "

Neumann et al. (2014); Marine litter ensemble transport simulations [45]

Van Tol (2016) also extensively searched for quantitative data for the conduction of his research, hereby a number of river related studies were explored, from which calculated assumptions regarding the quantity of marine litter for the model its input were made [18]. Moreover, since the PoR is now implementing a number of newly created systems, it is still very interesting to develop a simulation model because the results can be compared to gathered data in the near future.

Although the findings of the studies conducted by Deltares are confidential, as goes for the PoR study, the advantages of using a hydrodynamic modeling software environment are quite straightforward. Furthermore, as will be explained in the next chapter, a lot can be learned from previous studies regarding performing simulations without the certainty of available real world data.

2.6. CONCLUSION

Recapping this chapter it can be concluded that, in terms of consistency the percentage of plastic keeps increasing and hazardous materials remain in the ocean. In terms of origins it is difficult to assess exactly where items came from, but both land based and sea based sources are present all over the world. Finally maybe the most alarming fact of all, in terms of quantity it has been found that over the last 12 years no significant decrease can be seen.

Various aspects influence the dynamic movements of marine litter in their own way. First of all, the design of the port structure determines the boundaries of the marine litter flow environment. Tidal ranges mainly influence the transportation of litter items on beaches and along coast lines, as do waves, however the influence in port areas of these two factors has not been determined. Given that plastic items tend to drift and are easily picked up by streams, plus their relatively high buoyancy potential, it can be reasoned that both the river current and wind forces have a large influence on the dynamical behavior. Furthermore, it has been found that 98% of all litter items (in the Dutch river the Maas) flows in the top meter water column and 95% in the top half meter water column.

Regarding the literature on earlier performed modeling studies it has been determined that various simulation studies regarding marine litter have been performed over the years. The majority are distributions studies where a distinction can be made between spatial distributions and percentile distributions. These studies have mainly been conducted in order to predict the quantity and consistency of the marine litter in the (near) future. Furthermore many drift simulations have been performed using different techniques that have been rapidly improved in the last decade. With these techniques a few forecast models have been found in literature regarding marine litter flows from the ocean towards coastlines. Rather few propagation and accumulation models have been developed, let only ones that focus on port areas. This can be explained by the lacking of available real world data and in general because the marine litter in oceans is presumed to be a bigger problem. Figure 2.7 illustrates all different aspects that were investigated in this literature study.

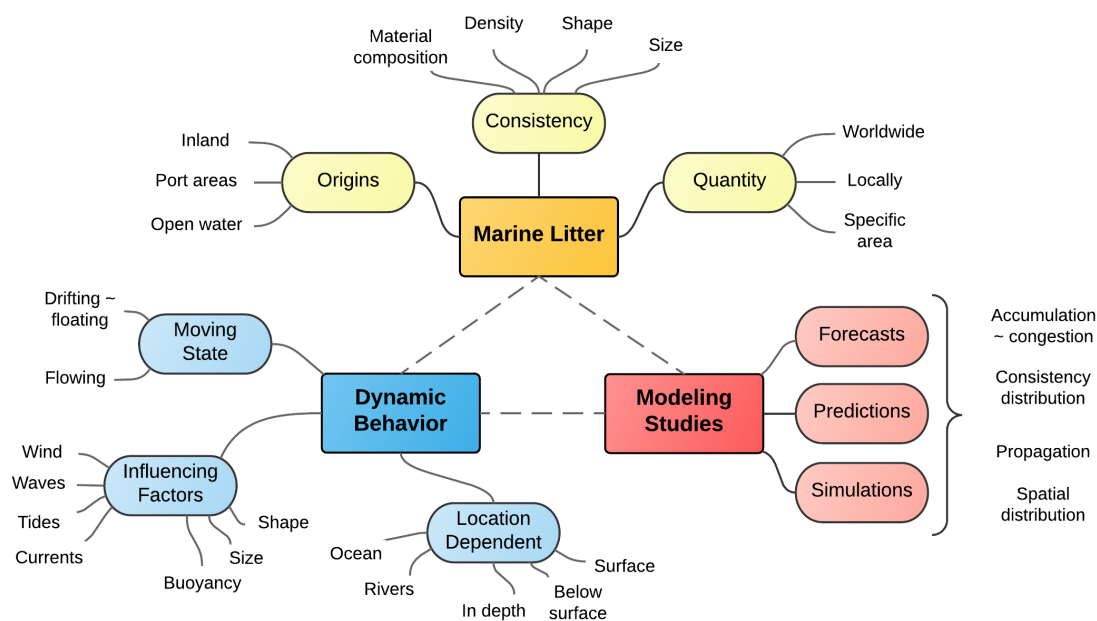


Figure 2.7: Marine litter characteristics

Given the complexity of the port environments and the dynamic entities of the water movements, let alone the dynamic movements of marine litter, the numerical model of this research will be incorporating a hydrodynamic model in order to achieve the most realistic results. The next chapter will elaborate on the advantages of using the combination of a hydrodynamic model with a particle tracking system. Later on in this report, in chapter 4, it is explained how the findings of this literature study, such as the different factors that influence the movements of the marine litter, are considered when creating a numerical model.

3

HYDRODYNAMICS AND MODELING

In order to assess what qualifies as the best modeling strategy, the basic concepts of the involved dynamic aspects need to be understood. Considering the dynamic movements of marine litter in a water environment, and for that matter the dynamical behavior of water itself, the hydrodynamic aspect should be investigated.

3.1. HYDRODYNAMICS THEORY

By definition, hydrodynamics is the study of fluids in motion. A hydrodynamic model therefore can be considered a tool with the ability to describe or simulate the motion of a certain liquid, water for example. This tool could either be a physical scale model or a computational numerical model. Given the quickly rising technological developments and innovations in the last decades, hydrodynamic modeling in a digital environment has become a valuable asset to simulate complicated real world processes in the field of computational fluid dynamics.

The essence of computational hydrodynamics contains equations describing the fluid motions, known as the Navier-Stokes equations. These equations are derived from Newton his laws of motion and describe the event of forces that are applied to fluids resulting in flow changes [50]. Furthermore, computational hydrodynamic models also comprise continuity equations which state that mass and energy are always conserved, unless they disappear from of the environment in some way [51].

From the theorem of hydrodynamics it can be seen that the complexity of the various environments of interest, such as a river or coastal area, complicates solving the corresponding equations analytically [52]. As stated before, the scientific computing possibilities of the current technology enable researchers to compute and analyze these complex processes by means of numerical methods. According to the National Oceanic and Atmospheric Administration (NOAA) Office of Coast Survey, two different methods are widely applied in hydrodynamic modeling. On the one hand structured grid approaches could be followed using primarily finite difference algorithms, and on the other hand there are unstructured grid approaches, which include finite element and finite volume methods. Both of these numerical approaches have been used in high performance computing systems, hereby enabling simulations of complex environments at high resolutions [53].

The accuracy of a hydrodynamic numerical model of a specific environment strongly depends on its input characteristics, such as meteorological conditions. Coastal models for example can incorporate various observational data sources and meteorological models when defining the characteristics of the hydrodynamic model. Furthermore, specific data regarding for example the riverine flux and tidal ranges are required to define the boundaries of the model in order to perform accurate simulations. Therefore, it can be argued that the output accuracy of any model is constrained by the available data quality and quantity. Validation of a hydrodynamic model can be pursued by comparing simulation results with real life observations.

The key asset of a hydrodynamic model is the capability to describe, define and simulate the motion of a fluid such as water in multiple environments. Depending on the sophistication of the developed model various output files can be generated. The results can be used to analyze certain circumstances or scenarios.

3.2. HYDRODYNAMIC MODELING SOFTWARE

Achieving the main research objective requires the development of a numerical model. This model could be developed using a software system, therefore it should be investigated which potential applications are suited best to reach the desired research result. As introduced in the previous chapter, Deltares is a Dutch independent institute for applied research in the field of water and subsurface. They believe in openness and transparency, which can be seen from their open source software availability. An extensive range of software simulation products and solutions, applied in over 140 countries by both professionals and occasional users, supports various commercial projects as well as research studies. As a welcome consequence from this sharing and collaborating community, a lot expertise and in-depth knowledge regarding extensive fields of applications is available [54]. A number of software applications are visualized in figure 3.1.

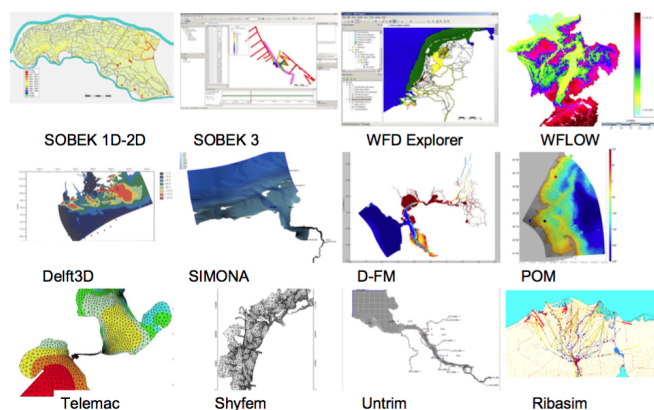


Figure 3.1: Various software applications of Deltares [55]

3.3. DELFT3D

One of these applications developed by Deltares is a numerical modeling software called Delft3D that mainly focuses on applications in the free surface water environment. This software enables the modeling of natural phenomena in the horizontal or vertical plane, or a combination of those. Since natural phenomena contain interrelated dimensional characteristics, variations could occur in both two horizontal axes and along the vertical plane. This potential of the software is visualized in figure 3.2. Moreover, as elementary natural processes are time dependent and mostly inherent, they also fit a three dimensional description in most cases. Delft3D enables to perform high-end simulations on the interaction between water and natural phenomena in time and space, simulating both two-dimensional and three-dimensional water flows.

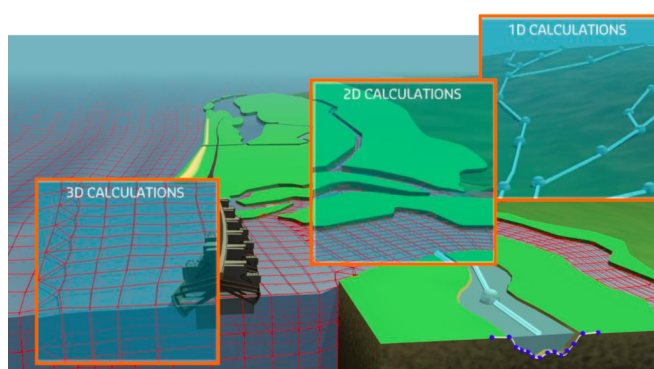


Figure 3.2: The potential of modeling in different dimensions [55]

Therefor the modeling environment is mainly consulted for modeling natural environments such as coastal areas and inland rivers but it is also capable of modeling port areas [56]. The software incorporates of a number of thoroughly tested and validated modules, which can be consulted for their own specific capabilities. Relevant modules for this research are the *FLOW* and *PART* module, they will be discussed in the coming sections.

3.3.1. THE FLOW MODULE

FLOW is a hydrodynamic module that is able to simulate inconsistent water flows in relatively shallow areas such as rivers. It could incorporate multiple effects such as wind forces, tidal ranges, waves, air pressure, even density variations. Given that these aspects influence the movements of marine litter, as explained in section 2.3.3, the *FLOW* module can be presumed a valuable tool. Furthermore an integrated heat and mass transport algorithm enables the use of specific hydrodynamic knowledge within the Delft3D software [56]. With this *FLOW* module, multiple existing hydrodynamic models can be coupled to create a new more extensive or more precise model. During a corporate presentation this potential was demonstrated, one of the slides that summarizes the various capabilities is given in figure 3.3.

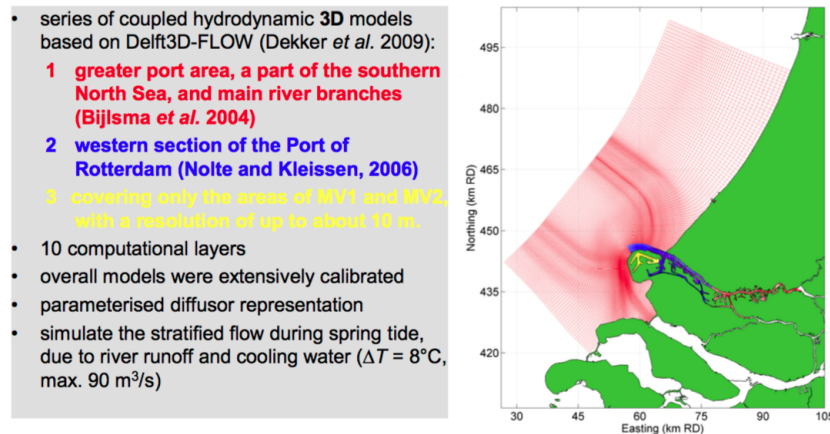


Figure 3.3: Delft3D-FLOW potential, coupling different models [55]

According to its user manual: *"The hydrodynamic module FLOW is a multidimensional hydrodynamic simulation program that calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a curve linear, boundary-fitted grid. In three-dimensional simulations, the hydrodynamic module applies the so-called sigma coordinate transformation in the vertical, which results in a smooth representation of the bottom topography. It also results in a high computing efficiency because of the constant number of vertical layers over the whole computational domain."* [Delft3D-FLOW, User Manual (2014) [57]]

As the module simulates the hydrodynamic entities of the environment and contains multiple boundary conditions settings, it can be seen that hydrodynamic modeling a specific environment has many advantages.

3.3.2. THE PART MODULE

PART is the particle tracking module of the Delft3D software. This module can be used to estimate the dynamical spatial distribution of up to thousands of separate particles by tracking their path in time. Since it is capable to describe the concentration entities of both periodically and constantly releases of particles into high detail, it could simulate various transport processes, such as wasted materials due to human activities or present marine litter behavior. The physical components in the module contain the water environment of lakes, rivers and even port areas. Natural phenomena such as river currents, varying wind forces and friction between water and the particles can be described with this module [56].

According to its user manual: *"The particle tracking module PART simulates transport and simple water quality processes by means of a particle tracking method using two- or three-dimensional flow data from the FLOW module. The tracks are followed in three dimensions over time, whereby a dynamic concentration distribution is obtained by calculating the mass of particles in the model grid cells. The processes are assumed to be deterministic except for a random displacement of the particle at each time step. The particle tracking method is based on a random walk method since the simulated behavior is stochastic and the number of particles is limited."* [Delft3D-PART, User Manual (2014) [58]]

As this model describes the dynamic behavior of particles that are released at a number of source locations and focuses on the path that these particles follow, it can be argued that simulating marine litter with this software could lead to accurate simulation results.

3.3.3. OPERATING THE SOFTWARE

In order to operate the modeling and simulation processes and analyze the obtained results a menu driven Graphical User Interface (GUI) is included in the Delft3D software. It enables to define, inspect and analyze any model and hereby the specific functions of the different modules can be consulted. The GUI allows the visualizations of the model input, reference data and simulation results in the form of animations available in one-, two- and three-dimensional data sets for different times series. A partial example window of the GUI is given in figure 3.4.

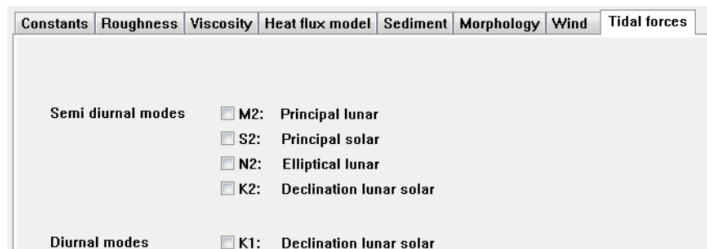


Figure 3.4: GUI example window showing partial tidal options [57]

Furthermore the Delft3D software provides several post-processing modules. These modules enable among others visualizations, grid generations, data analyses and manipulations.

The general post-processor (GPP) module of Delft3D enables access to various forms of data files, and hereby allows selections and visualizations of the measurements and simulation results. A number of possible output forms are for example: flow velocity vector plots, time history result plots for individual or multiple runs, vertical profiles for three-dimensional grid quantities, and geometric plots of the modeled grids including tidal ranges and environment boundaries [56].

Another post-processing module of Delft3D, called QUICKPLOT, enables plotting and animating data obtained from the simulated output files and even, if desired, also from a number of input files. Desired generated results could be two- or three-dimensional visual plots, time-series plots, and the module enables both scalar and vector results. Hereby scalar results could contain for example contour lines and patches, grid cells and colored marked fields. Whereas vector results can be generated as colored or normalized vectors, then when a individual vector component is selected, scalar quantities can be obtained [56].

The transport model for predicting plastic distribution in the North Sea, resulting from the research as described in chapter 2, was developed using the Delft3D software. When verifying the input conditions and analyzing the simulation results a number of plots were generated using the modules that were just described. Figure 3.5 displays two of these plots to demonstrate examples of possible outputs.

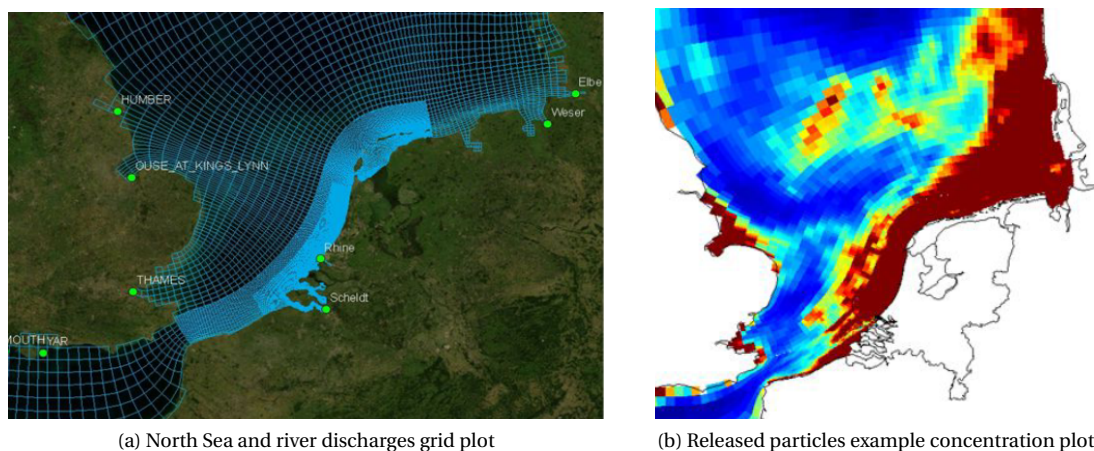


Figure 3.5: North Sea transportation modeling study using the Delft3D software [48]

3.4. VALIDATION OF THE SOFTWARE

According to Deltares, the validation of modeling software such as Delft3D maintains a high priority. They state that the individual modules of the software have been tested into high detail during the development process and afterwards during improvement and maintenance stages as well. The entire software application as a package requires thorough test phases and also multiple validation steps. In order to achieve this, an extensive program has been created where various tests of likely combinations are constantly performed. An example of one of the test environments can be seen in figure 3.6.



Figure 3.6: Deltares experimental setup for model validations [49]

3.5. CONCLUSION

A hydrodynamic model can be used to describe, define and simulate water movements in multiple and various environments. Digital hydrodynamic modeling has become a valuable asset to simulate complicated real world processes in this field of computational fluid dynamics. The accuracy of a hydrodynamic model of a specific environment strongly depends on its input characteristics, such as meteorological conditions. Furthermore, specific data regarding for example the riverine flux and tidal ranges are required to define the boundaries of the model in order to perform accurate simulations. Validation of a hydrodynamic model can be pursued by comparing simulation results with real life observations. Therefore, it can be argued that the simulation accuracy of any model is constrained by the available data quality and quantity.

Regarding the hydrodynamic modeling software, the described modules and displayed examples demonstrate the potential of the Delft3D applications. Although the numerical modeling software focuses on free surface water environment applications, due to the high level of detail possibilities it is also capable of modeling port areas. It can be seen that one of the advantages of this software package is the capability of incorporating hydrodynamic models of specific areas using the FLOW module. This allows extensive modeling hereby including the influences of tides, currents, wind forces, water densities, and waves such that no questionable assumptions need to be made. Furthermore the particle tracking module PART can be combined with the FLOW module to estimate the dynamical spatial distribution of up to thousands of individual particles by tracking their path in time. This enables the simulation of various dynamic processes, such as for example the transport of wasted materials due to human activities.

The combination of the graphical user interface and several post-processing modules allows a wide variety of possibilities regarding analyzing and displaying modeling results. These can be for example visualizations of the model input, reference data files, logged and visual simulation results and a variety of plots and grid generations, which enables to generate both comprehensive as well as brief simulation results.

Using the Delft3D software in combination with the FLOW module enables to simulate the hydrodynamic entities of a specific environment while setting the boundary conditions. The PART module hereby describes the dynamic behavior of particles that are released at a number of source locations and focuses on the path that these particles follow. Given these capabilities it can be argued that simulating marine litter with this software is the preferred method since it could lead to accurate simulation results. The approach and development of the model, using the FLOW module, are therefore presented in the coming chapter 4. Chapter 5 then elaborates on the simulations of the different scenarios using the PART module.

4

DEVELOPING THE PROPAGATION MODEL

In order to answer the main research question a numerical model should be developed. In theory, this model could be designed from scratch or an already existing model could be used, improved or redeveloped. The propagation model should describe how marine litter moves inside a port environment as it is influenced by different aspects affecting the transportation flow, which are identified and investigated in chapter 2. This chapter describes the approach of the development of the model, and presents the application of a specific case study model.

4.1. THE GENERIC PROPAGATION MODEL

As introduced in the previous chapter, the propagation model of this research will be incorporating a hydrodynamic model. Since developing a new hydrodynamic model from scratch is a tremendous task, an existing hydrodynamic model is redeveloped and subjected to calculated boundary conditions in order to answer the main research question. The Delft3D software is used for the model development such that the combination of the Delft3D applications with a hydrodynamic model can be considered the generic model for describing the propagation of marine litter in a port environment. In order to verify the application of the generic model, a specific case study will be presented. The coming sections explain the various steps for the development of the specific model.

4.2. SPECIFIC CASE STUDY

As introduced in chapter 1, the Port of Rotterdam has begun implementing novel systems to reduce the amount of marine litter from the port area. Since these systems will provide quantitative data in the near future, this port area is chosen as case study environment for this research. Figure 4.1 visualizes the different parts of the entire port environment.



Figure 4.1: Port of Rotterdam; research environment [59]

It can be seen that this port area consists of multiple rivers, various port compartments and of course the North Sea. Given that this environment is still quite large, a specific area of interest was chosen to focus on the marine litter propagating behavior. This area of interest is visualized by the black frame in figure 4.2.



Figure 4.2: Specific case study area of interest [60]

This area of interest primarily focuses on the port compartments of the *Eemhaven*, *Waalhaven* and the *Nieuw-Mathenesse*, which are indicated in pink and red in figure 4.1. These port compartments adjoin the *Nieuwe Maas* river, which is fed by and/or split into different rivers on both ends as can be seen in figure 4.2. Upstream the Nieuwe Maas is fed by the *Hollandse IJssel* and the river *Lek*. Downstream the Nieuwe Maas (NM) blends with the *Oude Maas* (OM) and continues as the *Nieuwe Waterweg* (NWW).

4.3. EXISTING HYDRODYNAMIC MODELS

Since the case study environment of this research beholds the Port of Rotterdam area, the author has contacted the Port Authorities to acquire more information regarding the hydrodynamics inside the port area. The Port Authorities of the PoR possesses a number of hydrodynamic models, which describe the hydrodynamics as explained in section 3.1. The models are used by the PoR among others for predicting water levels in the port area and the navigation of shipping, however all these models are developed for the *entire* port area. As the area of interest of this case study focuses on a specific part of the port area rather than the entire port, developing a numerical model could be performed with the use of an existing hydrodynamic model.

According to hydrodynamic specialists of the PoR, these models have been developed using a validated hydrodynamic model of Rijkswaterstaat (Dutch Ministry of Infrastructure and the Environment). This model describes a much larger area from which the boundary conditions were derived and imposed on the different port models in order to validate them. One of these three-dimensional models describes the entire port area into high detail, this model is called the *fine PoR* model. Due to this high level of detailed hydrodynamics, it is too excessive for simulating the whole port area as it does require a lot of computational power and data storage. Therefore another model was developed for the same area, the *coarse PoR* model, describing the hydrodynamic into less detail but accurate enough for modeling the water movements itself. In the fine model, the numerical grid cells are divided into longitudinal and lateral direction in three ways. Therefore this fine model is nine times more accurate than the coarse model.

4.4. DEVELOPING APPROACH

Since marine litter items (especially plastic particles) are quite small, solely using a part of the fine hydrodynamic model would be preferred, as it could simulate the propagation of marine litter into high detail. Unfortunately, an existing hydrodynamic model can not just be cropped as that would disturb the dynamical behaviors at the boundaries. It is however possible to redevelop a model into a more specific model as was performed by the PoR before.

As mentioned in the previous section, the coarse model describes the hydrodynamic into less detail than the fine model, but still accurately simulates the water movements in the port area. Running this coarse model therefore requires less computational power and data storage while the water movements in the PoR area are described almost equally compared to the fine model. When simulating the marine litter propagation in the form of releasing particles however, much more precise results can be obtained using the fine model since marine litter items are quite small and the fine model is nine times more accurate than the coarse model. Given that the area of interest of this case study is relatively small compared to the entire PoR area, the new hydrodynamic model will be developed with grid specifications of the fine model. The boundary conditions will be derived from the coarse model in order to limit the required computational time and data storage, without the risk of a significant loss of accuracy. Then the input characteristics for the specific model can be chosen in order to run the model. With this reasoning, the approach of redeveloping an existing hydrodynamic model into a new specific model and running it, is the following:

1. Determining precise scope area for the new hydrodynamic model based on specific area of interest
2. Adopting attributes from the *fine PoR* model to create a new grid of the model scope area
3. Generating boundary conditions by nesting the *new* model with the *coarse PoR* model
4. Defining input characteristics for the new hydrodynamic model of scope area

Important remark:

Given that the Port of Rotterdam owns (the license of) the models, their approval is necessary for this redevelopment. Since this study is conducted as a university research, the Port of Rotterdam allowed the author to use the existing model(s) for the development of a new specific model, with the remark that neither of these models may be passed on to third parties without the approval of the Port of Rotterdam.

4.5. MODEL SCOPE AREA

As stated in chapter 3, a hydrodynamic model could be used to describe, define and simulate water movements in multiple- and various environments. In order for a hydrodynamic model to run properly, that is simulating the real world processes as real as possible, the actual boundaries of the model should not be chosen close to the area of interest. The boundaries represent the locations of the grid borders where water flows in and out. Since these boundaries of the hydrodynamic model are imposed with boundary conditions, the transport behavior of water (and thus the marine litter drifting in water) may depend too much on those conditions in the boundary sectors. Furthermore, since a mayor part of the total amount of marine litter is transported by rivers from land based sources (see chapter 2.2.2), simulating this process is performed by releasing particles upstream from the area of interest.

4.5.1. TIDAL RIVERS

The transportation of floating litter at the surface is mainly affected by wind conditions as explained in chapter 2. The movements of roaming litter items below the water surface on the other hand, are constrained by the river flow rate. If tidal ranges result in significant variations of river flow rate and directions (downstream vs. upstream), the river in dispute is called a tidal river [61]. Since for some tidal rivers the effect of a high tide can be noticed several dozen kilometers upstream, it is important to investigate these changes for port area rivers. This data is constantly being monitored by the PoR on multiple locations in the different rivers and it can be concluded that the rivers flowing through the port area are indeed tidal rivers, see figure 4.3.

4.5.2. DETERMINING THE BOUNDARY LOCATIONS

Assuming that a large part of the marine litter enters the port area via the Nieuwe Maas river, the river flow transports this litter downstream towards the North Sea. Due to the tidal ranges the marine litter could flow back upstream when the river flow direction changes. If the downstream boundary towards the North Sea (~NWW) of the hydrodynamic model is chosen too close to the area of interest, the particles presenting the litter may pass the boundary and disappear from the simulation. Therefore it should be calculated how far the litter presumably flows back upstream during a period of high tidal current.

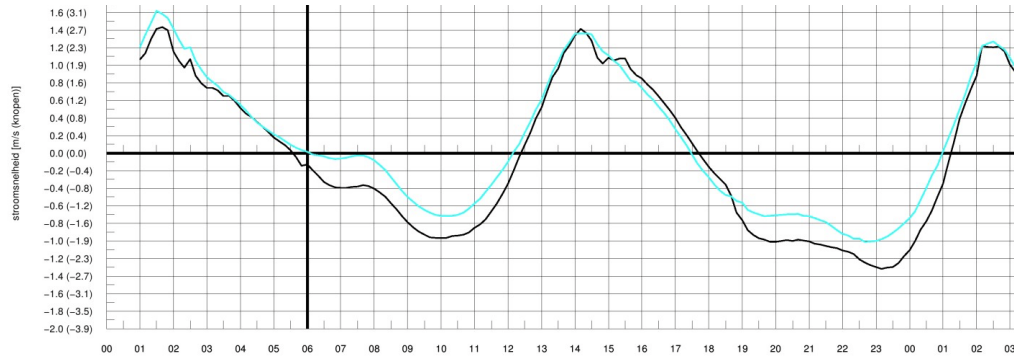


Figure 4.3: River flow rate measurements of the Nieuwe Maas [62]

NIEUWE WATERWEG

Figure 4.3 demonstrates a flow velocity measurement in the Nieuwe Waterweg river. It can be derived that the average velocity upstream (indicated in values larger than zero) during a high tidal current, is less than 0.75 m/s for a period of approximately 6 hours. The dominant tide signal is the M2-tide and has a period of 12 hours and 25 minutes [63]. This signal contains the strongest flow velocities and therefore 6,5 hours is a safe representative period for performing this calculation. Hence during this period, marine litter flows approximately: $0.75 * 6.5 * 3.6 \approx 18$ kilometers upstream. Consequently the NWW-boundary has been determined 18 kilometers downstream the area of interest towards the North Sea.

NIEUWE MAAS

The upstream NM-boundary on the other hand does not require the same approach since the particles are discharged upstream of the area of interest. Thus the amount of particles disappearing from the simulation during a period of high tidal current could be compensated with an additional discharge during the low tidal current. Therefore the NM-boundary is strategically chosen just after the river aggregation, this is indicated in figure 4.4 by the two vertical purple lines.

OUDE MAAS

For the same reason, the third boundary enclosing the hydrodynamic model is also chosen strategically, namely after the river junction of the Oude Maas. This OM-boundary is indicated by the two horizontal purple lines in figure 4.4. The particles disappearing from the simulation via this boundary during a period of high tidal current could also be compensated with an additional discharge during the low tidal current.

4.5.3. SPECIFIC MODEL BOUNDARY LOCATIONS

Unfortunately this method for compensating lost particles can not be applied downstream of the area of interest since it is uncertain how many, or which type, of the disappearing particles would reenter the area in real life, as eventually all river water flows towards the North Sea. With these arguments the boundaries of the hydrodynamic model for this specific case study have been determined and are visualized in figure 4.4. The green arrow visualizes the path and direction towards the location of the NWW-boundary which is 18 kilometers far from the area of interest border indicated by the vertical black line.



Figure 4.4: Boundaries indications for of the hydrodynamic model area [60]

4.6. NUMERICAL GRID AND ATTRIBUTES

As explained in section 4.4 an existing hydrodynamic model can not be cropped due to the boundary condition disturbance which would occur. Since the Port of Rotterdam allowed the author to use the existing model(s) for the development of a new specific model, and solely using a part of the fine hydrodynamic model would be preferred, a number of attributes were adopted from the fine model in order to create a numerical grid for the new specific model. With these attributes and the boundaries that were determined in the previous section, a new grid was created in Delft3D, this is visualized in figure 4.5.



Figure 4.5: Scope numerical grid created in Delft3D

This numerical grid composition contains the following five attributes:

- Curvilinear grid; the model structure generated as a numerical grid
- Grid enclosure; determines the (open and closed) grid borders
- Thin dams; infinitely thin objects representing small obstacles such as dams
- Dry points; permanently dry grid cells centered in between water cells
- Bathymetry; the measurement of depth defined on the numerical grid

4.7. BOUNDARY CONDITIONS

To describe the movements of litter particles through the area of interest in the Nieuwe Maas, flow data from two hydrodynamic models is used to develop a new specific hydrodynamic model. A number of attributes were adapted from the fine model in order to generate a new grid as explained in the previous section. This grid and its attributes need to be imposed to certain boundary conditions to generate a hydrodynamic model that can be used for performing simulations. Since the output accuracy of a hydrodynamic model of a specific environment strongly depends on its input characteristics, these boundary conditions have to be determined with much care. Therefore, as stated in section 4.4, for this specific case study the boundary conditions are adopted from the validated model of Rijkswaterstaat. This grid was so-called *nested* with the coarse model to generate the boundary conditions for the new specific model. These boundary conditions are basically defined by specific input values that are required in order to perform accurate simulations. The input requirements for the developed three-dimensional hydrodynamic model are the following:

- Riverine flux; amount of water volume per time (m^3/s)
- Water level; due to tidal ranges (m)
- Wind forces; velocity (m/s) and direction ($degrees$)
- Salinity; amount of salt in units of parts per thousands (ppt)

4.8. MODEL INPUT CHARACTERISTICS

Apart from input requirements, the performance of an hydrodynamic model also depends on its input characteristics. These input characteristics are entered using the Delft3D *FLOW* module. The relevant characteristics and the values for this specific model are discussed in this section.

4.8.1. TIME FRAME

The time frame of the hydrodynamic model determines the duration for which the model describes the reality. As explained in section 4.5.2, during the dominant tide signal M2 the strongest flow velocities are present. In order to simulate the M2-tide and ‘normal’ tides in the model, one spring-neap tide cycle will be chosen as the time frame. The generation of this hydrodynamic model begins at December 1st 2015 and ends on the 22nd of that same month. After a start-up period of one week, the output of the hydrodynamic model contains a period of 14 days, which equals one spring-neap tide cycle. With a time interval of 30 minutes the hydrodynamic output is logged, which is sufficient when simulating the particle tracking and results in a realistic representation of the tidal movement. The 30 minute time interval is determined based on a sensitivity study conducted by Deltares [64]. This data is then read by the particle tracking routine as will be explained in the next chapter.

4.8.2. TIME STEP

A time step for the model is calculated with the Courant-Friedrichs-Lewy number (C) for the numerical grid, see equation 4.1. In this equation Δt represents; the time step in seconds, $\{\Delta x, \Delta y\}$; the minimum grid cell length in meters, g ; the gravitational constant in m/s^2 , and H ; the water depth in meters. Since the grid cell sizes and bathymetry vary significantly for this specific model, the minimum grid cell length and depth are chosen for the dominant model area where most numerical calculations need to be performed.

$$C = \frac{\Delta t \sqrt{gH}}{\{\Delta x, \Delta y\}} \quad (4.1)$$

According to the user manual of the *FLOW* module, it is advised to assign the Courant number with a maximum value of 10 in order to perform decent calculations [57]. With an average depth of 16 meters, a minimum grid cell length of 11 meters and a safe Courant number of 9, the time step is calculated as in equation 4.2.

$$\Delta t = \frac{C\{\Delta x, \Delta y\}}{\sqrt{gH}} = \frac{9 * 11}{\sqrt{9.81 * 16}} = 7.9 \approx 7.5 \text{ sec} \cong 0.125 \text{ min} \quad (4.2)$$

4.8.3. DEPTH LAYERS

As explained in section 3.3, the Delft3D hydrodynamic modeling software can model environments in two- and three-dimensional planes. To simulate the movements of plastic particles through the port of Rotterdam area, three-dimensional modeling is desired since the particles are mainly floating at the surface, and drifting in the top water column of approximately 0.5 ~ 1 meter. In the *FLOW* module of Delft3D, 10 different layers of depth can be distinguished and are determined in percentiles of the bathymetry. For this specific model the top two columns have been determined as 5% of the water depth, determined per grid cell, in order to simulate the marine litter in the different water columns of the rivers.

4.8.4. WIND CONDITIONS

As discussed in section 3.3, the particle tracking module *PART* can be used to discharge separate particles and tracking their path in time. The hydrodynamic model developed with the *FLOW* module hereby serves as input for the particle tracking model. Since different scenarios can be simulated using the *PART* module, the output will be constrained by the input characteristics of the *FLOW* module as discussed in this section 4.8. During the configuration in the *PART* module to perform different scenarios, wind conditions can be imposed for each specific scenario. Therefore, no wind condition is incorporated during the generation of this hydrodynamic model in the *FLOW* module.

4.8.5. OTHER FLOW PARAMETERS

The values of other input parameters, necessary to set up the *FLOW* module in order to describe the movements of water, have been determined together with experts of Deltares during interviews. These values can be found in the *FLOW* input files given in the Appendix (not publicly available).

4.9. HYDRODYNAMIC MODEL OUTPUT

This section demonstrates the output of the hydrodynamic model. A number of possible output files are demonstrated in order to visualize the potential of the model. Figure 4.6 displays the *water level* of the model area captured on December 14th 2015 at 16:00 hours. It can be seen that, between the downstream boundary of the Nieuwe Waterweg and the upstream boundary of the Nieuwe Maas, a difference in water level of approximately 1 meter is present. Figure 4.7 displays the *flow velocity* on that same moment.

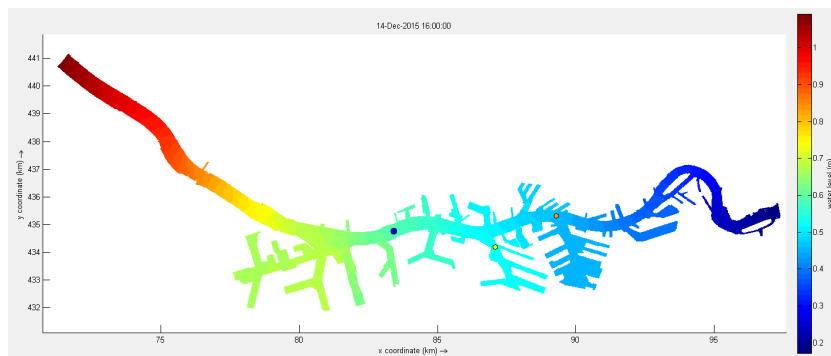


Figure 4.6: Hydrodynamic model map; water level output of December 14th at 16:00h

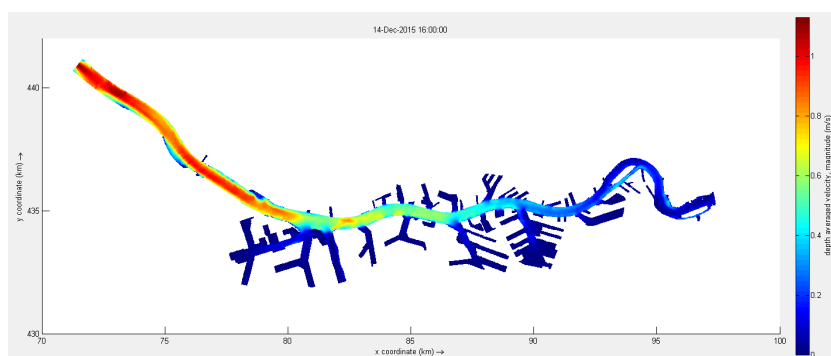


Figure 4.7: Hydrodynamic model map; flow velocity output of December 14th at 16:00h

From this it can be derived that the flow velocity in the main rivers is much higher than in the port compartments. Therefore, in theory it is expected that the litter drifting below the surface follows the river flow more than floating litter since wind also has an influence on litter at surface level. Figure 4.8 displays a graph of the modeled *flow velocity* over time, captured on a location across the entrance of the Waalhaven, indicated by the orange circle displayed in figure 4.6. This graph implies that the flow velocity is influenced by tidal ranges, which in reality is also the case. In order to verify the application, the next section explains the validation process of this hydrodynamic model.

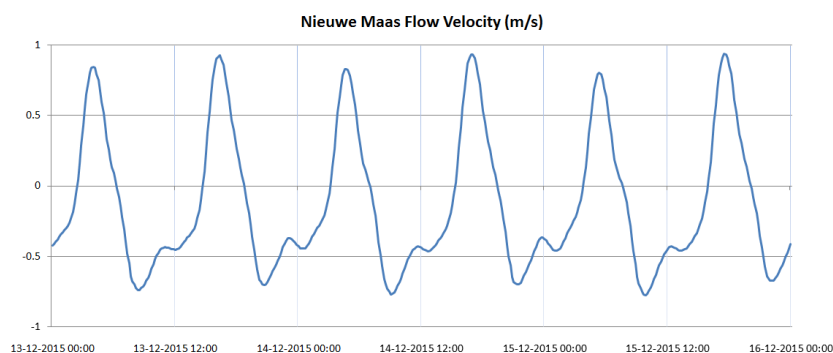


Figure 4.8: Hydrodynamic model graph; flow velocity output at the Nieuwe Maas river

4.10. VALIDATION

Section 4.1 stated that the combination of the Delft3D applications with a hydrodynamic model can be considered the *generic* model for describing the propagation of marine litter in a port environment. Since the individual modules of the Delft3D software have been validated by thorough test phases and multiple validation steps (see section 3.4), the generic model can be considered validated when the incorporated hydrodynamic model has been validated as well.

In general, validation of any model can be achieved by comparing simulation results with real life observations and measurements. One possible method is to compare the model output to tidal data regarding the water level, which is made publicly available by Rijkswaterstaat [65]. Figure 4.9 displays the tidal information of Vlaardingen on December 14th 2015.

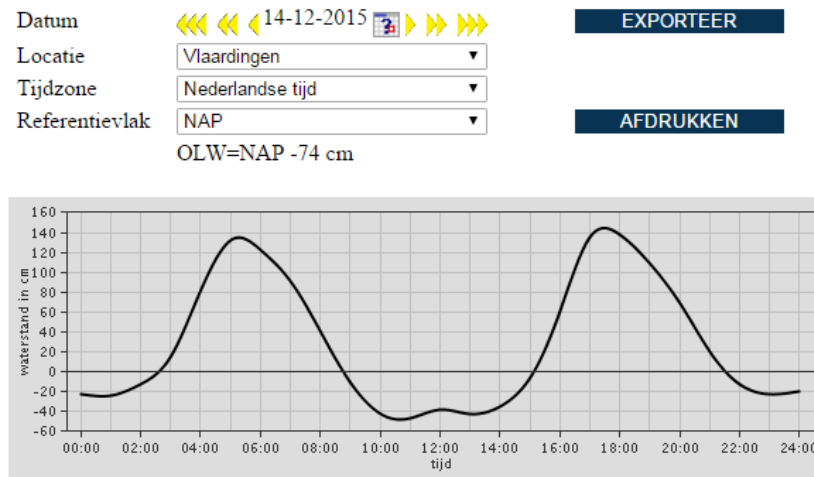


Figure 4.9: Tidal data from Rijkswaterstaat of Vlaardingen on December 14th [65]

Comparing this data with the model output given in the figure 4.10 shows that the developed hydrodynamic model accurately describes the water level. This model output is generated from the observation point near Vlaardingen, indicated by the blue circle displayed in figure 4.6.

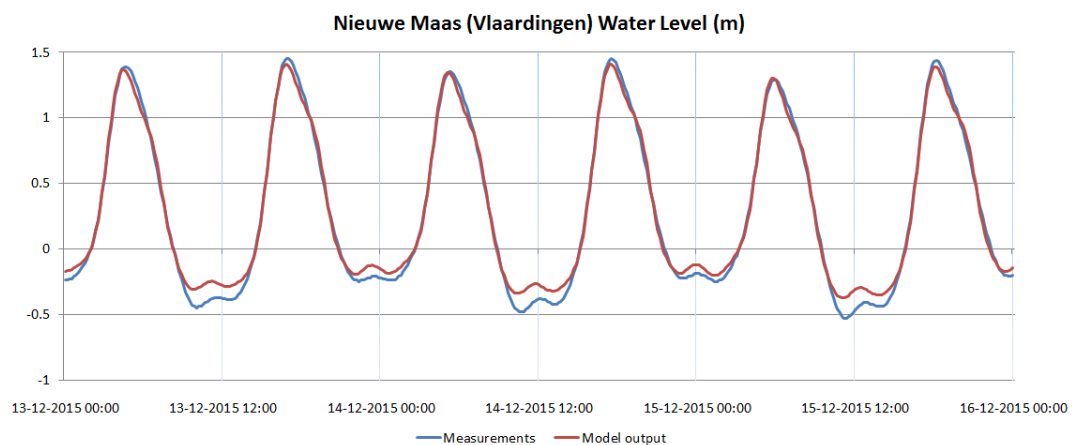


Figure 4.10: Tidal data comparison of Vlaardingen

Another method for performing the validation is to compare the model output to measurements that the Port of Rotterdam performs as explained in section 4.5.3. Therefor the author has contacted the Port Authorities and received two data sets in order to perform the comparison. Figure 4.11 displays the measured- and simulated water level of the Nieuwe Maas river. This data has been measured and simulated in the first Eemhaven, indicated by the yellow circle displayed in figure 4.6.

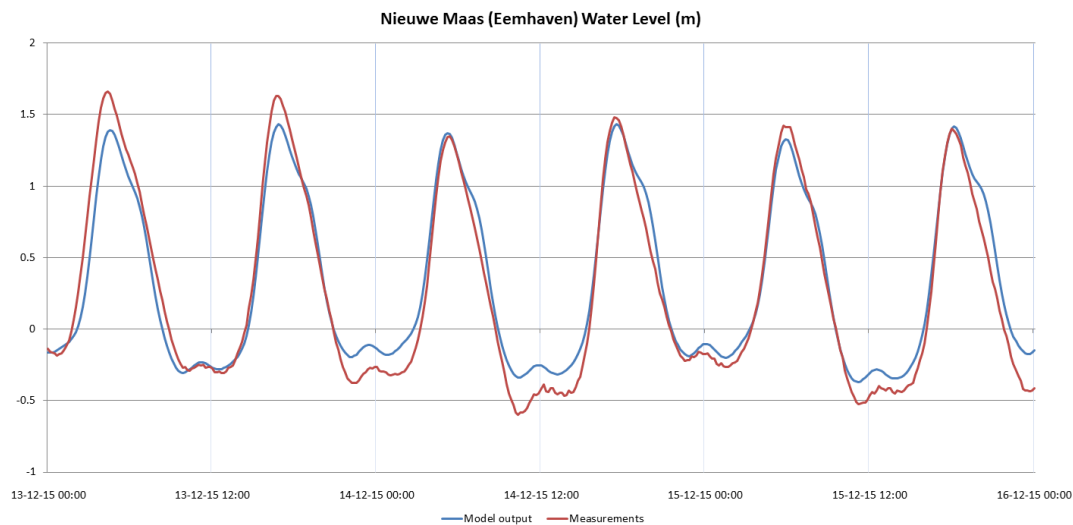


Figure 4.11: Data validation of the water level at the first Eemhaven

Figure 4.12 displays the measured- and simulated flow velocity of the Nieuwe Maas river. This data has been measured across the entrance of the Waalhaven, indicated by the orange circle displayed in figure 4.6, at a local depth of 4.5 meters. According to the bathymetry of the model, the river depth at that location is approximately 10 meters. As the hydrodynamic model contains 10 depth layers (see section 4.8.3), the model output was generated from the 6th layer, which describes the water flow between 40 and 50% of the river depth.

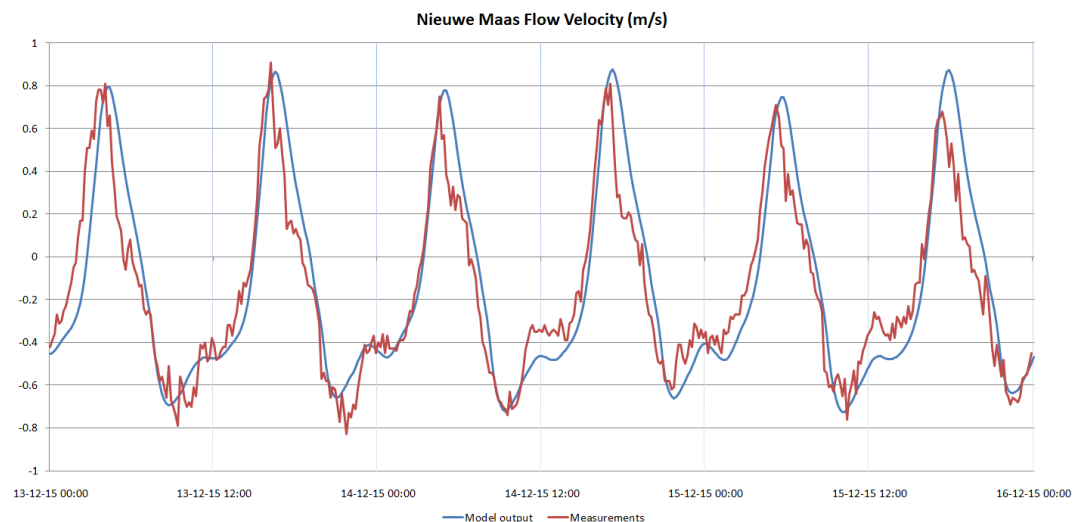


Figure 4.12: Data validation of the flow velocity of the Nieuwe Maas

From this comparison it can be concluded that the developed model is accurately describing the water level and river flow velocity. In the next chapter it is explained how simulations are performed using this model.

5

PERFORMING MODEL SIMULATIONS

Early on in this report it has been made clear that the availability of quantitative data regarding marine litter is very limited, and for the case study environment it is not yet available. Furthermore, the actual impact of the different aspects on the movements of marine litter, as recapped in section 2.3.3, are rather unknown to date. Assumptions regarding the quantity and influences of these aspects are made in order to perform simulations, however, these results could not be verified due to the lack of existing data. Moreover, since the simulation results depend on the input values, i.e. the marine litter quantity and the influencing aspects impacts, these results would be too uncertain. Given these arguments it is more valuable to propose and simulate a number of scenarios in order to explore the impact of the different aspects, such that more purposeful researches could be performed. The objective when performing these scenarios therefore, is to determine how the model and marine litter behave under the different influences, such that when additional research is conducted more accurate results can be achieved. This chapter introduces the different scenarios and elaborates on how the simulations are performed. In the last section, the results of the simulations are compared.

5.1. SIMULATION SCENARIOS

According to literature, as stated in section 2.3, the aspects that influence the marine litter movements are:

- Port structure characteristics; locations- and dimensions of port compartments
- River flow rate; water velocity in m/s
- Tidal ranges; water level differences due to tides in meters
- Wind conditions; wind force in m/s and source direction in degrees

Furthermore, the marine litter either floats at the surface or drifts in the top meter water column, as explained in section 2.3.2. As literature only reveals that these different movement states exist rather than how they actual influence the movements of the litter, it would be interesting to investigate the difference between these moving states. Since the port characteristics, river flow rate and tidal ranges are known and can be simulated with certainty using the hydrodynamic model presented in the previous chapter, investigating the effect of several wind conditions and different moving states of the marine litter is preferred. With this reasoning 6 different scenarios have been proposed, they are presented in table 5.1.

Table 5.1: Simulation scenarios

Scenarios		Wind condition		
		None ·	SW ↗	NE ↗
<i>Litter depth level</i>	At surface ~	1	2	3
	Top 5% $\simeq$	4	5	-
	In 5-10 % $\cong$	6	-	

5.1.1. SURFACE SCENARIOS

The first three scenarios focus on litter items that are floating at the surface. This floating litter is simulated using the *oil* function within the PART module. Particles are discharged at surface level such that they disperse under the influence of three different wind conditions. Scenario 1 disregards the influence of wind in order to see how litter floats without any wind conditions. This simulation provides a baseline output, which can be compared to the other simulation results in order to make statements regarding the different observations. In order to decide which wind conditions are representative to impose, wind data from the last five years was obtained by the Royal Dutch Meteorological Institute (KNMI). From this data the graph displayed in figure 5.1 was constructed.

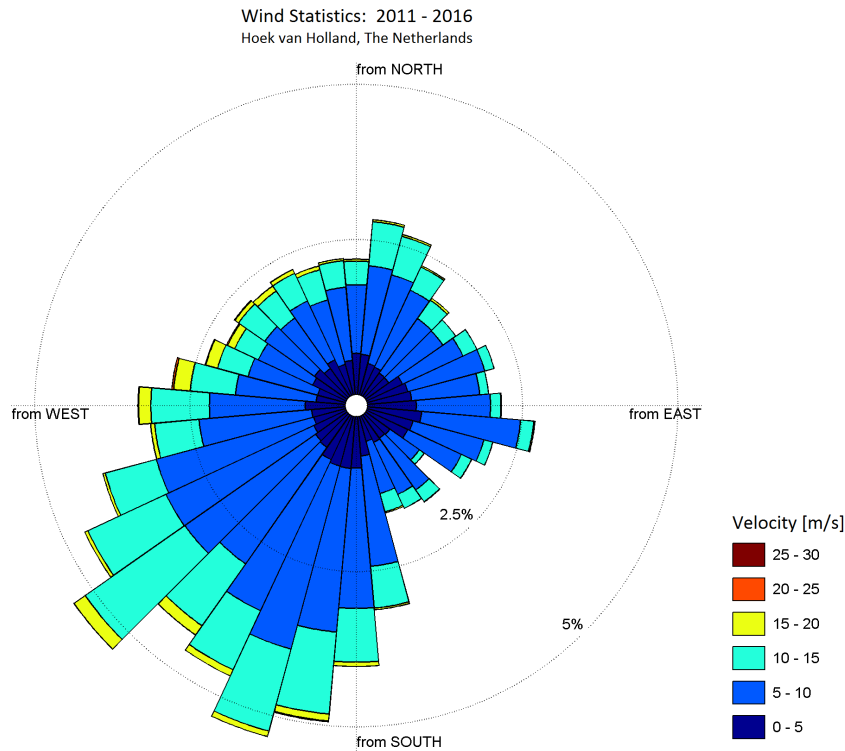


Figure 5.1: Wind data gathered by the KNMI [66]

The second scenario incorporates a constant wind condition from the South-Western (SW) direction, since this is the most dominant wind condition in this case study environment. The wind is imposed with a velocity of 5 m/s and a direction reference angle of 225 degrees, as Northern wind corresponds with 0 degrees. The third scenario incorporates a constant North-Eastern (NE) wind, with a velocity 5 m/s and with a direction angle of 45 degrees, because this is the opposite direction of the SW wind. No scenario with inconsistent wind conditions has been investigated during this research, since this does not guarantee accurate simulations at this moment due to the lack of available data to verify the outcomes.

5.1.2. IN DEPTH SCENARIOS

The remaining scenarios focus on litter items that move below the water surface. These scenarios consider different layers of river depths as stated in table 5.1. This roaming litter is simulated using the *tracer* function within the PART module. With this function, particles are discharged in the different depth layers (see section 4.8.3), in order to investigate the differences of the litter movements in multiple water levels. Particles are discharged in the first depth layer when performing scenario 4 and 5. The fourth scenario disregards the wind condition since it is expected that litter drifting below the surface is not affected by wind as much as floating litter items. To verify this hypothesis, scenario 5 does incorporate the influence of wind as it is imposed with the NE wind according the third scenario. Scenario 6 is performed under the same conditions as scenario 4, only the particles are discharged in the second depth layer.

5.2. PARTICLE MODEL CHARACTERISTICS

The scenarios are performed using the Delft3D *PART* module, simulating the movements of particles in three dimensions. After the particles are discharged at a particular location in the water, they move independently of each other as they are influenced by the different aspects listed in section 5.1. The particle movements are tracked in time from which an image is obtained in order to analyze the results of the different scenarios. The hydrodynamic output of the model that was presented in the previous chapter, is used as input for the particle tracking model. This section elaborates on the deciding characteristics that are set in the *PART* module in order to perform the simulations.

5.2.1. TIME FRAME

The time frame of the particle simulation model determines the duration for which the discharged particles are tracked in the hydrodynamic model. As explained in section 4.8, the output of the hydrodynamic model contains a period of 2 weeks, namely between the 8th and 22nd of December 2015. During these 14 days the path of the discharged particles are tracked and logged according a 30 minute time interval. At the start of the simulation, no particles are present in the model area but in reality however litter items are already spread throughout the port environment. Therefor the first 3 days are meant to disperse particles in order to generate representative initial conditions in the system. The mentioned initial period has been determined via experiment simulations with an experimental discharge quantity. From these experiments it was concluded that after approximately 3 days the initial discharged particles were dispersed throughout the entire model such that it is impossible to distinguish between freshly discharged particles and particles discharged in the beginning. Then during the latter 11 days, the output of the model is logged for analysis.

5.2.2. PARTICLE DISCHARGE LOCATION

As explained in section 3.3.2, with the *PART* module, simulations can be based on instantaneous and continuous discharges. Assuming that the majority of the marine litter enters the area of interest via the Nieuwe Maas river constantly (see section 2.2.2), the simulations are performed with one discharge location that is characterized by continuous discharging of particles during the chosen time frame. Conducted experiments of the dispersing effect of different discharge locations show that the released particles disperse sufficiently, that is follow their own independent path, within approximately 1 hour after the discharge.

Therefor, the source location has been determined at a distance from the upstream border of the area of interest (as displayed in figure 4.2) of approximately 2 kilometers. This location is indicated by the green dot in figure 5.2. After the particles are discharged, assuming an average flow velocity of 0.55 m/s (see figure 4.12), they disperse for a minimum (during low tidal current) of approximately $\frac{1.8}{0.55 * 3.6} \approx 1$ hour before they enter the area of interest.



Figure 5.2: Particle discharge location

5.2.3. DISCHARGE CHARACTERISTICS

Since no measured data regarding the influx rate, nor the size or quantity, of the marine litter items in the case study environment is available at the time of this research, overestimated values have been chosen for the discharge characteristics. Due to the larger values than in reality, each particle in the simulation represents of a group of litter items in reality such that comparisons regarding the different scenarios can be made, and probable accumulation sites could be indicated. Given this reasoning, and some discharge experiments, for each scenario the following discharge characteristics have been chosen:

- Amount of discharged particles; 100,000
- Discharge rate; $1\text{ m}^3/\text{s}$
- Concentration; $100\text{ kg}/\text{m}^3$

5.2.4. OTHER PART PARAMETERS

The values of other input parameters, necessary to set up the PART module in order to perform the simulations, have been determined together with experts of Deltares during interviews. These values can be found in the PART input files given in the Appendix (not publicly available).

5.3. PERFORMING THE SCENARIOS

Due to the chosen overestimated discharge characteristic input values, as explained in section 5.2, and the fact that particles are not removed from the model its port compartments during the simulation, it is expected that after a certain period the discharged particles accumulate at several locations. By comparing the visualizations of these accumulations areas, statements can be made regarding the different scenarios and thus regarding the influencing aspects that were simulated. This section presents the individual results of the different scenarios, in the next section an evaluation of the scenario outputs is made.

5.3.1. SCENARIO 1: SURFACE BASELINE OUTPUT

The first scenario disregards the influence of wind in order to see how litter floats at the surface without any wind conditions. This simulation provides a baseline output, which is compared to the other simulations in section 5.4. The figure on the right indicates the presence of the discharged particles for this scenario, as well as for the other scenarios that are presented in the remainder of this chapter. For scenarios 1, 2 and 3 the presence is given in kg/m^2 since for those scenarios the litter is simulated as oil which floats at the surface. The simulation output of scenarios 4, 5 and 6 is given in kg/m^3 as they simulate litter items drifting below the surface. Figure 5.3 presents the simulation output of scenario 1, captured on December 14th 2015 at 16:00 hours.

It should be clear however, that the simulation outputs solely present an indication of where the particles could accumulate, rather than how many litter items actually are present in those areas. This is due to the fact that the actual quantity of litter items is unknown, and thus an overestimated amount of particles has been discharged during simulations as explained in section 5.2.

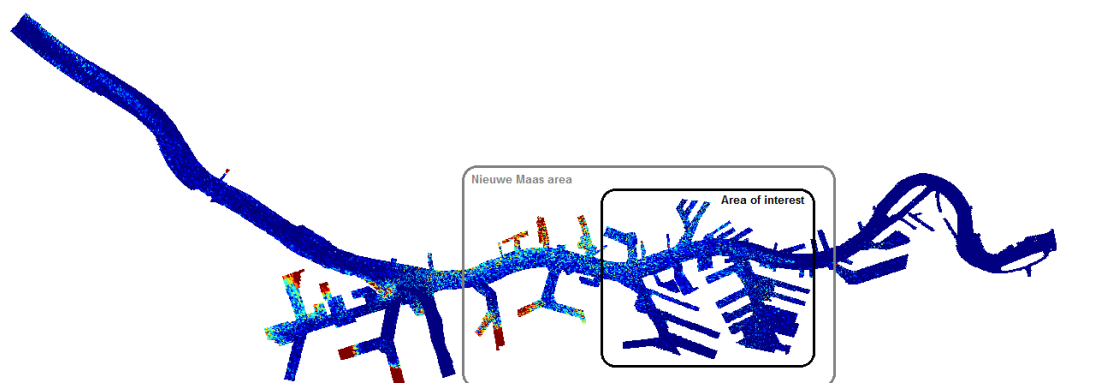


Figure 5.3: Simulation output scenario 1

Naturally, without any wind condition it is expected that the marine litter is transported through the water primarily by the river flow. Looking at the results for this scenario without any wind condition, it can be concluded that the marine litter tends to accumulate in certain port compartments. This can be explained by the almost stagnant flow in those compartments as can be seen in figure 4.7. When the flow velocity is low and no changes of directions occur over time, the litter items float into the port compartments and accumulate at the ends. The gray- and black frame in the figure indicate the Nieuwe Maas area respectively the specific area of interest of this case study. The model outputs of some scenarios of these areas are framed in order to clarify the simulation results.

5.3.2. SCENARIO 2: SURFACE / WIND

The second scenario incorporates a constant wind condition from the SW direction. The wind is imposed with a velocity of 5 m/s and a direction reference angle of 225 degrees. Figure 5.4 presents the simulation output of scenario 2, also captured on December 14th 2015 at 16:00 hours. This time moment has been chosen since it is in the middle of the simulation period, and will apply for the other following outputs as well.

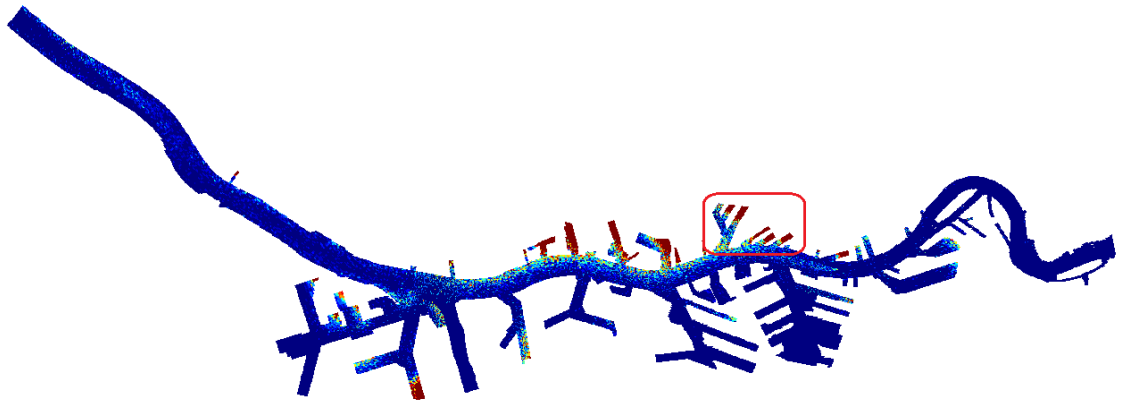


Figure 5.4: Simulation output scenario 2

Analyzing this figure it can be seen that the particles tend to accumulate in certain port compartments. Since the wind has been imposed with a constant direction this can easily be explained. Zooming in on the north part of the area of interest, as displayed in figure 5.5, it seems that litter items floating at the surface are highly influenced by wind conditions.

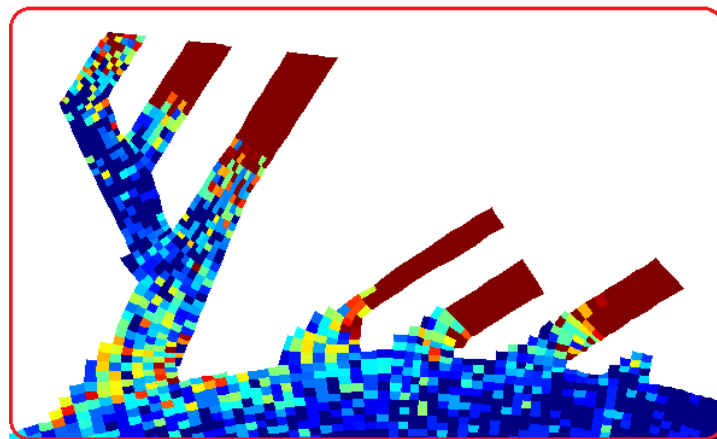


Figure 5.5: Simulation output scenario 2; north part of the area of interest

5.3.3. SCENARIO 3: SURFACE / WIND

The third scenario incorporates a constant NE wind, with a velocity 5 m/s and with a direction angle of 45 degrees. Figure 5.6 presents the simulation output of scenario 3.

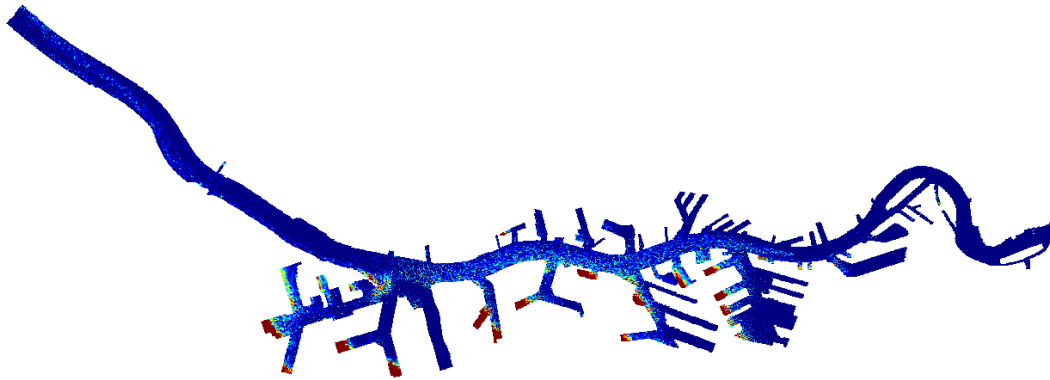


Figure 5.6: Simulation output scenario 3

Analyzing this output individually it can be seen that the particles tend to accumulate in certain port compartments. As for the second scenario, this can easily be derived from the fact that the wind has been imposed with a constant direction. Focusing on the area of interest (see figure 5.7) it indeed seems that the movements of litter floating at the surface are highly influenced by wind conditions since the particles accumulate at the end of port compartments, which are situated parallel to the wind direction.

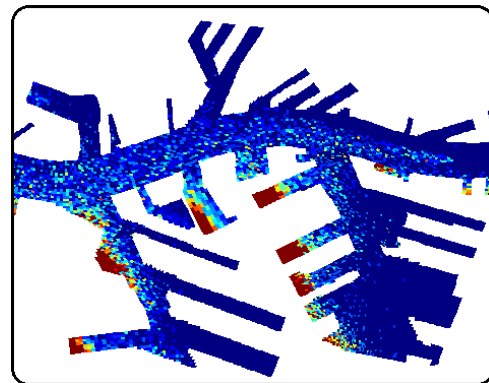


Figure 5.7: Simulation output scenario 3; area of interest

5.3.4. SCENARIO 4: FIRST LAYER

Scenario 4 disregards the wind condition and particles are discharged in the first depth layer, the results are displayed in figure 5.8. Looking at this output it can be seen that, generally, the particles tend to follow the river flow as they are quite evenly spread within the model. Given that it is too early to make statements regarding this behavior, a comparison with other scenarios is made in the final section of the chapter.

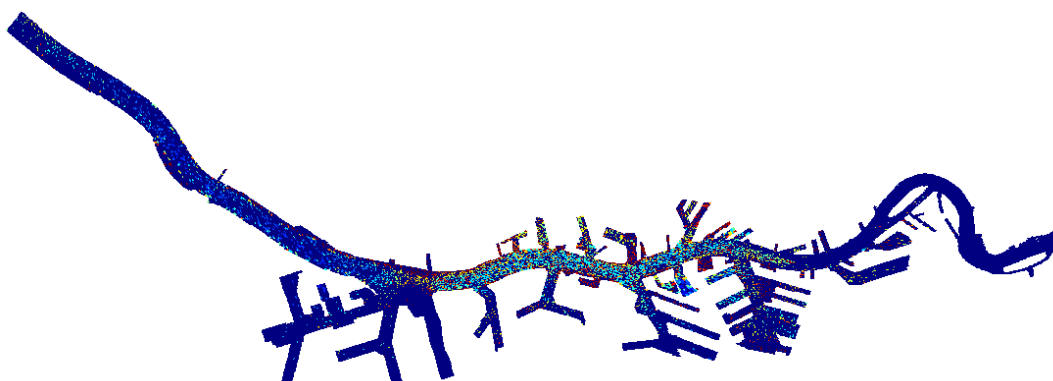


Figure 5.8: Simulation output scenario 4

5.3.5. SCENARIO 5 FIRST LAYER $\swarrow$ WIND

Scenario 5 does incorporate the influence of wind as it is imposed with a NE $\swarrow$ wind, with a velocity 5 m/s and with a direction angle of 45 degrees. Figure 5.9 presents the simulation output of scenario 5.

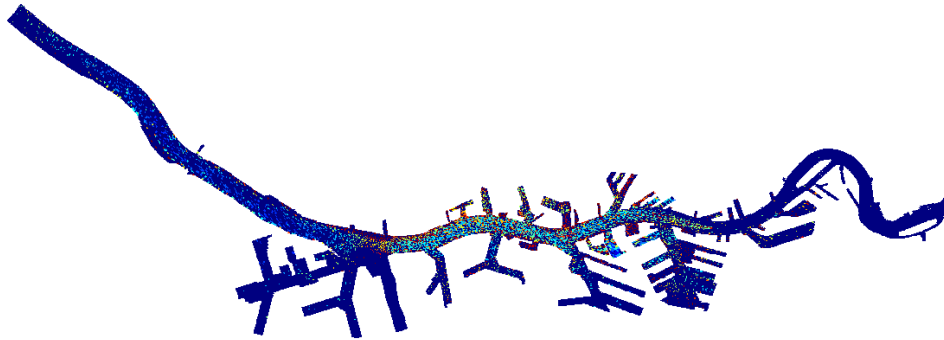


Figure 5.9: Simulation output scenario 5

Analyzing this output it seems that, even though a constant wind condition was imposed, litter items drifting below the surface tend to follow the river flow. Focusing on the Nieuwe Maas area, as displayed in figure 5.10, reveals that although the particles are spread within the model, some port compartment contain a higher presence of particles than others. However, since this goes for compartments situated both on the north- and the south side of the Nieuwe Maas, it seems that the movements of litter items drifting below the surface are mainly influenced by the river flow.

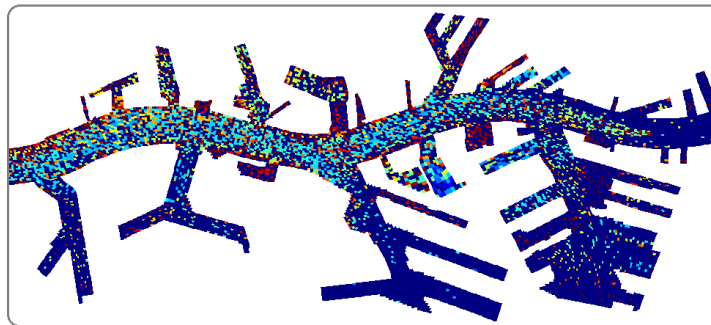


Figure 5.10: Simulation output scenario 5; Nieuwe Maas area

5.3.6. SCENARIO 6: SECOND LAYER $\cdot$

Scenario 6 disregards the wind condition and particles are discharged in the second depth layer, the results are displayed in figure 5.11. Looking at this figure it immediately can be seen that the particles follow the river flow as they are spread randomly within the model, and no really dominant accumulation sites are present.

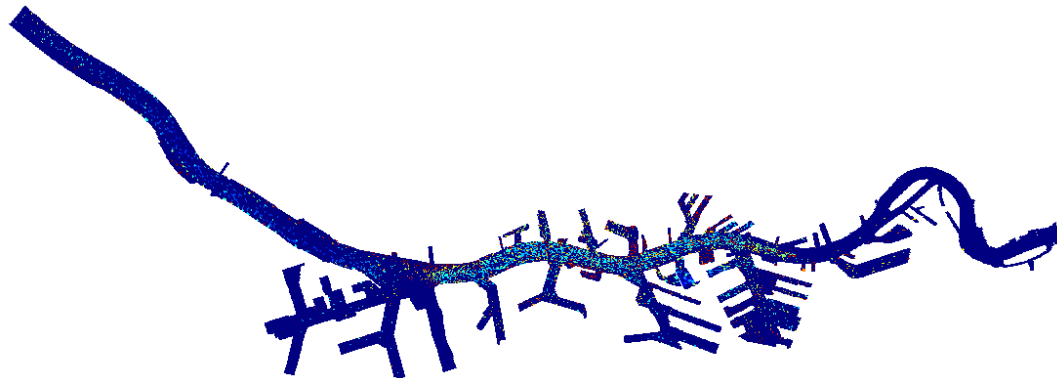


Figure 5.11: Simulation output scenario 6

5.4. COMPARING THE RESULTS

As stated when introducing this chapter, the objective of performing the different scenarios is to determine how the marine litter items behave under the different influences. Therefore, analyzing the simulation results is performed by comparing the different scenarios to the baseline output of the first scenario, and to each other, in order to reveal the impact of the different aspects. Figure 5.12 presents the simulation output of this baseline scenario 1 and is framed at the Nieuwe Maas area.

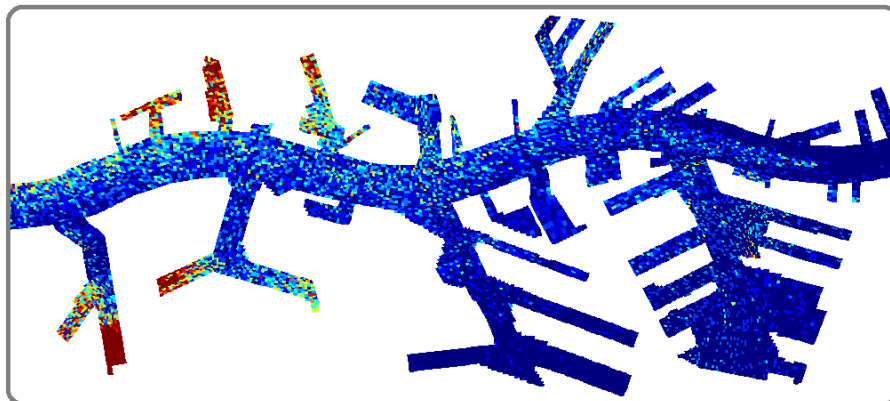
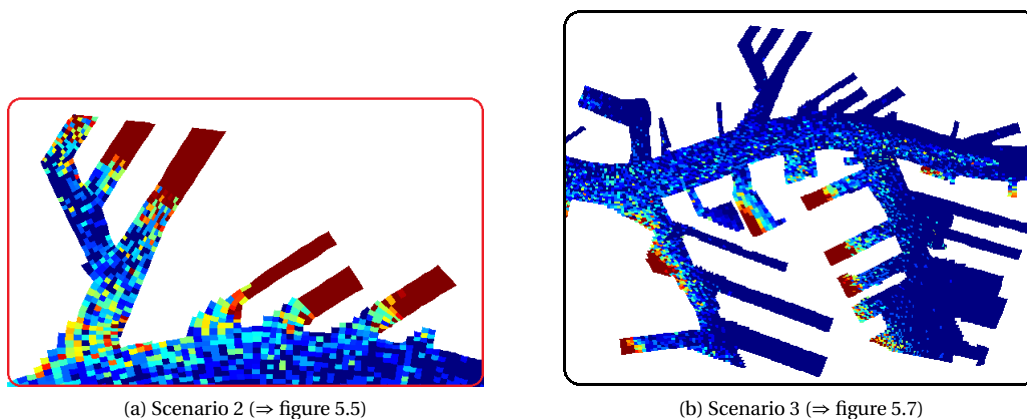


Figure 5.12: Simulation output baseline scenario 1; Nieuwe Maas area

5.4.1. SURFACE SIMULATIONS

Scenarios 1, 2 and 3 focused on litter items floating at the surface. Particles were discharged at surface level and dispersed under the influence of three different wind conditions, where the first scenario did not incorporate any wind. The second scenario incorporated a constant wind condition from the South-Western (SW) direction, as it is the most dominant wind condition in this case study environment. The wind was imposed with a velocity of 5 m/s and a direction reference angle of 225 degrees in order to analyze the movements of marine litter and compare the results to the first scenario output. The third scenario incorporated a constant North-Eastern (NE) wind, with the same velocity and with a direction angle of 45 degrees, since this is the opposite direction of the SW wind.

Comparing scenarios 1 and 2 immediately reveals that the wind condition plays a very important role when simulating litter items at the surface. Looking at the differences between figure 5.12 and 5.5 it can be seen that the port compartments located at the north side of the area of interest would contain significantly more litter when the winds constantly comes from the SW direction. The same can be said for the port compartments at the SW side (see figure 5.7), when the wind comes from the NE direction. From this it can therefore be concluded that wind conditions are very dominant for the movements of marine litter drifting at the surface. Comparing scenario 2 with 3, for example by looking at figure 5.13 strengthens this statement.



(a) Scenario 2 (⇒ figure 5.5)

(b) Scenario 3 (⇒ figure 5.7)

Figure 5.13: Comparing scenarios 2 and 3

The influence of wind could be revealed even more by comparing the amount of litter items that passes a certain location in the model. The graph in figure 5.14 displays the amount of particles passing the downstream area of interest border over time. Also for this graph it should be clear that the simulation outputs solely present a comparison between the different simulations, rather than the actual amount of items passing the location. The black line represents the output for the first scenario where wind does not play a role. The blue line represents the output for the second scenario, and the red line represents the third one.

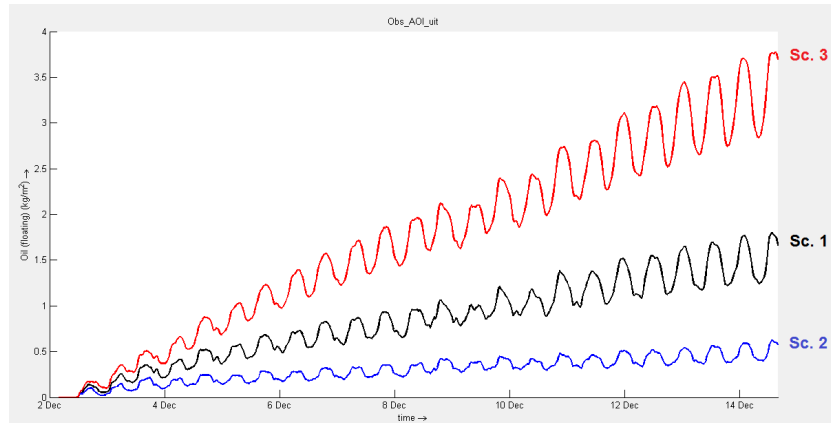


Figure 5.14: Simulation output graph of particles passing the downstream area of interest border over time

It can be seen that when the wind blows the litter in the direction upstream the river (blue), less particles pass the location in the same time period than when wind is disregarded (black). On the contrary, when the wind comes from the upstream direction and thus blows the litter downstream (red), significantly more particles pass the observation location. Furthermore, this graph also reveals that the tidal ranges, which are visualized by the sinusoidal curves, also affect the marine litter drifting at the surface. From this it can be concluded that the tidal ranges therefore influence the marine litter movements inside port areas. Which of the aspects is the most dominant one however, can not be concluded yet.

5.4.2. IN DEPTH SIMULATIONS

Scenarios 4, 5 and 6 focused on litter items moving below the water surface. The particles were discharged in two different layers of the river depth in order to investigate the litter movements in different water levels. Scenario 4 hereby disregarded the wind condition since it was expected that litter drifting below the surface is not affected by wind as much as floating litter items. To verify this hypothesis, the fifth scenario did incorporate the influence of wind as it was imposed with the same NE wind as scenario number 3. The last scenario number 6 was performed with the same conditions as the fourth scenario, only the particles were discharged in the second depth layer.

Comparing scenarios 4 and 5, by looking at the differences between figure 5.15 and 5.10, shows that the wind condition does not affect litter items drifting below the surface. Therefore it is not necessary to simulate a seventh scenario that would incorporate wind when simulating litter items drifting one depth layer lower.

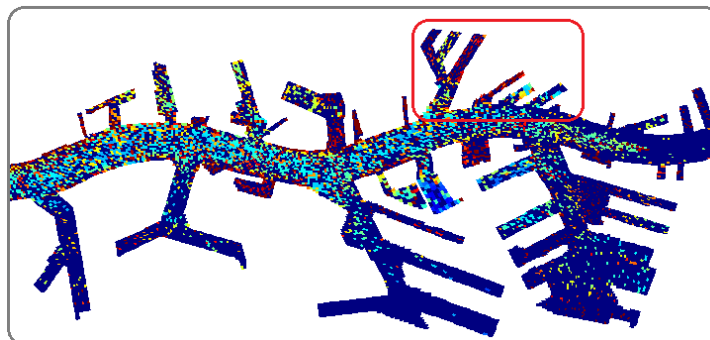


Figure 5.15: Simulation output scenario 4; Nieuwe Maas area

The red frame in figure 5.15 zooms in on specific port compartments in order to compare the litter items below the surface level with floating litter items. This close up image is displayed in figure 5.16. Looking at this figure it can be seen that, although no wind conditions had been imposed, a part of the marine litter items drifting below the surface tends to accumulate in certain port compartments. This could potentially be explained by the structure and entrance direction of these compartments, as these entrances are quite invitingly orientated for the drifting marine litter during a period of high tidal current. Although it is obvious it verifies that the port structure indeed plays a role in the movements of marine litter.

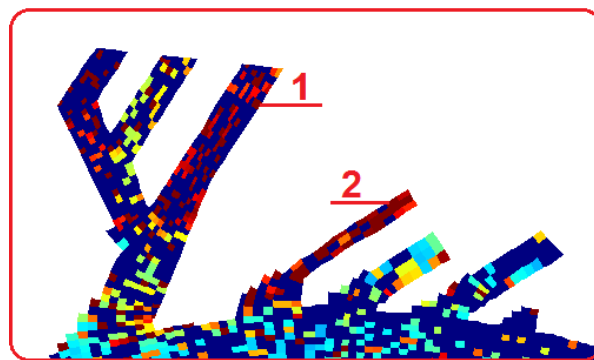


Figure 5.16: Simulation output scenario 4; specific port compartments

For the in depth simulations, comparing scenario 4 and 6 by looking at figures 5.8 and 5.11 does not show any remarkable occurrence. The differences between the two depth levels could be revealed by comparing the amount of litter items passing a certain location. The graph in figure 5.17 displays the amount of particles passing the downstream area of interest border over time. Again, the graph solely presents a comparison between the different simulations, rather than the actual amount of items passing the location. The black line represents the output for the fourth scenario in the top depth layer where no wind was imposed. The blue line represents the output for the fifth scenario where a SW was imposed. The red line represents the sixth scenario where litter items drift in the second depth layer.

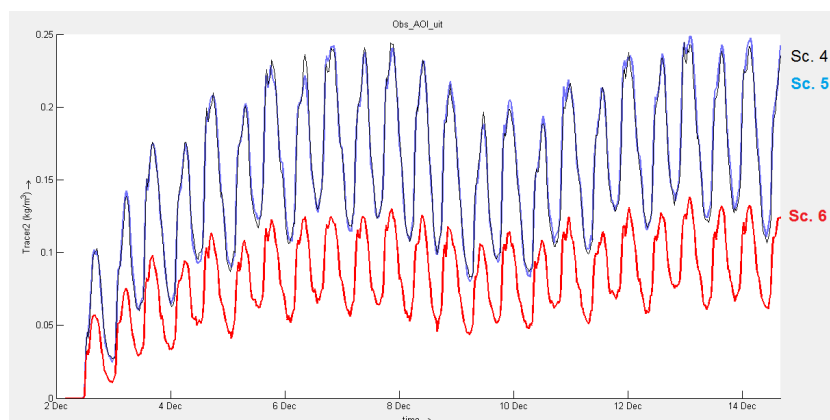


Figure 5.17: Simulation output graph of particles passing the downstream area of interest border over time

Looking at the graph it is revealed that in the second depth layer, less particles pass the downstream area of interest border over time than in the first depth layer. The reason for this phenomenon is unknown but could be related to the tidal ranges, as they cause fluctuations in the different currents of the several depth layers. As stated earlier, it can indeed be concluded that the wind does not affect the litter items drifting below the surface level since, the blue line and the black line are overlapping almost perfectly. It had already be concluded that the wind influence is dominant for litter items drifting at the surface, and therefore consequently, it can be concluded that the river flow is dominant for litter items drifting below the surface level.

6

CONCLUSION

Marine litter consists of various items that have been deliberately discarded, were unintentionally lost, or are transported into the naval environment. The materials vary from metals to wood, paper, glass, rope, rubber, and of course plastics which account for the vast majority. According to literature, approximately 80% of solid litter on a global scale is transported via rivers and originated from land bases sources. Quantifying the total amount of marine litter that is present in the world has proved to be difficult, however it has been found that over the last 12 years no significant decrease can be seen, which raises the global awareness momentarily. Drifting towards the ocean, the marine litter flows through port areas, which are the main link with the inland waterways. As seaports are generally designed like tree structures with many branches, the litter gets divided when entering a port area. With the creation of the Port Waste Catch project, the Port of Rotterdam initiated the development of novel techniques to reduce the amount of marine litter from seaports all over the world. It has triggered researchers to create innovative solutions and hereby a number of waste reduce systems were invented. Some of them can be implemented on fixed positions, others are moving throughout the port area. The added value of a marine litter propagation model is that it could indicate the accumulation locations in a specific port area, such that the waste reduce systems can operate optimally.

Previously performed studies indicate that several aspects influence the movements of marine litter in their own way. The direct environment of the marine litter, in this case the port structure, determines the boundaries of the marine litter flow. Both the water flow velocity and wind conditions have a large impact, especially on items with a high buoyancy such as plastics, since they tend to drift easily. Tidal ranges affect the transportation of litter items on beaches and along coast lines, the impact in port areas however has not yet been investigated. A research conducted in the Dutch river the Maas, showed that 98% of all litter items flows in the top meter water column, and 95% in the top half meter water column. Furthermore, other studies in literature confirm that a large part of the litter floats at sea level and a part drifts just below the surface, hence not all items are affected in the same manner. The exact impact of the different aspects in port areas, or which is the most dominant, has not been found in literature. During an interview with an expert of Deltares, specialized in applied research in the field of water and subsurface, it was revealed that conducting marine litter studies is highly complicated. This is due to the fact that very few quantitative data on port areas is known, since a lack of systems registering marine litter exists. As the Port of Rotterdam is now implementing a number of systems as a result of the Port Waste Catch project, real quantitative data will be available in the near future.

In order to answer the main research question a propagation model was proposed. Given the complexity of the port environment and the the dynamic movements of marine litter, the propagation model incorporates a hydrodynamic model. A hydrodynamic model can be used to describe, define and simulate water movements in multiple and various environments, in this case a port area, in order to achieve the most realistic results. The port area of Rotterdam was chosen as a specific case study environment in order to verify the application of the generic model. Therefor, a hydrodynamic model was developed using an existing model of the Port of Rotterdam from which the main attributes, such as the numerical grid composition, were adopted.

The model has been developed using the Delft3D hydrodynamic modeling software and was imposed to boundary conditions in order to accurately describe the water movements in the scope area. The main boundary conditions are the variable riverine influx and water levels, which are fluctuating due to tidal ranges. After defining the input characteristics such as a chosen time frame of 14 days (equaling one spring-neap tide cycle) and a calculated time step of 0.125 minutes, the model output demonstrated and visualized the application of the developed hydrodynamic model. The developed model has been validated by comparing simulation results with real life observations and measurements. The model output was compared to tidal data regarding the water level of the Nieuwe Maas, obtained from Rijkswaterstaat. Furthermore, two data sets containing measurements of both the water level and the flow velocity were obtained from the Port Authorities. From the comparisons of these measurements with the model output, it was concluded that the developed hydrodynamic model accurately describes water movements in the port area of Rotterdam.

In order to simulate the marine litter propagation within the port area, a particle tracking tool was used to discharge separate particles and tracking their path in time. Since any quantitative data regarding marine litter in the case study environment is not yet available, a number of scenarios have been proposed in order to determine how the litter items behave under the influences of the different aspects. A distinction was made between the movements of marine litter in several depth levels, since these different moving states were mentioned in literature. The simulations of these scenarios have been imposed to several wind conditions in order to investigate the wind influence as well. This could be achieved since the port structure characteristics, river flow rate and tidal ranges were known. Therefore, the marine litter propagation was simulated using the developed hydrodynamic model which serves as input for the particle tracking tool. By choosing overestimated discharge input values, the discharged particles accumulated at several locations, such that by comparing the output of the different scenarios, the impact of the influencing aspects on the marine litter movements could be analyzed. Comparing the results of the different scenarios has led to the following conclusions in terms of the different influencing aspects:

1. It has been verified that the port structure affects the movements of marine litter, however it can not be said to what degree, as some compartments seem to contain more accumulation potential than others.
2. It has been concluded that wind conditions are a dominant factor for the movements of marine litter floating at the surface, since the model output showed a very clear distinction of accumulation areas between the scenarios with different wind directions.
3. Consequently it has been concluded that the river flow is dominant for litter items drifting below the surface level, as the wind does not affect those items and thus they are guided by the river flow.
4. The simulation results of all scenarios showed that the tidal ranges affect the marine litter inside port areas on a relatively short term, that is for a period of high- and low tidal current as the litter follows the river flow in general.

These observations and conclusions are briefly summarized in the table displayed here below. The column certainty indicates whether the aspect is known or can be anticipated.

Aspect	Certainty	Observation	Influence
Port structure	Known	Compartment dependent	Low
Wind conditions	Statistical	Dominant at surface	High
River flow rate	Measurable	Dominant below surface	High
Tidal ranges	Predictable	Short term impact	Low

From the validated model and the observations it can be concluded that the proposed propagation model is capable of describing the movements of marine litter in port environments. The generic propagation model takes advantage of hydrodynamic modeling software and incorporates a hydrodynamic model depending on the investigation area.

7

RECOMMENDATIONS

During the conductance of this research a lot of knowledge regarding marine litter in general has been gathered. It also has become clear that the availability of quantitative data within port environments is very limited. Due to the Port Waste Catch project a number of waste removers will be implemented in the Port of Rotterdam and they will provide quantitative data in the near future. Moreover, during this research case study a marine litter propagation model was developed for a specific area in the Port of Rotterdam. By simulating overestimated litter quantities, the impact of the influencing aspects on the marine litter movements was revealed. When accurate predictions are desired however, knowing the actual amount of marine litter entering the port area is vital. With these thoughts the following recommendations are made:

- Implementation of measurement systems in order to assess the marine litter quantity entering the port area. It should be investigated which locations are most suitable to measure the litter items in the rivers.
- Consideration of a system that is capable of registering and documenting the measured data. This system could create a clear overview of: the marine litter quantity entering the port area, the locations from where it enters, how many litter is present and an evaluation of the litter material and size.

In this report the hydrodynamic model- and particle tracking model input characteristics have been discussed. It was explained that many input parameters are necessary to set up the models and therefore they have been determined together with experts of Deltares, based on the experience acquired over the years during conducted projects. However, since only a few researches regarding marine litter have been performed, a possibility exists that the values of some parameters behave differently when simulating the movements of marine litter. As it was concluded that the river flow is dominant for litter items drifting below the surface level, it could be rewarding to perform the following recommendations:

- Investigation of the effect of the diffusion coefficient on the marine litter movements.
- Verification of the dispersion parameters especially for the marine litter movements.

During this research several scenarios imposed to various conditions were investigated. Three scenarios focused on litter items floating at the surface, where one scenario disregarded the wind influence and two others incorporated a constant wind condition, from opposite directions. No scenario with inconsistent wind conditions has been investigated during this research, as the results could not be verified due to the lack of available data. Since it was concluded that wind conditions are a dominant factor for the movements of marine litter floating at the surface, the following recommendations are made:

- Investigation of the effect of the wind drag coefficient on the marine litter movements.
- Investigation of scenarios with variable wind conditions.

It should be noticed that the wind influence is the most difficult one to simulate accurately, as it is the most inconsistent one. Furthermore, since the marine litter items vary in size and material, certain assumptions always have to be made. However, since only a few researches have been conducted on the marine litter propagation in port environments, every newly acquired knowledge is a step forward. Therefore, any type of research in this area is considered valuable and should be stimulated.

BIBLIOGRAPHY

- [1] National Academy of Sciences, *Assessing Potential Ocean Pollutants* (1974) Chap. 8, pp. 405–431.
- [2] A. Cheshire, E. Adler, J. Barbière, and Y. Cohen, *UNEP Regional Seas Reports and Studies, No. 186; IOC Technical Series*, 186 (2009) p. 120 pp.
- [3] National Research Council, *Tackling Marine Debris in the 21st Century* (The National Academies Press, 2008).
- [4] Great Barrier Reef Marine Park Authority, *Litter*, (2006), fact Sheet No17.
- [5] J. Mouat, R. Lopez Lozano, and H. Bateson, *Economic Impacts of Marine Litter*, *Kommunenenes Internasjonale Miljøorganisasjon (KIMO)*, 105 (2010).
- [6] S. Rech, V. Macaya-Caquilpan, J. F. Pantoja, M. M. Rivadeneira, D. Jofre Madariaga, and M. Thiel, *Rivers as a source of marine litter - A study from the SE Pacific*, *Marine Pollution Bulletin* **82**, 66 (2014).
- [7] C. E. Balas, A. T. Williams, S. L. Simmons, and A. Ergin, *A statistical riverine litter propagation model*, *Marine Pollution Bulletin* **42**, 1169 (2001).
- [8] M. Thiel, I. A. Hinojosa, T. Joschko, and L. Gutow, *Spatio-temporal distribution of floating objects in the German Bight (North Sea)*, *Journal of Sea Research* **65**, 368 (2011).
- [9] D. K. a. Barnes, F. Galgani, R. C. Thompson, and M. Barlaz, *Accumulation and fragmentation of plastic debris in global environments*. *Philosophical transactions of the Royal Society of London. Series B, Biological sciences* **364**, 1985 (2009).
- [10] J. Jambeck, R. Geyer, C. Wilcox, T. Siegler, M. Perryman, A. Andrady, R. Narayan, and K. Law, *Plastic waste inputs from land into the ocean*, *Science* **347**, 768 (2015).
- [11] M. Boonstra, F. van Hest, and M. Hougee, *Wat spoelt er aan op het strand?* *Stichting De Noordzee*, 13 (2016).
- [12] A. Turner and K. R. Solman, *Analysis of the elemental composition of marine litter by field-portable-XRF*, *Talanta* **159**, 262 (2016).
- [13] C. Moore, G. Lattin, and A. Zellers, *Quantity and type of plastic debris flowing from two urban rivers to coastal waters and beaches of Southern California*, *Revista de Gestão Costeira Integrada* **11**, 65 (2011).
- [14] M. van der Wal, M. van der Meulen, E. Roex, Y. Wolthuis, G. Tweehuysen, and A. Vethaak, *Statewide Agricultural Land Use Baseline 2015*, Tech. Rep. (Deltares, 2013).
- [15] M. Claessens, S. D. Meester, L. V. Landuyt, K. D. Clerck, and C. R. Janssen, *Occurrence and distribution of microplastics in marine sediments along the Belgian coast*, *Marine Pollution Bulletin* **62**, 2199 (2011).
- [16] Port of Rotterdam, *Port waste catch*, (2015).
- [17] SK International, *Zwerfvuil uit de rivier*, *Recycling magazine benelux* **4**, 20 (2013).
- [18] M. van Tol, *Vessel routing for sweeping of marine litter in a port area*, Master thesis, Delft University of Technology (2016).
- [19] Ocean Conservancy, *25 years of debris collected*, (2016).
- [20] M. C. Araújo and M. Costa, *An analysis of the riverine contribution to the solid wastes contamination of an isolated beach at the Brazilian Northeast*, *Management of Environmental Quality: An International Journal* **18**, 6 (2007).

- [21] G. J. M. Vauk and E. Schrey, *Litter pollution from ships in the German Bight*, [Marine Pollution Bulletin](#) **18**, 316 (1987).
- [22] J. G. Derraik, *The pollution of the marine environment by plastic debris: a review*, [Marine Pollution Bulletin](#) **44**, 842 (2002).
- [23] A. L. Andrady, *Microplastics in the marine environment*, [Marine Pollution Bulletin](#) **62**, 1596 (2011).
- [24] P. G. Ryan, C. J. Moore, J. a. van Franeker, and C. L. Moloney, *Monitoring the abundance of plastic debris in the marine environment*. [Philosophical transactions of the Royal Society of London. Series B, Biological sciences](#) **364**, 1999 (2009).
- [25] M. Thiel, I. A. Hinojosa, L. Miranda, J. F. Pantoja, M. M. Rivadeneira, and N. Vasquez, *Anthropogenic marine debris in the coastal environment: A multi-year comparison between coastal waters and local shores*, [Marine Pollution Bulletin](#) **71**, 307 (2013).
- [26] M. Schulz, D. Neumann, D. M. Fleet, and M. Matthies, *A multi-criteria evaluation system for marine litter pollution based on statistical analyses of OSPAR beach litter monitoring time series*, [Marine Environmental Research](#) **92**, 61 (2013).
- [27] Stichting De Noordzee, [Publicaties](#), .
- [28] H. Leslie, M. van der Meulen, F. Kleissen, and A. Vethaak, *Microplastic Litter in the Dutch Marine Environment Providing facts and analysis for with marine microplastic litter*, [Deltares](#) , 104 (2011).
- [29] I. Langelaan, I. Nuytens, and M. Jansen, *Microplastics in de Nederlandse zoete wateren: Herkomst en samenstelling van microplastics in relatie tot degradatie van plastics, en de mogelijke gevolgen van (micro)plastics voor mens en milieu*, [Adviesrapport InCompany Milieuadvies](#) (2014).
- [30] R. Falconer and J. Jiang, *On the Tidal Exchange Characteristics of Model Rectangular Harbours*. [ICE Proceedings](#) **75**, 475 (1983).
- [31] J. Yin, R. A. Falconer, Y. Chen, and S. D. Probert, *Water and sediment movements in harbours*, [Applied Energy](#) **67**, 341 (2000).
- [32] O. Stoschek and C. Zimmermann, *Water Exchange and Sedimentation in an Estuarine Tidal Harbor Using Three-Dimensional Simulation*, [Journal of Waterway, Port, Coastal, and Ocean Engineering](#) **132**, 410 (2006).
- [33] M. A. Browne, T. S. Galloway, and R. C. Thompson, *Spatial patterns of plastic debris along estuarine shorelines*, [Environmental Science and Technology](#) **44**, 3404 (2010).
- [34] J. C. Astudillo, M. Bravo, C. P. Dumont, and M. Thiel, *Detached aquaculture buoys in the SE Pacific: Potential dispersal vehicles for associated organisms*, [Aquatic Biology](#) **5**, 219 (2009).
- [35] I. A. Hinojosa, M. M. Rivadeneira, and M. Thiel, *Temporal and spatial distribution of floating objects in coastal waters of central-southern Chile and Patagonian fjords*, [Continental Shelf Research](#) **31**, 172 (2011).
- [36] R. E. Bilby and J. T. Heffner, *Factors influencing litter delivery to streams*, [Forest Ecology and Management](#) **369**, 29 (2016).
- [37] E. Martinez, K. Maamaatuaiahutapu, and V. Taillandier, *Floating marine debris surface drift: Convergence and accumulation toward the South Pacific subtropical gyre*, [Marine Pollution Bulletin](#) **58**, 1347 (2009).
- [38] F. Galgani, J. P. Leaute, P. Moguedet, A. Souplet, Y. Verin, A. Carpentier, H. Goraguer, D. Latrouite, B. Andral, Y. Cadiou, J. C. Mahe, J. C. Poulard, and P. Nerisson, *Litter on the sea floor along European coasts*, [Marine Pollution Bulletin](#) **40**, 516 (2000).
- [39] C. K. Pham, E. Ramirez-Llodra, C. H. S. Alt, T. Amaro, M. Bergmann, M. Canals, J. B. Company, J. Davies, G. Duineveld, F. Galgani, K. L. Howell, V. A. I. Huvenne, E. Isidro, D. O. B. Jones, G. Lastras, T. Morato, J. N. Gomes-Pereira, A. Purser, H. Stewart, I. Tojeira, X. Tubau, D. Van Rooij, and P. A. Tyler, *Marine litter distribution and density in European seas, from the shelves to deep basins*, [PLoS ONE](#) **9** (2014).

- [40] O. J. Dameron, M. Parke, M. A. Albins, and R. Brainard, *Marine debris accumulation in the Northwestern Hawaiian Islands: An examination of rates and processes*, [Marine Pollution Bulletin](#) **54**, 423 (2007).
- [41] J. T. Potemra, *Numerical modeling with application to tracking marine debris*, [Marine Pollution Bulletin](#) **65**, 42 (2012).
- [42] J. H. Yoon, S. Kawano, and S. Igawa, *Modeling of marine litter drift and beaching in the Japan Sea*, [Marine Pollution Bulletin](#) **60**, 448 (2010).
- [43] L. C. M. Lebreton and J. C. Borrero, *Modeling the transport and accumulation floating debris generated by the 11 March 2011 Tohoku tsunami*, [Marine Pollution Bulletin](#) **66**, 53 (2013).
- [44] S. Kako, A. Isobe, S. Magome, H. Hinata, S. Seino, and A. Kojima, *Establishment of numerical beach-litter hindcast/forecast models: An application to Goto Islands, Japan*, [Marine Pollution Bulletin](#) **62**, 293 (2011).
- [45] D. Neumann, U. Callies, and M. Matthies, *Marine litter ensemble transport simulations in the southern North Sea*, [Marine Pollution Bulletin](#) **86**, 219 (2014).
- [46] K. Critchell, A. Grech, J. Schlaefel, F. P. Andutta, J. Lambrechts, E. Wolanski, and M. Hamann, *Modelling the fate of marine debris along a complex shoreline: Lessons from the Great Barrier Reef*, [Estuarine, Coastal and Shelf Science](#) **167**, 414 (2015).
- [47] J. Lambrechts, E. Hanert, E. Deleersnijder, P.-E. Bernard, V. Legat, J.-F. Remacle, and E. Wolanski, *A multi-scale model of the hydrodynamics of the whole Great Barrier Reef*, [Estuarine, Coastal and Shelf Science](#) **79**, 1 (2008).
- [48] D. Stuparu, M. V. A. N. D. E. R. Meulen, F. Kleissen, and D. Vethaak, *Developing a transport model for plastic distribution in the North Sea*, [E-proceedings of the 36th IAHR World Congress](#) (2015).
- [49] Deltares, *Delft3D, Brochure*, (2014).
- [50] Wikipedia, [Navier–stokes equations](#), (2016).
- [51] Wikipedia, [Continuity equation](#), (2016).
- [52] J. Braithwaite, *An Introduction To Hydrodynamics*, (2011).
- [53] NOAA Office of Coast Survey, [How hydrodynamic models are used](#), (2016).
- [54] Deltares, [Enabling delta life](#), (2016).
- [55] Deltares, [Xbeach open source community](#), (2016).
- [56] Deltares, *Delft3D, Functional Specification*, (2014).
- [57] Deltares, *Delft3D-FLOW, User Manual*, (2014).
- [58] Deltares, *Delft3D-PART, User Manual*, (2014).
- [59] Port of Rotterdam, [An overview in history](#), (2015).
- [60] Google, [Google maps](#), (2016).
- [61] Wikipedia, [Tidal rivers](#), (2016).
- [62] Port of Rotterdam, [Operationeel stromingsmodel rotterdam](#), (2016).
- [63] Wikipedia, [Tide](#), (2016).
- [64] C. Chrzanowski, D. Stuparu, M. Tiessen, and W. Kranenburg, *Transport van plastics in de Haven van Rotterdam*, Tech. Rep. (Deltares, 2016).
- [65] Rijkswaterstaat, [Tidal data](#), (2016).
- [66] KNMI, [The netherlands climate](#), (2016).