Modelling the dispersion and deposition of solid wastes from fish farming with a continuum approach

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Declaration

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Abstract

The sustainability of the environment in coastal ecosystems is of great concern due to aquaculture. There are many unknowns and constraints in the predictive modelling of fish farm waste due to the limitations of obtaining information in the farming area. By understanding the gaps in the information, the necessary research projects can be established, therefore improving the predictive modelling.

This project presents an academic case for Delft3D-FLOW to predict the dispersion and deposition of organic mariculture waste using a continuum approach. The continuum approach allows us to model the waste interaction with the seabed as a cohesive sediment, which can be done using Delft3D-FLOW. More information is needed on how the wastes interact with the seabed as it has been observed that the erosion and deposition of the waste is sensitive to the cohesive properties.

Delft3D-FLOW was used for the simulation as it includes modules of multi-dimensional hydrodynamic flows and transport phenomena, including the transport of cohesive and non-cohesive sediments. The simulation represents a growth cycle of six months for Atlantic salmon within a simple rectangular grid, using the background currents of a fjord in the Faroe Islands. A six month simulation period was chosen due to time constraints, allowing for a feasible simulation time and time to conduct a sensitivity analysis on the interaction of the waste with the seabed. The growth data of the simulation period was gathered from existing data in order to determine the amount of feed used, therefore representing the growth cycle of the Atlantic salmon. Using the feed cycle and information from literature, the corresponding waste output of the farm was calculated.

Observing the output from the simulations, the waste has been completely dispersed from the grid at the end of the cycle, indication a highly dispersive site. These results correlates with the high currents that were calculated within the fjord. Further, an investigation was conducted into the critical deposition and erosion stresses in order to observe the affect the stresses have on the resultant deposition and dispersion of the waste at the seabed. The results of the sensitivity analysis of the shear stresses result in validation that low critical shear stresses were chosen.

Uittreksel

Die volhoubaarheid van die natuurskoon in kus-ekosisteme word bedreig as gevolg van akwakultuur boerdery. Met betrekking tot die modellering van vis afval in vis boerdery, vir die doel van voorspelling, is daar vele onbekendes en beperkings wat bestaan. Daar is groot leemtes in die verkryging en versameling van inligting oor vis boerdery. Om al die leemtes te verstaan, kan vele navorsingsprojekte daarvoor bemagtig word, om die skep van voorspellingsmodelle te verbeter. Dié projek stel 'n akademise toetsgeval voor vir die Delft3D-FLOW sagteware om die dispersie en deposisie van organsiese materiaal te voorspel, met behulp van 'n kontinuum benadering. Die kontinuum benadering laat toe dat ons nie net die afval modelleer nie, maar ook die interasie daarvan met die seebodem as 'n kohesiewe sediment. Meer informasie word benodig ten opsigte van die interaksie van die vis afval met die seebodem, aangesien die erosie en ontbinding daarvan sensitief is tot kohesie eienskappe.

Ons maak gebruik van Delft3D-FLOW vir die simulasies aangesien dit modules bevat vir die modellering van multi-dimensionele hidrodinamika en transport verskynsels. Die transport verskynsels sluit in die vervoer van kohesiewe en nie-kohesiewe sedimente. Die simulasie bestaan uit 'n ses maande groeisiklus van Atlantiese salm, binne 'n eenvoudige reghoekige area (rooster). Die simulasie maak gebruik van waterstrome in die agtergrond van 'n fjord in die Faroe Eilande. 'n Ses maande simulasie periode word gebruik as gevolg van tyd beperkinge. Die simulasie periode laat nie net toe vir ‘n realistiese simulasie tydperk nie maar ook om sensitiwiteits analise te doen oor die interaksie van die vis afval met die seebodem. Die groei data vir die simulasie was verkry vanaf reeds bestaande data, om die hoeveelheid voer wat gebruik is te bepaal. Dit verteenwoordig die groeisiklus van Altantiese salm. Deur van die groeisiklus gebruik te maak en inligting beskikbaar in literatuur, kon die resultante vis afval gegenereer deur vis boerdery bereken word.

Deur na die uitsette van die simulasies te kyk, het ons gesien dat die afval heeltemal versprei het vanaf die reghoekige area teen die einde van die ses maande siklus. Dus, stel dit ‘n hoë verspreidings area voor. Die resultate was gekorreleer met die hoë water spoede in die fjord. Daar was verder ondersoek ingestel na die kritiese deposisie en erosie stresse wat ervaar word deur die vis afval en die impak daarvan op die seebodem. Die resultate van die sensitiwiteits analiese van die stresse, bevestig dat lae kritiese sleurspanning gekies was.

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Contents

Chapter 1

Introduction

1.1 Background

Aquaculture, the farming of fish and aquatic plants, is a growing industry and globally provides 50 % of the fish consumed by humans, with expectations to increase for the growing global population. Norway provides an estimated 1.3 million tons of biomass annually, which is predicted to further expand to an annual production of 5 million tons by 2050 [2]. As the world's demand for seafood grows, aquaculture becomes a significant contributor for bridging the gap between supply and demand. Aquaculture is an umbrella term referring to the farming of aquatic organisms and fauna, with fish farming sometimes being synonymous with aquaculture, where fish farming refers more to the raising of fish. Aquaculture is divided into two main operations, inland and marine aquaculture, with inland aquaculture focusing mainly on fresh water species. The raising of fish inland can be done in multiple ways, for example using ponds or flow-through channels where the water is continuously moving. Other methods include using tanks and aquaponic systems allowing for fish farming to occur indoors [43]. Marine aquaculture, or mariculture, refers specifically to the farming of marine plants and fish in their natural environment [28]. Just like their fresh water counterparts, marine fish are farmed in multiple different ways. For example, closed systems are designed with re-circulatory systems that continuously filter and recycle the water and waste by-products. The focus for this project is cage culture, which is a net-pen like enclosed cage, submerged in offshore and coastal areas [31].

Not only does mariculture provide food for a growing population but also creates jobs in coastal and waterfront communities. Former fishermen are taking to aquaculture as a substitute for previous fishing livelihoods [31]. However, with the increased demand and supply, not to mention the competition for economic benefits, rising pressure is put on coastal resources. Therefore attention is necessary on the management of mariculture, which can be accomplished by environmentally conscious technology to better manage the by-products and impact of mariculture on coastal regions [33]. In order to expand and meet the rising demand, the mariculture sector needs to develop sustainable practices that are innovative, responsible and still profitable while still being societally beneficial [11].

Mariculture affects the environment by introducing organic waste into the water column, where the waste is made up of the effluents produced by the fish combined with uneaten feed. This waste is then spread and distributed by the surrounding currents, eventually sinking to the ocean floor. The waste produced by mariculture has the possibility of negatively impacting the environment and thereby affecting the species that subside in the area, especially in intensive farming areas. Many production areas, for example Southeast Asia, China, and South America, have already reached, or are approaching, the surrounding area's environmental capacity for added waste created by these mariculture practices. The capability of mariculture to negatively affect the surrounding environment has started a debate on how the sites are selected for future farms. The major issue to focus on being the accumulation and distribution of the waste produced from the farms [11]. The regulation of mariculture is becoming more important with the increase of more intensive fish farms, hereby increasing the deposition of waste and hence increasing the environmental burden. This increase has been well documented [40] and carries an urgency for stricter regulation or change in the current mariculture practices. An area of great and growing interest is improving the management of mariculture through the improvement of farming practices.

Achieving environmentally sustainable mariculture is constrained by a limited knowledge of the regional interactions and fate of the waste on ecosystems, which is due to the difficulty in obtaining and monitoring information on a large scale in the ocean. A step to improve the lack of knowledge is to establish accurate predictive modelling tools that enable a better understanding of the local and regional dispersion of waste. More value needs to be placed on the dispersion of waste from the farms and how the waste interacts with the broader ecosystem. Therefore, improving the estimates of the physical characteristics of the by-products is required in order to limit the environmental impact. The management of industrial-scale mariculture requires accurate predictions of environmental footprints of the waste on the benthic environment, where the benthic environment is the zone at the seabed including the sediments. Bottlenecks have been caused by the lack of detailed knowledge on the parameters to predict the dispersion and impacts on the benthic environment [2]. This bottleneck is likely caused by the farms' expensiveness and length of time it takes to obtain accurate details of the effects that the waste has on the environment.

Predictive modelling of fish waste dispersion and deposition is an effective tool for estimating the environmental impact of mariculture, though the validation of the modelling is still necessary. Sediment transport models have been established as modelling tools that simulate the transport of waste as particles. Generally, a sediment transport model is combined with the use of hydrodynamic data or a hydrodynamic model for the interaction of the waste with the currents and flow field. Coastal areas have been seen to have complex flow-fields, raising the need for more accurate and efficient mathematical models than produced in the past. The complexity of coastal areas arises from many factors such as wind, tides, and seasonal effects, as well as the difficulty in measurement studies. Another important factor to consider for a comprehensive modeling strategy is the waste transport mechanisms, such as the deposition, erosion, and dispersion. Since these factors involve complex mechanisms, simplifications have to be made, although people are continuously attempting to recreate more complicated and appropriate models. The dispersion and deposition of waste has been observed to be very sensitive when dealing with the transport factors and this could limit the usefulness of predictive models [16]. In this study a model and method are provided that includes accurate hydrodynamics and an alternative representation of waste transport mechanisms.

1.2 Problem statement

As part of a joint research project managed by Professor Neil Goosen, funded by Aqua Vitae in Europe, hydrodynamic modelling is conducted in Sørvágsfjørd̄ur in the Faroe Islands. The present research draws on ideas from this project and the aim is to simulate a simple representation of the dispersion and deposition of the solid wastes produced by the mariculture farm in the fjord. By using data from an existing farm to simulate the growth of the fish in the farm, a simple academic case is presented for the dispersion and deposition of the waste. For this project a continuum method was selected instead of the general use of a particle tracking model. Since a simple replication of a hydrodynamic domain is used, this project stands as a basis for the modelling of mariculture waste as a continuum method, allowing for others to replicate and expand on this topic.

Therefore, we investigate in this project whether it is feasible to simulate the transport, deposition and resuspension of fish farm effluents, using a continuum approach. The interaction of the waste with the seabed is considered to be similar to that of a cohesive material rather than a particulate material. Therefore, waste will be considered as a continuous constituent and the concentration of the material will be simulated using an advection-diffusion equation. By using the Delft3D-FLOW model, we can simulate 3D hydrodynamics, while simultaneously simulating the advection-diffusion of the waste. Delft3D-FLOW allows the simulation of the material and close investigation of the deposition, erosion, and dispersion of the waste. Therefore, by using Delft3D-FLOW we can fully investigate the continuum approach and whether the results correspond to the spreading of waste from mariculture.

1.3 Objectives

The two main objectives of this study are:

- to produce a clear exposition of the feasibility to simulate the behaviour of mariculture waste by using a continuum model,
- and investigate the sensitivity of the deposition and erosion on the dispersion of the waste.

The approach how these objectives shall be completed can be broken down as follows:

- addressing how the physical properties of the waste affect dispersion and environmental impact,
- providing a summary on sediment transport methods and models,
- investigating the transport mechanics of cohesive sediments and interactions with the seabed,
- describing how to use Delft3D-FLOW for cohesive sediments,
- simulating the currents and waste dispersal for an idealised farm using Delft3D-FLOW,
- and observing the sensitivity of the deposition and erosion parameters of the simulation.

1.4 Thesis overview

This thesis presents an alternate method for modelling the waste produced by mariculture. Chapter 2 presents a study of mariculture with the necessary background on the environmental impact, regulatory bodies, and the environmental standard. In Chapter 3 is a study of the by-products and how the properties of the waste influence the dispersion and deposition, as well as how particle tracking models are used for the simulation of mariculture waste. Chapter 4 is the investigation into how to model the waste as a continuum, as well as information on the transport properties of cohesive sediments. Chapter 5 is how Delft3D-FLOW shall be used to simulate the mariculture waste as a continuum and the information and inputs needed for an accurate simulation. Chapter 6 presents the simulation results and a sensitivity analysis into the shear stresses that affect the dispersion and deposition. Chapter 7 is the conclusion to the work conducted for this thesis and suggestions for future research.

Chapter 2

Mariculture

2.1 Introduction

For this chapter, an overview of the literature related to mariculture, the resultant environmental impact and the regulatory bodies and environmental standards is presented. Using this research, we can create a guide for us to follow in order to understand the impact of mariculture and the resultant steps needed to fall within environmental guidelines. Firstly, a description of mariculture, the subsequent environmental impact and the importance of site selection and carrying capacity is provided in Section 2.2. Then we delve, in Section 2.3, into the Environmental Quality Standard which regulatory bodies use and how it was derived and applied today.

2.2 Basics of mariculture

Mariculture dates back to the 10th century when Chinese fishermen built bamboo cages in order to fatten up the fish. Since then, there has been a huge expansion in mariculture over the past three decades. The expansion is due to several factors, such as the high demand for seafood and the high market value. Another factor is the improvement in technology of cages, allowing for farming in different oceanographic conditions, especially offshore areas [38]. Modern day mariculture employs a number enclosed circular net-like cages called open-net pens, with a diameter of up to 50 m. Depending on whether juveniles or adults are stocked, depth and mesh size of the net may vary. For example, an adult cage can have a volume of 88 000 m^3, which allows for 200 000 fish to be stocked inside [23]. The net like structure allows for the currents in the surrounding area to flow through and remove the waste created by the fish. Many different species are farmed in this way, for example Atlantic salmon and rainbow trout are popular mariculture finfish in Norway [5]. An example of a cultivation cycle for Atlantic salmon is a 18-month-grow-out cycle, where a 100 g juvenile salmon is stocked in the net. The salmon when harvested at the end of the cycle ends up being 4 to 5 kg [2].

The expansion and rise in the popularity of mariculture is followed by the increased interest in the fate of the by-products. The waste produced by the farms could affect the surrounding environment, by for example increasing the organic material, which often leads to anoxic conditions. Due to the impact of mariculture being well studied and documented, from the increased involvement of developed countries, there are many reports and studies available on the environmental assessment of mariculture [38], specifically the benthic impacts within the vicinity of farms [27]. Well researched information and technological improvements are aspects that allow for innovation in both siting and culture practice [22].

Another aspect is the consideration of constraints when monitoring of existing mariculture sites and when deciding to set up a new facility. When an area becomes of interest for mariculture, approaches, such as site selection and carrying capacity, are used to analyse the various aspects of the offshore area. These approaches are a few of the important constraints when dealing with the success of mariculture. Site selection and estimating the carrying capacity need to be carried out when dealing with the sustainability, resilience and best practice guidelines [20]. Both site selection and carrying capacity have been placed in guidelines in order to protect the environment from the impacts of mariculture, though we must first research into how the environment is impacted by mariculture by-products.

2.2.1 The environmental impact

Monitoring the environmental impact of mariculture has shown that it affects different ecological processes and biotic communities. How the mariculture affect marine benthic environments has been a topic of study for many years. The effects on the surrounding water quality is also cause for concern and has not been as studied as the benthic impact. Due to mariculture farms employing multiple cages, large quantities of waste and dissolved nutrients are released, where the waste is eroded, deposited, and dispersed possibly over large areas. The impact on the benthos, the organisms that live within the benthic environment, when in small areas, is easily detected and monitored. For example, the monitoring of the macrofauna underneath and around the cages. Due to the high dispersion of the nutrients, the quality control of the water needs new protocols, and further research, in order to understand and easily detect the degree of impact from mariculture [27].

Concerning the benthic zone, the lowest ecological zone within a body of water, large deposits of waste on the seabed could cause a decrease in the oxygen supply thus impacting the native creatures and fauna adversely [36]. The by-products of mariculture are largely enriched in carbon, nitrogen and phosphorus relative to the amounts found in the natural sediments [1]. Some deposition is acceptable around the cage as long as there is a sufficient density and diversity of creatures that assist in reworking waste to maintain a turnover of carbon in the water column. By predicting the location of the deposited wastes, using the bathymetry, currents and settling velocities of the waste, one can identify the areas where any negative effects could occur. The area of deposition might be large due to the the waste possibly being resuspended by the near-bed currents and possibly dispersing the waste a few hundred metres from the cages, though the majority of the deposited waste is found in the area underneath and surrounding the cages [36].

The cost of investigating the environmental impact is a major concern when dealing with sustainable mariculture practices. Monitoring the environment with the effects of the by-products can be improved by implementing geochemical variables to reflect the waste, instead of employing a benthic model. A benthic model is designed to assist the user in the impact assessment of the benthic environment, for example DEPOMOD [9]. The total organic carbon (TOC) or organic matter can be measured by the loss on ignition (LOI) method [27], which is a method commonly used to estimate the organic and carbon content of sediments. LOI provides straight forward results [27] and has been concluded as a fast and inexpensive means which has a precision and accuracy comparable to more sophisticated methods [25]. TOC is a reliable predictor for macrofaunal diversity and can therefore be used as a quality indicator of the benthic environment. Benthic modelling is being added to monitoring systems, for example both Norway and Canada have constructed systems which allow for a more detailed analysis of the sediments [27].

2.2.2 Site selection

Site selection is the investigation and gathering information on the hydrodynamic data, such as the currents, tides and waves, topography, and properties of the water column, at the site before or after the farm is installed. The hydrodynamic data is key for how the waste is dispersed and deposited, as well as important for increasing the scientific knowledge of the effect of the hydrodynamics on the dispersion of the effluents [2]. The properties of the water column, such as the salinity and temperature, affect the dispersal and deposition of the effluents, albeit not as much as the hydrodynamic properties [2]. The water column's density and salinity content appear to play a role in the velocity range at which the effluent settles on the sea floor, such as having a high salinity will cause the effluents velocity to decrease when released [35]. Collecting the information on the temperature and salinity ranges in the area could increase the accuracy of the predictions, especially for complex models used for commercial purposes.

By establishing the hydrodynamic data of the site, the management system can create a hydrodynamic model to accurately predict the hydrodynamics before adding the effluents, which then allows for the observation of potential benthic impacts, such as the nutrient overloading. Information of the currents, tides and waves can be collected from weather services in the site's area or by installing custom measuring devices [5]. Installing measuring devices is costly and time consuming, therefore is not done regularly. Generally weather services are used, for example the Weather Research and Forecast model has been used to provide wind-forcing [2], which in turn is used to simulate the currents at the site's location.

The hydrodynamics can then be simulated by a 2D, or 3D model for hydrodynamic current fields. Some previous studies have employed data from point measurements of currents, for a short time period [5] due to the constraints of installing measuring devices. A disadvantage found in this measurement technique is that only one measurement location is selected at the farm, and this is used as a constant flow field for the dispersion modelling, creating a large area for error within the predictions. The modelled hydrodynamics aid in projecting the trajectories of the effluents and provides information on the vertical layering, due to the stratification of water, and vertical gradients, which are both driving forces generating the currents in the area. The main forces for generating currents are tides, horizontal pressure gradients, created by density differences, and wind stress at the surface [2]. Therefore, there are many factors influencing the hydrodynamics that need to be considered for an accurate prediction.

It is encouraged, for aquaculture facilities in Norway, to find a site with high dispersion in order to have the maximum dispersion of the mariculture waste. In order to aid the Norwegian authorities, the AkvaVIS system, a web-based geographic information system (GIS) tool, was developed and initiated allowing for the authorities to manage fish and mussel farms [2]. Having a simulated model of the currents is a largely important aspect for the accurate modelling of the dispersion of the wastes. The more accurate the hydrodynamic model simulates the real-life hydrodynamics, the more accurate the modelling of the dispersal of the waste.

2.2.3 Carrying capacity

While site selection focuses on the hydrodynamic data, the carrying capacity focuses on the benthic data. Using the hydrodynamic data collected during the site selection, the areas where the wastes will be deposited and dispersed can be analyzed in terms of the benthos. While the waste might have been dispersed well, the area in which it has been deposited in must be investigated for sensitivity. as well as the location of the farm, as the area might have natural accumulation due to the topography. Areas with natural accumulation have a higher chance of ecological changes, which increases with the number of cages employed within the farm [2]. A way to measure the change in the environment is by determining the areas carrying capacity, which is the amount of biomass that the environment can support without any adverse impacts, such as a loss of a species [40].

There are three main physical processes which affect the carrying capacity, one being the dispersion, rate of dilution and biological processes, though dispersion has the highest impact of all the processes. The rate of dilution is influenced by the composition of the waste and the biological processes are for example the consumption by organisms. Higher rates of dispersion allow for a higher carrying capacity, which in turn allows for a larger deposit of waste into the system and vice versa. Therefore, fish farms rely on the natural processes in the area to render the affects of the waste safe. In order to prevent exceeding the environments carrying capacity, the dispersion and deposition of the waste is modelled in order to predict the area of impact [40].

A benefit of the knowledge of the deposition and dispersal is for Integrated Multi-Trophic Aquaculture (IMTA). IMTA is the use of deposit feeders, which feed on the waste produced by the farm and are harvested after cultivation. Deposit feeders are another biomass that can be sold for economic benefit, for example, sea cucumbers, seaweeds, mussels, and shellfish are popular IMTA deposit feeders. The use of IMTA promotes the re-use of materials and has had an increase in attention as a tool for improving the sustainability of aquaculture. Sea cucumbers are capable of a significant removal of carbon loading, which is the overloading of carbon within the water column and benthic zone from mariculture by-products. Cultivating seaweeds gain a stimulus in growth from the added nitrogen and is a clear stimulus for kelp production. Mussels that are cultivated close to the farm are capable of ingesting at least 20 % of the diet from the waste [11].

There seems to be variability in studies for the evidence of growth benefits as it is difficult to establish the benefits with open-net pens and coastal farms. The successful utilization of the generated waste as a food source for deposit feeders is limited to the size range, time of interception and concentration of these particles. Co-culturing deposit feeders have shown benefits with the variability of the particles, for example co-culturing sea cucumbers and shrimps. Mathematical models have been applied to predict yield, environmental effects and economic optimisation of IMTA, but only few combinations have been studied. IMTA allows for recapturing the inorganic and organic nutrients for the growth of co-cultured species [11].

2.3 The Environmental Quality Standards (EQS)

In order to maintain a standard within mariculture farms, regulatory bodies were created to manage the environmental impacts of mariculture. The European Union manage and regulate through a variety of European Commission Directives and International Conventions. At the European level, there are three International Conventions on mariculture pollution covering the European Union coastal waters, as well as more than thirty international agreements that monitor and regulate the mariculture [27]. This is due to many directives, decisions and regulations have been added over the years as an attempt to lessen the environmental impact of mariculture in order to be within the integrated coastal management framework [1].

Most countries use a form of Environmental Quality Objectives and Environmental

Quality standards (EQS), though the regulations controlling the mariculture do vary. A few requirements included in most regulations are stocking density, feed type, sediment and water quality standards. It has been suggested that applying a carrying capacity be included for future regulations, though a few countries currently incorporate it. Some countries prioritise optimizing feed efficiency, so the regulations are based on the discharges, for example the releasing of nitrogen and phosphorus per kilogram of fish biomass harvested. The strategies of monitoring the mariculture are dependent on the regulatory body, where a country might use self-monitoring, which is submitted to the authorities, or is controlled on-site by the authorities. For example, in 1993 the Norwegian authorities decided on environmental objectives for Norwegian aquaculture and were divided into five major areas: escapees, diseases, medicines, chemicals and organic waste and nutrients. These environmental objectives present an important overview of the situation with regard to the problem areas and have been used as guidelines for what should be monitored [27].

A few examples of organizations tasked with maintaining, monitoring, and researching sustainable mariculture practices within countries are the Scottish Environment Protection agency and the Food and Agriculture Organization of the United Nations. The Scottish Environment Protection Agency (SEPA) is Scotland's principal environmental regulator, protecting and improving Scotland's environment [37]. SEPA allows the use of their documents, for example *Regulation and monitoring of marine cage fish farming in Scotland* [36], which relates to mariculture modelling and the regulation and monitoring of mariculture, in order for parties outside SEPA to assess maximum biomass of a site [36]. The Food and Agriculture Organization of the United Nations (FAO) is an agency of the United Nations specializing in international efforts to defeat hunger [21]. The FAO *Code of conduct for responsible fisheries* [18] and the *Ecosystem approach to aquaculture* (EAA) [19] are available as technical guidelines and reference documents. These are useful when approaching the sustainability of mariculture though each country and region might differ and require specific consideration into the factors [20]. FAO [20] presents guidelines for site selection and carrying capacity for both inland and offshore aquaculture and was the proceedings of a workshop and global review on the issues of site selection and carrying capacity. The objective was to prepare a draft of guidelines for aquaculture site selection and carrying capacity, as more explicit guidelines are needed for better estimates with inland and coastal aquaculture [20]. This highlights the importance of site selection and carrying capacity within mariculture.

In order to minimise the negative impact of the waste produced, the resultant dispersion and deposition needs to hold to the standard used. For the EQS of mariculture waste, which is organic matter, a suitable indicator is required, such as the Infaunal Trophic Index (ITI) and solids flux. The ITI and solids flux are correlated where the solids flux is the mass of solids exiting the farm and the ITI is a biotic index that indicates the changes in the benthic organisms dependence on their way of feeding. The indicator requires a limit, for example 800 g waste $\mathrm{m}^{-2}\mathrm{y}^{-1}$, and a zone where the indicator must not exceed the limit. Correlating the ITI with the solid flux of the farm is a useful regulatory tool since it can be measured and predicted using models [36].

2.3.1 The Infaunal Trophic Index (ITI)

The ITI correlates to changes in the feeding of benthic infaunal organisms [9] [36] [45]. A diverse number of organisms were categorized into four groups based on the strategy of feeding. This being their response to organic matter in an area, such as suspension feeders that feed on matter suspended or surface-deposit feeders that feed on matter deposited on the surface of the seafloor. The ITI is not an index that measures the amount of pollution, although with sufficient data the ITI values can be used to delineate areas of pollution. The ITI provides a good characterization of benthic communities and responds delicately to shifts in the species composition [45].

The four groups of organisms are suspension feeders, interface detrital feeders, meaning they feed on suspended and deposited matter, deposit feeders, and feeders of matter beneath the sediment surface. According to Word [45] the calculation of the ITI is then as follows:

$$\mathrm{ITI} = 100 - \frac{100}{3}\left(\frac{0n_1 + 1n_2 + 2n_3 + 3n_4}{n_1 + n_2 + n_4 + n_4}\right), \tag{2.1}$$

where n_i correlates to the number of organisms in the organisms specific Group i, $i = 1, 2, 3, 4$, and the corresponding coefficient is a simple scaling factor explaining how the deposited material will affect the organisms. So deposited material will not affect suspension feeders but will have a large influence on the feeders below the surface. The coefficients are there in order to generate a range of ITI values that relates to the changes in feeding strategies. The resultant ITI has values from 0 to 100, from 'Degraded' for values less than 30 to 'Changed' for 30 to 60 and 'Normal' for 60 to 100. This correlating to the group that dominates the area near the cage [36]. For example, when the area is dominated by below surface feeders and deposition of waste occurs, the resultant ITI is 0, which indicates an extreme degraded area.

Once the ITI has been established, a limit is applied at a locus that depends on the site-specific distribution of waste [36]. The corresponding solids' flux amount is from a benthic module done by Cromey et al. for DEPOMOD [9], where relationships for ITI and solids flux were correlated. General ecosystems have a balance of species, and by incorporating a fish farm at a site; deposit, suspension and interface detrital feeders thrive due to the high deposit underneath and surrounding the fish farm. By implementing sediment traps beneath the cages, Cromey could validate the model by comparing the predicted and observed solids' flux for a day. Model predictions of flux ($\mathrm{g/m^2/day}$) generally agreed well with field data with accuracy of 13 to 20%. The solids flux was measured and modelled for (g/m^2/day) and scaled to a year, assuming linearly since there is no clarification by Cromey et al. [9], to fit (g/m^2/year) [9]. As the goal is to create a sustainable limit, the ITI limit is denoted as 30, where this is regarded as the brink of a community degradation according to SEPA, (2005). Following from Cromey et al., [9], the corresponding flux is 191.8 (g/m^2/year). The Allowed Zone of Effect is then derived, which is site-specific, relative to the intensity of the impact per site [36].

2.3.2 The Allowed Zone of Effect (AZE)

After simulating the dispersion of the waste, one can estimate where the main areas of deposition will occur. Areas with higher rates of dispersion could allow for larger amounts of waste to be released and therefore will have less of a depositional area with a high concentration of waste [36]. Areas with less of a dispersive water column will have a more severe reaction to the waste [1], and that is too be avoided. Using the information of the deposition from a simulation one could calculate the Allowed Zone of Effect (AZE). The AZE is the area in which the EQS is allowed to be breached due to high levels of dispersion. The area not covered by the AZE is where high levels of waste will be deposited and not dispersed and could therefore have negative impacts. The AZE is an area around a site and as time passes, changes according to the release of wastes. The AZE is calculated per site at different times during the simulation and weekly averages should be calculated. This should be done with the simulation while attempting to reproduce the discharge of the material as realistically as possible [36].

From modelling tests the main variables that will determine the AZE size and shape are the settling velocities of the waste, which influence the time it takes for the waste to settle, and the hydrodynamics, which influence the subsequent advection. However, since most mariculture sites have multiple cages, the settling data being the same for each cage, the hydrodynamics mainly determine the shape of the AZE. The size of the AZE is dependent on the amount of waste released from the site, as a larger number of cages increases the waste produced. In order for the shape of the AZE to be more resultant of the hydrodynamics, there are criteria of the EQS that are required. The levels of EQS are then separated into two different areas: the near-field, focusing on the area beneath and close the cages, and the far-field, which focuses on the area at a further distance from the cages [36].

A site is classified as dispersive if high near-bed currents are observed, which results in the resuspension of the waste at the seabed and a low impact can be observed within the resultant AZE. An intermediate site is when high currents and low near-bed currents are found, which results in high dispersion when suspended but a low resuspension occurs at the seabed. The resultant AZE is of a large area but with a low impact. A depositional site is when there are few strong and near-bed currents, therefore resulting in a small area

AZE with a high impact [36].

2.4 Chapter summary

In Section 2.2 the basics of mariculture were discussed, as well as a brief history of the rise in popularity and the subsequent rise in concern for the environment. When observing at the environmental impact, it can be broken into two zones of concern, the benthic zone and water quality supply. Examples are provided on how the mariculture by-products could have a negative effect by polluting both zones. Site selection and carrying capacity are conditions that should be used by a company before implementing a mariculture site as well as methods to continuously monitor existing sites. An explanation of site selection and carrying capacity are given, as well as how both are carried out and why they should be implemented. Both methods require the modelling of the site's hydrodynamics and resultant dispersion and deposition of the by-products. In Section 2.3 the Environmental Quality Standard (EQS) is introduced through reviewing how mariculture is regulated throughout the world, with a few examples of organizations and papers that available to the public. These papers highlight why regulation and monitoring of mariculture are of utmost importance, where the focus is to minimise the overall impact on the environment and create sustainable farming practices. For the EQS of mariculture by-products, the indicator, the Infaunal Trophic Index (ITI), was reviewed and deemed suitable. The ITI is an index that reflects environmental changes on benthic organisms at the seabed. The ITI is then correlated with the solids flux from the farm in order to produce a limit of solids flux. SEPA recommends an ITI of 30, which correlates to a flux of 191.8 (g/m^2/year). This flux amount is the limit of solids flux the farm can sustain without degrading impacts on the benthic communities. Using this limit, the Allowed Zone of Effect (AZE) can be plotted, which is the area where the limit will be surpassed but due to the dispersion will be negated.

Chapter 3

Mariculture by-products

3.1 Introduction

For this chapter, a review of the literature related to the by-products, the solid waste, produced by mariculture is presented, as well as a background on particle transport models. This information will allow us to understand how mariculture is modelled and to understand how the by-products are transported within these models. In Section 3.2, the properties of the by-products of mariculture and the subsequent effect on the dispersion and deposition was investigated, as well as the values for the properties used in research. In Section 3.3 we introduce and review mathematical models and how they are used for modelling dispersion and deposition.

3.2 The by-products

Mariculture by-products are composed of uneaten feed pellets and faeces produced by the fish, where faeces is the largest component. Understanding the properties of the waste emanating from the farms is key to increasing the accuracy of the prediction modelling. The physical properties, which are the physical characteristics and composition, are the factors dictating how the waste will interact with the environment. The physical characteristics or properties dictate how the hydrodynamic data will influence the path of the waste as it settles to the ocean floor. The composition will affect the water quality in the surrounding area on the path that the waste travels. The diet of the fish is the main component dictating the resultant composition, density and thus the rate at which the waste settles [35]. Therefore, the physical properties are key aspects for calculating the hydrodynamic property, which is the settling velocity, where the settling velocity is the speed at which the waste will travel to the seabed. The velocity of the faeces is influenced by variations in each operation, such as the size range of the fish in the cage and the feed that is digested by the fish. The shape and size of the faeces is dependent on the type and size of fish, which also dictates the feed that is fed. The settling velocity of the waste is an important property of the waste needed for modelling the dispersion and deposition.

3.2.1 Composition

The uneaten feed pellets, called the feed loss, was first estimated to be around 20% of the feed fed to the fish, which has now been reduced due to improved detection mechanisms, such as machine vision. Now feed loss is estimated to be lower than 5% [35], therefore, a feed loss of 3% is generally used within models [2]. The amount of feed loss is difficult to determine since feeding occurs daily and varies with each day and operation. The feed loss indicates if there are any issues with the fish eating, for example the size of the pellets might be too large for the fish to easily consume. The feeding may be reduced when the fish are sick or prior to live transport or the amount of feed is increased alongside the growth of the fish to keep a healthy growth cycle [35]. Therefore, the growth cycle is important in the calculation of the waste produced.

The uneaten feed pellets and faeces impact the marine environment by elevating the nutrients and therapeutic chemicals [2], especially the feed and artificial as well as containing medication [1]. Therapeutic chemicals and minerals are supplemented within the feed for medicinal purposes, such as antibiotics and balancing nutrients for healthy fish. The reduction in the feeding could be accompanied by a reduction in nutrient loading, which reduces the concentration of nutrients loaded into the water column. The nutrients from the waste and feed are either soluble and dissolve into the water column or transported by the currents. Minerals, for example copper and zinc, are supplemented in the diet since not all essential minerals can be absorbed by the fish from the water column. Aquatic organisms are sensitive to copper and zinc and therefore, the deposition of copper and zinc can be toxic to the benthos [35].

A method of quantifying the feed loss, or rates of feed digestion, is the Feed Conversion Ratio (FCR). The FCR calculates the ratio between the amount of feed used and the amount of biomass produced. The amount of feed used is denoted as its dry weight, meaning the weight of the feed before saturated with water. The amount of biomass produced is denoted as wet weight. Feed that is not digested efficiently will decrease the amount of biomass produced therefore increasing the FCR. Therefore FCR is best used for the measure of nutritional efficiency of the feed. In 2003, world production of salmonids was 1.46 million tonnes and aquafeeds used was 1.9 million tonnes, making the global Salmonid, feed conversion about 1.3. This is a significant improvement from in 1993 when the FCR was 1.7, though these are average values [35].

3.2.2 Physical properties

The physical properties of the waste have important implications for the dispersal in the water column, where the main important physical properties include shape and size, density and the settling velocity of the waste. These properties affect how the waste will be deposited and dispersed by the currents [35].

Shape and size

To determine the shape and size of the waste, both faecal pellets and feed, the waste has to be collected after release. The collection method is generally a custom sampling device, which is deployed in or underneath the fish cage. The device could be deployed at the start of feeding to ensure that a few whole or fragmented pellets could be randomly collected. The physical properties, such as dimensions and dry weight, is obtained from drying the waste at 60°C [2].

The shape of the effluents is generally in the shape of a pellet, with many variations as the faeces start as a cylinder from evacuation then proceed to break apart becoming pellets of different sizes. The shape of the feed is spherical or cylindrical depending on the feed used, though some of the feed breaks apart and become ground up in the transport process, creating fines. Fines are generally regarded as a waste of feed as the fish do not eat the fines and are too soluble. Therefore, the fines go straight into the water column, creating a greater effect on the environment [35].

Density

The larger and denser the waste is, the faster it will settle to the bottom and will not be easily resuspended. The lighter and smaller the waste is, the waste will then be suspended for longer, have a larger dispersal area and will be easily resuspended after deposition [35]. Since feed loss is assumed to be 3% of the released waste, the assumption that the uneaten feed has the same density and size distribution as faeces has little importance [5]. Since the waste is introduced into water, there are two densities needed for the simulation, the wet and dry densities respectively. To determine the difference, one gathers a sample of the sediment and drying it out until there is no liquid inside the sample and calculate the resultant density. If the densities are the same, then the sample had no liquid and the density is the dry density. If the first density is larger, then that density was the wet density. The difference between the wet and dry densities is when wet the density has liquid with the sediment particles while dry has only the sediment particles and nothing else. For mariculture waste a dry density of 108 $\mathrm{kg/cm^3}$ [2] and a wet density of 1033 $\mathrm{kg/cm^3}$ [5] are commonly used.

Settling velocities

The speed at which the faeces is released, is the evacuation velocity. The evacuation velocity has a short span inside the cage before the dynamics of the waste influence the falling velocity, becoming the settling velocity. The settling velocity gradually decreases as the faeces is incorporated, dispersed and deposited by the hydrodynamics. With the feed loss, the settling velocity is more difficult to be detected. The feed is thrown into the cage and the uneaten pellets sinks through the cage with the faeces. Therefore, separating the faeces and the feed loss is difficult when observing the cage.

A way to determine the settling velocity is by using a custom settling column. A replicate of the faecal matter or feed, or a sample of both, is placed into the column and the proportion of waste settled is estimated using discrete time intervals. Using this method, it is possible to generate a settling distribution curve and then using a mass fraction approach to calculate the settling velocity for each class size of fish. Since the feed is assumed to have small variations in shape and size, the settling velocity of the feed loss is assumed to be constant [2].

A settling distribution curve has less limitations than using a single settling velocity [2] [9]. Using a single settling velocity, does not take into account that the settling velocity differs between fish size which influences the faeces size, therefore influencing the settling velocity. By using a single settling velocity the simulations become skewed and this influences the area where the waste will settle at the ocean floor. The skewed output will either show a smaller dispersal area or a larger one to a more correctly modelled dispersal area. Therefore, over or under predicting the deposition and dispersion. The mass fraction approach provides a more realistic approach and a more accurate simulation. Therefore, to model the dispersion it is more useful to use the full range of settling velocities from the size classes in the farm for the simulations. The differences in the ranges of settling velocities from different studies are due to differences in testing methods, feed properties and water density [2].

In Table 3.1 are settling velocities from different studies, some used a constant settling velocity for the faeces and others employed a range of settling velocities. Bannister et al. modified a settling column, with construction details from Wong and Piedrahita [2]. Wong and Piedrahita presents a methodology for characterizing the settling velocities of solid waste discharged from a rainbow trout farm. A settling velocity test allows for the observation of the behaviour under the influence of gravity, with which the recorded data can then be used to construct a settling velocity curve [44]. Bannister et al. then characterized the settling and non-settling mass fractions and established a settling distribution curve [2].

These settling velocities are ensured to be in range of observed particle organic matter (POM) flux over a production cycle. According to Bannister et al. it is evident that the

Table 3.1: Settling velocities of effluents and feed

Study	Settling rate of effluents	Settling rate of feed
[2]	Constant: 3.2 cm/s ±1.1 cm/s 78%: 7.5 cm/s (5 – 10 cm/s) 10%: 3.75 cm/s (2.5 – 5 cm/s) 12%: 0.8 cm/s (0 – 2.5 cm/s)	10 cm/s
[8]	Constant: 3.2 cm/s ±1.1 cm/s	8 – 13 cm/s
[9]	Range: 1.5 – 6.3 cm/s	10.8 cm/s
[24]	Constant: 2 cm/s	5.5 – 15.5 cm/s

use of measured mass fraction settling velocities are required in order to simulate the influence of the mariculture on the dispersal process [2].

3.3 The modelling of mariculture by-products

A critical component for sustainability of fish farms is the prediction of the dispersal, deposition, and accumulation of organic waste to the benthic habitat in order to forecast the impacts [2]. The use of mathematical models to predict the dispersion of pollutants has been around for some time. Depth-averaged two-dimensional models, originating mainly for river engineering, were developed in the 1980s and 1990s. The development of morphodynamic models, morphology and hydrodynamics combined, from simple analytical models to highly advanced models have seen the increase in the indispensability and improvement of these models [29]. From the use of air pollution to fish eggs, one-dimensional to three-dimensional networks, mathematical dispersion models have been useful for the protection of the environment.

There are many strategies to modelling dispersion and deposition, some include coupling multiple models, or using a model that has a variety of components and online modules available. For example, coupling a near-field and far-field model, or Delft3D that contains multiple modules. Coupling models allows for hydrodynamic models and waste simulation models to work together. Some models have both hydrodynamic and waste components. The increases in computing power available is allowing simulations of years to decades to become feasible. Computer modelling of the waste is a valuable tool for understanding and predicting the dispersion, but predicting complex systems, such as conditions near the mouths of rivers and coastal environments, requires the use of numerical models or model systems that are able to simulate combinations of processes that include a broad range of problems [29]. These processes in the systems dictate the transport of the waste matter.

An understanding is needed of these physical transport processes in order to understand how the model simulates the problem.

3.3.1 Suspended transport processes

The main physical processes that transport sediments, or wastes, suspended in a moving fluid are advection and diffusion. Advection is how the current will carry the waste by the velocity of the flow. Diffusion is how the waste are spread by random motions in the fluid. An increase in turbulence will create a more vigorous diffusion called turbulent diffusion, where in a natural water source turbulent diffusion is generally the dominant mechanism. Turbulent diffusion mixes the material longitudinally, transversely, and vertically [26].

In the context of the spreading of mariculture waste, the interaction of advection and diffusion creates dispersion, which carries the waste with the velocity of the flow in a turbulent manner [26]. The general advection-diffusion equation for suspended transport is:

$$\frac{\partial p}{\partial t} = \nabla \cdot (D \nabla p) - \nabla \cdot (\mathbf{v} p) + R, \tag{3.1}$$

where:

- p is the suspended variable,
- D is the diffusion coefficient,
- $\mathbf{v}$ is the velocity field for the suspended variable,
- R represents a source or sink within the water column,
- ∇ represents gradient,
- and $\nabla\cdot$ represents divergence [4].

An initially small and concentrated path of waste evolves into a much diluted and larger cloud. From when the waste is first released to deposition, the waste passes through different zones, where advection and diffusion can be used to calculate the transport of the waste. These zones are according to what is the main transport process that drive the dispersion. The first zone, the Advection zone, is where the transport is heavily influenced by the local conditions and by any momentum imparted to the solute during its release. The waste enters the water column, and the mixing is dominated by the momentum of the release and the local transport processes. As the waste mixes the influences reduce and eventually disappear. Due to transverse mixing, the waste is influenced increasingly by the local transport processes. The second zone, the Equilibrium zone, is when the transport processes are in balance. The waste has then encountered the entire transverse distribution of flow and mixing field. The sediments are now more spread out from each other, creating a cloud. The final zone, the Gaussian zone, is if the balance is maintained [26]. Models have been designed to investigate the dispersion within a few kilometres or over an entire system [40]. Knowing which zone needs to be investigated is important for the choice in the model that will be used as well the data that needs to be collected.

3.3.2 Particle transport models

Generally, a particle transport model is used to simulate the dispersion and deposition of mariculture waste. A specific concentration of the mariculture waste is represented in the model as a particle and are released from a specified source location. The basic structure of a particle transport model is a bathymetric region, meaning the topography of the region is defined, and data of the particle. These particles are then subjected to hydrodynamic forcing, which is when they enter the flow. The flow field itself must be prescribed as an input to the model. The behaviour of the particles in the flow is defined by the user such that each particle is subjected to the same forces [30]. The flow field is not always available for the study area, and it is common instead to use measured hydrodynamic conditions but it is not applicable to assume a constant flow field for coastal areas as they have complex flow patterns [40].

The computations then proceed though time, modelling the behaviour (advection, diffusion, settling, deposition, etc.) of the released particles. There are two types of calculations that can be performed at each time-step depending on the type of the particle transport model; Eulerian, which is mesh-based, calculations that are required to determine the local characteristics of the environment, and Lagrangian, which is particle-based, calculations that are required to determine the behaviour of each particle. The two-dimensional representation of the particles' behaviour is the simplest, providing a preliminary assessment of the motions and pathways undertaken. A three-dimensional approach is required more for applications where the interaction with the seabed is significant, or where the vertical movement and settling of the particles are concerned [30].

Particle transport modelling should focus on the validation of the predicted fate of the dispersed effluents. This will enhance the ability to predict the carrying capacity of fjord systems and provide a tool to maximise the selected sites efficiency, as well as help shape the environmental sustainability action in a rapidly expanding and important marine industry [2].

Near-field models

The near-field region is where the initial momentum and outfall geometry influence the trajectory and mixing of the particles. A near-field model is used to simulate the flow behaviour in the area close to the point of discharge [34]. The model ignores the cumulative impacts of other fish farms in the area and assesses the fate of the particles from the farm in a small area around the farm. The amount of waste released is calculated based on assessment of allowable biomass and feed input by the near-field model. Near-field modelling has the potential to underestimate impacts on the benthic environment. The models can overestimate the number of particles lost as the model does not calculate particles that are transported back into the system at the boundaries. This highlights a potential impact that near-field excludes. It is important to consider the sensitivity of near-field models to tidal currents, especially when a lack of reliability in some measured data is often evident [40].

Far-field models

The far-field region is where the spreading motions and passive diffusion control the trajectory and dilution of the particles. A far-field model is used to simulate behaviour in the region that is at a distance away from the discharge point, allowing for a large simulation area. The flow behavior is dominated by the ambient water conditions, tidal currents, water temperature and density. The far-field model is generally a multi-dimensional hydrodynamic model of two or three dimensions. The non-steady flow and transport phenomena are simulated with tidal and meteorological forcing [34].

The use of a far-field model increases confidence in that locations outside the near-field area are not subject to high benthic impacts. Far-field modelling ensures that spatially varying tidal currents are include in the model. Far-field models are capable of modelling the impact of multiple fish farms over a large spatial area with future predicted increases in the farm size and densities. Therefore, cumulative effects of the farms are identified. Far-field models demonstrated that the wastes can be transported back in the system and have provided a better description of tidal currents for the purpose of assessing the impacts of fish farms [40].

3.3.3 Resuspension transport

An important consideration in the transport of mariculture waste, is the fate once it has reached the seabed, specifically the physical parameters. Once the wastes have settled on the seabed, resuspension might occur, further dispersing the wastes. Sophisticated sediment transport models, which include the associated resuspension processes that occurs with complex hydrodynamics, are uncommon [9]. Two examples of models that include resuspension parameters are DEPOMOD and AWATS. When excluding resuspension parameter or a resuspension module, the final modelled dispersion area should not be seen as the final area of the modelled seabed. Understanding resuspension as a transport process should be focused on when validating a model and would enhance the prediction of carrying capacities and a tool to maximise site selection efficiency [2].

DEPOMOD was developed to predict the impact of mariculture on the benthos as

DEPOMOD predicts the accumulation of waste on the seabed as well as the impact on the benthic communities. A particle tracking module is used to model the wastes as particles and simulates the initial deposition of the particles. A resuspension module is then employed to redistribute the particles using the hydrodynamics, specifically the near-bed currents. The resuspension module consists of erosion, transport, deposition, and consolidation components of the waste at the seabed, where consolidation is the compressing of a sediment that then becomes more compact and solid and only occurs after a given time period. The way the module simulates resuspension is by incorporating a shear stress, which is determined by the near-bed velocities. The erosion and deposition, which occurs mutually exclusively, occur when the shear stress is above or below a critical shear stress for erosion and deposition respectively [9].

Incipient motion of sediment is the initial motion that occurs and can be calculated using the Shields parameter. The Shields parameter is named after Albert F. Shields, who derived the relationship of incipient motion to the near bed shear stress, τ_b. The derivation of the Shields formula can be seen in "Application of similarity principles and turbulence research to bed-load movement (translated version)", 1936 by Shields [39]. The Shields diagram, or Shields parameter, is the most widely used criterion for the incipient motion of a sediment [6].

The Shields formula is given by:

$$\theta = \frac{\tau_b}{(\rho_s - \rho) g D}, \tag{3.2}$$

where:

- θ is the shields parameter,
- τ_b is the bed shear stress,
- ρ_s is the density of the sediment,
- ρ is the density of the fluid,
- g is the acceleration due to gravity,
- D is particle diameter of the sediment.

By nondimensionalization of the critical bed shear stress τ_c, the critical condition for the incipient motion can be found and is referred to as the critical Shields parameter θ_c. This is the critical stress needed to resuspend a particle from the seabed. Though there have been inconsistencies and discrepancies made, at present the Shields diagram is still widely used. To find the critical bed shear stress requires trial and error iterations, which makes the application tedious for use for coastal engineering [6].

3.4 Chapter summary

In Section 3.2 the hydrodynamic properties of the solid waste from mariculture farms are introduced where the waste from mariculture is composed of effluents from the fish and uneaten feed pellets. The uneaten feed pellets (the feed loss) are estimated to be lower than 5% in recent observations and generally are assumed to be 3%. Feed and faeces have nutrients, minerals and chemicals that possibly could overload the environment and have a negative impact and are determined by the diet and species of the fish. The physical properties of feed and faeces are generally in round pellets, but for an in-depth analysis a collection method is needed, samples of the waste and feed should be gathered and dried. An important physical property is the density, which impacts the dispersal and deposition. An investigation should be completed in order to determine the dry and wet densities. Another important property of the waste is the settling velocity, where the settling velocity will be different for the feed and effluents due to the differences in composition. By establishing a settling distribution curve for the effluents, the simulation will have a more accurate dispersion and deposition, as the effluents are not of equal size and shape, due to the differences in the sizes of the fish.

In Section 3.3 the way mariculture wastes are modelled are explained. Some models have components for the hydrodynamics and for the waste simulation, while others are one or the other and are required to be coupled with each other. How the waste is transported within the water column is through advection and diffusion, where advection is the transport from the velocity of the water and diffusion is the spreading of the waste by the random motions. The interaction of advection and diffusion creates the dispersion of the waste, and the general advection-diffusion equation is given. Then the different zones of transport are given, where each zone represents which velocity field the waste is transported by. The Advection zone is where the zone where the sediment is only influenced by the released momentum. Then the Equilibrium zone is where the initial release and water column are in balance. If the balance is maintained, then the final zone is the Gaussian zone. The basics of particle transport models are then given, where particle tracking models are generally used for the modelling of the transport of mariculture waste. Then the definition of near-field and far-field models are given, where near-field models model the initial momentum of the sediments, therefore focusing on the area close to the point of discharge (the Advection Zone). Far-field models focus on the Equilibrium and Gaussian zones. How particle tracking models simulate transport at the seabed is explained as resuspension. Transport from resuspension is explained and DEPOMOD, a model that incorporates a resuspension module, is described. Particle tracking models calculate the resuspension of the particles using the Shields formula producing the Shields parameter. The Shields parameter uses the shear stress generated from the near-bed currents to calculate the incipient motion of the sediment grain.

Chapter 4

Modelling waste as a continuum

4.1 Introduction

For this chapter, the method of modelling mariculture waste as a continuum is investigated. In order for us to model the waste correctly we must understand how cohesive sediments are transported and then subsequently modelled. Firstly, in Section 4.2, an introduction into sediments is given. Then in Section 4.3, cohesive sediments and their hydrodynamic properties are explained. How cohesive sediments are transported by suspension is then introduced in Section 4.4 as well as the process of deposition. In Section 4.5 we delve into the complicated process on how cohesive sediments are resuspended through erosion.

4.2 Introduction to sediments

A sediment is classified as a granular material, that is not consolidated, where consolidated is the term for sediments that have been compressed and drained of water. The properties of the sediment define whether the sediment is a cohesive or a non-cohesive sediment. A non-cohesive sediment consists of just the sediment grains, where all forces act on each individual grain, for example sand and gravel [41].

A cohesive sediment, generally a mixture of clay and silt, are grains that when mixed with water becomes a mud, where predominantly a electrochemical force bonds the grains. The strength of the bond is a function of grain mineralogy, water chemistry and salinity, and therefore all forces act on the body of the sediment, as a constituent, rather than the individual grains [41].

4.3 Cohesive sediments

Generally cohesive sediments are created by a cycle that is continuously happening where a hard consolidated sediment is eroded. For example, a clay that has been subjected to a large amount of pressure for many years, until all the water has been compressed out. The erosion of the consolidated sediment creates individual grains that are then dispersed and transported in suspension, that then join other grains within the water column. The groups of sediments are transported by the currents, joining and breaking apart by the forces. When deposited, cohesive sediments can be transported as a fluid mud, flowing in the direction of the near-bed currents. This mass of sediment and trapped water behaves like a uniform dense viscous fluid. Over many years this fluid mud will deposit fully and will be ready for consolidation and erosion, starting the cycle again [41]. In order to understand the transport of cohesive sediments, the hydrodynamic properties must be investigated. These include the composition, the physical characteristics such as shape and size, density and settling velocities.

4.3.1 Composition

Cohesive sediments, commonly known as a mud, are mixtures of inorganic and organic materials, and are found in two phases, solid or liquid. Cohesive sediments are a porous material and the solid phase consists of weathered bedrock, mineral particles, and organic material. The weathering of primary minerals produces the inorganic materials, where chemical weathering forms clays and the physically weathering forms silt particles, generally composed of quartz. The organic components include living organisms, faeces and other biological structures and compounds [14].

The state of consolidation of a cohesive sediment is enhanced by the presence of organisms like diatoms, which can bind the sediment particles together with mucus. The extent of the data required for understanding the cohesive sediment will vary depending on the nature of the coastal engineering problem. As with salt water, the conductivity of the sediments is greater due to increase of conductivity from the increase in salinity. Bonds may be enhanced, specifically when at rest on the seabed, by diatoms for example. Mud may also be biologically cohesive, also by diatoms, though biological cohesion is more difficult to predict that electrochemical cohesion [41].

4.3.2 Physical properties

Important physical properties of cohesive sediments are the settling velocity, grain size, shape, and density. Though the cohesive sediment grain size and shape is not a measurable physical constant unless the origin of the sediment is known. The settling velocity is the most important hydrodynamic property of cohesive sediment. The settling velocity is a measure of the sediment's behaviour in suspension, while the grain size only allows a guess to the settling velocity. Small cohesive sediments in salt water do not stay dispersed for long. Cohesive sediments are not transported as bed load, except when in the form of fluid mud. Cohesive sediments are transported in suspension by advection, where the sediments are carried by the flow velocity, and dispersion, where mixing moves the sediments from a high concentration area to low [41].

Density

For a cohesive sediment the density is a measure of the proportions of the solid and liquid within the sediment and is dependent on the particle density, the amount of water and the amount of air pockets. A dry or wet bulk density can be calculated depending on the investigation being conducted [14]. Typically, a saturated bulk density for a suspended cohesive sediment is 1020 kg/m^3 and for a fluid mud is 1100 kg/m^3. For a consolidated cohesive sediment, the saturated bulk density ranges from 1500 to 2200 kg/m^3, depending on the state of consolidated and the grain mineralogy [41].

Flocculation

Cohesive sediments rarely settle as individual grains in nature as collision between sediment grains are encouraged by the differences in settling velocity, turbulence, Brownian motion, and electrochemical attraction or cohesion. When cohesive grains collide, they tend to stick together, which is the process of individual cohesive particles agglomerating while settling. This process is called flocculation and results in large particles with entrapped water, called flocs. The settling velocity of a floc is a function of its size, shape, and relative density. A floc usually settles faster than its single particles; but because of the entrapped water, its density is less than that of the sediment mineral. The size and shape of flocs, and their settling velocity, are hydrodynamic sediment properties which must be measured or determined by model calibrations [41].

When observing the by-products of the farm, the released waste are individual wastes. Through the settling process and flocculation, the waste gathers and settles in flocs. These flocs behave as a fluid mud on the seabed, therefore when the waste has been introduced into the water column for long enough, it behaves as a cohesive sediment. The settling velocity when introduced into the water is of a non-cohesive sediment and therefore research into settling velocities of the waste wastes is needed. This brings up a possible further research topic, where the settling velocities of waste was concluded from small samples of waste and in order to test the flocculation for a cohesive sediment, one requires larger samples to be gathered. This also will confirm the how the individual wastes combine and create flocs as the flocs settling velocity might be lower than the individual settling velocities.

4.4 Suspended transport of cohesive sediments

Suspended cohesive sediments are transported by the advection-diffusion equation:

$$\frac{\partial c}{\partial t} = \nabla \cdot (\epsilon_s \nabla c) - \nabla \cdot (\mathbf{v}c), \tag{4.1}$$

where:

- c is the mass concentration of the sediment,
- ϵ_s is the vertical mixing coefficient,
- $\mathbf{v}$ is the velocity field $(u, v, w - w_m)$ of the sediment,

where the vertical mixing coefficient is equal to the vertical fluid mixing coefficient that is calculated by the selected turbulence model[12]. Vertical mixing is produced from the density of the fluid increasing in the upper layer [3], while horizontal mixing is produced by the shear of the currents. The velocity field incorporates the settling velocity w_m as the horizontal mixing coefficient due to flocculation, and current shear, occurring within the settling process for a cohesive sediment [12].

4.5 Resuspension transport of cohesive sediments

For noncohesive sand and gravel, sediment mobility can be estimated by just knowing the grain size and shape, specific gravities of the sediment and water, and the viscosity or temperature of the water. The mobility of cohesive sediments is a more complex phenomenon. The principal indicator of cohesive sediment is the critical shear for erosion of bed sediment, τ_c, and the relationship to the critical shear for deposition, τ_s. In general, the relationship can be written as $\tau_c >> \tau_s$ [41].

4.5.1 The erosion of cohesive sediments

For cohesive sediments, the sediment is eroded by the shear stress and then transported. Due to the cohesive bonds, cohesive sediments are more resistant to erosion than non-cohesive sediment. Once deposited the cohesive bond with bed particles makes more difficult to remove than particle mass would suggest. As water flows on the boundary of the mud, it exerts a shear stress τ due to the viscosity, and the possible turbulence created. Shear stress is a real physical stress and is empirical shorthand for the level of turbulence in a flow. Shear stress is a useful parameter in describing the erosion and deposition. The flow field is a mechanism for transport of cohesive sediments. Fluid mud is dragged along by the shearing of the water above it, though how it flows is determined by its rheology, which is the deformation and flow of matter. Therefore, it is needed to look into the sediment properties as it affects the transportation of the mud when being eroded and deposited. For erosion and deposition of cohesive sediment the model of Partheniades-Krone is generally used [41].

The model of Partheniades-Krone model makes use of Partheniades equation for mud erosion [13], which describes the erosion rate of a cohesive sediment, and is given by:

$$e = M\left(\frac{\tau}{\tau_c} - 1\right), \quad \text{for} \quad \tau > \tau_c, \tag{4.2}$$

where e is the erosion flux and M is the erosion parameter. This equation allows for models to calculate the erosion of cohesive sediments at the seabed when the shear stress, τ, exceeds the critical shear stress for erosion τ_c [12].

Many studies have been conducted on erosion resistance of cohesive sediments in flowing water, but a few were done with consideration to the more complex flow conditions encountered in the coastal zone. A basic understanding of the complex process of erosion of cohesive solids provides a basis for assessing the erosion resistance of cohesive mud in the coastal environment. For a stationary particle on the bed, the shear forces are balanced by the forces of gravity, interparticle friction, and cohesion. The shear stress is then augmented by the lift and drag, balancing the forces as

$$\text{shear stress} + \text{lift} + \text{drag} < \text{gravity} + \text{friction} + \text{cohesion}. \tag{4.3}$$

Equation (4.3) is the same as noncohesive sand and gravel but with cohesion due to the electrochemical forces. As flow increases, the left-hand side of equation (4.3) increases, until both sides are equal and the stationary particle leaves the bed and moves. The shear stress, when this occurs, is the critical shear stress for erosion, τ_c, which is shorthand for the whole left-hand side of equation (4.3), not just the shear alone. This particle might be a grain, or a floc, made up of several grains held together by cohesion. The cohesion is a major important factor for the right-hand side of equation (4.3) and erosion will occur where the cohesion is the weakest [41].

4.5.2 The deposition of cohesive sediments

The deposition shear stress τ_s, is not obvious at first. In a non-cohesive sediment, the critical shear stress for deposition is less than that for erosion: a non-cohesive particle will come to rest almost as soon as the shear stress is too small to move it. Therefore, the shear stress has to be less than the critical shear stress for deposition. The process of deposition for a cohesive sediment floc is quite different since τ_s is generally on the order of one fourth of the critical shear for erosion. This high shear near the bed breaks up the large flocs before they can settle. The smaller flocs and individual particles are then resuspended. The critical shear for deposition is that which large flocs can pass without being broken up and is the shorthand for the shear stress in the bottom boundary layer which cannot overcome cohesion in the settling flocs [41].

The Partheniades-Krone model utilizes the Krone equation for mud deposition [13], which describes the deposition rate of a cohesive sediment, and is given by:

$$d = \left(1 - \frac{\tau}{\tau_s}\right) w_m c, \quad \text{for} \quad \tau < \tau_c, \tag{4.4}$$

where d is the deposition flux, w_m is the settling velocity and c is the concentration. This equation allows for models to calculate the deposition of cohesive sediments at the sea bed when the shear stress, τ, is below the critical shear stress for deposition τ_s [12].

4.6 Chapter summary

In Section 4.2 an introduction to sediments is provided. Section 4.3 the hydrodynamic properties of cohesive sediments are explained, where the properties are composition, physical characteristics and its settling velocities. The composition of a cohesive sediment is generally a mud mixture of inorganic and organic materials. The physical shape and size of a cohesive sediment is not a measurable physical constant. Cohesive sediments differ from non-cohesive sediments in that the cohesive bonds are strong enough to group the individual grains, such that cohesive sediments generally group together creating flocs. Flocs are groups of cohesive sediment grains that agglomerate during the settling process and usually settle faster than the single grains. When in suspension, cohesive sediments are described by the advection-diffusion equation where the vertical mixing is calculated by the selected turbulence model. The resuspension of a cohesive sediment is by erosion and deposition, which both are dependent on the near bed shear stress. As a cohesive sediment on the bed is a fluid mud, erosion of the mud creates flocs that are then dispersed. The erosion occurs when the near bed shear stress is higher than the critical shear for erosion. A high near bed shear will break up a settling floc, therefore the critical shear for deposition is generally one fourth of the critical shear for erosion.

Chapter 5

Hydrodynamics and sediment transport

5.1 Introduction

In this chapter, how the hydrodynamics will be modelled by the software package, Delft3D-FLOW is investigated to understand how the model works and what is required in order for a simulation of sediments. Firstly, an introduction to how the hydrodynamics shall be modelled is explained in Section 5.2. In Section 5.3, T_TIDE is investigated as a tool to calculate the tidal constituents. Then in Section 5.4, the basics of Delft3D-FLOW are given, as well as the different data groups needed for a simulation.

5.2 Modelling of hydrodynamics

The hydrodynamics of an area is a combination of the water levels, background currents and the velocities. The background currents and velocities, specifically at the bed, were provided by a previous project conducted at the Faroe islands. A software package called Delft3D will be used to simulate the currents for the fjord but needs the water levels as boundaries input condition as the water levels are the driving forces behind the currents. For calculating the water levels, there are two options available: gathering the water level data or through calculating the astronomical tidal influence at the boundaries. For the project we chose to use the later method. The astronomical tide influence is then calculated by using data from TPXO, which is a series of fully-global models of ocean tides [17]. With this data, we can calculate and analyse the astronomical tidal influence using a MATLAB analysis package called T_TIDE, widely used by oceanographers [32].

Body forces from the sun and moon, act on the ocean generating a forced elevation and current response primarily at diurnal and semi-diurnal frequencies. Diurnal meaning that during the day there is one high and low tide. Semi-diurnal meaning there are two high and low tides during the day. The body forces act directly on deep oceanic waters. Tides in coastal regions are not directly forced by these astronomical forces. Instead arising as a side-effect of deep oceanic variability, propagating as a wave or a combination of waves. Separation is required of the tidal signal from the sub-tidal variations for dynamical analysis. In classical harmonic analysis, the tidal forcing is modelled as a set of spectral lines, the sum of a finite set of sinusoids at specific frequencies. These frequencies are different combinations of 6 fundamental frequencies arising from the planetary motions [32].

These fundamental parameters represent the effects of rotation of the earth, orbit of the moon around the earth and the earth around the sun, and others. The phase and amplitude is what are required for the water level calculations. The output constituents of T_TIDE are the major tidal constituents, the shallow-water tides and including compound tides which arise in shallow water [32], thus giving us the water levels needed for the tidal forcing of the simulation and a sample of the water levels for a period at a point can be seen in Figure (5.1).

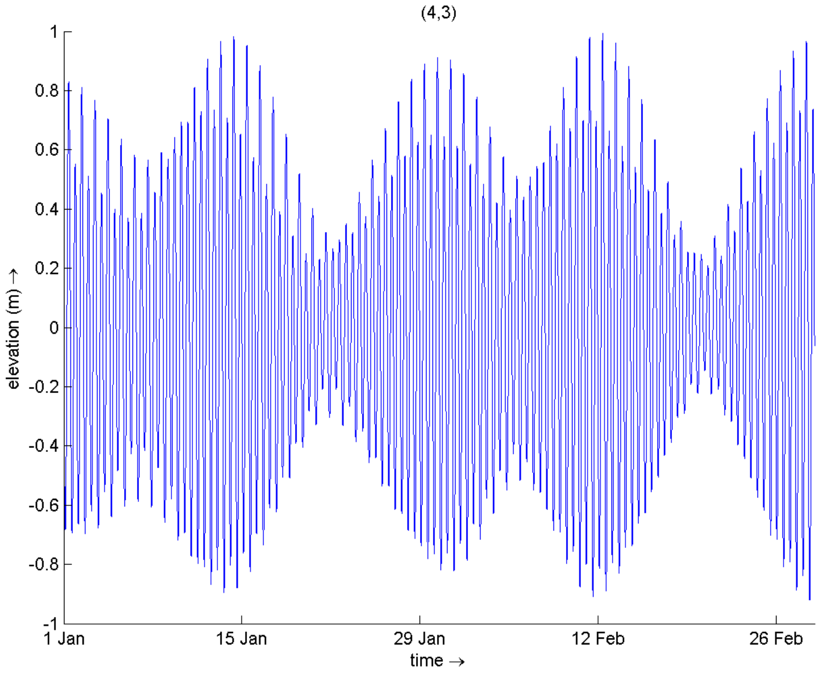


Figure 5.1: Sample of the water levels used for a period

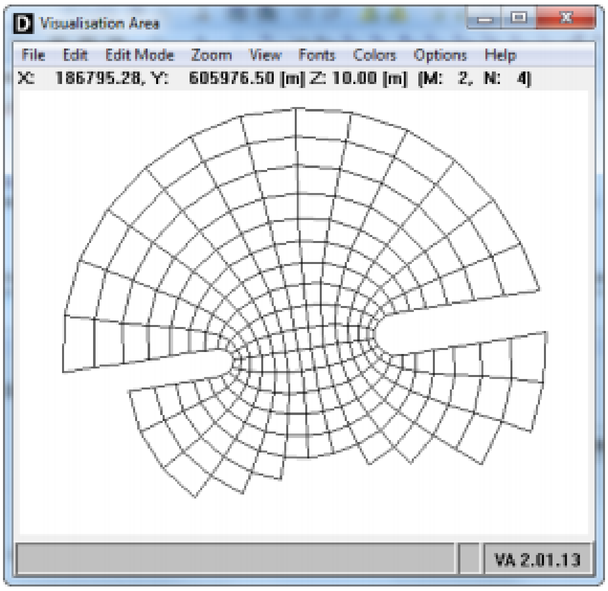
5.3 Delft3D-FLOW

The company Deltares in the Netherlands has developed a computer software suite, called Delft3D, for many different approaches and for three-dimensional computations for coastal, river and estuarine areas. It can carry out simulations of flows, sediment transports, waves, water quality and ecology. Delft3D-FLOW is a component of Deflt3D that we will be using for most of the simulations. Delft3D-FLOW is a multi-dimensional (two or three-dimensional) hydrodynamic, transport, and simulation program. It can calculate non-steady flow and transport processes that result from tidal and meteorological forcing on rectilinear or curvilinear, boundary fitted grid. The hydrodynamic conditions calculated in Delft3D-FLOW can be used as input to the other modules of Delft3D [12].

The Master Definition FLOW file (MDF-file) is the input file for Deflt3D-FLOW. This file contains all the data groups needed to define the hydrodynamic model and running the simulation. The MDF-file allows for physical parameters to be inputted for a simulation, most importantly the sediment properties, that will influence the distribution of the faeces in the simulation. Deflt3D-FLOW then uses algorithms to simulate the hydrodynamics of the area and the distribution of the faeces from the farms [12].

5.3.1 Domain and time frame

The *Domain* Data Group contains the data to define the *Grid*, *Bathymetry*, *Dry points* and *Thin dams*. For our project we will focus on the *Grid* sub-data group, where the grid will be loaded, edited or created. The grid loaded will represent the are to be simulated and input is required for the number and thickness of the vertical layers. The grid is stored in the grid file, which includes the type of co-ordinate system and the grid dimensions to be used [12]. Figure (5.2) is an example of a grid loaded into the MDF-file from the Deflt3D-FLOW manual [12]. The vertical layers divide the vertical domain into layers, where the user can specify the layers thickness. For the layers of this project, 13 were chosen with varying percentages, where the bottom layers, layers 4 to 10, are the thickest with percentages ranging from 8 to 10%.



```
X:   186795.28, Y:   605976.50 [m] Z: 10.00 [m]  (M:  2,  N:  4)
```

Figure 5.2: Example of a grid [12]

For our project a simple rectangular grid was created and each cell is 20 m by 20 m, which can be seen in Figure 5.3. The length and width of the grid is three and one kilometre respectively. The length being the largest due to our currents traveling in the Eastern direction, allowing for a larger area to observe the dispersion of the farms waste.

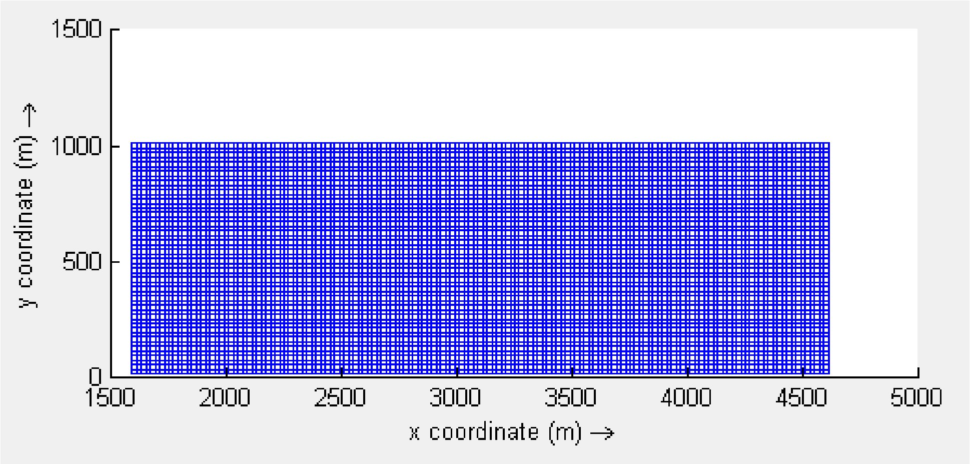


Figure 5.3: The grid used in the simulation

For the sub-data group *Bathymetry* we will be only defining the depth of the area, which is 50 m to represent the fjord as a rectangular domain. The Data Group *Time frame* is where you specify the time frame for the computation. This is done by specifying the simulation start and stop times, reference date and time step. The time step is the change in time for which the program simulates [12]. The smaller the time step, the more steps are taken in the time frame, therefore creating a longer simulation time with more simulated data and vice versa. For this project a time step of 1 minute was chosen for accuracy and for the time constraint of the project.

Our simulation will run for an 8 month period, therefore the time frame is from the 1st of January to the 31st of August. On the 1st of January we are starting with zero initial conditions because we are 'inserting' the fish on the 1st of February and 'removing' the fish on the 1st of July. Therefore there will only be a 6 month period with the farm releasing waste until the 1st of August. The first empty month allows for the spin up of the hydrodynamics in the system.

5.3.2 Processes, initial conditions, and boundaries

The Data Group *Processes* is where you specify the processes or quantities that might influence the simulation. There are constituents (salinity, temperature, pollutants and tracers, and sediments) and physical processes (wind, wave, and tidal forces, etc.) that you can select. Once you have selected a constituent or process, you must define the constituents or processes in the selected field [12]. For this project we have four different constituents, or sediments, namely the feed loss and the three different sized faeces.

For the Data Group *Initial conditions* you specify the initial values for the simulation. The initial values are for the constituents defined in the Data group *Process*. The values can either be a uniform value or loaded in from the results of a previous computation [12]. For the beginning of the simulation, the initial conditions will be set as zero since we are starting with an empty grid.

The Data Group *Boundaries* is where you can define the open boundaries, location, type and input data related to forcing the simulation. Open boundaries are defined in sections of one or more grid cells. Boundary conditions are then inputted for the ends of the grid section [12]. The input data for the boundary definitions, flow conditions and transport conditions can be loaded in as files.

For the boundaries, we have two zero boundaries at the right and left sides of the grid, where the velocity is changed to zero, removing the components at the boundary. The location of the cages in the grid represents where Delft3D-FLOW will input the waste into the hydrodynamics for the simulation, simulating the fish releasing waste. The boundaries and location of cages are plotted in Figure 5.4. The cages in the simulation, the release points, will be one grid cell and is plotted in more detail in Figure 5.5.

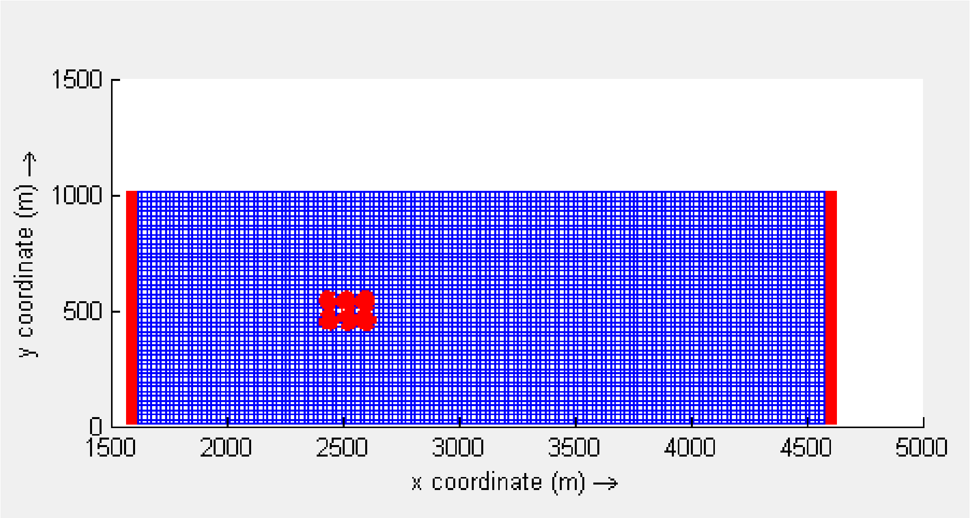


Figure 5.4: The grid used in the simulation with the open boundaries and cages displayed in red

5.3.3 Physical parameters

In the Deflt3D-FLOW interface, one can select the *Physical parameters* Data Group, which contains multiple sub-data groups. There one can specify the data for the simulation relating to the physical parameters.

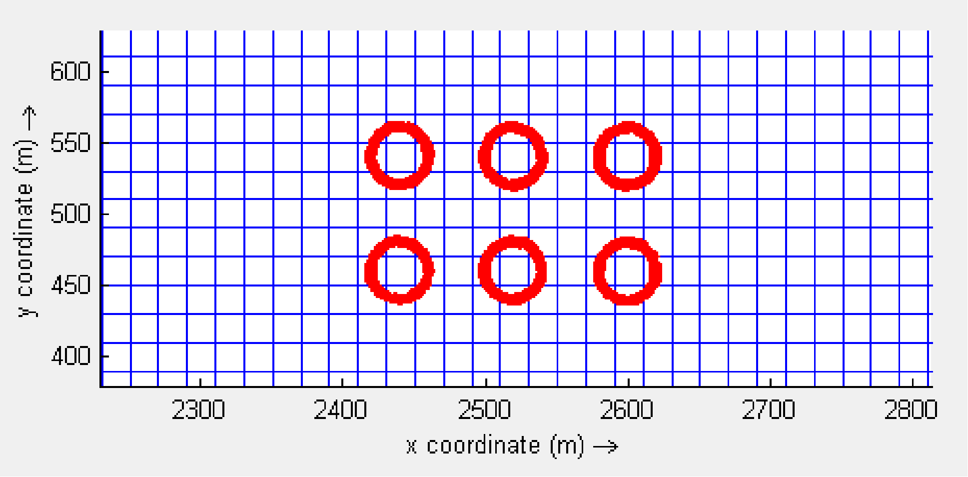


Figure 5.5: The cages in the grid

Constants and roughness

In a simulation there are a few data items that do not undergo change, these can be inputted in the *Constants* sub-data group. A few common constant items include the acceleration of gravity, the water density and air density if needed [12]. For this project, out constants were gravity, 9.81 m/s^2, and a sea water density of 1024 kg/m^3.

The *Roughness* sub-data group specifies the roughness of the seabed of the simulation. For specific simulations one can specify the roughness of the side walls. The roughness of the seabed can be specified to be uniform or as a space varying value [12]. For this project a uniform roughness was chosen, with the roughness of 65 for both the **U-** and **V-**direction.

Viscosity and morphology

For the *Viscosity* sub-data group, one can specify the eddy viscosity and the eddy diffusivity in the horizontal and vertical directions [12]. In this group one can select the model for three-dimensional turbulence. For this project we did not concentrate on the viscosity and the k-epsilon model is chosen for the turbulence.

In the sub-data group *Morphology* is where the morphological file is loaded in. The morphological input is an option to allow the simulation to update the bathymetry during the simulation [12].

5.3.4 Sediment

In the *Sediment* sub-data group is where one stores all information regarding to the sediments that need to be simulated. The sub-data group *Sediments* stores the most important data that influences the simulation for this project. Each type of constituent, created at the *Processes* sub-data group, has data that needs to be inputted. There is an overall sediment data component needed and that is the reference density for hindered settling. This is for when there is a high concentration of sediment and the resultant settling velocity for a particle is reduced by the high concentration. The constant data needed for each sediment is the density, dry bed density, fresh water settling velocity and the saline water settling velocity.

For this project we did not use a different settling velocity for saline and fresh water as we have no interaction of fresh and salt water. For the settling velocities we used the data measured by Bannister et al, [2], in Table (3.1). For the densities we employed the dry density of $108\,\mathrm{kg/m^3}$ from Bannister et al, [2] and the wet density of $1033\,\mathrm{kg/m^3}$ from Broch et al [5]. The wet density fits within the range for a wet bulk density of a cohesive sediment. For the dry bed density, the value of $600\,\mathrm{kg/m^3}$ was used, which according to the Delft3D-FLOW Manual is in the range for the dry bed density of a mud. Since we are modelling the interaction at the bed as a cohesive then we shall use this value as there is not much literature available on dry bed density. This raises another research opportunity for the investigation of the mariculture waste at the seabed.

The rest of the data that is needed is the critical bed shear stress for sedimentation and erosion, and the erosion parameter. The last set of data can be uniform or of a time-series. If it is a time-series, then it must be in a file to be selected. For this project the input for the critical shear stresses is 0.0179 and $0.004\,\mathrm{Nm^{-2}}$ for erosion and deposition respectively and a erosion parameter of $7 \times 10^{-7}\,\mathrm{kg/m^2/s}$ [9] [10]. The parameters for the stresses were validated in Cromey et al. [9], which correlate to near-bed current speeds of 4.5 to $9.5\,\mathrm{cm/s}$ [9].

5.3.5 Operations

For the Data Group *Operations*, you specify the location and properties of the discharges from the sub-data group *Processes*. Each location created will have a volumetric flow rate input and a concentration for each constituent, which can be constant or a time-series. For this project the grid cell that the cages are located at are the release points, though at a depth of 15 m will be used to simulate the depth of the cage in the water column. For the volumetric flow rate and concentration, we shall calculate those in the following chapter when we employ a growth model to simulate the growth of the fish.

5.3.6 Output

After the simulation is complete, the data is stored in a few files depending on the information of the data. There is the history file, which stores the time series data at a point, which can be used for small intervals to produce smoother time functions of the results.

The map file store snap shots of the simulation over the entire area of the grid. Since the computation uses grid points, the map file contains all grid points over the entire simulation period, therefore will be very large, possibly being a few gigabytes of storage [12].

5.3.7 Post-processing

There are a few components of Delft3D that can be used for plotting and animation, where we will use QUICKPLOT. QUICKPLOT can be used to visualise and animate numerical results produced by the Delft3D modules. This is useful for observing the results from time-series data in a cross section of the grid area [15].

5.4 Chapter summary

In this chapter it was discussed how the hydrodynamics and sediment transport are modelled. How the modelling of the hydrodynamics was achieved was explained in Section 5.2 using T_TIDE, the MATLAB function, to calculate the tidal constituents from the water levels. In Section 5.3 the model Delft3D-FLOW was investigated as a sediment transport model for our simulation. We then concluded what data we needed from the previous chapters. The data is mainly the properties of the waste, such as the densities, settling velocities and critical shear stresses for erosion and deposition. How Delft3D-FLOW was set up was explained and what is still needed for a complete simulation is the volumetric flow rate and the concentrations of the faeces and feed loss.

Chapter 6

Simulation

6.1 Introduction

In this chapter all information that is still required to run the simulation is gathered and then simulated using Delft3D-FLOW. In Section 6.2 we calculate the discharge operation, which requires the volumetric flow rate and concentrations. Once the simulation was completed, we analysed the results of the simulation in Section 6.3. Then in Section 6.4 we performed three more simulations in order to investigate the sensitivity of the critical shear stresses for erosion and deposition. Since the many researchers use the solids flux of 191.8 g/m^2/year as a basis for sustainability, we discuss the use of this in Section 6.5.

6.2 The discharge operation

In order to simulate the dispersion of the waste we need the amount of waste to be inputted. For Delft3D-FLOW the amount of waste is inputted as a discharge concentration at a point. There are two methods we chose to research; the first is a mass balance calculation done by Wang *et al.* [42] using the information on how the fish species assimilates the feed. The second method is using software to simulate the growth of the fish, by inputting the feed, which then outputs the amount of waste the fish will produce. From the amount of waste we can then calculate the discharge concentration that Delft3D-FLOW requires.

6.2.1 Mass balance

By quantifying the release rates of the nutrients one could estimate the release rates of waste from the farm. A simple mass balance principle is used with input of the release rates of waste and dissolved carbon, nitrogen and phosphorus. Other inputs required are the digestibility of the carbon, nitrogen and phosphorus components of the feed and feed loss. Information on the relationships between the reactants, and data on the water content of feed and fish are important in understanding the process on how the fish create waste from the food that they eat.

An expression for the amount of nutrients, excreted can be generated from manipulating the mass balance for carbon, nitrogen and phosphorus. The amount of nutrients excreted is equal to the amount of assimilated nutrients minus the amount of nutrients retained by the fish. Assimilated nutrients are the part of the feed that are ingested and taken up into the tissues of the fish. The amount of feed that is fed to the fish is equal to the amount retained, defecated and lost. Of the feed ingested, a proportion will not be digested but released as waste, this is the indigestible part of the feed. The indigestible content in the feed will mainly determine the main fraction of faeces produced per feed consumed. The ingestible content of the feed will then determine a small fraction of the faeces produced per amount of feed consumed as nutrients are excreted from the fish from its tissues. From these relationships, the amount of waste from the farm is equal to the total defecation, excretion and feed loss. The amount of feed that is not lost is the food intake. From the faecal matter approximately 15% will dissolve, leaving 75% as waste matter [42].

The mass balance for consumed feed can be then represented by:

$$\text{food intake} = \text{assimilated food} + \text{waste} = \text{growth} + \text{excretion} + \text{defecation}. \tag{6.1}$$

The assimilated food that is digested is compatible to the digestion efficiency reported by the feed manufacturers, which can be calculated as:

$$\text{digestion efficiency} = \text{assimilated food} \ / \ \text{food intake}. \tag{6.2}$$

The growth efficiency is calculated as:

$$\text{growth efficiency} = \text{growth} \ / \ \text{food intake}. \tag{6.3}$$

The amount of nutrients excreted becomes:

$$\text{excreted nutrients} = \text{assimilated nutrients - retained nutrients}. \tag{6.4}$$

Therefore, the excreted nutrients is:

$$\text{excreted nutrients} = \text{dry food intake} \times \text{digestible efficiency - wet biomass}. \tag{6.5}$$

Using this definition of excreted nutrients and substituting it into the mass balance for fish food consumption produces an expression for the amount of waste produced. The waste is then calculated as $1-$ digestibility of the food [42].

6.2.2 WinFish

WinFish, is an individual growth model for finfish, which includes all fish with a vertebrae, developed by Longline Environment (Pty) Ltd [22]. There is a model called AquaShell that is for shellfish and both can be coupled for modelling an Intgrated Multi-Trophic Aquaculture (IMTA). Aquafish and AquaShell use similar rationale, while Winfish is based on net energy balance. There are many components for AquaFish, the feeding and digestion, and the fish's swimming and metabolism. The feeding is function of stomach volume and Aquafish uses allometry to govern the stomach capacity. Allometry is the different rates at which different body parts grow. The food that then enters the intestine is either assimilated or excreted as faeces. The swimming is critical to the quality of the fish, each type of fish needs a certain current speed. For rapid swimming salmon, slow currents lead to higher muscle fat content and swift currents might create an excessive metabolic cost. In Winfish, metabolism is divided into three parts to meet the various components of fish metabolism [22]. Using WinFish we modelled the growth of the salmon over a period of time. Comparing this to data we had for a previous salmon farm, we found that the WinFish gave similar results to the observed farm.

In Table (6.1) are two different percentage tables from Wang et al. [42] and Ferreira et al. [22] respectively, where the percentages relate to the feed supplied that becomes faeces, feed loss or assimilated feed. For our simulation we chose the first by Wang et al. [42], where the calculated final percentages is then shown in Table (6.2). These percentages are then combined with the growth modelling results from WinFish and the results are plotted in Figure (6.1).

Table 6.1: Different feed percentages

Feed	**Defecated waste**	
Feed loss 3%	Dissolved 15%	[42]
Digested 80%	waste 85%	
Defecated 17%		

Feed	
Feed loss 9.1 – 12%	[22]
Digested 88%	
Defecated 15 – 17.6%	

Table 6.2: Final ratio from Wang *et al.*, (2012)

Waste
Feed loss 3%
Faeces 14.5%

Now that we have a growth curve that has the shape corresponding to the available data we had from the previous farm, we can create a growth curve for a shorter time

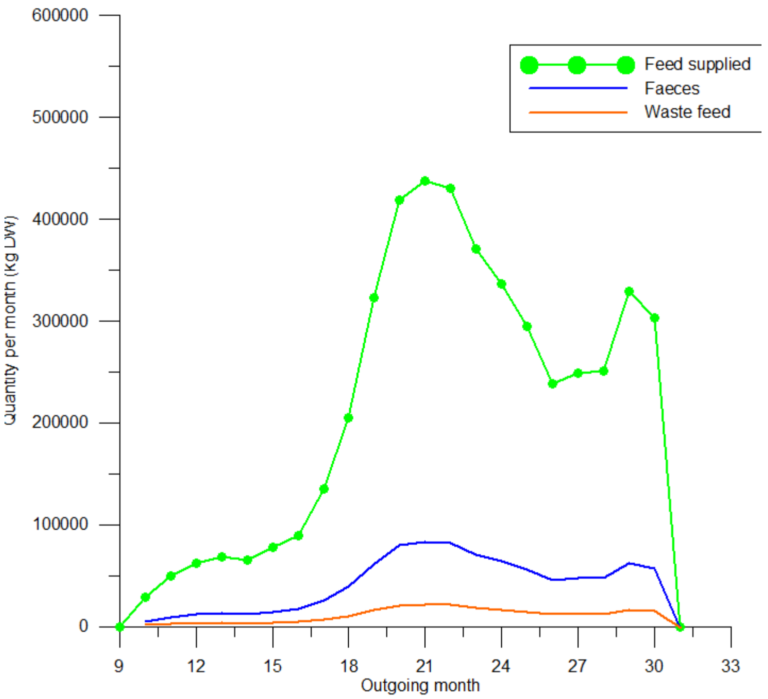


Figure 6.1: The WinFish growth curve with feed loss and faeces quantities

period in order to decrease simulation time by taking only every fourth month, which is plotted in Figure (6.2).

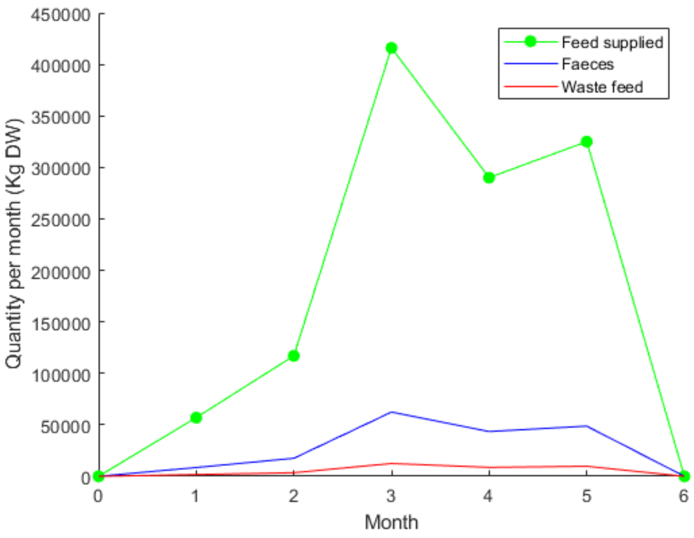


Figure 6.2: The WinFish growth curve with feed loss and faeces quantities for 6 months

6.2.3 Calculating the discharge

In order to calculate the discharge concentration, we need to calculate the volumetric flow rate, Q, and the mass flow rate, $\dot{m}$, for the faeces and feed for the fish farm. The volumetric flow rate is the volume moving with time and the mass flow rate is the rate of flow of the mass. From conservation of mass one can calculate the volumetric flow rate Q as:

$$Q = \dot{\mathrm{m}}/\rho, \tag{6.6}$$

where ρ is the density.

Volumetric flow rate

Conservation of mass is that the mass is conserved within a volume for constant density fluids, thus the mass entering must equal the mass exiting the volume. Using the conservation of mass, the mass flow rate can be expressed as (6.7)

$$\dot{\mathrm{m}} = \rho \times v \times A. \tag{6.7}$$

Since $Q = v \times A$, therefore $Q = \dot{\mathrm{m}}/\rho$. For Q, the velocity is the evacuation velocity of the faeces, which is difficult to calculate. Therefore, we shall be using $Q = \dot{\mathrm{m}}/\rho$, since we already have the values for $\dot{\mathrm{m}}$ and ρ. The total mass flow rate is given to us from the growth model, where we are given a mass per day. Calculating the mass flow rate is then converting the mass per day to kilogram per second (kg/s). Combining the flow rate for the faeces and feed gives us the total mass flow rate. Dividing the total mass flow rate by the dry weight density results in the volumetric flow rate.

For this project we are simulating for 8 months and will be inputting no waste discharge in the first and last month. The first month "without fish" allows us to spin up the hydrodynamics without the waste, while the last month allows us to examine the post farming redistribution of the waste. In Delft3D-FLOW, the input for the volumetric flow rate is given for the first of each month, which is then connected linearly to calculate the volumetric flow rate of every time step. Therefore, to have a complete month with no input into the farm, the second month starts also with zero input. Each day then will gradually increase linearly to the next volumetric flow rate for the first of the following month. Each month will in turn have a different volumetric flow rate due to change in amount of mass exiting the farm. The change in mass flow rate is from multiple reasons, for example due to the change in feeding, size of the fish and the amount of growth in the fish. Using the growth model outputs for the faeces and feed loss gives us the mass flow rate and therefore we have the following volumetric flow rates in Table (6.3). F1, F2, F3 refer to the fractions of the faeces.

6.2.4 The discharge input

To calculate the discharge, the mass flow rate for each faces fraction is divided by the volumetric flow rate. The discharge for each month can be seen in Table (6.4). The discharge, or mass concentration kg/m^3, for each waste by product is the same for each

Table 6.3: The volumetric flow rate and mass flow rates

	Q m^3/s	**F1** kg/s	**F2** kg/s	**F3** kg/s	**Feed** kg/s
Month 1	0	0	0	0	0
Month 2	0	0	0	0	0
Month 3	0.00018	0.07719	0.00990	0.01188	0.01979
Month 4	0.00038	0.15844	0.02031	0.02438	0.04063
Month 5	0.00134	0.56333	0.07222	0.08667	0.14444
Month 6	0.00093	0.39271	0.05035	0.06042	0.10069
Month 7	0.00104	0.44010	0.05642	0.06771	0.11285
Month 8	0	0	0	0	0

month since each faeces fraction comprises of the total mass flow rate and can be seen in

$$c = \dot{m}_f/Q = \dot{m}_f\rho/\dot{m}, \tag{6.8}$$

where $\dot{m}_f$ is the mass flow rate of the faeces fraction or the feed loss.

Table 6.4: The discharge inputs

	Q m^3/s	**F1** kg/m^3	**F2** kg/m^3	**F3** kg/m^3	**Feed** kg/m^3
Month 1	0	0	0	0	0
Month 2	0	0	0	0	0
Month 3	0.00018	70.2	9.0	10.8	18.0
Month 4	0.00038	70.2	9.0	10.8	18.0
Month 5	0.00134	70.2	9.0	10.8	18.0
Month 6	0.00093	70.2	9.0	10.8	18.0
Month 7	0.00104	70.2	9.0	10.8	18.0
Month 8	0	0	0	0	0

6.3 Analysis of model results

The final results of the model are presented in Appendix B. In order to analyze the dispersion and deposition of the farm, the bottom layer and the middle cross-section have been plotted to show the maximum dispersion and deposition respectively. For the sediment that is plotted, it is a combination of all faeces fractions and the feed loss.

To reflect the changes in feed pattern, from Figure (6.1), the first of March, May and July were plotted. This is due to March being the first peak, May being the first dip and July being the last peak in feeding within the farm, for the reduced six-month cycle. Thus, with these plots we can analyse the dispersion and deposition for the cycle of the farm and therefore conclude whether the use of a continuum method is feasible.

With this setup of the model, it was expected that the model might display a highly dispersive farm, due to the high near-bed currents. This was observed in the final result, as the 1^{st} of August, just 30 days after the 1^{st} of July, seen in Figure (B.3), has extremely low amounts of waste left within the grid. The final dispersion plot for the 1^{st} of August can be seen in Figure (6.3), and Figure (B.4), where the final amounts of waste are dispersing out of the grid area. From comparing Figures (B.1) to (B.4), it is observed that the spreading of the waste creates a larger and larger oblong shape as time passes till the largest is seen in Figure (6.3). The spreading of the waste follows the main direction of the currents and shows a high diffusion of the waste.

Figures (6.4), (B.5), (B.6), (B.8) and (B.7) are cross-section plots of the simulation. The waste is observed to be deposited directly underneath the farm, where the release point is at $-30\,\text{m}$. The low amount of waste floating above the waste at the seabed is the result of the resuspension of the waste from the shear stress created by the near-bed currents. In Figure (B.8) it can be seen that the waste is continuously being resuspended and deposited as the majority of the waste is dispersed with the currents at the end of the simulation.

Just for confirmation the velocity magnitude of the currents and the bed shear stresses are plotted in Figures (6.5) and (6.6) respectively. It is observed that the bed shear stress generally is in the range 0.035 to $0.05\,\text{Nm}^{-2}$ which follows the same trend of the velocity magnitude. The bed shear stress range also indicates that deposition will barely occur due to the high near-bed currents and that the waste is constantly being eroded as the shear stress is always higher than the critical shear stress for erosion. This confirms that the waste is not being deposited and is following the flow of the currents.

6.4 Sensitivity analysis

Due to the affect of the deposition and erosion stresses on the output of the simulation, an investigation was done into the sensitivity of the stresses. The original critical shear stresses values and the new inputs for the sensitivity analysis are listed in Table (6.5). Since we observed that the waste did not stay deposited for long, this could be due to the critical erosion and deposition shear stresses being very low. Deposition occurs when the shear stress is lower than the critical deposition shear stress, which was originally

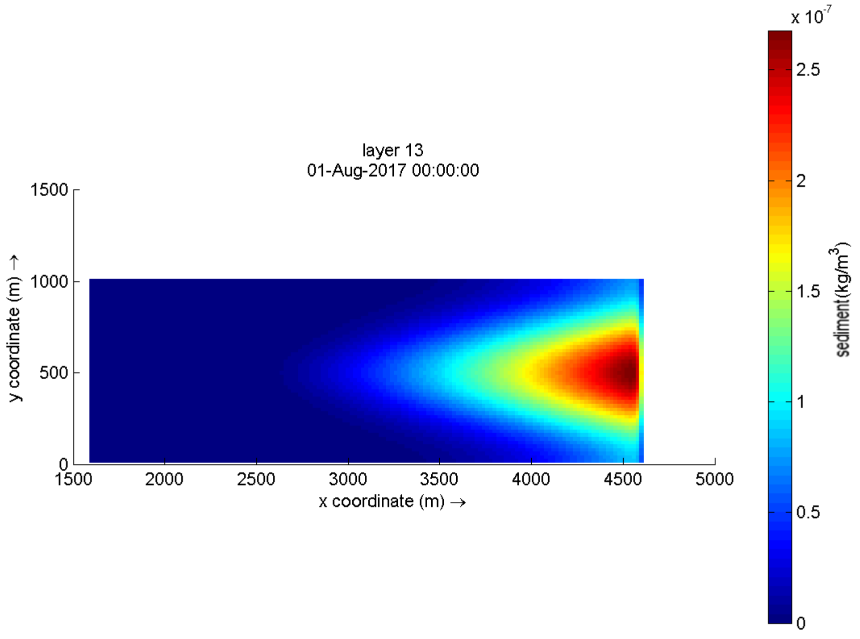


Figure 6.3: Bottom layer at last day of simulation showing the dispersed waste left in system

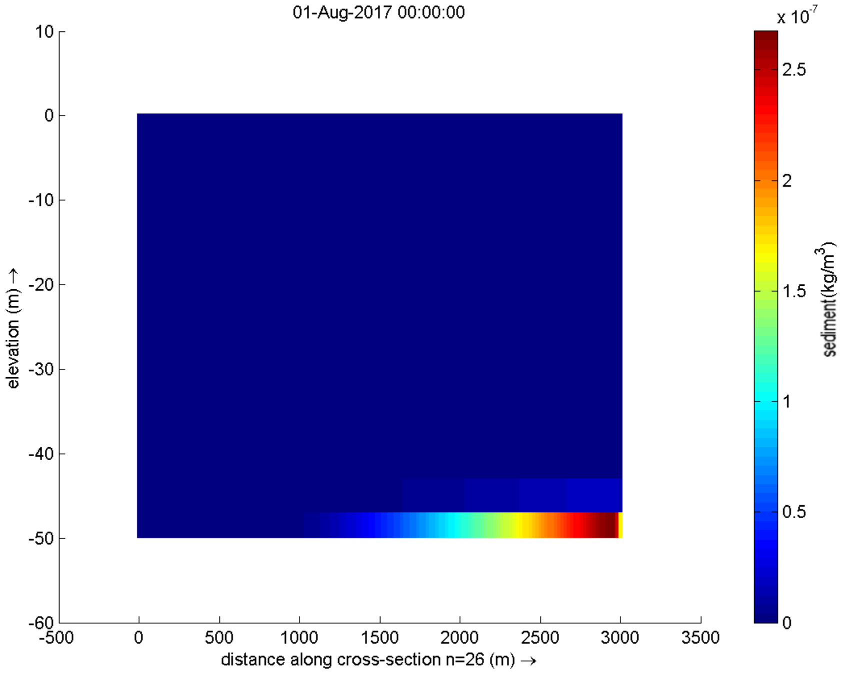


Figure 6.4: Middle cross-section at last day of simulation showing the deposited waste left in system

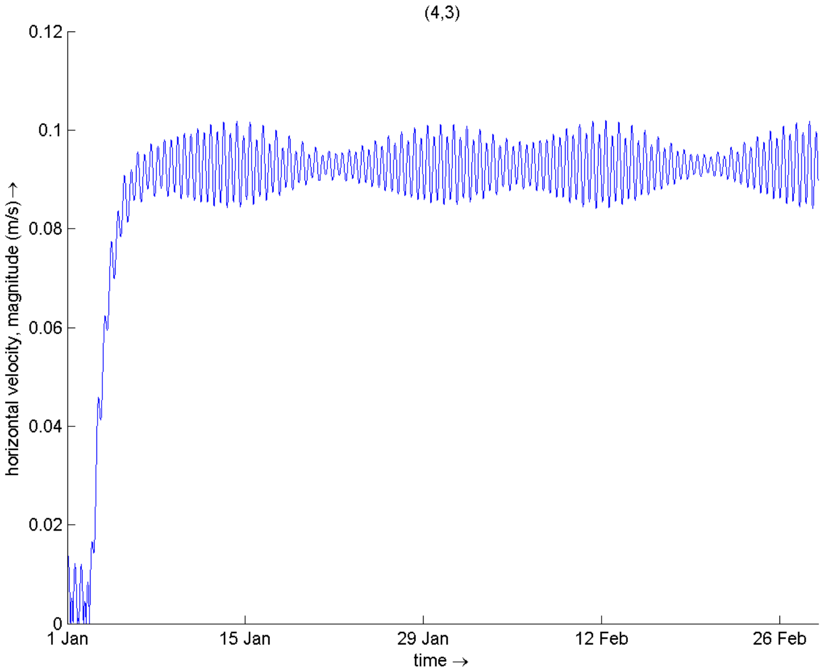


Figure 6.5: Velocity magnitude at beginning of simulation at a point

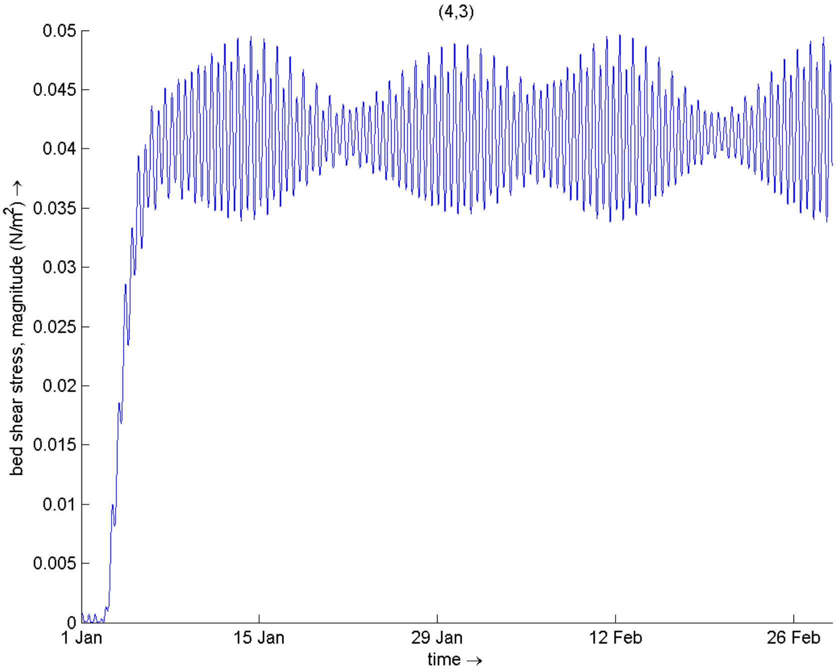


Figure 6.6: Bed shear stress at beginning of simulation at a point

0.004 $\mathrm{Nm^{-2}}$. This extremely low critical stress for deposition means that there is barely any deposition with the high near-bed currents. Meanwhile erosion occurs when the shear stress is above the critical erosion shear stress, originally 0.0179 $\mathrm{Nm^{-2}}$. The low critical erosion shear stress, combined with the high near-bed currents, means that the shear stress is continuously higher, therefore there is a continuous erosion of the bed load. The combination of both low critical shear stresses could mean that this site is extremely dispersive. Using our modelling results as a control, we can compare the test and model results to observe if this statement is true.

Table 6.5: The inputs for the sensitivity analysis on the critical shear stresses

Stress $\mathrm{Nm^{-2}}$	**Original** $\mathrm{Nm^{-2}}$	**Test1** $\mathrm{Nm^{-2}}$	**Test2** $\mathrm{Nm^{-2}}$	**Test3** $\mathrm{Nm^{-2}}$
Deposition shear stress	0.004	0.001	0.04	0.04
Erosion shear stress	0.0179	0.02	0.02	0.04

The reason for the first test is to check that the lower critical bed shear stress for deposition does result in little to none deposition due to the bed shear stress. For the second test, the a higher critical shear stress for deposition is tested to allow for the critical to be higher than the bed shear stress to allow for deposition to occur. The third values was chosen to observe the effect of a high critical shear stress for both deposition and erosion.

6.4.1 Test 1 analysis

The final results of the Test 1 analysis are presented in Appendix C, with both sets of plots for the bottom layer and middle cross-section. For the first test, an investigation is done into the effect of a low critical deposition shear stress, with the new critical deposition shear stress of 0.001 $\mathrm{Nm^{-2}}$. Figures (6.7) and (6.8), show the results of the last day of the control and first test, respectively. It is observed that the Test 1 and control outputs the same results, from which we can deduce that reducing the critical deposition shear stress does not reduce the deposition of the waste. This is possibly because the shear stress does not become less than even the critical deposition of the control model, which indicates high near-bed currents.

6.4.2 Test 2 analysis

The final results for the Test 2 analysis are presented in Appendix D, with both sets of plots for the bottom layer and middle cross-section. For the second test, a higher critical deposition shear stress of 0.04 $\mathrm{Nm^{-2}}$ is used. Figure (6.9) is the last day of the second test and comparing Figure (6.9) to Figure (6.7), provides evidence that the higher

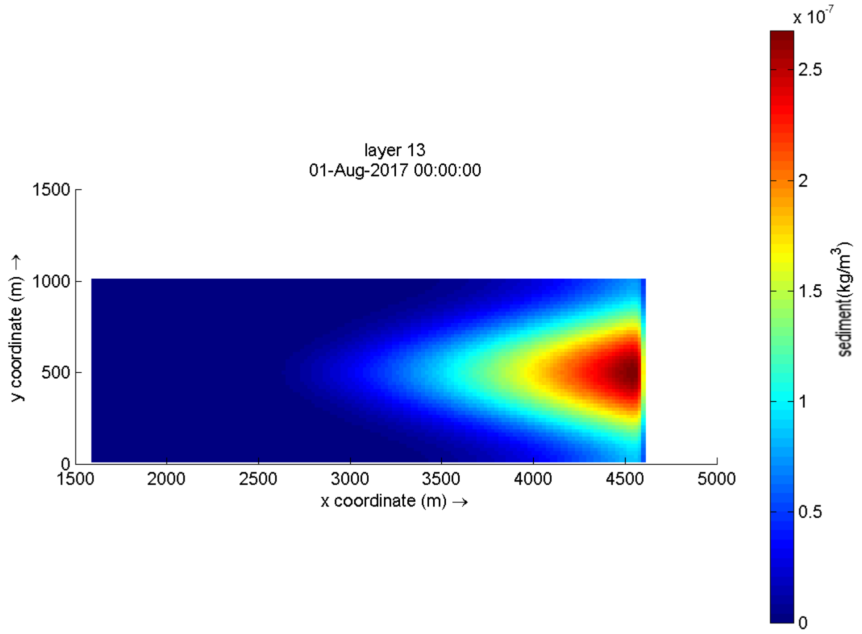


Figure 6.7: Bottom layer at last day of control simulation showing the dispersed waste left in system

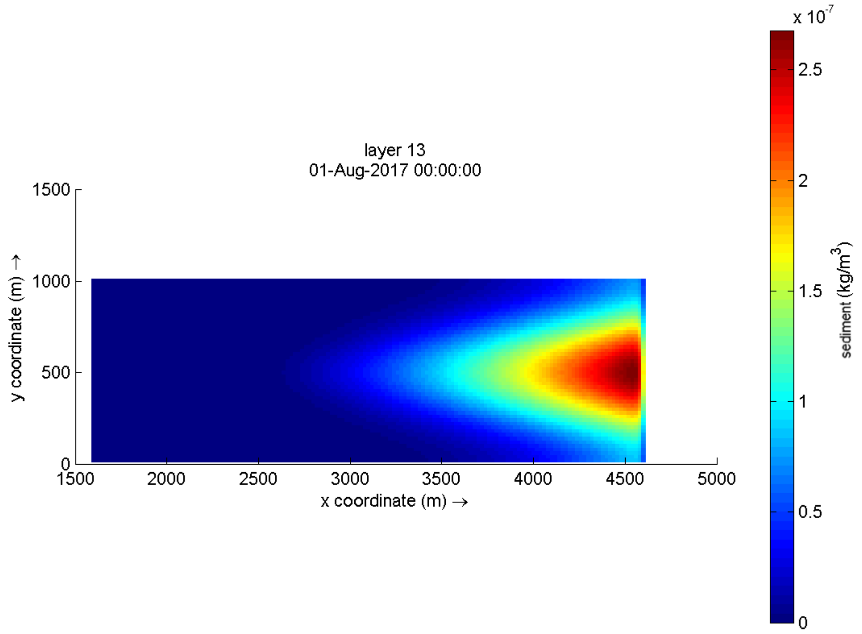


Figure 6.8: Bottom layer at last day of the first test simulation showing the dispersed waste left in system

critical deposition shear stress allows for a higher deposition of the waste, with very little dispersion out of the grid. Most of the waste collects in the area underneath the release point, with some of the waste being dispersed by the currents.

Figures (6.10) and (6.11) are cross-sections in July for the control and the second test, respectively. Comparing these figures allows for the confirmation that the higher critical deposition allows for a higher deposition of the waste with less dispersion.

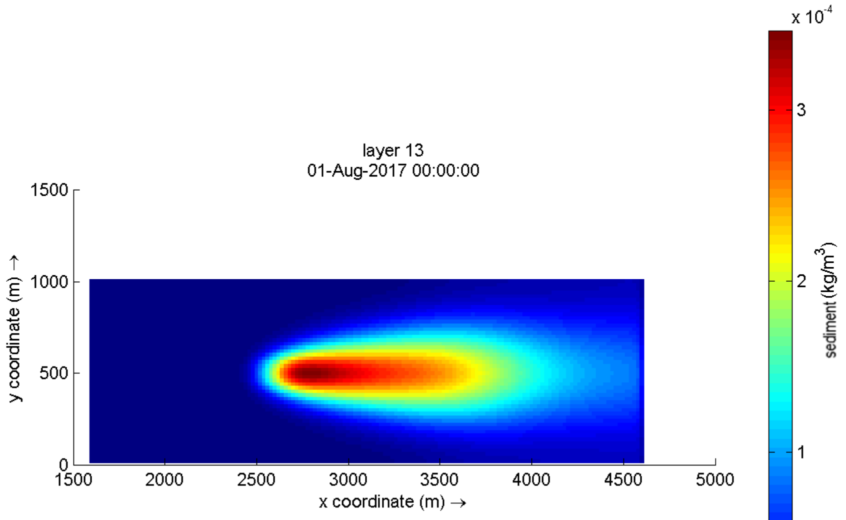


Figure 6.9: Bottom layer at last day of the second test simulation showing the dispersed waste left in system

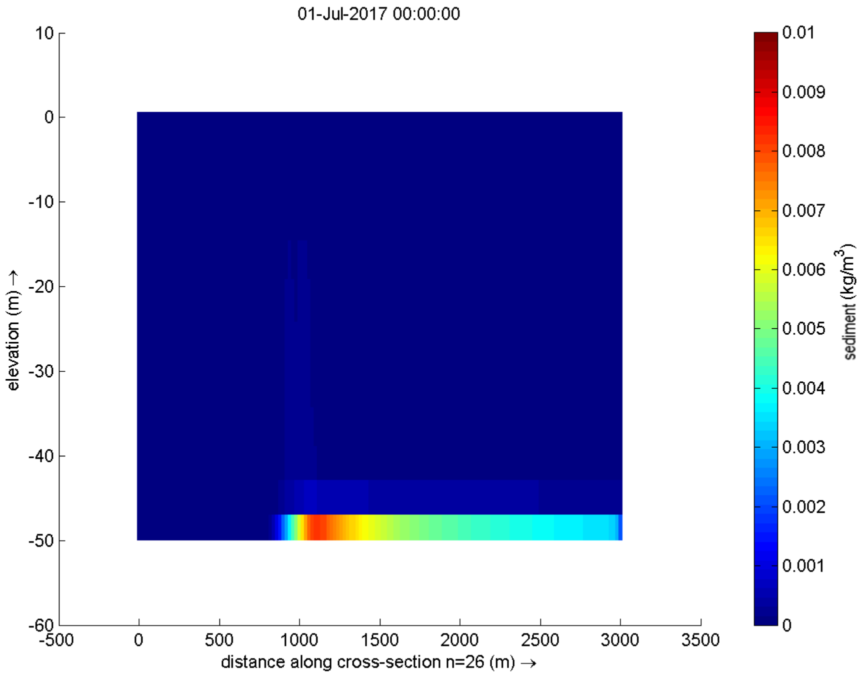


Figure 6.10: Middle cross-section for July of the control simulation showing the deposited waste

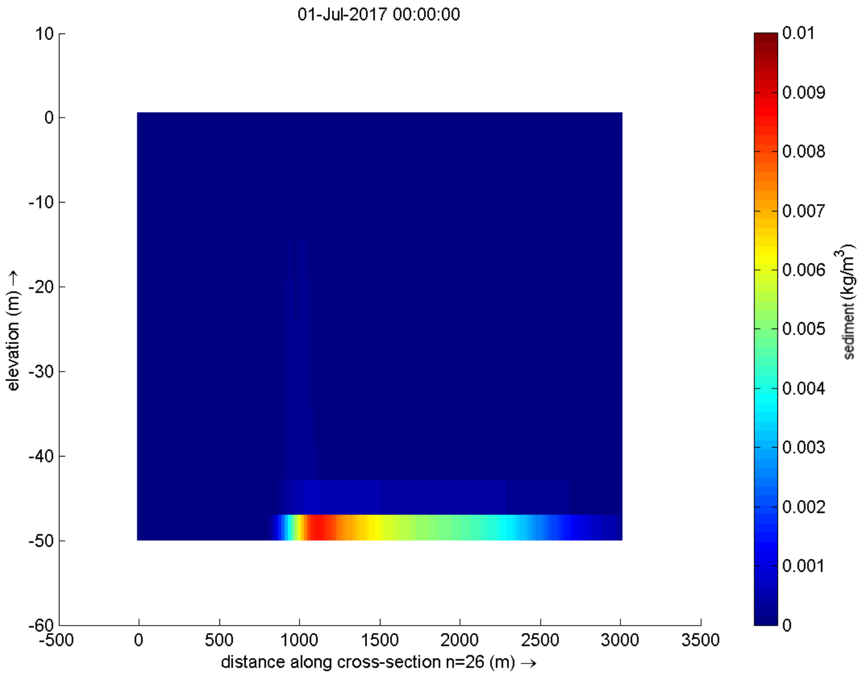


Figure 6.11: Middle cross-section for July of the second test showing the deposited waste

6.4.3 Test 3 analysis

The final results of the Test 3 analysis are presented in Appendix C, with both sets of plots for the bottom layer and middle cross-section. Figures (6.12) and (6.13) are the final results at the bottom layer for the control and the third test, respectively. In this third test, the critical erosion and deposition shear stresses were both increased. Comparing the two figures, we conclude that the high erosion removes most of the waste that is not in a high deposition area. Most of the waste was deposited underneath the release points and the high amount of waste allowed for the majority of the waste in the system to be dispersed except the last amount underneath the release point.

6.5 Calculating the flux for the year

DEPOMOD-modelling the deposition and biological effects of waste solids from marine cage farms by Cromey et al. [9], is a paper that is used a basis for investigating the environmental impact of a fish farm, specifically for the benthic model aspects of DEPOMOD. DEPOMOD predicts the solids accumulation on the seabed arising from a fish farm and associated changes in the benthic faunal community [9], which includes the ITI calculation and relation to the AZE, especially the waste flux (g/m^2/day). In DEPOMOD, Cromey simulates two farms at different sites, one a dispersive site and the other a depositional site. A quantitative relationship is established between the waste flux and the benthic index ITI. How Cromey calculates the ITI is discussed in Chapter 2, Section 2.3.1. With

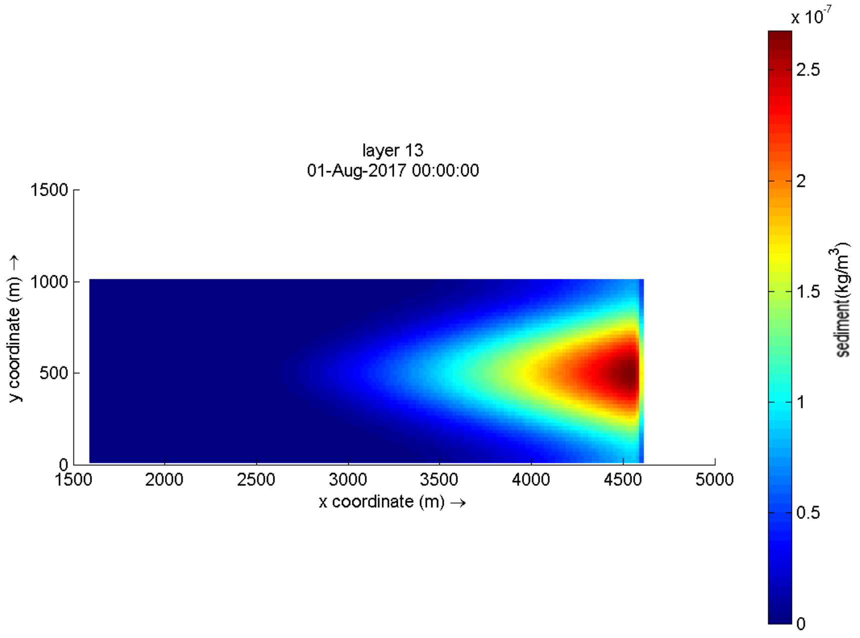


Figure 6.12: Bottom layer at last day of control simulation showing the dispersed waste left in system

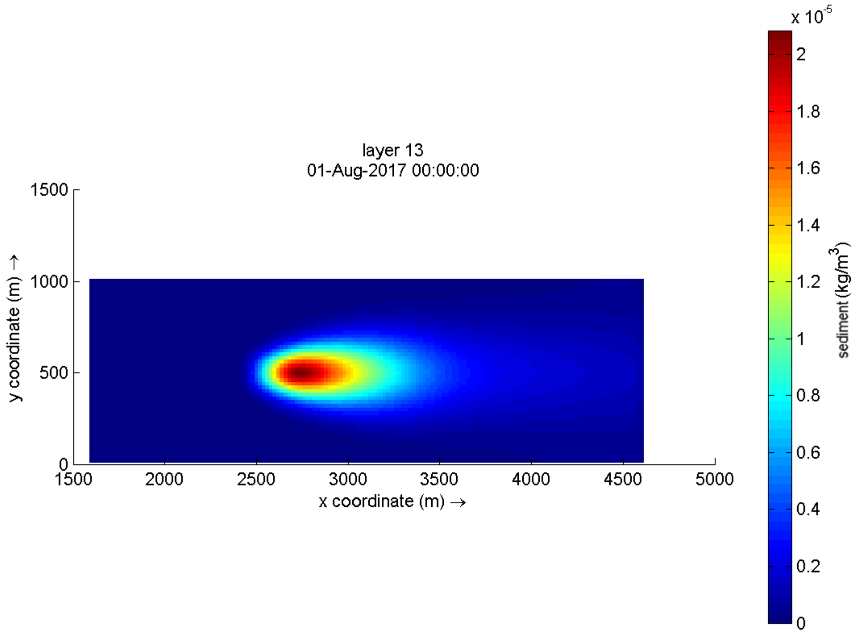


Figure 6.13: Bottom layer at last day of the third test simulation showing the dispersed waste left in system

this crucial information, one can look at their farm, or simulation, and see whether the waste flux is within the boundaries of the critical ITI number. The critical ITI number being 30, which correlates to a degrading environment. This was done by determining the lines of best fit for the ITI and total individual species abundance. The relationship between the observed ITI, abundance, and predicted solids accumulation for the sites investigated is plotted in Fig. 6. on page 226 of [9]. With these plots the waste flux 191.8 g/m^2/year corresponds with the ITI value of 30.

Issues with 191.8g/m^2/year

The way that 191.8g/m^2/year was calculated was by simulating the farm for one day and then scaling the result up to year. There are a few issues with this, mainly that the growth cycle of the fish in a farm is a time-series. Meaning that the feed input and growth output of the fish, therefore the waste output of the farm, changes due to variations in the daily environment and internal growth of the fish.

Having one day scaled does not show the variations in the waste of a general fish farm. This one day could be either in the beginning or end or even the middle of the cycle of the fish. The scaled output would then be underestimated, overestimated or even a median variation. Even taking an average of a cycle would not give a good representation of the waste dispersion and deposition. When modelling a cycle of a fish farm, it is imperative that the whole cycle is represented accurately due to the variations in the farm's factors over time. Therefore, further research is needed in order for a more accurate benthic model to be available.

6.6 Chapter summary

In this chapter the discharge was calculated by creating a growth model for the fish in order to calculate the feed input. Using percentages from Wang et al. [42], we were able to calculate the mass flux of the faeces and feed loss. From mass conservation, the volumetric flow rate was calculated. With both the volumetric flow rate and mass flux we could calculate the concentrations for Delft3D-FLOW. Once the simulation was completed, the results were analysed. Observing the bottom layer and middle cross-section, we concluded that the waste was effectively dispersed by the currents and that there was little deposition on the seabed. This is confirmed by observing at the bed shear stress magnitude, which never is lower than the critical shear stress for deposition. The waste at the bottom layer is confirmed to be continuously resuspended due to the high erosion caused by the high currents. Three different test simulations were then conducted to investigate the sensitivity for the critical shear stresses for deposition and erosion. The first test confirmed that if the critical shear stress for deposition is even lower, it did not change anything since the bed shear stress is still higher than the critical shear stress for deposition. The second test confirmed that raising the critical shear stress for deposition allows for more deposition in the system and therefore there was more waste left in the system at the end of the simulation. The erosion was still present but the higher critical shear for deposition allowed for a continuous erosion and deposition process of the waste. The third test confirmed that for high critical shear stresses there will be deposition and high amounts of erosion, leaving a small amount of waste left in the system at the end of the simulation.

Chapter 7

Conclusion

7.1 Introduction

In mariculture the waste produced by farms, when on the seabed, possibly behaves as a cohesive sediment. This raises the question about the use of particle tracking models that model the dispersion and deposition as a non-cohesive sediment. We were presented a fjord with which to model the dispersion and deposition of the resultant waste produced by the farm present in the fjord. Our research objective was to investigate the feasibility of modelling the dispersion and deposition with a continuum method in order to validate whether the waste behaves as a cohesive when in the water column.

7.2 Summary of findings

Due to the complexity of the fjord, a simple rectangular three-dimensional domain was chosen for the simulation. The difference between modelling the waste as a non-cohesive and cohesive was investigated while gathering data needed for the simulation. Non-cohesive and cohesive sediments are transported in suspension with the advection-diffusion equations, while non-cohesives are resuspended by the Shields parameter, calculated from the shear stress and cohesive sediments are resuspended by the Parthenaides-Krone equation for erosion and deposition, which is also calculated by the bottom shear stress.

The simulation results showed that the site is a highly dispersive area with most of the wastes being dispersed from the site at the end of the simulation. This is confirmed by Bannister et al. [2], that observed simulations predict that waste produced by mariculture may be dispersed over large areas [2]. Due to the simulation including resuspension parameters in the form of erosion for cohesive sediments, there was a continuous high erosion of the suspended waste at the seabed. This correlates to the high current speeds, which also confirm the lack of deposition due to the low critical shear stress for deposition that was used. Broch et al. [5] confirms that including resuspension within the model leads to increased erosion. Cromey et al. [9] also confirms that the use of a very low critical shear stress for deposition and erosion allows for high dispersion of the waste and that the erosion is highly frequent, with waste being continuously eroded and resuspended. The critical deposition and erosion shear stresses was also confirmed to correlate to near-bed currents of 4.5 to $9.5\,\mathrm{cm/s^{-1}}$. The shape of the waste also correlates to research and literature as it follows a truncated cone where the highest amount of waste is found beneath the release point.

The first test analysis confirmed that the high currents would not allow deposition. For the second test analysis, it is confirmed that the deposition was very low until the critical shear stress for deposition was increased, and then deposition could be observed with high amounts of waste deposited. The third test analysis confirm from Cromey et al. [9], that a site with high deposition and high erosion creates a depocenter, where a high rate of deposition occurs until it is eroded over time. It is useful to make comparisons of resuspension events for a similar coastal environment due to the waste having a low threshold for erosion. The analysis into the critical shear stresses for deposition and dispersion conclude that the critical shear stresses are too low for a realistic dispersion and deposition of farm wastes. Therefore, the values from Cromey et al. [10] apply to the case of a particle tracking module and not a continuum approach.

With this study it has shown that the use of a three-dimensional domain and model to accurately simulate the dispersion and deposition of the waste using a continuum approach as it follows the general description of research and literature results. It also has confirmed that better description of the resuspension of mariculture waste is needed, due to the high sensitivity to bed shear stress and the need for highly dispersive sites.

7.3 Suggestions for future research

With the research into cohesive sediments, it was found that the equivalent of non-cohesive sediments settling velocity is flocculation for cohesive sediments. This flocculation possibly has a different settling velocity to the individual sediments and should be investigated, especially since the generally used settling velocity for mariculture waste is measured using individual sediments and not a large sample of waste. This would confirm how the waste interacts with other waste sediments in the water column as it settles.

More case studies should be conducted into the critical shear stresses for dispersion and deposition to allow for more test cases when modelling the waste. Carvajalino-Fernández et al., [7], explained how the use of sediment-dependent thresholds could regulate the high levels of erosion that occurs with low level critical shear stress values [7]. Creating a module where the critical shear stress values change with the levels of deposited sediment, could allow for a more accurate prediction of the dispersion and deposition of the waste. Specifically with the use of a continuum approach, where the critical shear stress values from Cromey et al, [10] replicate an extremely dispersive system.

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Appendices

Appendix A

Variables

Greek alphabet

ϵ_s	vertical mixing coefficient of a sediment
ρ	density
ρ_s	density of a sediment
θ	Shields parameter
τ	shear stress
τ_b	bed shear stress
τ_c	critical shear stress for erosion
τ_s	critical shear stress for deposition

Latin alphabet

A	area
c	mass concentration
d	deposition flux,
D	particle diameter of a sediment
e	erosion flux
g	acceleration due to gravity
Q	volumetric flow rate
k	diffusion coefficient
$\dot{m}$	mass flow rate
M	erosion parameter
n_i	number of organisms in Group i
p	suspended particle
R	sources or sinks
v	velocity
$\mathbf{v} = u, v, w$	velocity field with three dimensional components u, v, w
w_m	settling velocity

Symbols

∇	gradient
$\cdot$	dot product

Chapter 8

Appendix B: Modelling results

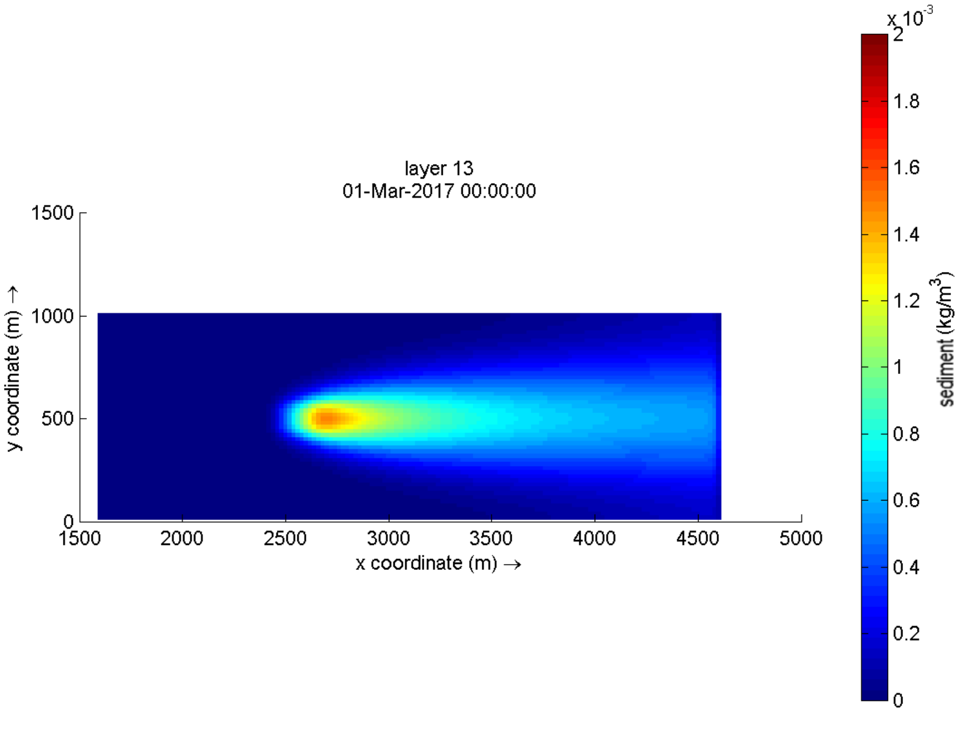


Figure B.1: Main simulation bottom layer at the end of March showing the dispersed waste

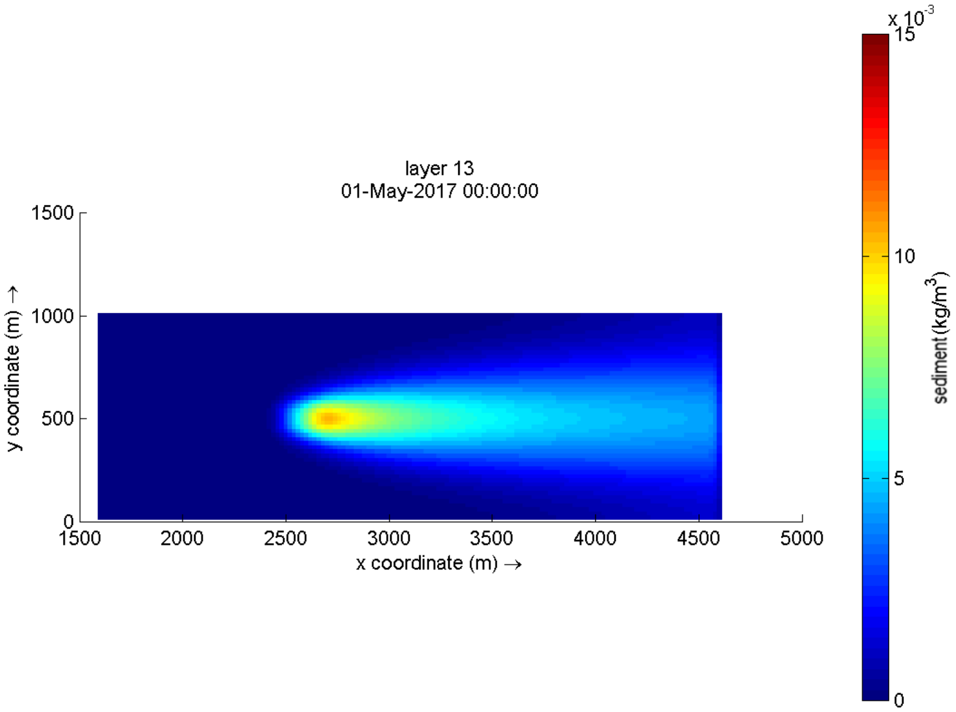


Figure B.2: Main simulation bottom layer at the end of May showing the dispersed waste

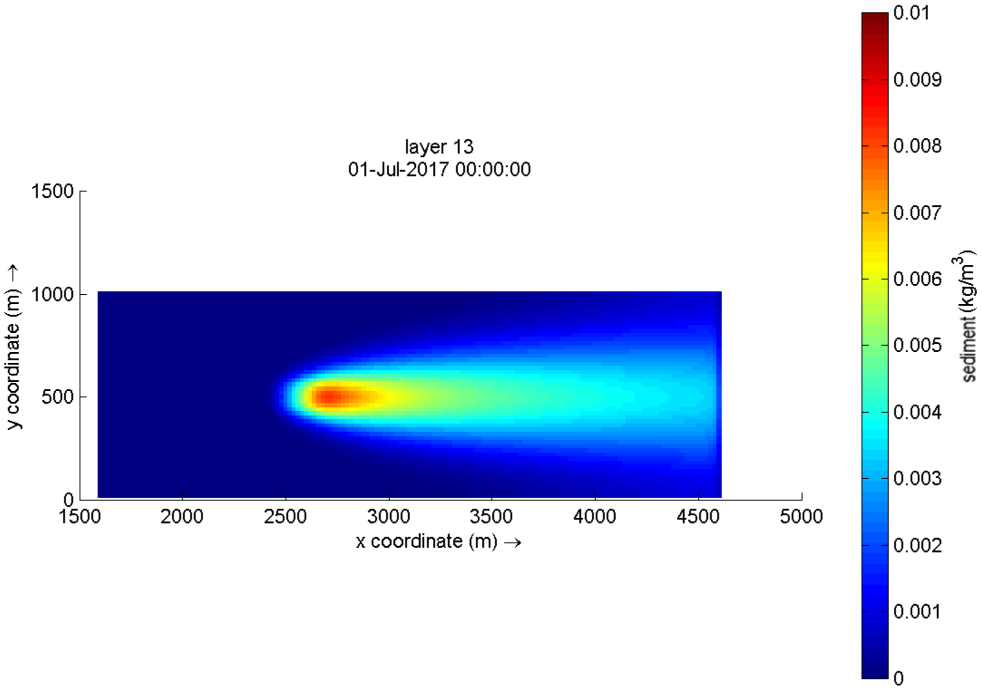
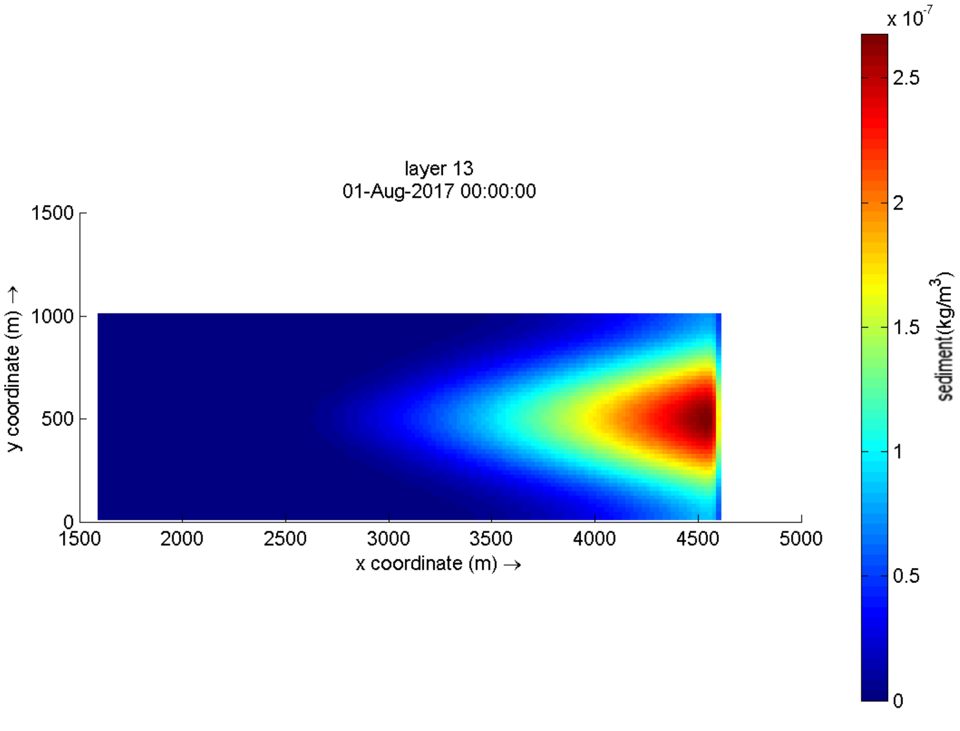


Figure B.3: Main simulation bottom layer at the end of July showing the dispersed waste



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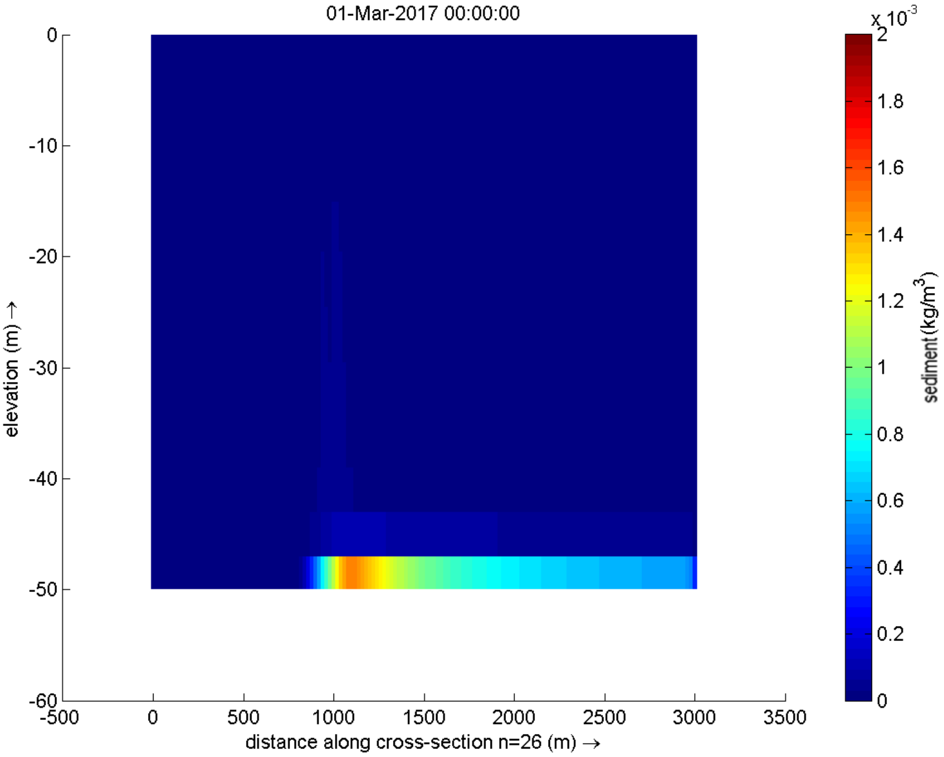


Figure B.5: Main simulation middle cross-section at the end of March showing the deposited waste

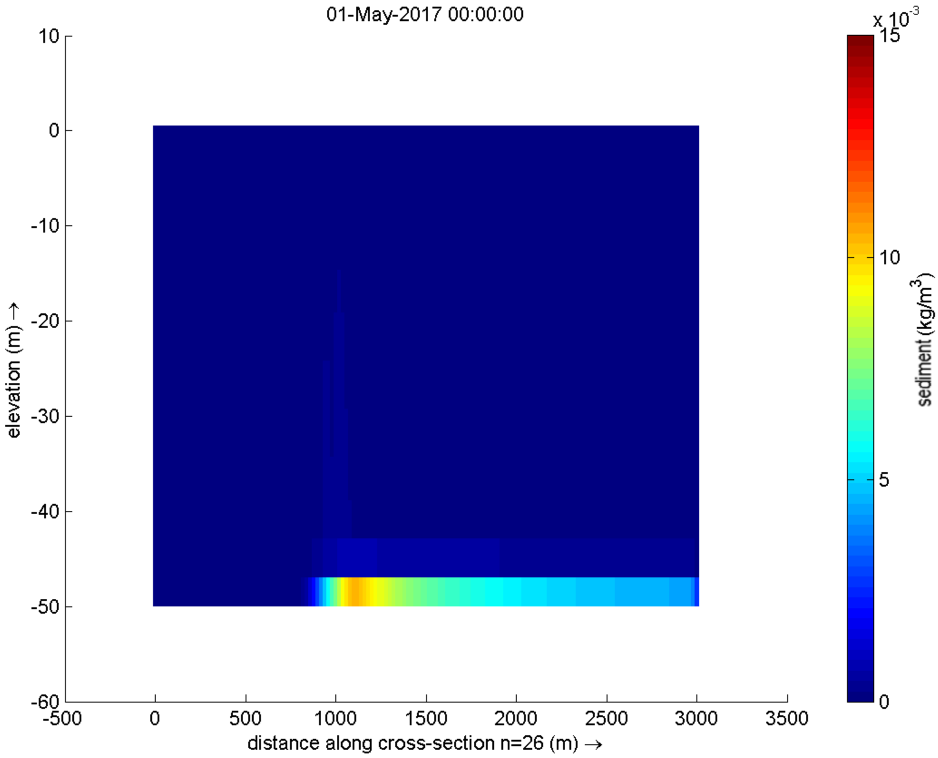


Figure B.6: Main simulation middle cross-section at the end of May showing the deposited waste

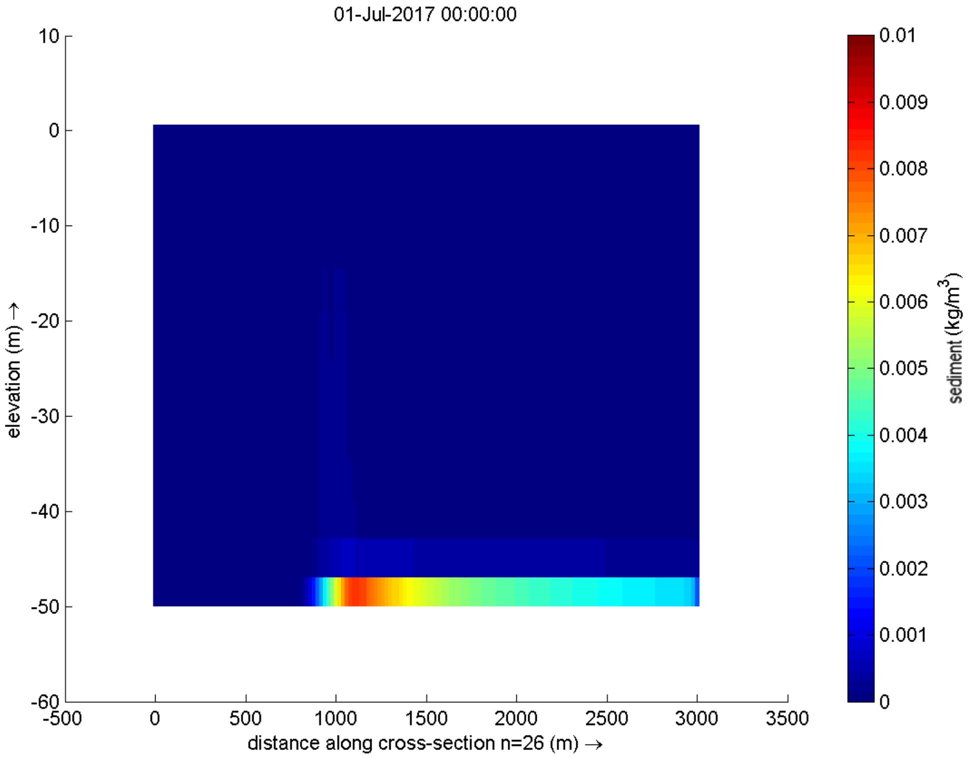


Figure B.7: Main simulation middle cross-section at the end of July showing the deposited waste

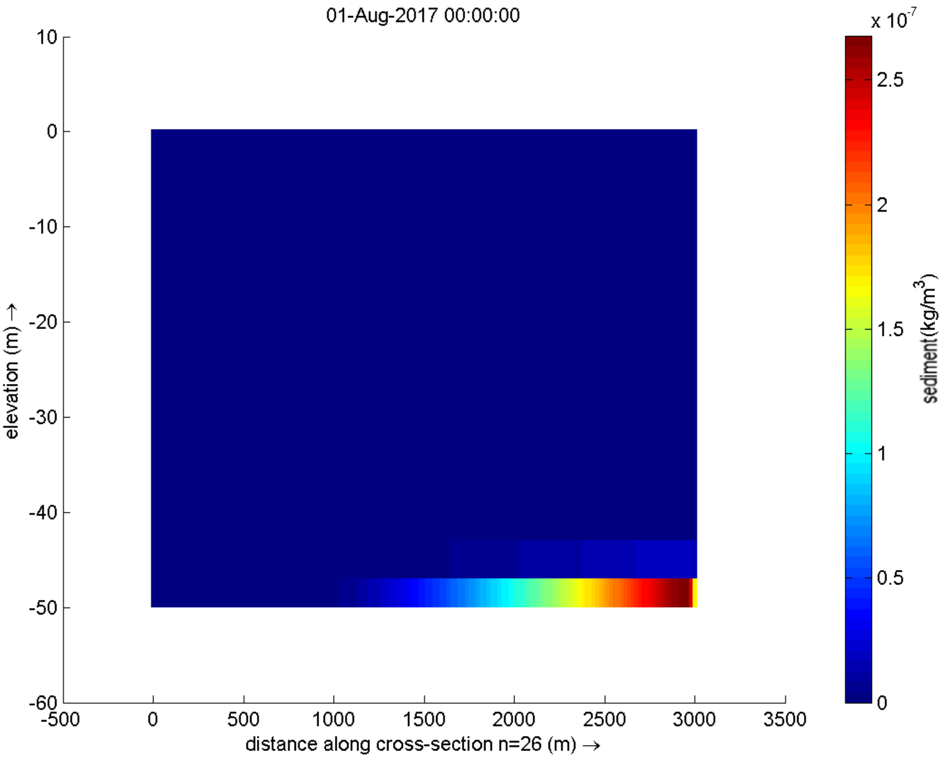


Figure B.8: Main simulation middle cross-section at the end of August showing the deposited waste

Chapter 9

Appendix C: Test 1 results

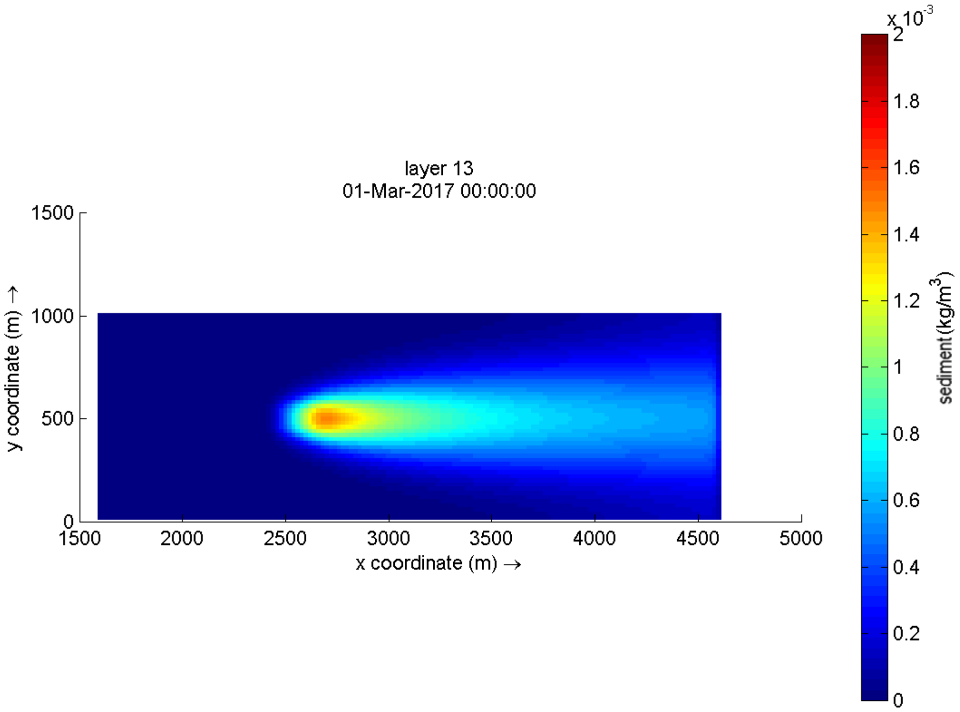


Figure C.1: Test 1 bottom layer at the end of March showing the dispersed waste

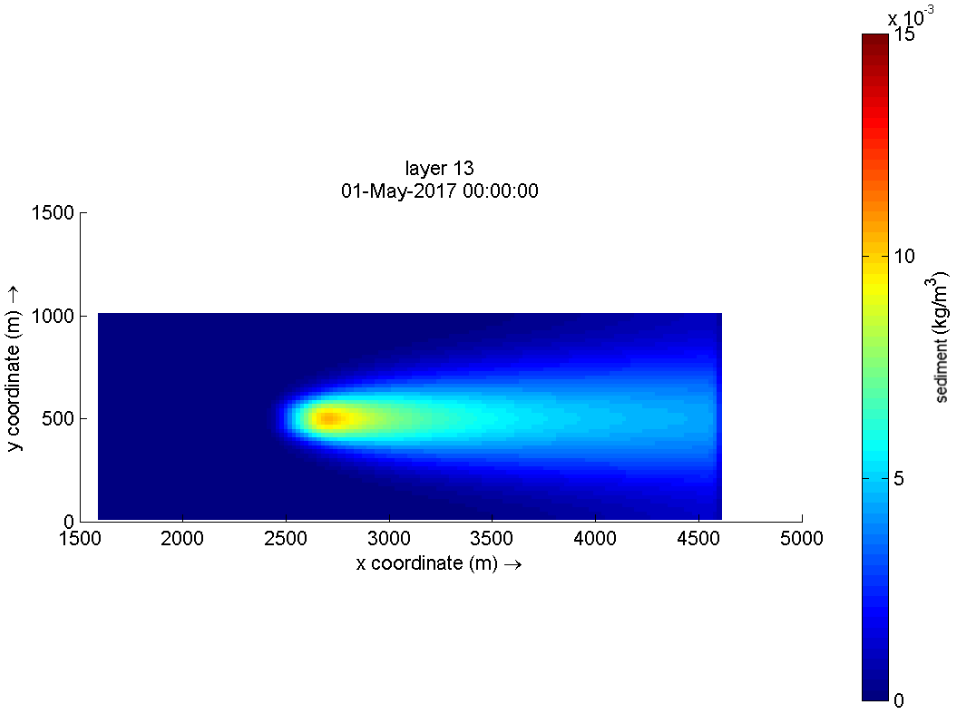
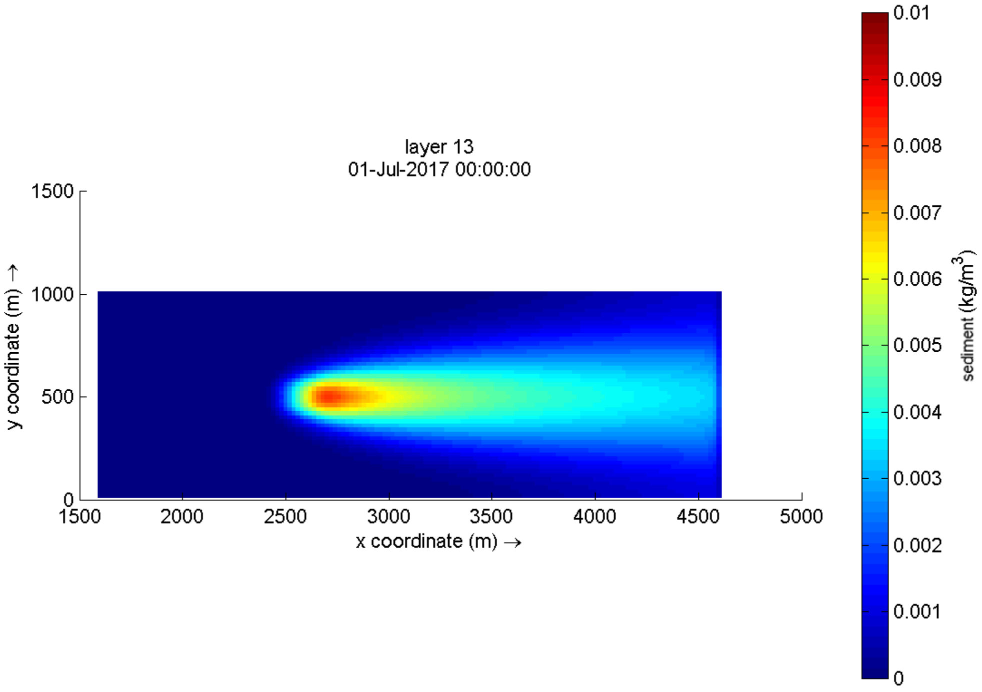


Figure C.2: Test 1 bottom layer at the end of May showing the dispersed waste



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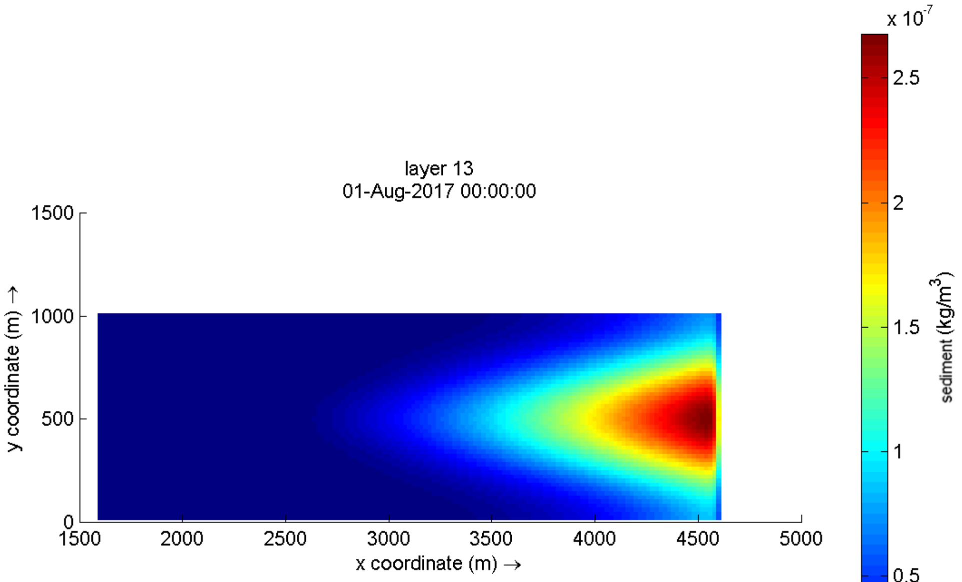


Figure C.4: Test 1 bottom layer at the end of August showing the dispersed waste

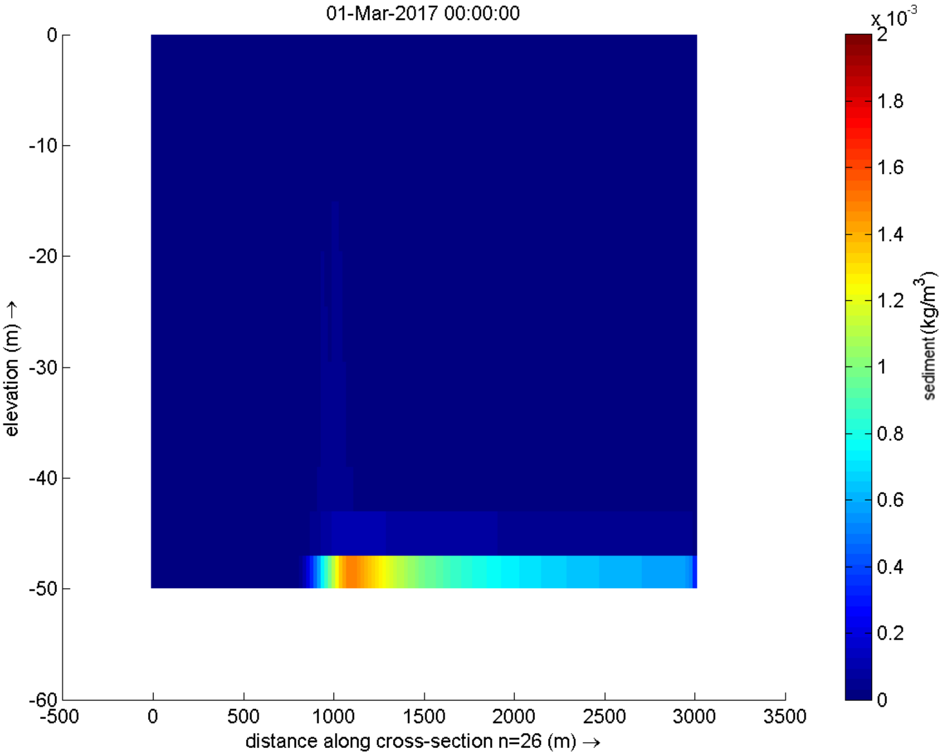
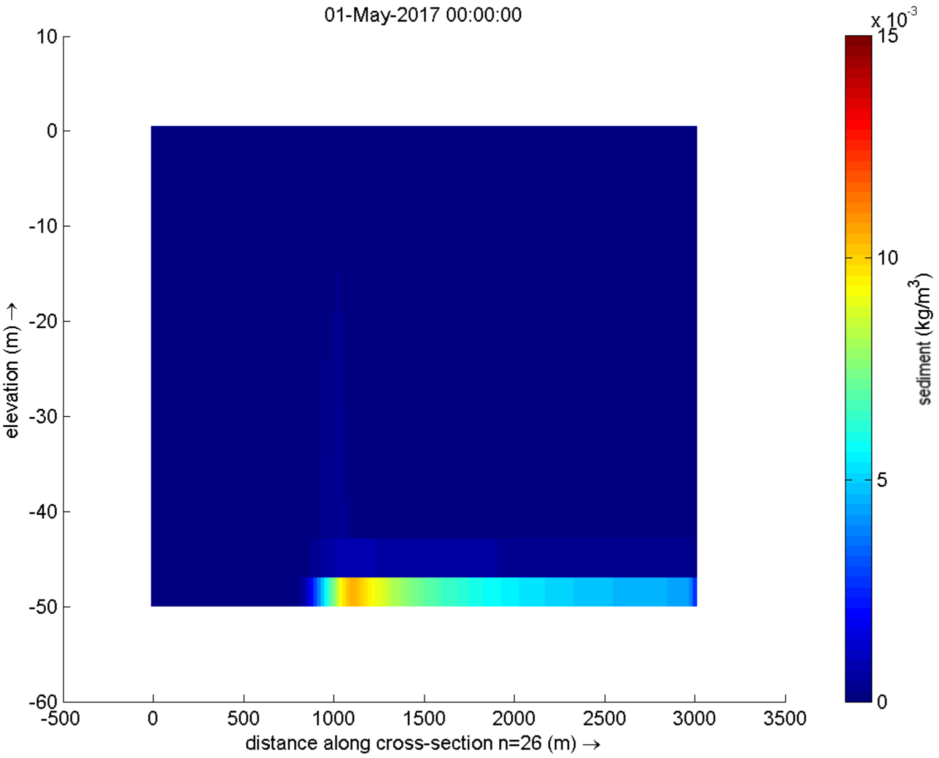


Figure C.5: Test 1 middle cross-section at the end of March showing the deposited waste



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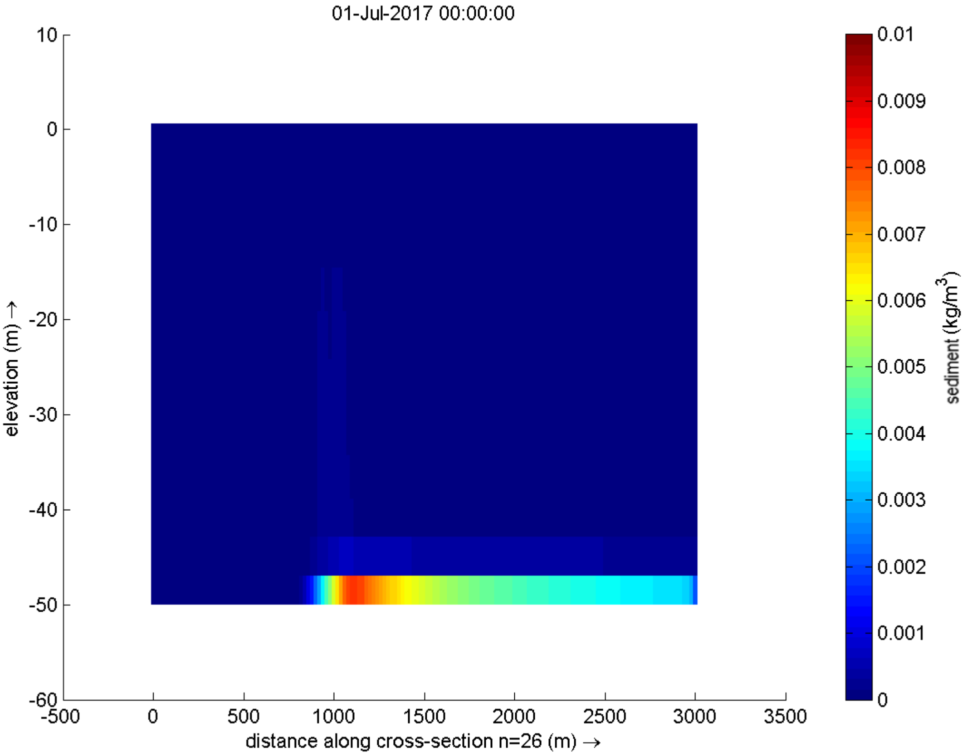


Figure C.7: Test 1 middle cross-section at the end of July showing the deposited waste

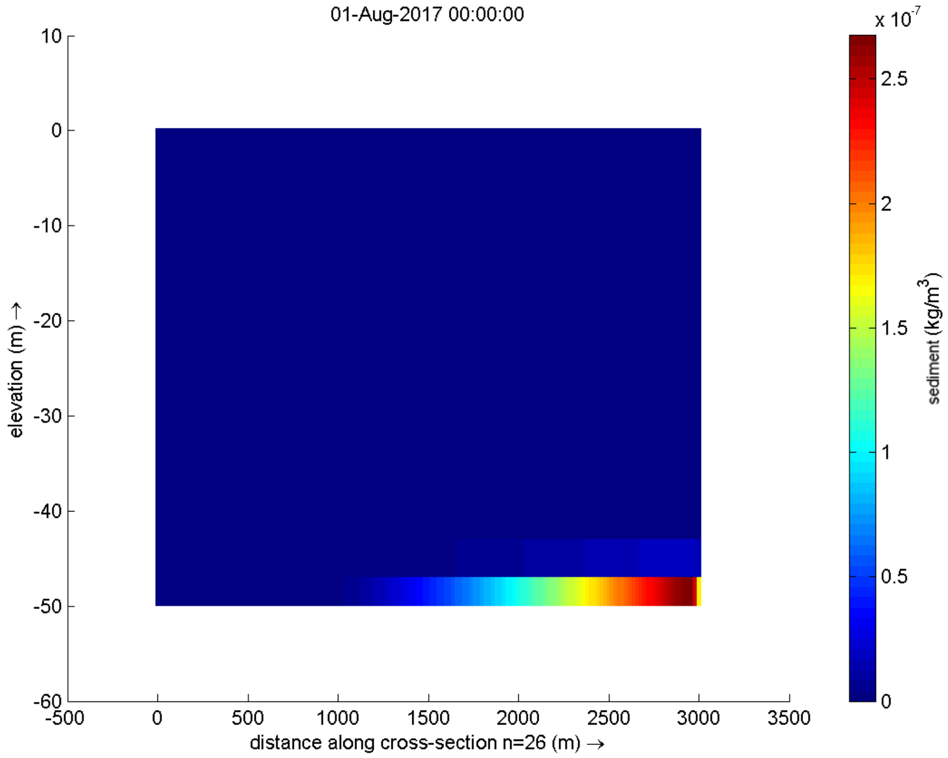


Figure C.8: Test 1 middle cross-section at the end of August showing the deposited waste

Chapter 10

Appendix D: Test 2 results

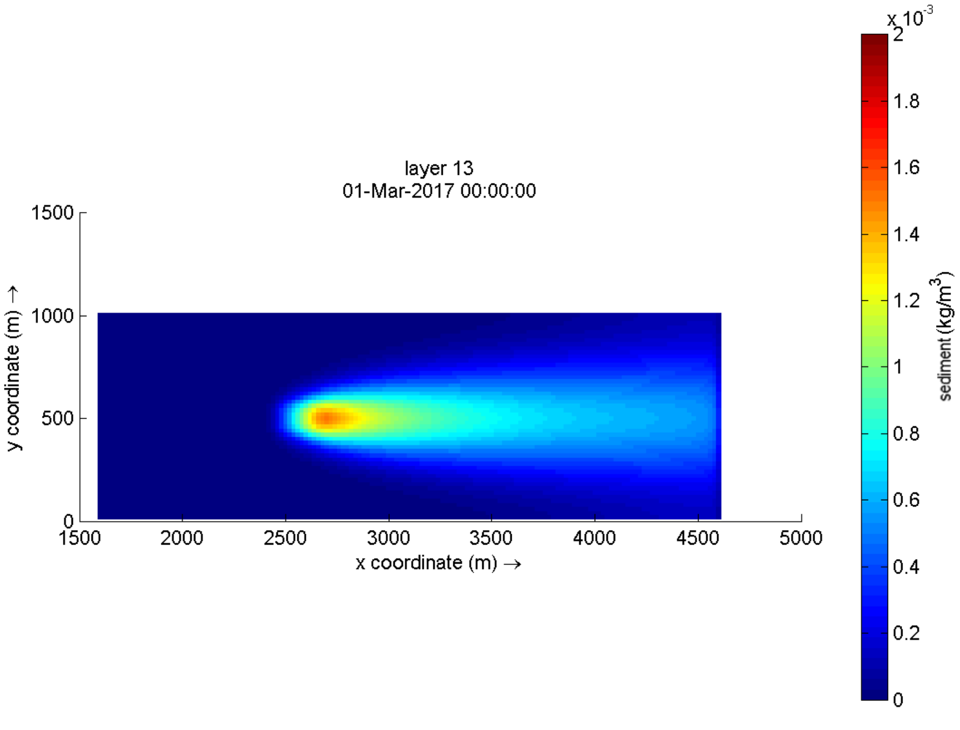
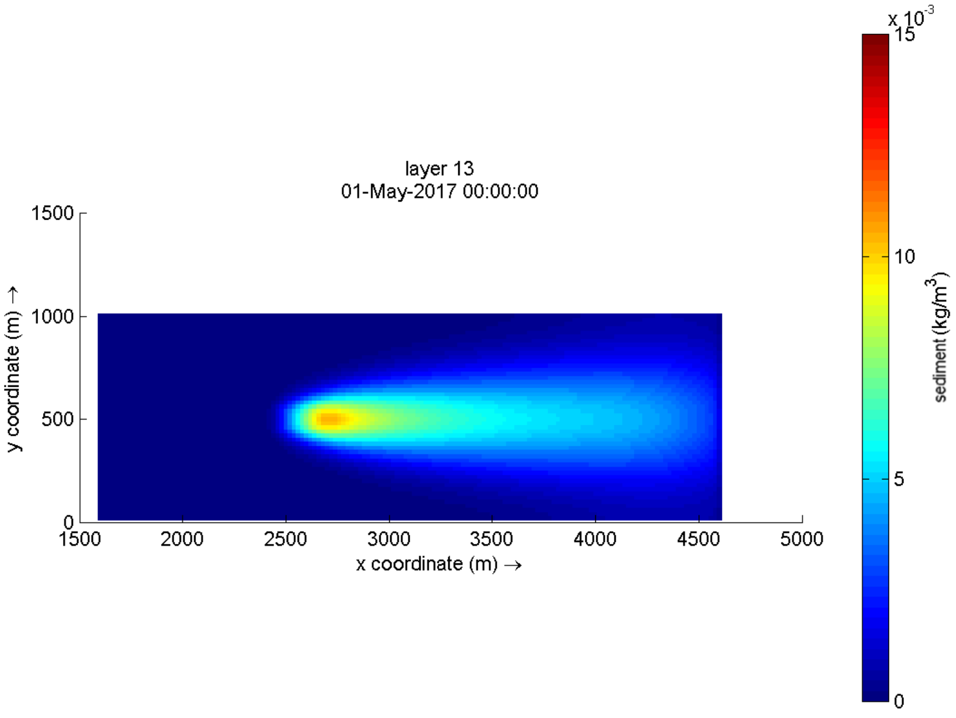


Figure D.1: Test 2 bottom layer at the end of March showing the dispersed waste



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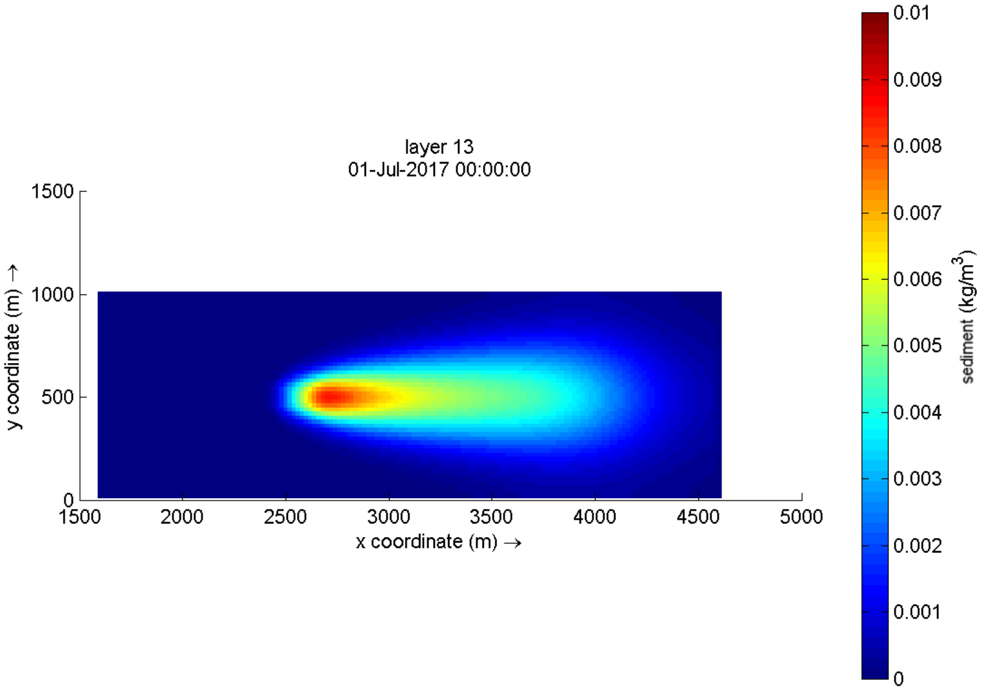

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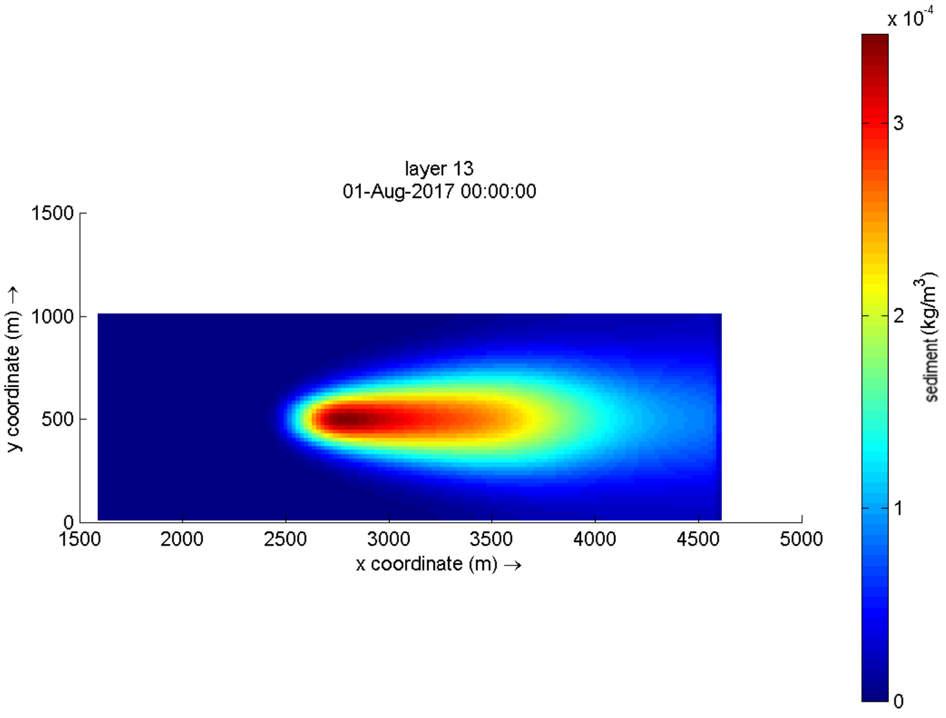


Figure D.4: Test 2 bottom layer at the end of August showing the dispersed waste

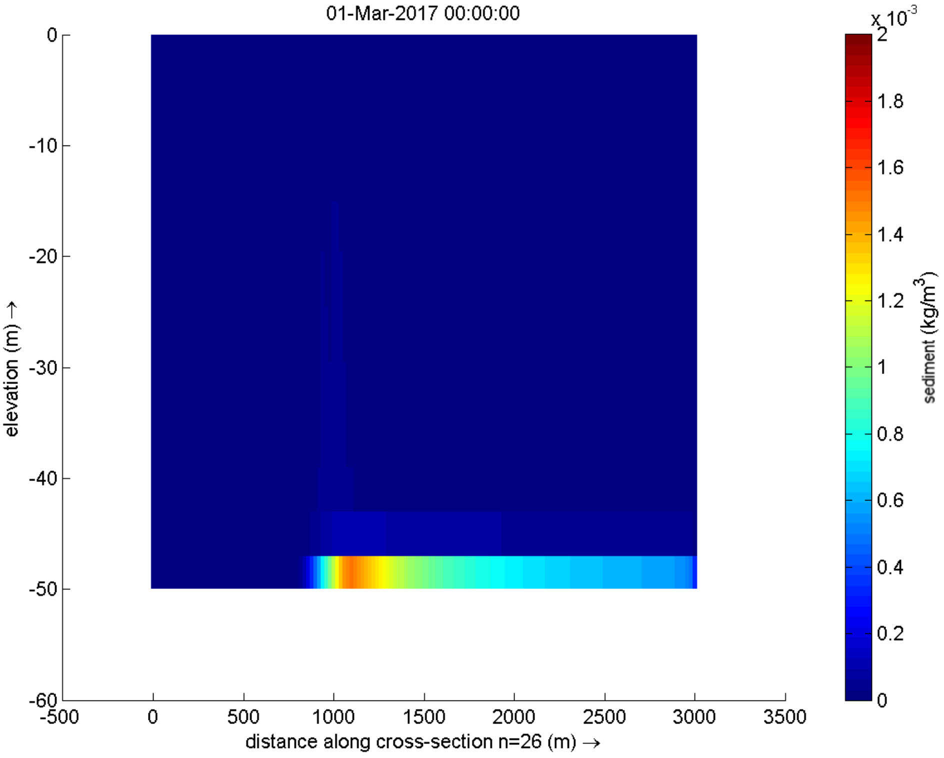
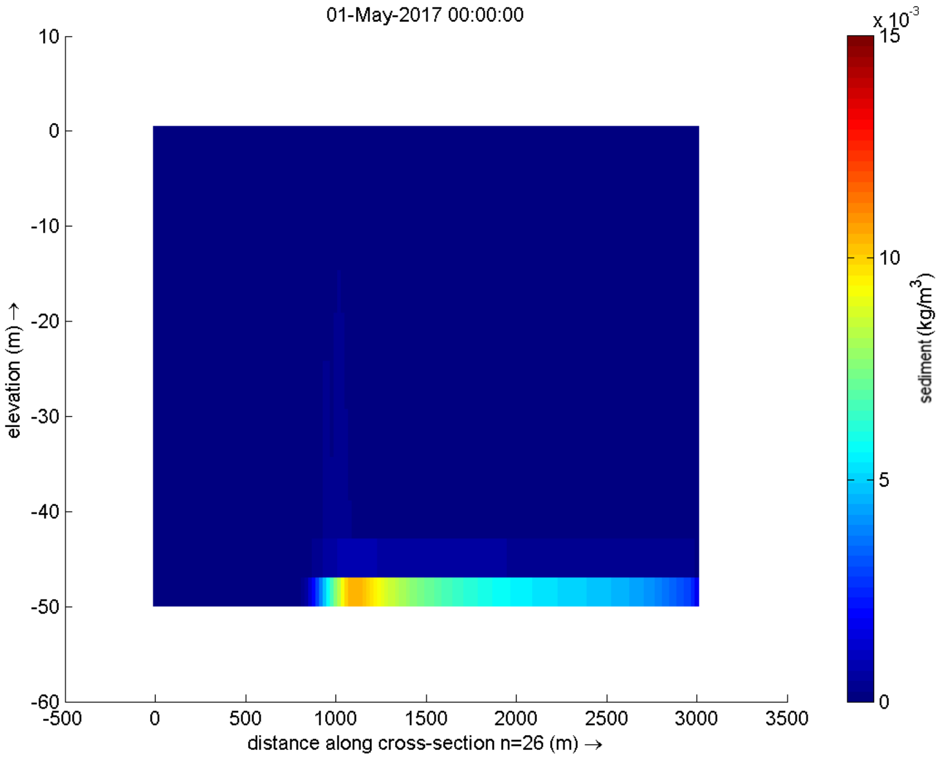


Figure D.5: Test 2 middle cross-section at the end of March showing the deposited waste



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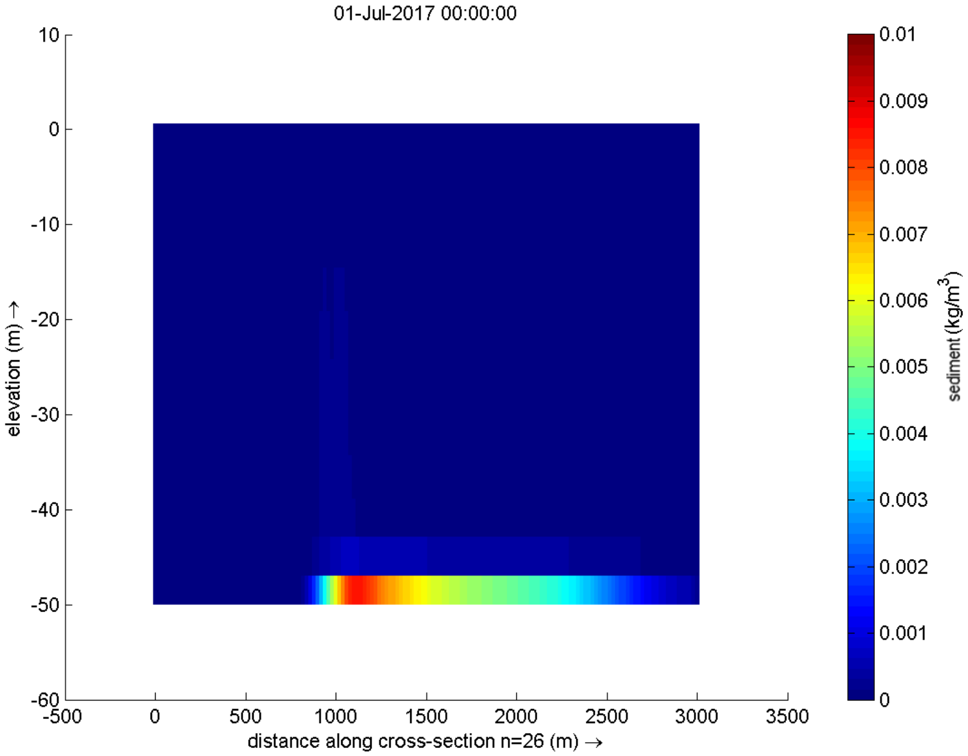

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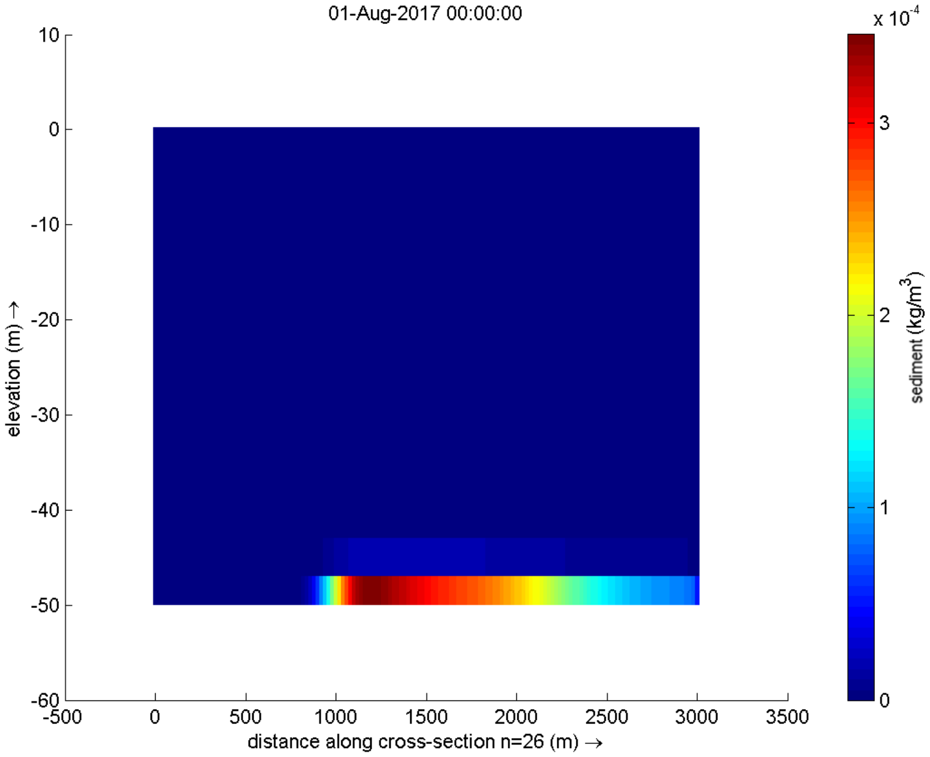


Figure D.8: Test 2 middle cross-section at the end of August showing the deposited waste

Chapter 11

Appendix E: Test 3 results

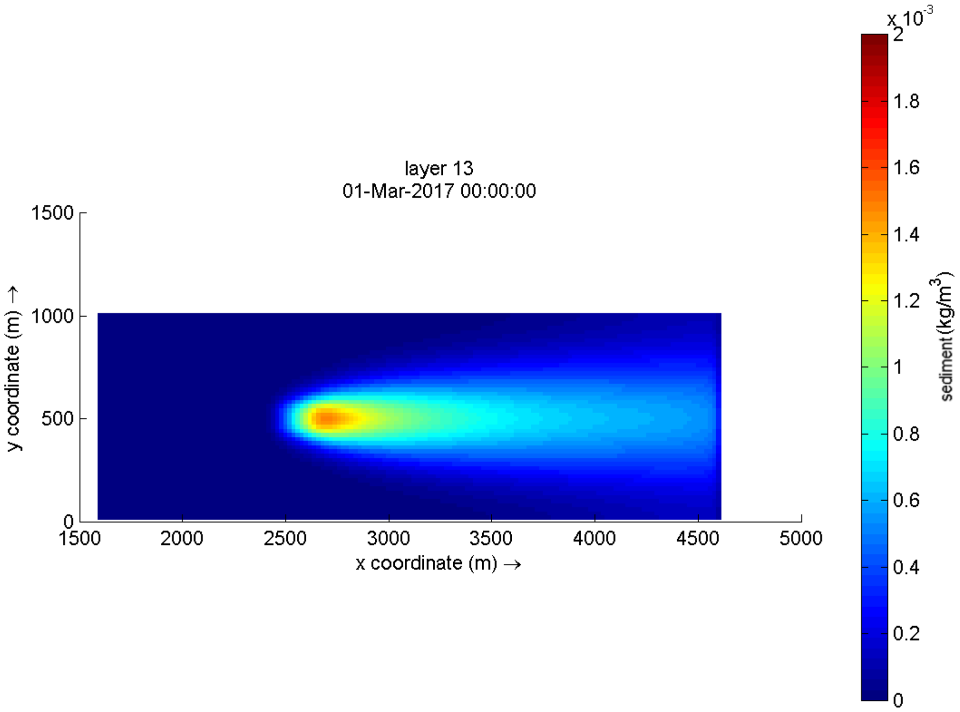


Figure E.1: Test 3 bottom layer at the end of March showing the dispersed waste

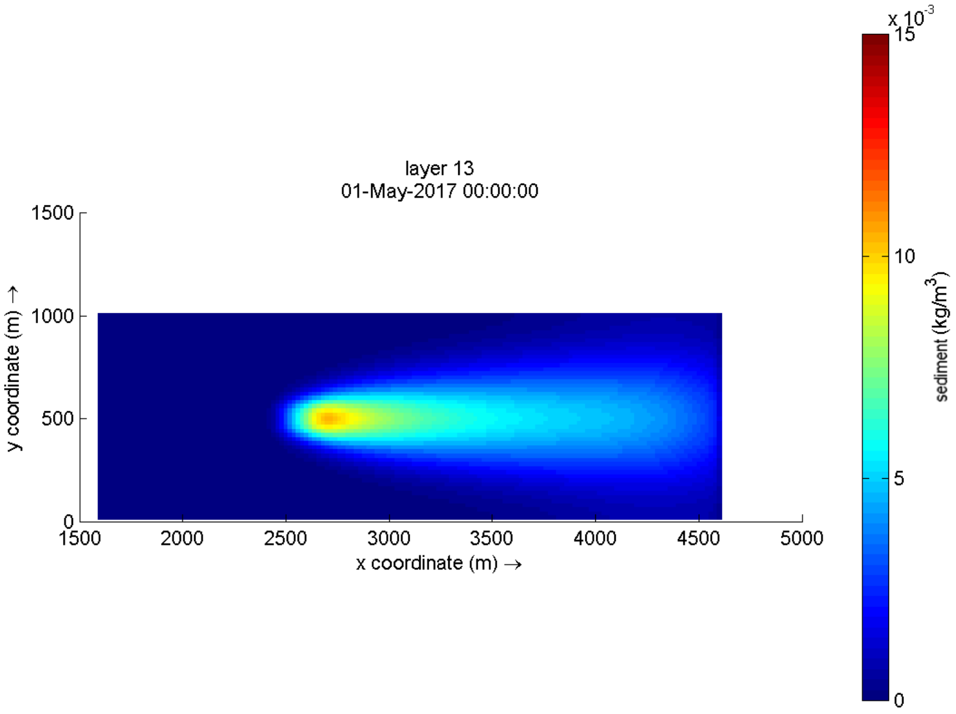
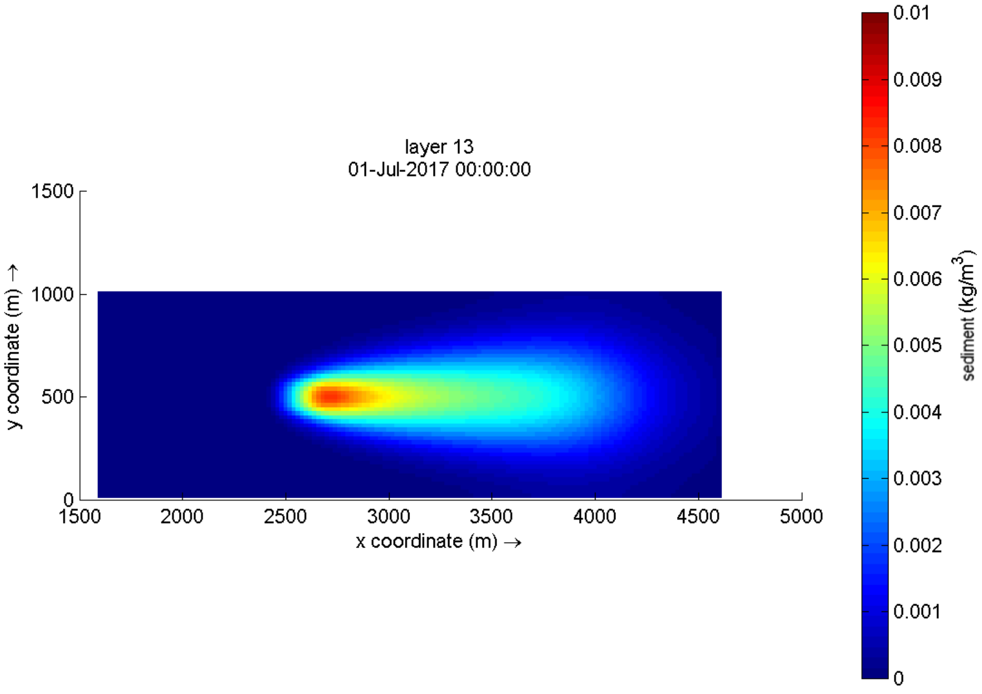


Figure E.2: Test 3 bottom layer at the end of May showing the dispersed waste



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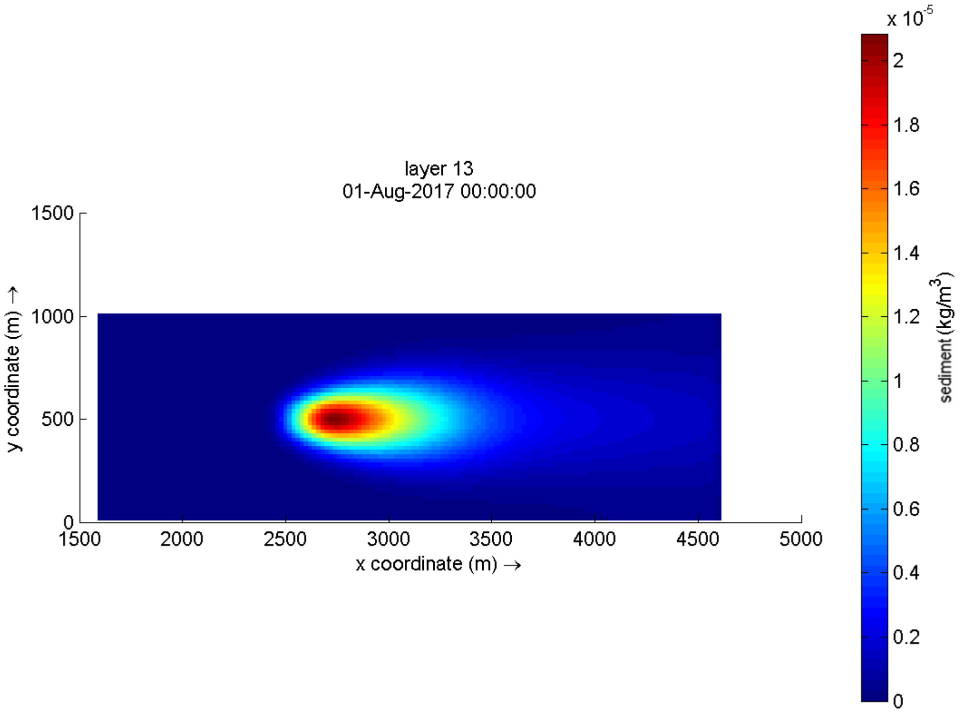

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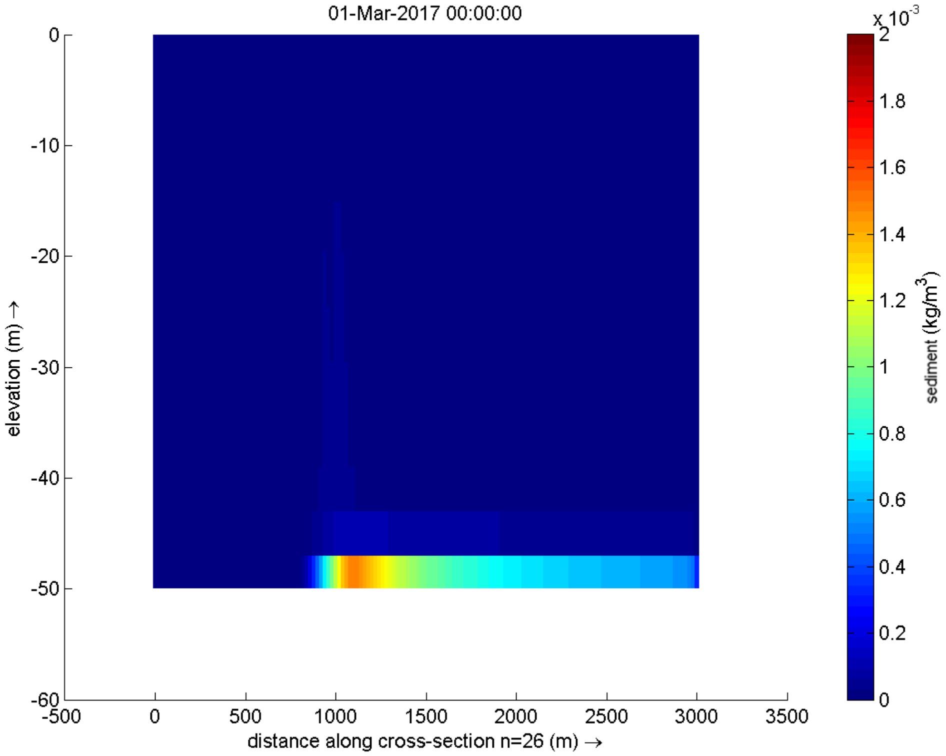
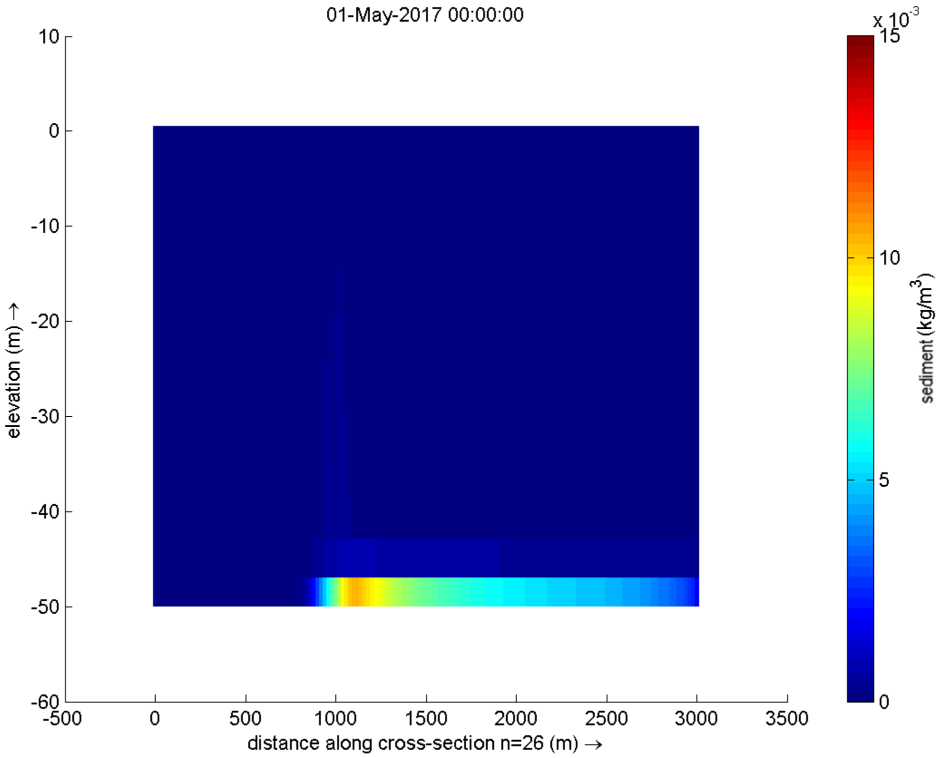


Figure E.5: Test 3 middle cross-section at the end of March showing the deposited waste



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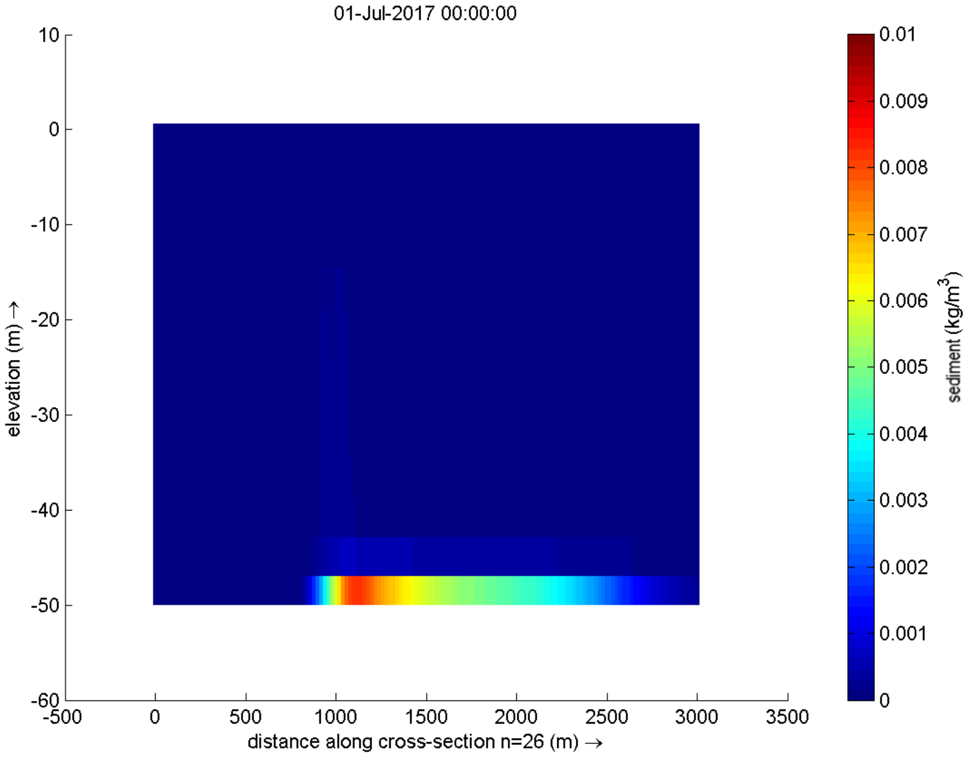

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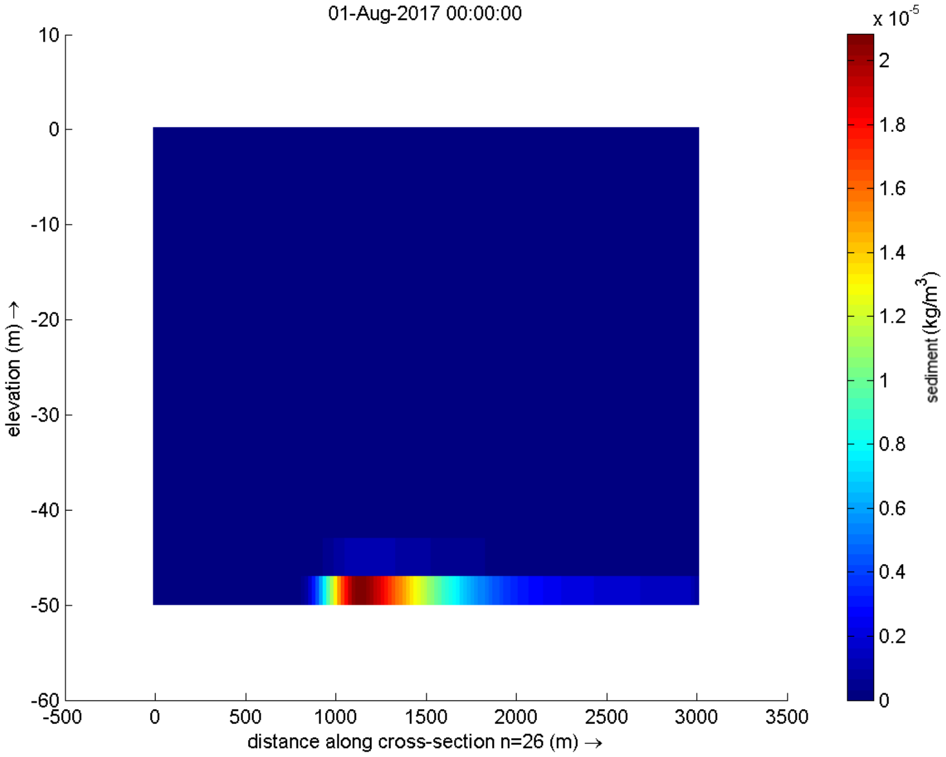

Figure E.8: Test 3 middle cross-section at the end of August showing the deposited waste