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Can state-of-the-art numerical modeling result in a more efficient and economic design of power plants?

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Abstract

In coastal regions, some power plants use ambient water for cooling, which increases the temperature of the water used. The behavior of the outfall plume has an indirect effect on the capital and operational cost of a power plant. The design of a power plant configurations is most often based on computer model predictions. Currently, separate models are available for the near field and far field, which are both dependent on the input values and assumptions made by the modeler. This makes it difficult for non-expert clients to judge the quality of the model outcomes. This study objectively investigated the added value of state-of-the-art recirculation modeling compared to a typical straightforward modeling approach for the optimization of the intake and outfall configuration of a power plant. Because of the wide range of variation in the above stated problem, the problem was assessed using a case study. This case was carefully chosen in order to capture the most important and relevant parameters such as the residual current, wind, ambient temperatures and a nearby river discharge.

Two models were set up, the first using a straightforward model approach (Approach A) and the second using state-of-the-art model approaches (Approach B). The aim of Approach A is to estimate the intake and outfall configuration with a quick and simple assessment. This was done by selecting a common consultancy practice model, a 3D far field model. The ambient conditions were selected based on common weather conditions. Approach B included state-of-the-art model approaches in order to assess the problems processes more physically correctly. This was achieved extending Approach A with a dynamically coupled near-far field model and selecting the ambient conditions with the SBAM-method.

In order to assure an objective design process, a design framework was set up beforehand, which included 18 predefined designs and fixed criteria to select the 'best' option. Based on the two models, two offshore intake and outfall configuration designs were proposed. The value of the two Approaches was evaluated base on offshore capital costs and recirculation costs.

In this case study, Approach A highly overestimated the temperature in the near field for all diffuser designs. Due to this, designs were rejected by our design framework that were found suitable in Approach B. The proposed design by Approach A will be located further into the sea resulting in a longer outfall pipeline. This results in an additional \$1.035 million capital costs for the Approach A based design compared to the Approach B based design, an increase of 23%. Furthermore, additional maintenance can be tens of thousands of dollars per year and the operational costs will also be larger for a design with a longer pipeline system.

For all investigated designs, the yearly averaged intake temperature assessed by Approach A was within 30% of the assessed intake temperatures of Approach B. In terms of recirculation costs, this amounts to a difference of \$300.000 in the lifetime of the power plant.

In conclusion, this case study helps to clarify that cases exist where an added-value for a state-of-the-art modeling approach can be found. In terms of capital costs, a state-of-the-art approach based design is expected to have smaller capital costs because suitable designs are rejected by the straightforward approach which are not rejected by a state-of-the-art model. This study also suggested, that the recirculation costs computed by a straightforward based model are overly optimistic, in case of a diffuser design. This could result in unforeseen costs for the operator. Finally, the results obtained from this case study suggest that a state-of-the-art approach has limit added value when designing an open surface outfall but it is expected to be more when less advantageously scenarios are selected in the straightforward approach. Finally, the model results of a state-of-the-art based model approach are less sensitive to the models input and thus expected to be more reliable.

Preface and acknowledgments

After two years of study, this thesis is my final project for the Master Civil Engineering and Management at the University of Twente. I am strongly interested in the mix between technology and management and this thesis is the perfect combinations of these two worlds. This master thesis has to goal to objectively investigate the differences between straightforward and state-of-the-art modeling methods when designing the intake and outfall configuration of a power plant. To this end, I set-up both a far and near field model, used a state-of-the-art coupling method and used the SBAM method to select ambient conditions. I was able to learn a lot about numerical modeling and I am all employees and students very grateful that they helped me in difficult times. Furthermore, working at Deltares gave me the opportunity to meet a lot of new interesting people with different backgrounds. I enjoyed to be able to participate and experience a famous consultancy company such as Deltares.

I would like to thank all the people who helped me with this thesis. First of all, Robin Morelissen for arranging this project, his expertise and time, the excellent help and keeping me positive in difficult times. I would like to thank Pieter Roos and Kathelijne Wijnberg for the good feedback and guidance. Thirdly, I would like to thank all the student at Deltares for the warm welcome, nice lunch breaks and the fun football tournament. Finally, I especially would like to thank Marnix for all his support, inexhaustible patience and interest.

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CHAPTER 1

Introduction

The number of power plants is globally increasing and the capacity of existing power plants is extended. In coastal regions, some of these power plants use ambient water for cooling, which increases the temperature of the water used. In the so-called once-through cooling method, the sea-water is discharged back into the sea after the cooling process. Power plants may thus have a large influence on the ambient environment because the typical temperature increase is around 10°C (Bleninger and Morelissen, 2015; World Nuclear Organisation, 2015). Furthermore, the discharge for newly built power plants can be up to hundreds of cubic meters per second (Morelissen et al., 2015). Therefore, environmental quality standards are set near the outfall location to protect to local natural environment. These standards have to be met to be allowed to build the power plant. High dilution rates are preferred in order to reduce the effects on the ambient environment as much as possible.

Regarding the plume's behavior, we distinguish three zones; the near, intermediate and far field. The near field is dominated by initial momentum and the far field behavior is governed by ambient flow conditions. The intermediate field is the transition zone between these fields. The effluent is relatively warm compared to the ambient water, which creates a positive buoyant plume that will rise to the surface. The outfall type, as well as other design parameters such as the discharge rate, has an influence on the plume's behavior. The most common outfall type is a surface outfall because it is cheap and easy to build. However, the outfall plume is not quickly diluted. By using a diffuser outfall instead, at least a 5-10 times higher mixing efficiency can be reached (Jones et al., 2007). A diffuser is a long pipe with a (large) number of outfall ports. However, the capital costs are much higher for a diffuser than for a surface port.

Additionally, the plume's behavior has an indirect effect on the capital and operational cost of a power plant. Operational costs are related to the energy needed for operation, e.g. the amount of pumping needed, and the required cooling capacity, e.g. the intake temperature. If the intake temperature is higher, the power plant condenser will be less efficient regarding heat transfer. This results in a lower efficiency rate and consequently less power output and a lower revenue. Assessing the plume's behavior can therefore help to make an optimal intake and outfall configuration in order to achieve the highest revenue. Computer models are an important tool for modeling the plume's behavior. The design of a power plants configuration is most often based on these computer model predictions. The different plume behavior zones and ambient conditions are a challenge for modelers. Currently, separate models are available for the near field and far field, which are both dependent on the input values and assumptions made by the modeler. This makes it difficult for non-expert clients to judge the quality of the model outcomes.

Problem statement and objective

The problem statement of this project is:
New modeling approaches have been developed to provide more accurate and comprehensive design information with the goal of a better design of the intake and outfall of a power plant. However, it is difficult for non-expert clients to identify the differences and possible benefits of the different

modeling approaches. Therefore, the added value of these improved modeling approaches should be objectively quantified to make the different model approaches distinguishable for non-expert clients.

Therefore, the research objective of this thesis is to objectively investigate the added value of state-of-the-art recirculation modeling compared to a typical straightforward modeling approach for the optimization of the intake and outfall configuration of a power plant.

The main research question of this thesis is:
Could the usage of a state-of-the-art recirculation modeling approach result in a better intake and outfall design, compared to a straightforward model approach?

Theoretical background and model definition
A thermal power plant produces electrical energy in 4 steps, based on the so-called Rankine cycle. First, the water is converted into steam inside a boiler, for example by burning fossil sources or by a nuclear process (Turchi et al., 2010). Hereafter, the steam is transported into a turbine, where a shaft is set to motion linked to a generator which produces electric energy (Mohsen, 2004). The steam leaves the turbine and is condensed into water (Mohsen, 2004). As the temperature difference between the condenser water and the external water decreases, the heat exchange also decreases resulting in a decreasing power plant efficiency. Therefore the external water temperature is preferred to be as low as possible. Only a few studies investigated the relation between intake temperature and the efficiency of a power plant. However, Tramel (2000) describes the relation between the heat rate of the condenser compared to the intake temperature. The heat rate is a unit that describes the amount of energy input needed to produce a certain output, which can be understood as the reverse of the efficiency of a power plant.

There are three commonly used numerical model approaches in the near field (Palomar et al., 2012). The integral model approach is a detailed, physically correct and typically used model approach. The differential equations of transport and water motion cross-sectionally integrated in order to make them easier to solve. Commonly used integral models are CORMIX (Jirka et al., 1996), VISJET (Cheung et al., 2000) or Visual Plumes (Frick, 2004). They all have their own approach and should be used with caution to avoid unreliable model results (Palomar et al., 2012; Schreiner et al., 2002). For quick understanding of a complex case, a dimensional analyis model approach could be used (Palomar et al., 2012). An example of this approach is the classification of the plume behavior by Jirka et al. (1991). Finally, a Computational Fluid Dynamics (CFD) model approach is the most comprehensive and accurate model approach. It computes all flow characteristics at defined points in a grid, but the computational time is longer. Therefore, this model approach is less commonly used in the near field (Palomar et al., 2012; Bleninger, 2006). However, it is becoming more used.

In the far field, a numerical model is recommended because the results are accurate and the grid sizes are larger resulting in acceptable computation time. Examples of this type of hydrostatic 3D-models are Delft3D, MIKE and EFDC. These models can be classified in terms of their numerical schemes (Bleninger, 2006).

A simple solution to model the entire plume trajectory is to use the far field model also in the near field. This has the disadvantage of the results becoming very sensitive to the chosen grid sizes, especially the dilution and plume width (Bleninger and Morelissen, 2015). These kinds of methods are often the foundation of the design of an intake and outfall configuration. In this MSc project, this approach will be called *Approach A*.

A state-of-the-art approach is coupling the near and far field. Each model is then used to predict the characteristics in their own zone but the models exchange relevant information to predict the entire plume trajectory. Blumberg et al. (1996) and Zhang (1995) were the first investigating the coupling of the near and far field. They found that the modeled trap height, i.e. the plume's rise, and initial dilution were similar for both near and far field models. Hereafter, Zhang and Adams (1999) introduced several coupling methods based on the predicted trap height of the near field model. Several later studies showed that coupling the near- and far-field models give accurate outcomes (Kim et al., 2002; Suh, 2006; Morelissen et al., 2013; Nekouee et al., 2015). A state-of-the-art coupling approach is the Distributed Entrainment Sinks Approach (DESA) (Choi and Lee, 2007). In this method entrainment sinks are incorporated to preserve the mass balance. It is considered to improve the physical representation of the plume's behavior (Choi and Lee, 2007; Bleninger and Morelissen, 2015).

Another state-of-the-art model approach is the so-called Scenario Based Adaptive Modelling (SBAM) (de Fockert et al., 2011; Verbruggen et al., 2014). This is a comprehensive approach to deal with varying ambient conditions. It involves incorporating the most common plume trajectories instead of the most common ambient conditions. Both de Fockert et al. (2011) and Verbruggen et al. (2014) state that this method results in more reliable and representative model outcomes than the traditional approach.

For this research, the *State-of-the-art approach* is a model that includes both a near and far field model. These are coupled with the DESA method in combination with ambient scenarios selected based on the SBAM method. This model approach will be referred to as *Approach B*.

Outline of methodology

Because of the wide range of variation in the above stated problem, we tackle this problem with a case study. This case was carefully chosen in order to capture the most important and interesting parameters. Two models were set up, the first using a straightforward approach (Approach A) and the second using state-of-the-art model approaches (Approach B). Approach A is a 3D far field model. This model is extended by a dynamically coupled near field model and the SBAM method to form Approach B. Based on these two models, two offshore intake and outfall configuration designs were made. In order to assure an objective design process, a design framework was set up beforehand. This framework includes 18 predefined designs and fixed criteria to select the 'best' design option. The differences between the two model approaches were estimated in terms of operational costs, based on the known relation between the heat rate and the intake temperature in the power plants condenser. Furthermore, the offshore capital costs were considered. The research choices that were made to create a feasible study are described in Chapter 2. The methodology and model set-up are described in more details in Chapter 3 and 4 respectively.

Relevance and innovation

This project will bring insight regarding the need for comprehensive models of plume behavior. This study is one of the first projects to link model approaches to operational costs of a power plant.

As well, this project is useful for both consultancy agencies and their non-expert clients, since it will give consultancy agencies an extra tool to show the quality of a model and it helps them to get insight in the effectiveness and need for comprehensive modeling.

This research could also be interesting for the desalination sector, where currently the same model approaches for the assessment of the plume behavior are used. Desalination is the production of fresh water by removing the salt from salty water, for example from seas or brackish estuaries. Currently the same model approaches for the plume behavior are used in this study field. Therefore, the outcomes of this study might also be valid for modeling a brine plume.

Reading guide
First, Chapter 2 will describe the research requirement and develops a rough research framework. Chapter 3 will give all used method in detail. In this chapter, the characteristics of the study area will be described followed a description of the optimization framework. This chapter ends with a section on the costs assessment and model description. Hereafter, Chapter 4 will describe the model set-up of both approaches. Chapter 5 presents all results. First by comparing the two approaches and then comparing the design choice. All findings will be discussed in Chapter 6. Finally, this reports ends with the conclusions and recommendations in Chapter 7.

CHAPTER 2

Research framework

The research objective described in the previous chapter covers a wide range of processes. Furthermore, the objectiveness of this study should be secured. Therefore, the used methods in this study should be chosen such that these requirements are met. This chapter describes the conditions which the methods should fulfill.

Case study

The introduced problem was investigated with a case study because the research objective set in Chapter 1 involves a wide range of variation in parameters. The disadvantage of a case study is that it is not all encompassing. Thus, the case area should be carefully chosen such that it is representative. Therefore, the case area should be a typical and complex area. It should be forced by several relevant and typical ambient processes. Furthermore, none of these processes should be highly dominating the system. The details of the chosen case area are given in Section 3.1.

The investigated power plant should have a typical temperature increase. The discharge should be relatively large because the effect on smaller discharges can be estimated based on this.

Optimization and selection framework

In this research, a 'best' design should be recommended to a fictions client. This involves an optimization process. However, the research objective asked for an objective and fair optimization process. Therefore, an optimization framework was set up. This framework should be feasible considering the amount of simulations because of the expected long simulation times. Furthermore, this framework should be able to handle the large amount of correlated variables. Therefore, 18 possible design options were set-up in advance of which the 'best' option will be chosen. The variables that are expected to cause the largest differences are the intake/outfall type and their location. It should be noted that this framework will not result in the optimal design, because the designing process is more iterative and more parameters are involved when a site specific design is made. However, such a precise optimization is not the goal of this project. Additionally, the objectivity of this study is guaranteed by the use of a selection scheme for selecting the 'best' design option. The scheme was set up based on common requirement from the power plant developers. This in order to simulate the design processes the most realistic. Section 3.2 will give the site specific characteristics of this framework and the used selection framework.

Cost assessment

In this study, we use the capital costs (CAPEX) and operational costs (OPEX) of a power plant to investigate the added value of state-of-the-art modeling. The scope of the research is to create a design of the intake and outfall configuration only. Therefore, only the offshore costs are considered in the cost assessment.

The operational costs of the intake and outfall configuration of a power plant consist of many elements such as; electricity costs for the pumps, head loss costs, cleaning of the intake screens and recirculation costs (DNVL-GL, 2015). In this study, only the recirculation costs are taken into account because this is strongly related to the modeled intake temperature. Furthermore, the relation between intake temperature and recirucaltion costs is not yet investigated and is therefore a new interesting element. Section 3.3 describes the costs assessment in detail.

Model requirements

Many models are available that assess the plume behavior. The accuracy and complexity are different per model approach. Figure 2.1 shows an overview of the available models. It is very important to note that the accuracy is highly depended on site specific characteristics.

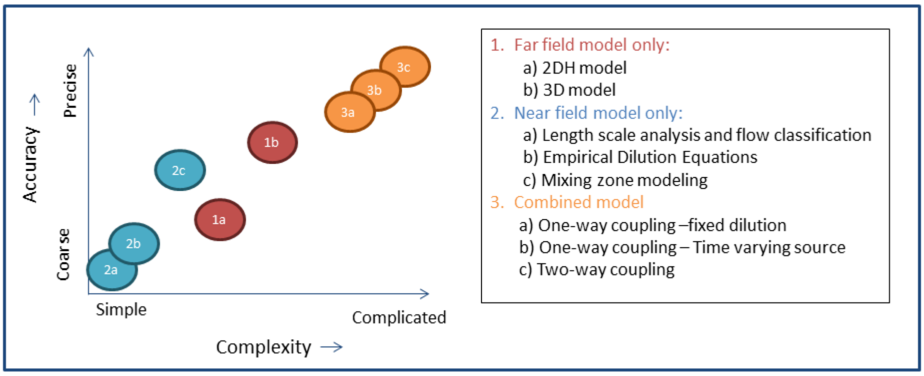


Figure 2.1: Very rough comparison of the available models to assess the plumes behavior. Please note that the accuracy is highly dependent on the ambient characteristics.

The most simple approach to model the plume behavior are Rapid Assessment Tools such as the Length scale analysis and flow classification or the use of Empirical Dilution Equations (Bleninger and Morelissen, 2015). For example, initial fluxes and ambient conditions are used to classify the plume behavior in the Length scale analysis. These tools can only incorporate simplified ambient conditions and are therefore only used for a quick initial assessment to identify unproblematic discharges. These approaches are not complex enough to be used for designing the intake and outfall configuration.

Most often, far field models are used to design the intake and outfall configuration. However, the accuracy of the far field model is dependent on the model choices. For example, the accuracy is lower if a 2D model is created instead of a 3D model. A 2D model is not capable to assess the plume behavior accurately because it is expected that the large water depth in the grid point dilutes the plume quickly. The disadvantage of a 3D far field model is that it is not able to assess the near field accurately. However, this model approach is a common consulting standard. Another option is to use a near field model only, but these models are less accurate in the far field. Therefore, they are less suitable

The most complex option is to couple a near and far field model. This can be carried out using a one-way or two-way coupling method (Morelissen et al., 2015). A one-way method includes a fixed diluted source, predicted by the near field model, as input for the far field model. Two-way coupling, also referred to as dynamic coupling, is a method that incorporates the interaction between the near and far field processes by updating the ambient conditions in a sufficiently small time interval (Zhao et al., 2011). Morelissen et al. (2015) showed, in a case study of a large outfall system of a power plant, that dynamic coupling represented the physical processes better than an one-way coupling method.

To be able to give a fair and reliable answer to the research question, the state-of-the-art model (Approach B) should be compared with a model that is a common consulting standard (Approach A) and is able to reasonably accurately assess the behavior of the plume. Furthermore, Approach A has the purpose to be a simple and quick model that is able to capture the thermal plume behavior and ambient conditions influencing this process. Therefore, Approach A will be a 3D far field model. Approach A is able to incorporate the variation of all ambient conditions in the case area and the differences in temperature and salinity. Furthermore, the model should have simulation duration of maximum 24 hours.

Approach B should be able to capture the same processes as Approach A. However, this model approach has to assess the physical process more accurately. Therefore, the far field model of Approach A is extended by state-of-the-art model approaches to form model Approach B. The state-of-the-art model approaches we use in this study will be the SBAM scenario selection method and the far field model is dynamically coupled with a near field model. The main difference between the scenario methods is thus that the scenarios of Approach A are chosen before modeling starts. Approach B includes SBAM which finds the best ambient conditions during modeling by uses an iterative approach.

Approach A: a 3D far field model forced by ambient scenarios that are selected based on common weather conditions, see details in Section 4.1 and 3.1.3 respectively.

Approach B: the far field model of Approach A is dynamically coupled with a near field model, see Section 4.2. In addition, the SBAM method is used to select the ambient scenario, see Section 5.1.1.

CHAPTER 3

Case description and optimization framework

This chapter describes the methods used in this study. First, the description of the study area is given. Hereafter, the selection framework is elaborated in section 3.2. Finally, the cost assessment is presented in section 3.3.

3.1 Case description

In order to answer the research questions, first a fictitious power plant and study area were chosen. Such study case represents a typical assignment for Deltares, as already stated in Chapter 2. The fictitious study area will be described first in Section 3.1.1, followed by the characteristics of the power plant in Section 3.1.2.

3.1.1 Study area

The selected case area is Vung Ang in the Northern half of Vietnam. This area fulfills all requirements set in the previous chapter. The Vung Ang area contains several relevant and typical ambient processes in this field of study. Some of these processes are: a river discharge near the power plant, a residual current and varying wind. None of these processes is highly dominating the system. This case was based on a typical assignment that Deltares carried out. An overview of the shoreline and an overview of the influencing processes are given in Figure 3.1, and details of the ambient processes will be discussed now. Detailed information is required in order to be able to perform a SBAM based data selection. Furthermore, this is required to keep this study realistic.

Wind Due to the positive buoyancy of the plume, the wind can have an influence in the far field. Changing wind conditions could alter the plume's direction. Furthermore, the cooling of the plume can intensified by a strong cool wind. For this case study, typical wind conditions were extracted from the CFSR database. A typical wind rose from the wind data between 2000-2010 is presented in Figure 3.2. The wind direction is strongly varying in the area with an average wind speed around $3m/s$. Storms seem to occur mostly from the North. Another remarkable feature of this area is that in some months the wind direction is varying during the day. A good example of this is March, as can be seen in Figure 3.3. This variation was found in March till May and in August and September. A hourly changing wind direction could have an impact on the plume dispersion.

Tide This study area is forced by an semidiurnal tide. The tidal range in the area is up to 1.6 meters. It is expected that the variation in the tide during the year has a relatively small impact on the plume's behavior compared to the other processes. However, the variation in the spring-neap circle will have an influence because of the changing water levels.

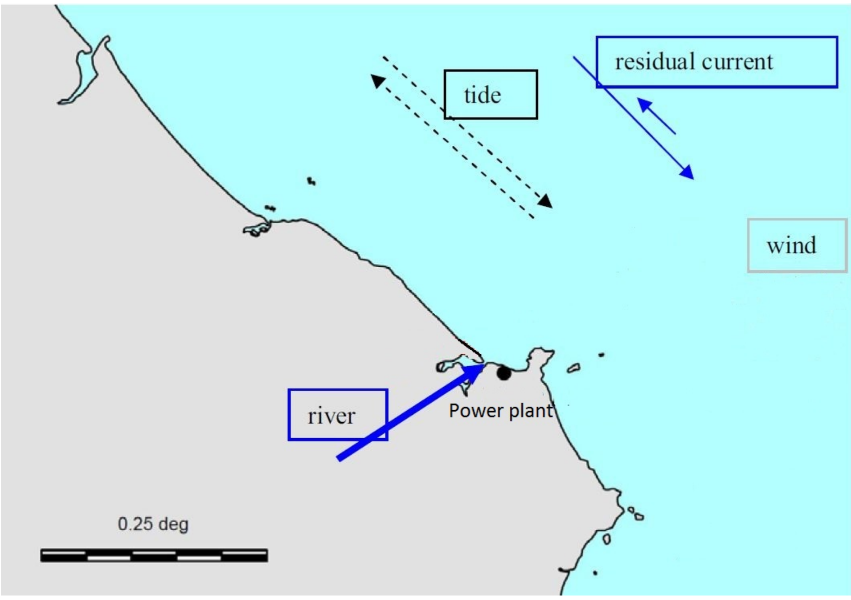


Figure 3.1: Overview of study area with ambient conditions, modified from de Fockert et al. (2011).

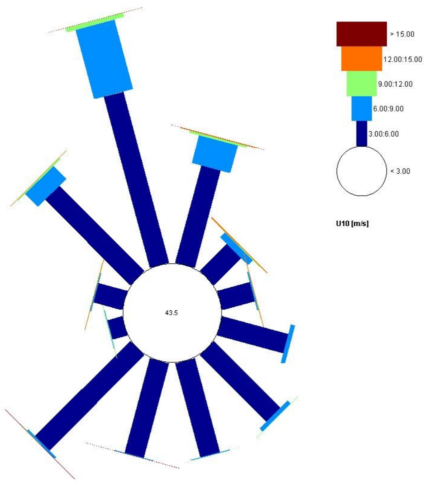


Figure 3.2: Wind Rose for this case study based on data 2000-2010 (CFSR, 2016).

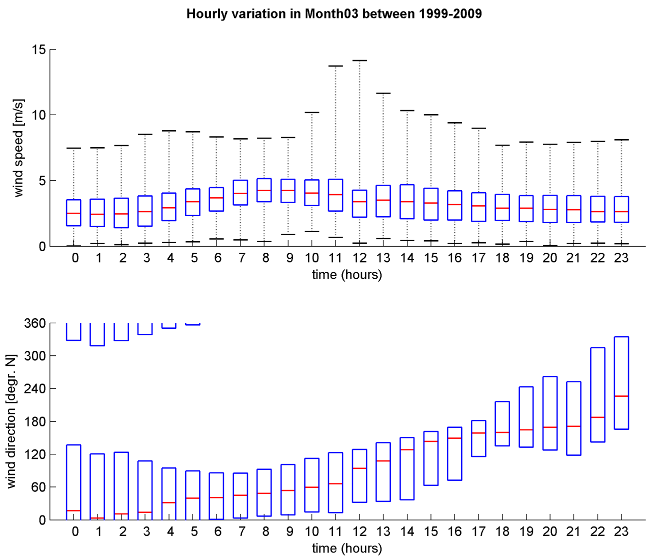


Figure 3.3: Hourly variation in March, produced from data between 1999-2009 (CFSR, 2016).

River Tropical regions generally have a dry and a wet season, hence the river discharge of this case can be classified into a dry, January till July, and a wet, August till December, season discharge. In Table 3.2, an overview is given of the river discharge of this fictitious river, based on Deltares (2010). It was estimated that in an extremely wet season the maximum discharge can be up to 170 m^3/s.

Water depth The case area consist of a gentle and constant slope. No large irregularity are noticeably besides the land abutment in the middle of the case area. The depth profile is given in Figure 4.3.

Residual Current Manh and Yanagi (2000) showed that residual current in the Gulf of Tongking is induced by wind. The case area in this study is located in this gulf, and therefore the residual current found by Manh and Yanagi (2000) are used in this study. The range of the residual current can be found in Table 3.1. The residual current in related to the seasonal variation in the wind field.

Temperature Table 3.2 shows some typical mean air and sea temperatures for a tropical region. The difference between the air and sea temperature is small or even equal.

3.1.2 Power plant

The intake and outfall configuration for this study will be carried out for a ficitous power plant with the following characteristics:

- A constant intake and outfall discharge of 50 m^3/s.
- A constant relative outfall temperature of $\Delta T = 8°C$ compared with the intake temperature. This is a typical value for power plants.

- The power plants consists of four units each producing 150 MW, producing 600MW in total.

Table 3.1: Residual current per month according to (Deltares, 2010) and hourly wind variation.

Month	Residual current velocity $[cm3/s]$	Residual current direction	Hourly wind variation
January	0/5	SE	Persistent
February	0/5	SE	Persistent
March	0/5	SE	Variable
April	0/5	SE	Variable
May	0/5	SE	Variable
June	0/3	SE/NW	Persistent
July	0/3	SE/NW	Persistent
August	0/3	SE/NW	Variable
September	0/3	SE/NW	Variable
October	0/5	SE	Persistent
November	0/5	SE	Persistent
December	0/5	SE	Persistent

Table 3.2: Typical river discharge, tropical air and sea temperatures used for this case study

Month	River discharge $[m^3/s]$ (Deltares, 2010)	Mean air temperature $[°C]$ (The Weather Company, 2016)	Mean sea temperature $[°C]$ (Deltares, 2010)
January	6	19	19
February	1	21	20
March	0	24	22
April	0	26	25
May	0	32	28
June	0	32	29
July	0	29	29
August	18	30	29
September	76	29	29
October	118	26	27
November	70	25	24
December	36	18	21

3.1.3 Straightforward selection of ambient scenarios

Based on the characteristics described in the previous chapter, a quick and commonly used method to select the ambient scenarios can be carried out. In this method, ambient scenarios are selected based on on non-extreme weather conditions. This is a common practice and will be used in Approach A. Therefore, the scenarios for Approach A are based on the two main seasons in a tropical region: the wet and the dry season. Looking at the river discharge, a clear distinction can be made; Augustus till January is the wet season and February till July is the dry season, see also Table 3.2. For the dry season, a river discharge of 0 m^3/s is the typical event, whereas the wet season will be represented by a discharge of 70 m^3/s.

Based on these two seasons, representative wind conditions are selected. From Table 3.1 it can be seen that within the dry and wet season the wind direction can highly differ. Therefore, different wind conditions have to be picked for both seasons to resemble scenarios for both seasons. The average wind speed is constant during the day in all months.

Based on this analysis, a varying and persistent wind direction was selected for each season. January represents a persistent wind condition in the wet season, the persistent wind condition for the dry season will be represented by the month July. A varying wind will be represented by the month September for the Wet season and March for the dry season. From the data, a representative year was chosen, this was based on the monthly variation. The applied water temperature differs per ambient scenario, see Table 3.2. Therefore, the corresponding averaged ambient temperatures for each season was imposed to assure the most realistic scenarios. The chosen ambient scenarios for Approach A can be found in Table 3.3.

Table 3.3: Ambient scenarios for Approach A

Scenario	Season	Discharge [m^3/s]	Wind condition	Ambient temperature [$°C$]
1	Dry	0	Persistent (July 2008)	29
2	Dry	0	Variable (March 2009)	22
3	Wet	70	Persistent (January 2007)	19
4	Wet	70	Variable (September 2006)	29

3.2 Optimization framework

Chapter 2 described that 18 possible design options were set-up in advance of which the 'best' option will be chosen. This section describes the site specific characteristics of these 18 design options. Parameters such as the diffuser orientation and angles are chosen to be constant because these can not be modeled in Approach A and are therefore less important. Thereafter, the site specific selection framework is presented. The following variables are different in each design:

Intake type Two intake types are combined for nine different outfall types. These intake designs are a channel intake and a submerged intake. An example of the intake types is presented in Figure 3.4 and 3.5. In general, it is expected that intake temperatures are lower when using a submerged intake because the water temperature is lower in the bottom layers. However, these are more expensive. The submerged intake will be 300 meter away from the coast and at 6.3 meter depth.

Outfall type We test two different outfall types; the diffuser and the surface outfall. Examples of the layout of these outfall types are given in Figure 3.6 and 3.7. These two are very common but differ in mixing capacity and capital costs. A diffuser is more expensive to build, however it has a high mixing capacity. The surface outfall is cheap, but has low mixing capacity. For simplicity, the diffuser and outfall dimensions are fixed. The typical diffuser used in this assessment has a length of 100 meter, a port diameter of 2 meter, and 6 openings. The vertical angel of the nozzles is 15° above the horizontal plane. All nozzles are orientated along the diffuser. A top view and side view of this diffuser is shown in Figure 3.8. The diffuser is laying 30° from North and submerged at the seabed.

Figure 3.4: Example of a channel intake (Canadianpond, 2016)

Figure 3.5: Example of submerged intake system (Bleninger and Jirka, 2010)

Figure 3.6: Example of a diffuser outfall pipe (Doneker, 2014)

Figure 3.7: Example of surface port outfall system (PembangkitListrik, 2015)

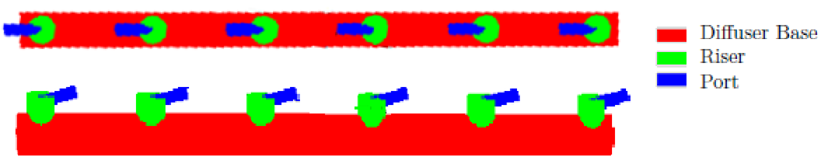


Figure 3.8: Top view and sideview of the designed diffuser.

Outfall location Because surface outfalls are always located at the shoreline, the location of the surface outfall along the coast is variable whereas this x-location at the coast is fixed for the diffuser outfalls. For submerged outfalls, the water depth has an influence on the initial mixing. Therefore, the diffuser design is tested for different location away from the coast. This results in 6 diffusers at a different distance from the coast between 1250m and 2400m with increments of 230m. Furthermore, 3 surface outfall at the coast line with increments of 250m will be tested. Different location in x-direction is less interesting because the differences are expected to be smaller. Figure 3.9 gives an overview of the different locations of the outfalls. The nearest and furthest diffuser from the coast are located at 9.6 and 11.9 meter depth respectively. An overview of the specification per design is given in Table 3.4.

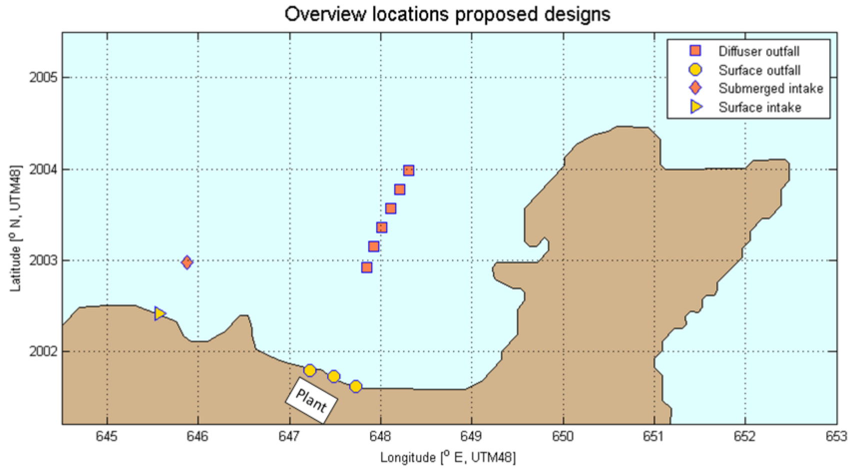


Figure 3.9: Overview of used locations of the different designs in the optimization process.

Selection criteria
From the 18 design options, one design will be selected as the one that is recommended to the fictitious client. A fixed selection scheme was produced to keep an objective view. This scheme was set up based on common requirement from the power plant developers. This results in the following scheme:

1. All designs that do not meet the environmental criteria are discarded. The World Bank Group (1998) recommends the following environmental criteria when no local criteria are set:

   "The effluent should result in a temperature increase of no more than 3°C at the edge of the zone where initial mixing and dilution take place. Where the zone is not defined, use 100 meters from the point of discharge when there are no sensitive aquatic ecosystems within this distance."

   In conclusion, the maximum excess temperature is not allowed to be more than $3°C$ at more than 100 meters from the discharge point at 1 meter below the surface.

2. All designs with a maximum exceedance temperature higher than 1 $°C$ at the intake, are omitted. This is a requirement that is often demanded by the power plants owners.

3. From the remaining designs, the most cost-efficient option is selected as the final design. In practice, this most often based on the capital cost only. However, this might not lead to the cheapest option in the long term. Therefore, it will be investigated whether a different design is selected when also the operational cost are considered in this step. Operational cost are in this study only estimated based on the recirculation costs. This results in two selection methods; one based on the common practice and one more sophisticated.

    a) Only the capital costs are included in the calculation, operational costs are excluded.

    b) Both the capital and operational costs are considered. The operational costs will be estimated based on the temperature at the intake according to the model that was used here. Furthermore, a service life of at least 25 years is assumed (International Energy Agency, 2005).

Table 3.4: Specifaction per design

Design #	**Intake**	**Outfall**	**Distance from coast [m]**	**Distance from base[m]**
1	Submerged	Diffuser	1250	
2	Submerged	Diffuser	1480	
3	Submerged	Diffuser	1710	
4	Submerged	Diffuser	1940	
5	Submerged	Diffuser	2170	
6	Submerged	Diffuser	2400	
7	Submerged	Surface		-250
8	Submerged	Surface		0
9	Submerged	Surface		250
10	Surface	Diffuser	1250	
11	Surface	Diffuser	1480	
12	Surface	Diffuser	1710	
13	Surface	Diffuser	1940	
14	Surface	Diffuser	2170	
15	Surface	Diffuser	2400	
16	Surface	Surface		-250
17	Surface	Surface		0
18	Surface	Surface		250

3.3 Costs assessment

For each design in the optimization process both the offshore capital and recirculation costs were estimated, as was described in Chapter 2. The following steps were taken considering the estimation of the recirculation costs:

The relationship between the intake temperature and the condenser can be described by the net unit heat rate (q), also called the the reverse of the power plants efficiency (η),

$$\eta = q^{-1} \tag{3.1}$$

where the efficiency (η) is a percentage and the Net Unit Heat Rate (q) is in kWh/kWh. In other words, the net unit heat rate represents the amount of energy needed to produce one kilowatthour of electricity. Thus, a power plant with a lower heat rate is able to produce more energy with he same mount of energy than a power plant with a higher heat rate (International Energy Agency, 2015). This is the initial concept of the assessment of the recirculation costs based. Knowing the Gross load (P) of the power plant and the power plants efficiency η, the Net power generation (P_g) was computed as follows,

$$P_g = P\eta. \tag{3.2}$$

In this case study, the Gross load (P) are 4 units of 150 MW. The Net power generation is therefore also in MW. To compute the yearly power output (E_y), the Net power generation is multiplied with the production time (t_p) of the power plant. It was assumed that the power plant operates all year through at full power,

$$E_y = P_g t_p. \tag{3.3}$$

The potential *Revenue* ($\$/year$) of a power plant can then be computed as:

$$Revenue = 84E_y \tag{3.4}$$

A selling price for electricity of 84 $\$/MWh$ was used in this formula. This is an estimation of the global selling price according to Department of Energy and Climate Change (2016).

Finally, the relation between the amount of recirculation and the additional operating costs, for the power plant as described in Section 3.1.2, can be assessed using the formulas above and the relation between intake temperature and the net unit heat rate. The net unit heat rate for a 150 MW power unit is 2370 $kCal/kWh$ at an intake temperature of 22 $°C$ (Tramel, 2000). The power plant is more efficient at an intake temperature of 18 $°C$, with a net unit heat rate of 2360 $kCal/kWh$. This net unit heat rate for an intake temperature of 22 and 18 is equal to an efficiency of 36.280% and 36.434% respectively. Due to a lack of more detailed information, the relation between these two parameters is assumed to be linear and valid for higher intake temperatures. The recirculation costs are estimated as the *additional* costs for an power plant compared to an ideal case with zero recirculation. The relation between intake temperature T and the Recirculation Costs (RC) in dollars can be described with the following formula:

$$RC = 84P\Delta\eta t_p T \tag{3.5}$$

$$RC = 170.000T \tag{3.6}$$

A yearly averaged recirculation temperature of $0.5°C$ would result in yearly costs of \$85.000. In 25 years, this rises to an additional cost of 2 million dollars compared to zero recirculation.

In the selection phase of this study, Section 5.3, the costs will be estimated with the temperature found by the model for which the design is selected. However, during the final evaluation between the two selected designs by the different approaches we consider the SotA-approach as the best estimation of the system because no measurements to validate are available. Studies showed that state-of-the-art approaches result in more accurate system estimation (Bleninger and Morelissen, 2015; de Fockert et al., 2011; Morelissen et al., 2015). Therefore, this was also assumed in this study.

To compute the costs per year for each design, the weighted average temperature will be multiplied with Equation 3.6. An inflation rate (i) of 3% is used to computed the total recirculation costs in the lifetime of the plant (San Diego County Water Authority, 2009). The total recirucaltion costs will be computed as:

$$RC_{lifetime} = RC_{yearly}\frac{1-(1+i)^n}{-i} \tag{3.7}$$

where n is the expected lifetime of 25 years of the power plant.

The offshore capital costs include the costs for the diffuser or surface outfall, the submerged intake or surface intake and the required pipeline length. The price per unit can be found in Table 3.5 and is obtained from feasibility studies.

Table 3.5: Price per unit for the offshore part of the intake and outfall configuration.

	Price per unit
Diffuser [1]	$ 1.500.000
Surface outfall [2]	$ 1.000.000
Submerged intake [2]	$ 3.000.000
Surface intake [2]	$ 1.000.000
Pipeline [per meter] [3]	$ 1.500

[1] Dannenbaum Engineering Corporation (2004)
[2] Watereuse Association (2012)
[3] Dannenbaum Engineering Corporation (2004); San Diego County Water Authority (2009)

CHAPTER 4

Model development

This chapter will present detailed information on the used models. First, the far-field model of Approach A will be described. Hereafter, the used extensions on this far field model to create Approach B is given in Section 4.2.

4.1 Approach A: common consultancy practice

As chosen in Chapter 2, Approach A is a 3D far field model. This section will will describe all settings in the model that are needed to meet the requirements set in Chapter 2. The model was built in the hydrostatic Delft3D software. Delft3D is an open source software package developed by Deltares (Lesser et al., 2004). It is a 2D (depth-averaged) or 3D model that can simulate unsteady flow and transport phenomena including density differences. The hydrodynamic part is computed with the use of horizontal equation of motion and the continuity equation. An advection/dispersion equation is incorporated to describe the transport phenomena. The resulting horizontal density differences are then included in the hydrodynamic part. Delft3D-FLOW was designed to describe phenomena where the vertical length and time scales are much smaller than the horizontal scales. This makes it useful for the far field modeling of the plume. Delft3D-FLOW uses the so-called "shallow water assumption" to simplify the vertical momentum equation. This assumption is valid when the vertical flow accelerations are negligible compared with gravity. In the near-field, this assumption in not valid because the buoyancy effects result in vertical acceleration. (Lesser et al., 2004; Morelissen et al., 2013; Bleninger and Morelissen, 2015)

The model incorporates the influence of wind.

- The temperature in vertical and horizontal direction of the ambient sea and river is uniform.
- The temperature of the river is equal to the ambient sea water.
- The salinity in the sea and river is uniform in horizontal and vertical direction.
- It is expected that the bed roughness has small influences on the model results and therefore it was chosen to keep the bed roughness constant in the whole domain. Furthermore, change in the system due to a changed bed roughness is not within the scope of this project.
- Changes in bed morphology over time do not influence the plume behavior. Therefore, this process can be neglected in the model.

Computational grid

A domain area of 20×30 km^2 was created to model the plume behavior, see Figure 4.1. The grid size near the outer boundaries are up to 500×300 m^2. To be able to capture the small scale plume behavior near the outfall, the grid size is decreasing towards the area of interest with the smallest grid size being 40×40 m^2. A detailed presentation of this part of the grid is presented in Figure 4.2. In this figure, also the modeled river is clearly visible. The river length is chosen to be as 1000 m long, such that the model captures the tidal influence on the river.

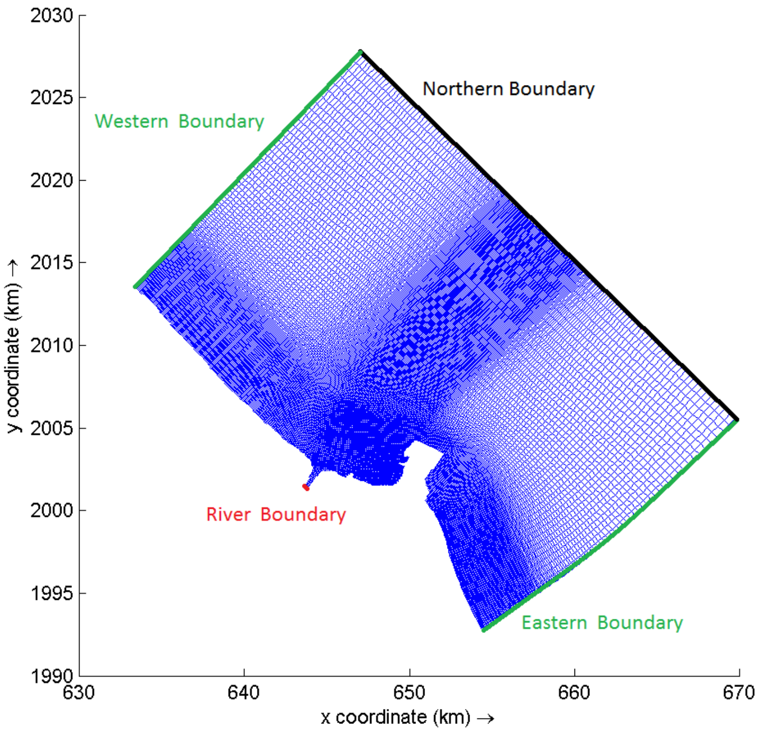


Figure 4.1: Overall grid.

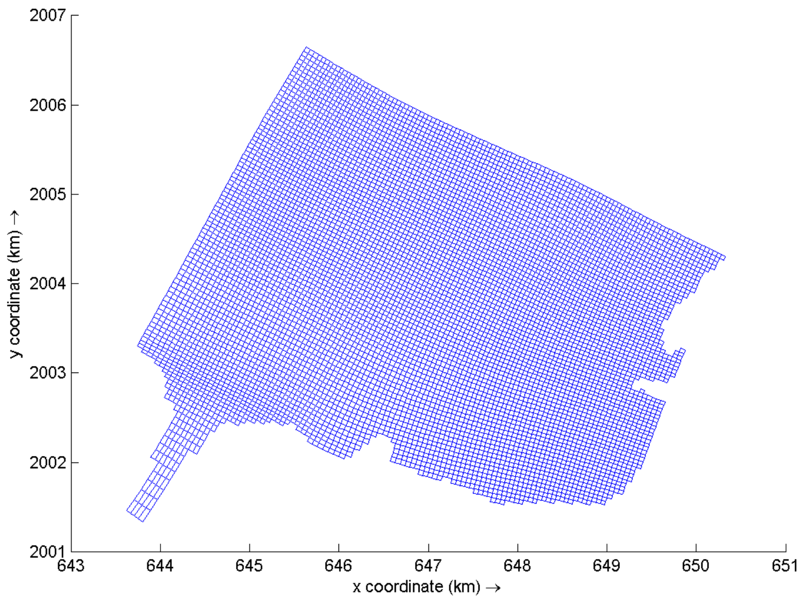


Figure 4.2: Refined grid in the area of interest.

The bathymetry was created by first extracting depth points from the Delft Dashboard software using the GEBCO 08 database as source. Next, these depth points were filtered, only negative values were kept in order to exclude dry areas inside the grid. These missing values were then interpolated with the surrounding values. The resulting depth contours of the whole domain can be found in Figure 4.3 and the depth contours of the detailed area is shown in Figure 4.4.

Vertically, the model includes 10 layers, with the purpose of accurately accounting for the stratification of the thermal plume. To be able to achieve an increasing vertical resolution towards the more shallow regions, a σ-layer setting was used to get a constant number of layers. Each vertical layers was set to represent 10% of the total local depth.

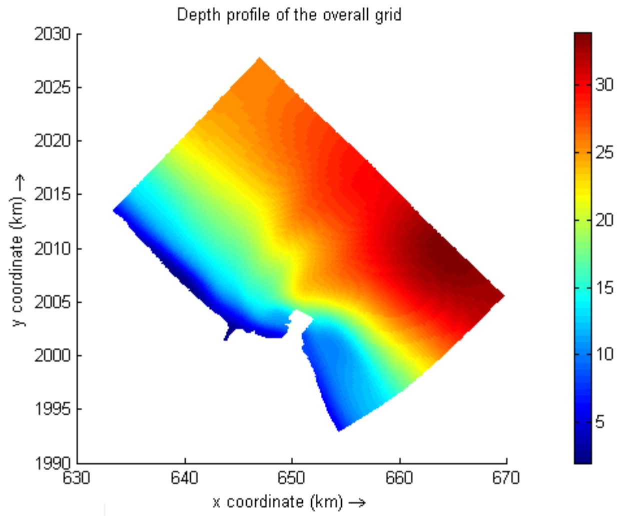


Figure 4.3: Depth profile of the overall grid.

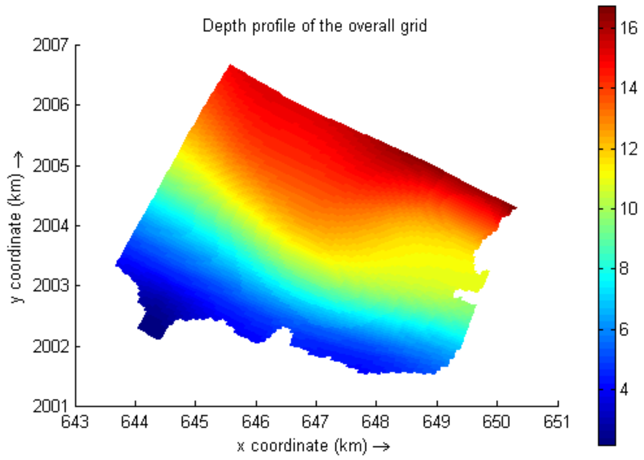


Figure 4.4: Depth profile of refined area of the grid.

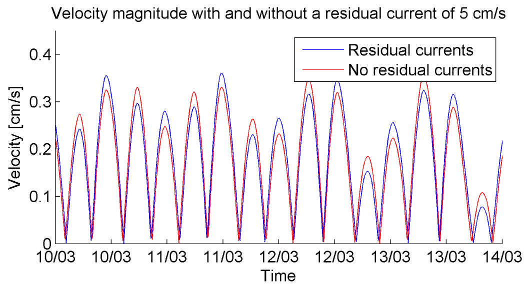


Figure 4.5: Model with and without residual current, example location in the North-West.

Time step and modeled period

Based on the Courant stability criteria, a time step of 0.25 min was used for all scenarios. No significant differences were found when comparing the model results of a reference run with a model run using a time step of 0.1 min. Therefore, the time step of 0.25 min was certified as appropriate for this problem whereas a larger time step, 0.5 min, did result in major differences and was not suitable. One month was modeled per simulation. From some test simulations it was concluded that the first week was required as spin-up time. The last three weeks were used to analyze the model results. The simulation time of the model is approximately 22 hours, run parallel on a 3 core cluster.

Tidal boundary conditions

The eastern and western open boundaries are forced with current data. On the northern boundary, the water level is prescribed. The input of these boundaries are based on a larger computation grid (300×400 km). This process is also called 'nesting'. This model was built in order to make more stable conditions near the edges of the computational grid. This large overall 2D grid had a resolution of 1000m. The tide forcing data on the boundary were obtained via Delft Dashboard from the TOPEX7.2 Global Inverse Tide model database. The large overall model was then run with the boundaries of the model grid boundaries as observation points. Hereafter, this modeled was nested and the boundaries were created. This means that the values imposed at the boundaries are based on a time series.

To reduce the amount of reflection in the boundaries of the overall, a reflection parameter α of 1500 was applied at the current boundaries, and 2500 at the northern water level boundary. The salinity and temperature are constant in time and depth. However, for the different scenarios, represented by a certain month, the applied ambient temperature differs. These different ambient temperatures are shown in Table 3.2.

Residual current

The residual current in Approach A is taken to be constant because the variation in the parameter is relatively small, see Table 3.1. A residual current of 3 cm/s SE was chosen as typical event. This phenomenon is included in the model by superposition of the velocity on the current boundaries, the result can be found in Figure 4.5. This figure shows the model velocity with and without the residual current in the North-West of the modeled area.

River discharge

The river was modeled as a boundary condition, a total discharge of boundary was used to include the extra discharge in the model. The salinity of the water was set to be 10 ppt, a representative value for brackish water.

Intake and outfall

The intake and outfall configuration was model by using the in-out discharge setting in Delft3D. This setting makes it possible to subtract a certain discharge and add this back into to the system at another location with an increase in temperature.

Ambient temperature and wind conditions

The ambient sea temperature is modeled as a constant. Varying temperature in one simulation is beyond the scope of this research. The wind speed and ambient air temperature are used to compute the heat exchange between the sea water and the ambient environment, also called the excess temperature model in Delft3D. The air and sea water are modeled with the same temperature for two reasons. First, it is undesirable that the sea water cools down as a result of lower ambient air temperatures, this will affect the ambient sea temperature near the outfall and is therefore not a good representation of the plumes ambient environment. Secondly, the differences are small as can be seen in Table 3.2.

Ambient scenarios

The ambient scenarios for Approach A are described in Section 3.1.3.

4.2 Approach B: state-of-the-art assesment

The aim of the state-of-the-art based model is to use up-to-date model techniques to assess the plume behavior as accurately as possible. Therefore, Approach B contains a near field and far field model. This section will describe the implementation of the near field and the applied coupling method. The far-field model that was used in Approach A, see Section 4.1, was also incorporated in Approach B.

Near field model

The Cornell Mixing Zone Expert System (CORMIX) software was selected to assess the near field plume behavior. This software was developed to predict the dilution characteristics and geometry of the initial mixing zone of an outfall plume (Doneker and Jirka, 2007). CORMIX computes the near field behavior of the plume, based on the characteristics of the outfall and discharge, such as nozzle orientation and initial density. Furthermore, CORMIX uses the ambient conditions such as the ambient velocity, density differences and the water depth to predict the near field behavior. With this input, momentum and buoyancy fluxes are used to develop length scales. The magnitudes of these length scale are used to classify the plume in different zones, as described by Jirka et al. (1991). Furthermore, CORMIX uses an additional integral approach (CorJET) to assess the intermediate zone of the plume. The output of CORMIX includes the direction, thickness and width of the plume as well as the dilution rates.

This software proved to predict the near field plume behavior accurately (Palomar et al., 2012; Doneker, 2014). The CORMIX software is suitable to model a multiport and positive buoyant effluent (Morelissen et al., 2015). Therefore, this method will only be applied on the diffuser outfall designs and not on the open surface outfalls.

Coupling method
Every 60 modeled minutes, the near and far field model were coupled. This is a small enough time step to capture the variability in the system but it is large enough to not increase the simulation time with more than half a day.

The two-way coupling was performed with the COupled SUbgrid MOdel (COSUMO) approach. This is an interface program for coupling Delft3D and CORMIX, see Figure 4.6 where the steps of the two-way coupling method are shown. The main advantage of this approach is that COSUMO translates and adapts the Delft3D output as CORMIX input and vice versa.

Pre- and post processing functions in COSUMO, make it possible for the user to define at which location the models are coupled. The coupling can be based on plume characteristics such as the width and dilutions rate or based on spatial characteristics such as the water depth or distance from the discharge point. Based on expert judgment, the couple location in this study is located once the plume fills less than half the water depth. At this location, the plume is restratified and most of the near field trajectory is formed. After trial simulations, it was found that for some time steps, the ambient velocity was very low. This is probably due to a change in tide direction. As a result, the recommended coupling location was far outside the near field zone, which is undesirable. Therefore, a post processing function was created where the maximum coupling location is 500 meter from the outfall. This ensures that CORMIX only predicts initial mixing in the zone where it proven to give valid answers. Hereafter, the simulation is taken over by the far field model.

Furthermore, the DESA method was applied in this study because it showed to improve the physical representation of the plume's behavior (Choi and Lee, 2007; Bleninger and Morelissen, 2015). In this method, entrainment sinks are incorporated to preserve the mass balance. This was incorporated in the post-processing function. The sinks were not placed on the center line as suggested by Choi and Lee (2007) but by a state-of-the-art 'spiral sink' method, a method where the entrainment sinks are placed around the outer perimiter of the plume. This is in order to achieve more accurate model results.

Ambient scenarios
The ambient scenarios for Approach B will be described in Section 5.1.1.

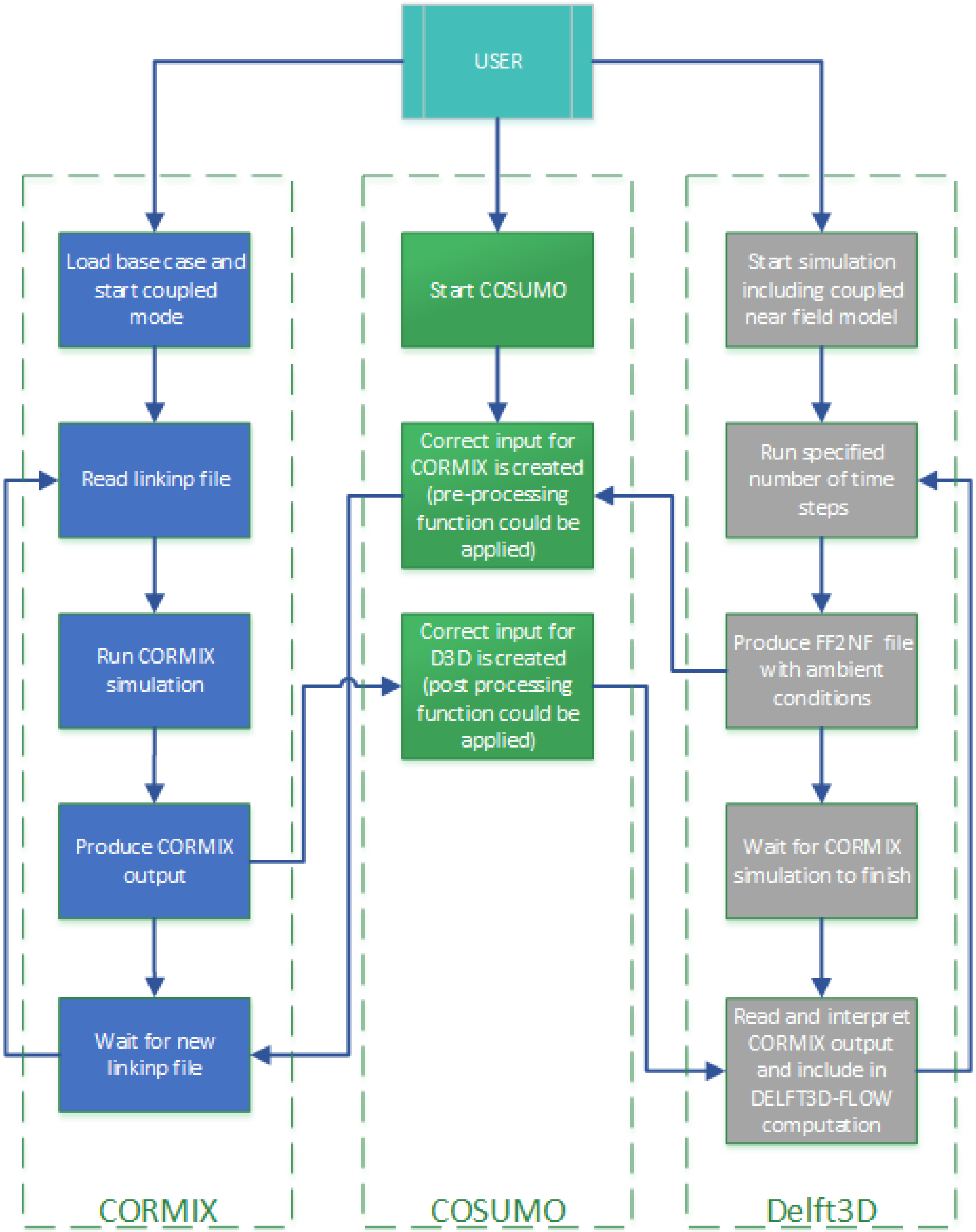


Figure 4.6: Flow chart showing the CORMIX-COSUMO-Delft3D interaction for the two-way coupling method.

CHAPTER 5

Results

This chapter provides the results found in this study. First, a brief general description of the plume behavior is given. Hereafter, the comprohensive ambient scenario selection for Approach B will be given in Section 5.1.1. The general differences found between the two approaches will be presented in Section 5.2. This includes a description of the consequences of the chosen scenarios in section 4.1 and 4.2 and the model outcome differences between Approach A and B based model. Based on the model results, the 'best' design for both approaches will be selected based on the framework given in section 3.2. Finally, these two chosen designs will be compared and the added value of the state-of-the-art modeling will be evaluated.

5.1 General behavior of the intake and outfall system

The density of the effluent is lower than that of the ambient water creating a positive buoyant plume. The plume is at the outfall not stratified by a linear layer. This means that the plume rises till the surface. CORMIX outcomes showed that in some cases the plume is shortly unstable, the plume is spread over the entire water depth. Furthermore, the undesired case where the plume is trapped against the shore line was not seen in the plumes simulated in this study. Finally, the current along the headland causes higher flow velocities resulting in more dispersion of the plume towards the North-East.

5.1.1 Representative selection of ambient conditions (SBAM)

A state-of-the-art method to select the ambient scenarios is the so-called *Scenario Based Adaptive Modelling (SBAM) approach*. The goal of this approach is to select the ambient conditions such that it describes the full range of the plumes behavior, instead of selecting the most common ambient conditions (Verbruggen et al., 2014). the SBAM method is used to select the ambient scenarios for Approach B. This is accomplished by using different combinations of ambient conditions for model simulations. The SBAM approach consist of three steps (de Fockert et al., 2011). The first step is to identity potential important parameters, the second step is to investigate the sensitivity of these parameters on the system and the last step is to create the scenarios based on the most governing parameters.

Step 1

In this step the available data are analyzed and the physical parameters that could influence the behavior of the plume are identified. Furthermore, the full range of these parameters are quantified. The hydrodynamic processes that are involved in this case are; ambient temperature, residual currents, river discharge, intake/outfall configuration and wind conditions. Furthermore, it is assumed that the imposed tide is a representative tide for this area. In addition, the variation in this parameter is assumed to be small and having low impact on the system. Therefore, this parameter is not included in this assessment. The possible effects of climate change are

Table 5.1: Range of physical parameters in the case.

Parameter	Minimum	Mean	Maximum
River discharge [m^3/s]	0	28	170
Wind speed [m/s]	0	3.5NW	20N
Residual current [cm/s]	3NW	3SE	5SE
Ambient Temperature [$°C$]	16	25	33
Outfall location from coast [m]	0 [1]	1250 [2]	2400 [2]
Outfall location along coast [m] [3]	-250	0	250

neglected for simplicity. The outfall configuration is taken into account. The submerged intake configuration has been used to limit the number of required simulations.

The range of the ambient processes occurring in this environment is described in detail in Chapter 3.1. A summery of the range of these processes is given in Table 5.1. It is estimated that in an extreme wet season the river discharge can go up to 170 m^3/s (Deltares, 2010).

Step 2

In this step, the impact of each parameter on the behavior of the plume is investigated by simulations. First, by individually running the range of parameters, Step 2a. Secondly, different combinations of ambient parameters are tested on the impact on the behavior of the plume, Step 2b-c. Hereafter, the most governing parameters are identified by the modeler. It is important to note that when the range of a parameter is found to be insignificant, the parameter can not be removed from the model set-up (de Fockert et al., 2011). Only the variation of this parameter can be neglected.

Step 2a: understanding the processes

Based on the parameters found in Step 1, an initial set-up was made. The main goal of this first assessment is to get an understanding of the impact of the individual parameters on the systems behavior. Therefore, the most extreme values were used, and not necessarily realistic combinations of parameters. The extreme values of the outfall configuration were set to be the diffuser design located the nearest and the furthest from the coast and the surface outfall in the middle. When considering wind, a typical event with a persistent (January) and hourly variable (May) was investigated. It is assumed that these wind conditions cover the entire range in wind directions. The month September was included in this study to see the effect of strong winds, where a Northern wind with a velocity higher than 6 m/s occurs for 1.5 days. For each configuration, the simulations as described in Table 5.2 were carried out, resulting in 30 simulations is total.

This first assessment was carried out with the far field model only and a large stable time step. This is valid because these simulations have the goal to understand the system, not to compute exact results. In this analysis, run 2 was used as the reference run. This makes it easier to compare the results.

[1] Surface outfalls
[2] Diffuser designs
[3] With reference point the location of the diffuser designs

Table 5.2: Initial simulations for the Designs 1, 6 and 8. Run 2 was used as reference run.

Simulation	Residual current $[cm/s]$	River discharge $[m^3/s]$	Wind	Ambient temperature $[°C]$
01	5SE	28	January	25
02	3NW	28	January	25
03	0	28	January	25
04	3NW	0	January	25
05	3NW	70	January	25
06	3NW	170	January	25
07	3NW	28	September	25
08	3NW	28	May	25
09	3NW	28	January	16
10	3NW	28	January	33

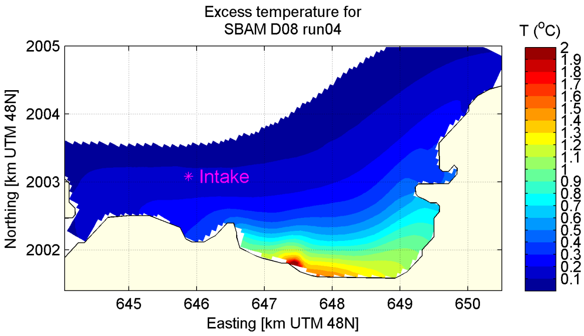
The outcomes of this first iteration step can be found in Appendix A. The main conclusion of this first assessment are:

- For all three investigated designs, the influence of a changing residual current on the plumes behavior is significant. The model results of the designs can be found in Figure A.1, A.2 and A.3. For a NW current, the plume disperses into the entire bay. Consequentially, it is dispersed towards the intake resulting in higher intake temperatures. On the contrary, the plume disperses towards the headland and away from the intake with an imposed SE residual current. The mean temperature in the intake layer shows this effect clearly, see Figure 5.4a and 5.4b.

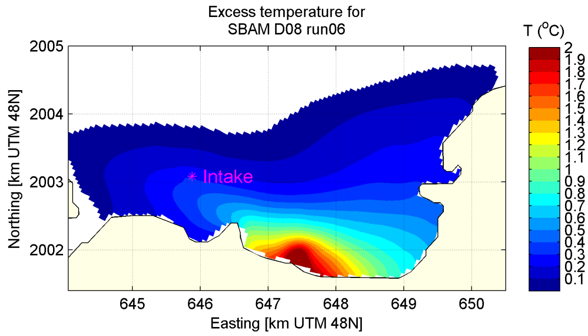
- For both diffuser designs, the river pushes the plume towards the North-East and has therefore and significant influence on the system. An example of this is shown in Figure 5.4c and 5.4d, and more simulation results can be found in A.4 and A.5. The difference between a normal discharge of 70 m^3/s and an extreme discharge of $170m^3/s$ is small and therefore only the small and medium discharge is investigated in the next step.

- For a surface outfall, the plume could get 'trapped' by the fresh water of the river. The fresh water from the river has a lower density than both the ambient sea water and buoyant plume. Consequentially, the fresh river water rises to the surface and forces the plume towards lower layers. For example, the excess temperature region in the intake layer is smaller when there is no river than when there is a river in the system, see Figure 5.1. Furthermore, at the surface the plume disperses further towards the river mouth when there is no discharge compared to a discharge, see Figure A.6b, A.5d and A.5f. The trapping can also be seen in Figure 5.2. At the 23$^{\text{th}}$ of March, a small increase in water temperature can be seen in the entire water column and at the same time the salinity is very low, see Figure 5.3. Furthermore, Figure 5.3 shows that the river discharge, which has a lower salinity, is at the top of the water column at the intake. This trapping phenomenon could be an important process in the behavior of the plume and should therefore be investigated in more detail.

- Results of the wind simulation can be found in Figure A.7, A.8 and A.9. The influence of the wind on the plumes direction is marginal compared to the influence of the residual current. In conclusion, the residual current is a dominating process compared to the influence of the wind on the behavior of the plume. Therefore, the wind is classified as an insignificant parameter for all designs.



(a) Mean temperature in intake layer, Q=0m^3/s



(b) Mean temperature in intake layer, Q=170m^3/s

Figure 5.1: Example of the plume trapping by the river, represented by the mean temperature at the intake layer for a surface outfall. Excess temperatures below 0.05 are marked in white to highlight the extent of the plume.

- Results of the variation in the ambient temperature can be found in Figure A.10 and A.11. As shown in Figure 5.4e and 5.4f, there is a small difference in plume behavior for different ambient temperatures, especially in the surface layer. The density differences are larger for higher ambient temperatures, effectively increasing the buoyancy of the plume at higher ambient temperatures. Therefore, a thinner plume for higher temperatures is expected. This theory will be validated in the next step.
- The ambient temperature also has an influence on the surface outfall. However, this seems to be less significant than for the diffuser designs, see Figure A.12. Therefore, this will not require additional research.
- The diffuser designs 1 and 6 respond similarly to the imposed parameter variation. Therefore, the diffuser designs are assumed to behave similarly and will be estimated with the middle diffuser design 3 in the next step. Nonetheless, the surface outfall design 8 showed different behavior for the river discharge compared to the diffuser outfalls. Therefore, the surface outfall designs will be assessed separately.

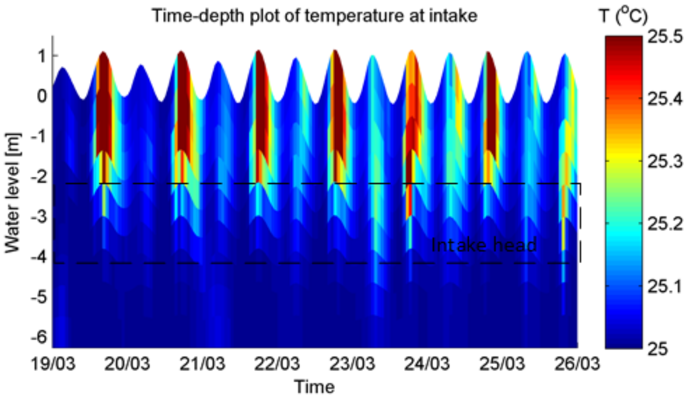


Figure 5.2: Depth-time plot at the intake for $70m^3/s$, middle open outfall design (8).

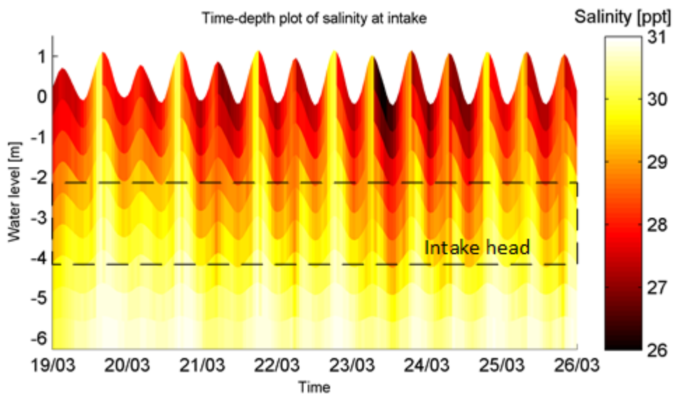
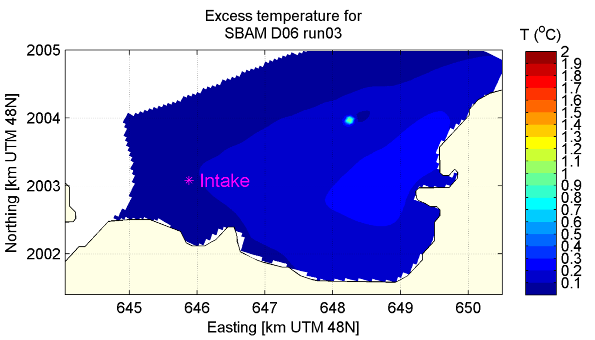
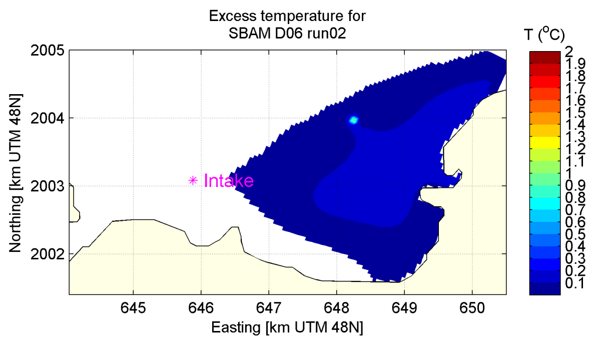


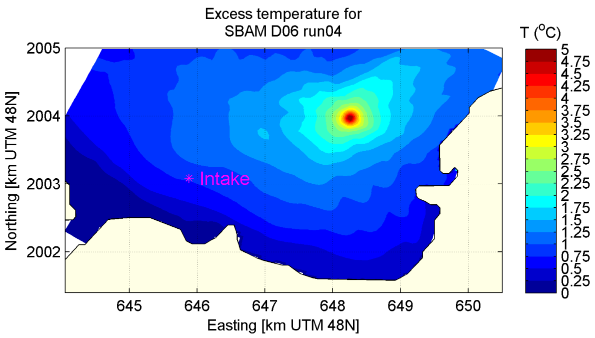
Figure 5.3: Depth-time plot at the intake for $70m^3/s$, middle open outfall design (8).



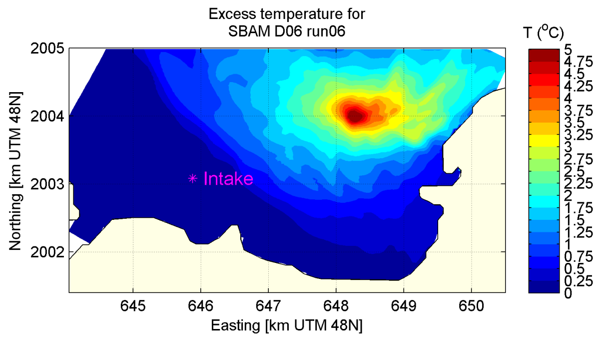
(a) Mean temperature in the intake layer, no residual current



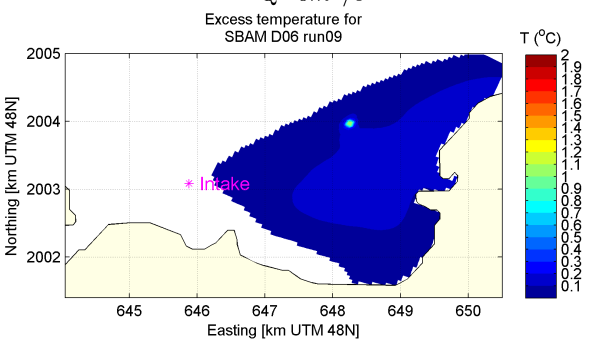
(b) Mean temperature in the surface layer, 5cm/s SE residual current



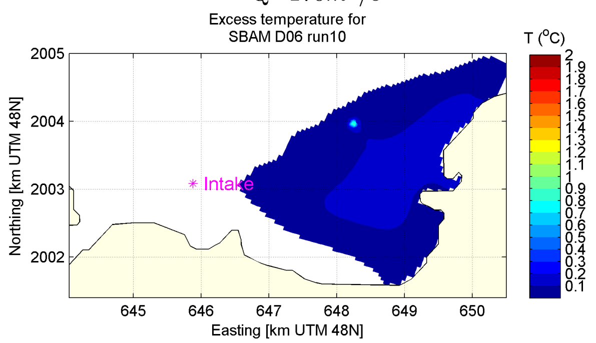
(c) Maximum temperature in the surface layer, Q=$0m^3/s$



(d) Maximum temperature in the surface layer, Q=$170m^3/s$



(e) Mean temperature in intake layer, T=16 $^{\circ}C$



(f) Mean temperature in intake layer, T=33 $^{\circ}C$

Figure 5.4: Influence of the residual current(a-b), river (c-d) and ambient temperature (e-f) on system behavior for diffuser design (6) furthest away from the coast. For top and bottom pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume.
5

Step 2b: Interaction between parameters for the diffuser outfall
A clear overview of the governing processes was formed in Step 2a. Based on this, the interaction among the parameters residual current, river discharge and ambient temperature are investigated for the middle diffuser design 3 in this step. The goal of this step is to select the ambient conditions that have the most influence on the intake temperature. Therefore, the intake temperature is the key indicator in this step. All realistic combinations of the processes parameters are considered in this analysis. Table 5.3 shows the simulations carried out in this step. It is important to note that there is no variation in the ambient temperature in the case of a NW residual current, see Table 3.2 and 3.1.

Table 5.3: Simulations to investigate the interaction between the governing processes for a diffuser design 3.

Simulation	Residual current $[cm/s]$	River discharge $[m^3/s]$	Ambient temperature $[^{\circ}C]$
31	3NW	0	25
32	5SE	0	25
33	3NW	70	25
34	5SE	70	25
35	5SE	28	16
36	5SE	28	33
37	3SE	0	16
38	3SE	70	16
39	3SE	0	33
40	3SE	70	33

The assessment in this step was performed using the dynamic coupling system between the near and far field model and the original time step. Differences between the far-field simulations and the coupled simulations were found, but the overall response of the system was still the same. Figure 5.5 shows the cumulative intake temperature for all simulations in this step. The main conclusions of this step are:

- The direction of the residual current is an important parameter when there is no river discharge. This is shown in Figure 5.5 by the solid red line and dashed blue line. As found in Step 2a, the north-western residual current disperses the plume to towards the entire bay and therefore the intake. This results in higher intake temperatures.
- The residual current becomes less governing when there is a large river discharge. This is illustrated by the solid black line and the bold red line in Figure 5.5. This can be explained by the effect that the residual current has on the river. With a SE-current, the river discharge gets disperses towards the intake and therefore the plume reaches less often the intake, see Figure 5.6. This is counteracting the effect of the residual current on the intake temperature. Therefore, it can be concluded that the river discharge is the most governing parameter in this system.
- Only when a SE-current is occurring in combination with no river discharge, the ambient temperature is of influence on the system, see the dashed red, black and blue line in comparison with the the solid blue and dashed pink line in Figure 5.5. The thickness of the plume has more influence on the plume because the plume is less dispersed by the SE residual current than by a NW current. Furthermore, the river is not 'pushing' the plume away.

- The variation in ambient temperature in combination with a river discharge and a SE residual current resulted in all similar intake temperatures but these simulations do differ from the other simulations, see the Figure 5.5. The river and residual current are more dominant processes.

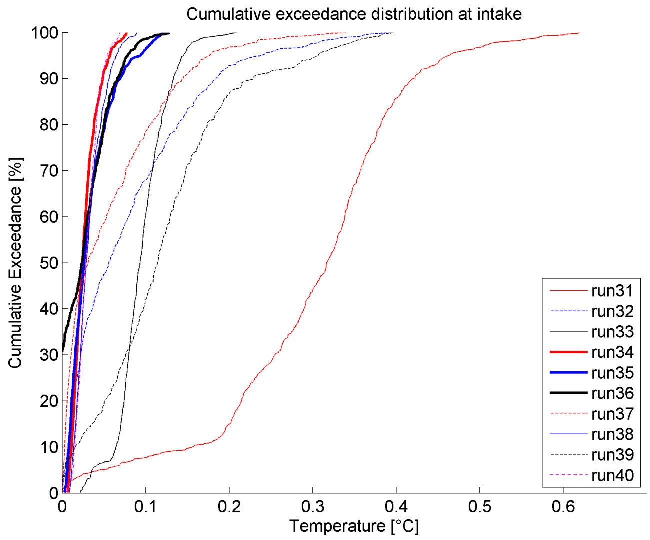
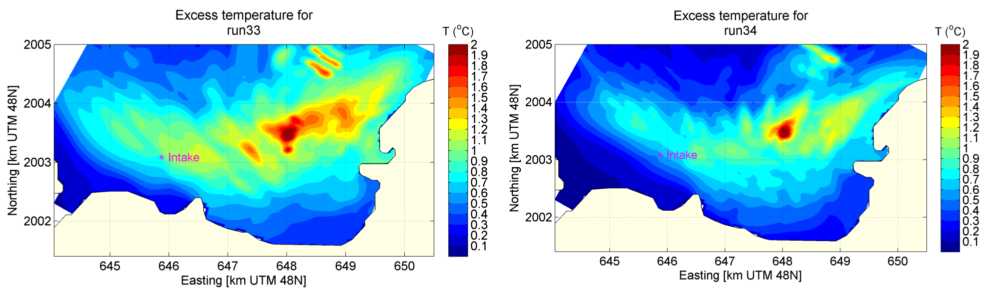


Figure 5.5: The cumulative excess temperature at intake for the simulations introduced in Table 5.3.



(a) Maximum temperature in intake layer, 3cm/s NW and Q=70 m^3/s

(b) Maximum temperature in intake layer, 3cm/s SE and Q=70 m^3/s

Figure 5.6: The combination of river discharge and the residual current

Step 2c: Interaction between parameters for the open outfall
The surface outfalls are assessed separately because different process behavior between the diffuser and surface outfall designs were found in Step 2a. As for the diffuser outfalls, the intake temperature is the key indicator the select the scenarios. The effect of the residual current in combination with the varying river discharge was investigated in this step. Because the CORMIX software is not designed to model a surface outfall, this assessment was carried out using the far field model only. The executed simulations in this step can be found in Table 5.4.

Table 5.4: Simulations to investigate the interaction between the residual current and the river discharge for open surface outfall design 8.

Simulation	Residual current $[cm/s]$	River discharge $[m^3/s]$
61	0	0
62	NW	0
63	SE	0
64	0	70
65	NW	70
66	SE	70
67	0	120
68	NW	120
69	SE	120

The different excess temperatures at the intake for these simulations can be found in Figure 5.7. A clear distinction in the behavior of the exeedance temperature can be seen between the model imposed with and without a river discharge, see solid lines compared with other lines in Figure 5.7. As an example the time-depth plot at the intake for the run with and without a river discharge are shown in Figure 5.8 and 5.9 respectively. The most remarkable difference is the intake temperature at the surface, this is much higher for the simulation without a river discharge. Furthermore, the plume is thicker in this scenario, it is almost 2 meters thick. The surface layer of the simulation shown in Figure 5.9 is lower whereas the ambient is still heated in the upper half. Therefore, it could be stated that the river both 'traps' and 'pushes' the plume; the surface is pushed away whereas the lower layers are still heated. This process was found for all combinations of residual current and river discharge. For zero and a NW current the differences between a medium, 70 m^3/s, and a large, 120 m^3/s, discharge are relatively small, see bold and dashed black and red lines in Figure 5.7.

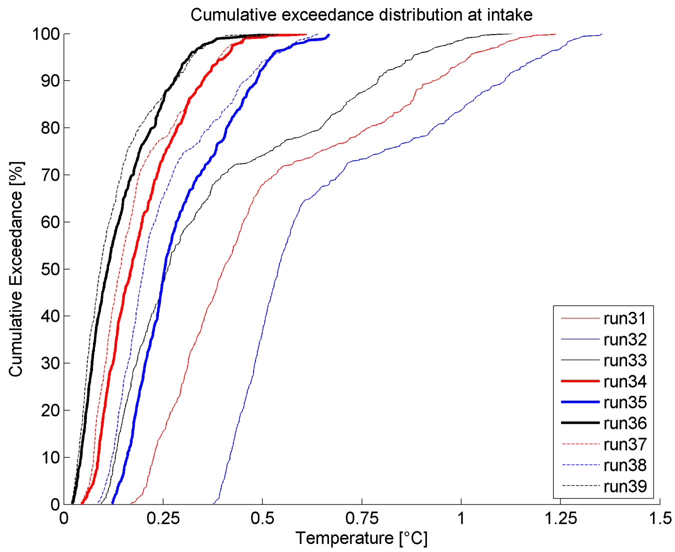


Figure 5.7: The cumulative excess temperature at intake for the simulations introduced in Table 5.3.

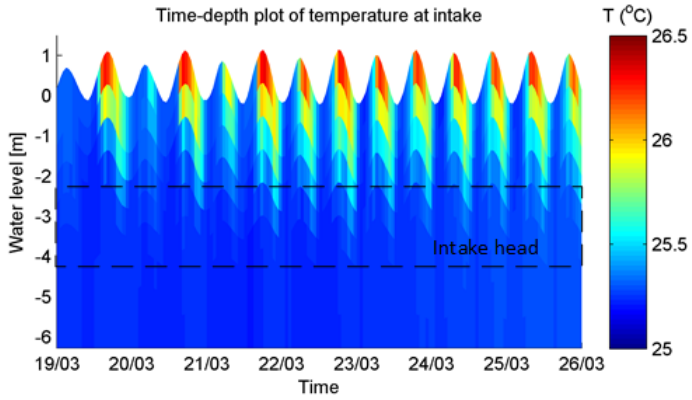


Figure 5.8: Depth-time plot at the intake for $0m^3/s$ and a NW current, design 8.

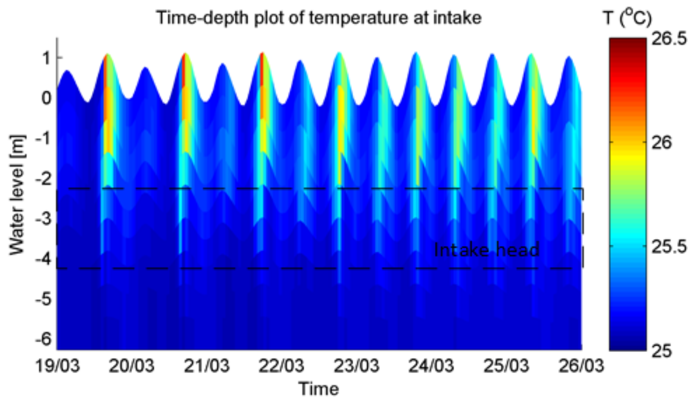


Figure 5.9: Depth-time plot at the intake for $70m^3/s$ and a NW current, design 8.

Step 3
Based on the analysis of Step 2, scenarios are set-up to define a representative combination of ambient conditions to get the full range of plume behavior. For each scenario, the probability of occurrence is assessed.

Scenarios for the diffuser designs
The following variation in the parameter should be accounted for in the scenarios:

- A NW-current with no river discharge
- A NW-current with a river discharge
- A SE-current with no river discharge and varying ambient temperatures
- A SE-current with a river discharge

To be able to create representative scenarios, typical ambient temperatures and wind conditions are included. The five proposed scenarios can be seen Table 5.5. Hereafter, the chance of occurrence per scenarios was estimated. This was based on the data of Table 3.2 and 3.1. Table 5.6 shows the corresponding season, months and occurrence time for each scenarios. Both a NW and SE current are possible in the months June till September, see Table 3.1. Because no more information is available of the occurrence time of these different directions, it is assumed that their occurrence time is equal in those months.

Table 5.5: Scenarios for Approach B for the diffuser designs.

Scenario	Residual current $[cm/s]$	River discharge $[m^3/s]$	Ambient temperature $[°C]$	Wind
S1	3NW	0	29	Persistent, 180° (Jun 2006)
S2	5SE	0	29	Persistent, 180° (Jun 2006)
S3	3NW	70	29	Variable (Sept 2006)
S4	5SE	0	19	Persistent, 30° (Feb 2006)
S5	3SE	70	25	Persistent, 0° (Oct 2006)

Table 5.6: Representing season per chosen scenario and occurrence time, or diffuser design.

Scenario	Representing season	Representing months	Occurrence time
1	Summer (NW current)	June and July	8%
2	Dry and hot	May, June and July	17%
3	Wet season (NW current)	August and September	8%
4	Dry and cooler	January, February, March and April	33%
5	Wet season	August, September, October, November and December	33%

Scenarios for the open surface designs
The following variation in the parameter should be accounted for when modeling an open surface outfall:

- A NW current with no river discharge

- A SE current with no river discharge
- A SE current with 70 m^3/s
- A NW current with 70 m^3/s

Eventually, the governing variation is similar with the variation for the diffuser designs. Only the variation found in the temperature was not found for the open surface outfalls. This is because of a thicker plume caused by a lower mixing efficiency by the surface outfall and a lower water depth at the discharge location. As for the diffuser designs, scenarios are created including typical wind and ambient temperature values. The final scenarios for Approach B for the open outfall designs can be found in Table 5.7. The corresponding occurrence time can be found in Table 5.8.

Table 5.7: Scenarios for Approach B for the surface outfall designs.

Scenario	Residual current $[cm/s]$	River discharge $[m^3/s]$	Ambient temperature $[°C]$	Wind
S1	3NW	0	29	Persistent, 180° (Jun 2006)
S2	5SE	0	23	Persistent, 180° (Feb 2006)
S3	3NW	70	29	Variable (Sept 2006)
S4	3SE	70	25	Persistent, 0° (Oct 2006)

Table 5.8: Representing season per chosen scenario and occurrence time, surface outfall outfall.

Scenario	Representing season	Representing months	Occurrence time
1	Dry season	June and July	8%
2	Dry season	January, February, March and April, May, June and July	50%
3	Wet season	August and September	8%
4	Wet season	January, February, March and April	33%

5.2 Comparison of the two approaches

This section will describe the general differences found between the two model approaches. The model results of both approaches will be evaluated on the chosen ambient scenarios and the differences in temperature in the near field an intake location.

Validation of ambient scenarios
The selected scenarios are not equal for the different model approaches, as can be seen from Table 3.3, 5.5 and 5.7. The most important difference between the chosen ambient scenarios is that the residual current is neglected by the chosen scenarios in Approach A and simulation results show it has a major effect on the intake temperature, discovered by the SBAM method. However, the occurrence time of this phenomenon was small, see Table 5.6, reducing the impact of this on the results. Furthermore, the parameter wind was marked as an important parameter in Approach A but was found to be insignificant in Approach B. In conclusion, the chosen ambient scenarios of Approach A would not result a model that captures the entire behavior of the plume.

Comparison in the near field region
To compare the effect of the near field model on the results, the ambient conditions of scenario 5 of Approach B, see details in Table 5.5, was here imposed on both models. Figure 5.10 and 5.11 show that the maximum excess temperature in the surface layer for design 6 is much higher for Approach A than for Approach B. The plume estimated by CORMIX entrains ambient water as is rises towards the surface resulting in lower temperatures at the surface. The far-field model is not able to capture buoyancy effects because this model uses the so-called ”shallow water assumption”. The model assumes that the vertical flow acceleration is small compared to the gravity and is therefore neglected. This is however not the case in the near field model, where the vertical velocity component is fully solved. The result is that the plume goes immediately towards the surface after discharge. Therefore, the initial mixing is not well assessed and the maximum surface temperature is around $5°C$ degrees whereas it is estimated as $3°C$ by Approach B. This difference was also found by Morelissen et al. (2015). The conclusion can be drawn that the far field model is not able to assess the near field accurately resulting in a large overestimation of the temperature near the outfall by Approach A.

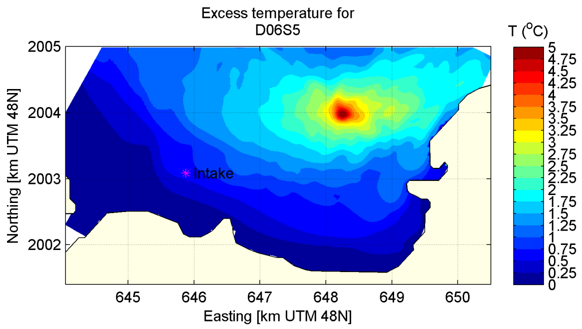


Figure 5.10: Maximum excess temperature in surface layer for design 6 and scenario 5, Approach A

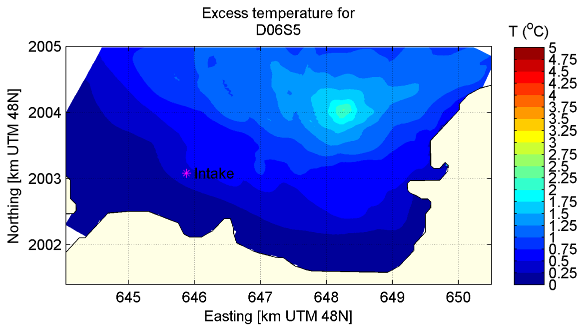


Figure 5.11: Maximum excess temperature in surface layer for design 6 and Approach B scenario 5, Approach B

Accuracy at the intake
The yearly averaged intake excess temperature assessed by Approach A was found to be within a range of 30% compared to Approach B, see Table 5.9. However, the absolute maximum values are found to be higher in Approach A. This is probably due to the higher values at the discharge location. Differences in accuracy where found between the different designs. Each design type will be elaborated separately below.

For a diffuser outfall, Figure 5.12 shows the excess temperature of design 2 at the intake, all other diffuser outfall designs show similar results. The characteristics of design 2 can be seen in Table 3.4. Remarkably, Approach A underestimates the intake temperature compared to Approach B for all diffuser designs. This is partly due to the accidentally advantageous chosen scenarios for Approach A and partly caused by the different behavior of the plume introduced by the Approach A based model. The neglected NW-current in Approach A causes high intake temperatures in Approach B. Secondly, the plume estimated by Approach A is flatter than the plume estimated by Approach B and is mainly situated in the top layer, and could be described as a ’pancake’ plume. Therefore, the very high temperatures are mainly located in the surface layer, see as an example the cross section from intake to outfall in Figure 5.14. This figure also shows that the temperatures in the lower layers are rapidly decreasing. In contrast to the Approach A based model, Approach B shows that temperature is dived more equally over the layers as a result of the the coupling, see Figure 5.15. This results in lower mean temperatures in the intake.

Table 5.9 shows that Approach A estimates the intake temperature of an open surface intake design better compared to a submerged intake. Approach A underestimates the intake temperature for design 1-6 (submerged intake), whereas design 10-15 (open surface intake) the plume is only underestimated at low temperatures. A typical result for such an underestimation is show in Figure 5.13. The higher intake temperatures found for design 10-15 in Approach A are caused by the fact that the intake is located in the entire water column. The warm 'pancake' Approach A computed plume results in high intake temperatures at the surface, and therefore in total in higher intake temperatures. This is an indication that indeed the plume computed based on Approach A behaves more like a 'pancake' and is not able to assess the temperature in the far field as accurate as the state-of-the-art approach.

When an open surface outfall in combination with an open intake is used (design 16-18), Approach A overestimates the temperature compared to Approach B as can be seen in Table 5.9. In this case, both plumes are thick because no near-field model was used and this outfall design cause typically low mixing efficiency. Therefore, the choice in scenarios has a larger influence on the model results designing an open outfall than for the diffuser designs. Scenario 2, which occurs 50% of the time in Approach B, results in low intake temperatures. The equivalent of scenario 2 in Approach A, scenario 1, only occurs 25% of the year. The scenarios with a NW-current resulting in high intake temperatures in Approach B occur only 8% of the year.

The distance between the outfall and intake has an influence on the intake temperature for all design types. At the surface layer, the plume cools within 2000-2500 meter to approximately the same temperatures as the Approach B plume, see Figure 5.10 and 5.11. Therefore, the closer the intake locations are located towards the outfall, the more the initial mixing rate influences the intake temperatures and larger differences would be found between Approach A and B, especially for the open surface intakes. In this study, the intake locations are far enough to minimize these differences.

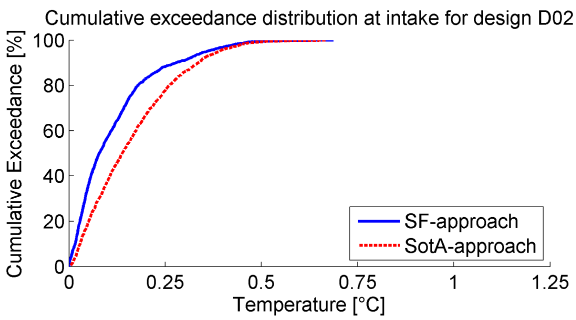


Figure 5.12: Yearly excess intake temperature for both approaches found for Design 2

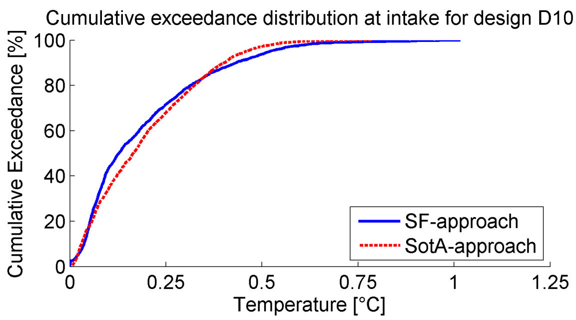


Figure 5.13: Yearly excess intake temperature for both approaches found for Design 10

Table 5.9: Deviation of Approach A from B, measured as the deviation from the mean temperature at the intake. The designs marked in bold indicate the diffuser designs, italics indicates an open surface outfall. The underlined designs consist of an open surface intake otherwise an submerged intake is proposed.

Design	**1**	**2**	**3**	**4**	**5**	**6**	*7*	*8*	*9*
Magnitude of T_{meanA} compared with T_{meanB}	73%	71%	71%	71%	69%	73%	99%	100%	92%
Design	**<u>10</u>**	**<u>11</u>**	**<u>12</u>**	**<u>13</u>**	**<u>14</u>**	**<u>15</u>**	*<u>16</u>*	*<u>17</u>*	*<u>18</u>*
Magnitude of T_{meanA} compared with T_{meanB}	98%	86%	79%	91%	73%	73%	116%	114%	110%

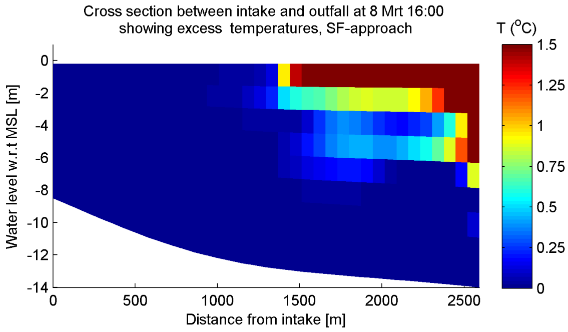


Figure 5.14: Cross section from intake to outfall, showing the the excess temperature at 8 March 16:00 for Design 5, scenario 5, Approach A.

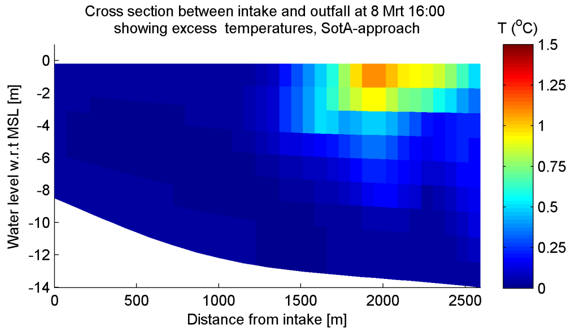


Figure 5.15: Cross section from intake to outfall, showing the the excess temperature at 8 March 16:00 for Design 5, scenario 5, Appraoch B.

5.3 Design choices

A selection framework was created in Section 3.2 to objectively determine the 'best' design. In this section, the framework will be used to select the 'best' design based on both Approach A and B. First the results of Approach A will be elaborated followed by Approach B. Finally, the differences in the chosen design will be elaborated.

Design choice based on Approach A
Table 5.10 shows the outcomes of the different designs valued by the criteria set in Section 3.2. Criteria one, the environmental criteria, turned out to be the most restraining criteria. Some of the findings will be explained in more detail:

- For all designs with a submerged intake, the environmental criteria were not met. A possibility is that this is due to a modeling inaccuracy. In Delft3D the intake is modeled as shown in Figure 5.16 (left), while a correct design is shown in Figure 5.16(right) is preferred. It is not possible to place vertical dams to correct this behavior. The result is that also water of the surface is sucked into the intake. This is a disadvantage because the plume often reaches the submerged intake. Therefore, the modeled intake temperature is higher, resulting in higher outfall temperatures. Consequentially, the environmental criteria are not met for design 1-6.

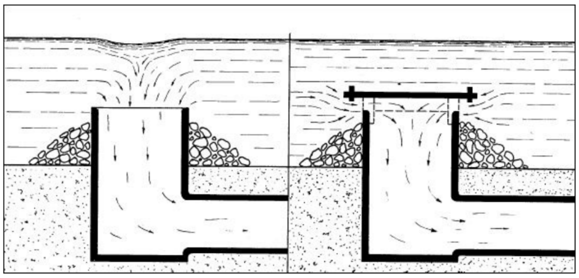


Figure 5.16: The submerged intake as modeled (left) and the reality (right)

- For a diffuser design with an open surface intake, the high temperature plume less often reached as far as the open surface intake, resulting in lower intake temperatures. As can be seen in Table 5.10, the environmental criteria is met for diffuser designs with an open intake which are located at least 1940 meter from the coast. The larger water depths at the outfall of designs located further into the sea result in more mixing of ambient water in the plume and therefore lower maximum excess temperatures at the surface.
- For the open surface outfall designs, the plume is thick and the intake is located in a zone where less mixing has taken place compared to the diffuser outfall designs. This is caused by the lower water depth at the open surface outfall compared to the diffuser designs. Furthermore, the dilution rate of a diffuser is at least 5-10 times higher than that of a surface outfall according to Jones et al. (2007). Therefore, the environmental criteria are not met for any of the open surface outfalls. Furthermore, for the open outfall designs, both intakes are in a zone where high temperatures are found. Therefore, taking the water in at the lower layers is an advantage. This results in the maximum temperatures just being under the maximum $1°C$ for the open surface outfall in combination with a submerged intake and being above this maximum for an open intake. Therefore, the second criteria was met for all designs except for the ones with both an open intake and outfall. Furthermore, the outfall location of design 10 is too close to the intake to meet the second criteria.

Finally, from the remaining designs 13-15, design 13 is selected as the 'best' design based on the capital costs. This is a diffuser located 1940 meter from the coast with an open surface intake. The recirculation costs corresponding to this design is $796.000, based on power plant life time of 25 year power plant. This is the costs estimation based on the model results of Approach A. The recirculation costs do not have an influence on the selection of the 'best' design when no or low inflation rates are assumed. Only in the case of more than 6% inflation in 25 years, the recirculation cost can influence the design selection. Design 14 would get marginally cheaper than design 13, a total capital and recirculaton cost of $6.631.000 and $6.622.000 for design 13 and 14 respectively. These large inflation rates are only expected in underdeveloped countries, in the developed countries this is not a realistic inflation rate (Karen Ward, 2012).

Table 5.10: Results Approach A, with 'best' scenario marked in yellow

Design	Outfall	Intake	Criteria 1: Environmental	Criteria 2: Maximum excess temperature	CAPEX	Recirculation costs (lifetime)
1	Diffuser	Submerged	no	yes	$ 7.500.000	$ 797.000
2	Diffuser	Submerged	no	yes	$ 7.845.000	$ 715.000
3	Diffuser	submerged	no	yes	$ 8.190.000	$ 645.000
4	Diffuser	Submerged	no	yes	$ 8.535.000	$ 587.000
5	Diffuser	Submerged	no	yes	$ 8.880.000	$ 548.000
6	Diffuser	Submerged	no	yes	$ 9.225.000	$ 518.000
7	Open	Submerged	no	yes	$ 5.125.000	$ 1.043.000
8	Open	Submerged	no	yes	$ 5.125.000	$ 959.000
9	Open	Submerged	no	yes	$ 5.125.000	$ 869.000
10	Diffuser	Open	no	no	$ 4.375.000	$ 1.162.000
11	Diffuser	Open	no	yes	$ 4.720.000	$ 957.000
12	Diffuser	Open	no	yes	$ 5.065.000	$ 796.000
13	Diffuser	Open	yes	yes	$ 5.410.000	$ 811.000
14	Diffuser	Open	yes	yes	$ 5.755.000	$ 576.000
15	Diffuser	Open	yes	yes	$ 6.100.000	$ 515.000
16	Open	Open	no	no	$ 2.000.000	$ 1.817.000
17	Open	Open	no	no	$ 2.000.000	$ 1.658.000
18	Open	Open	no	no	$ 2.000.000	$ 1.438.000

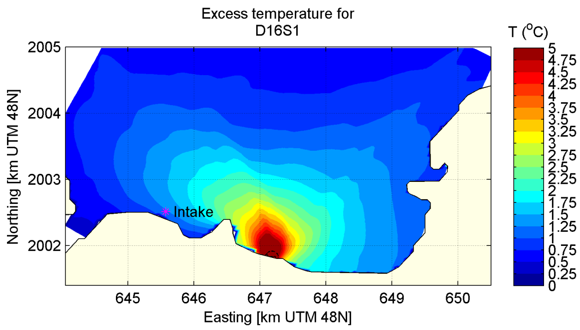


Figure 5.17: Maximum excess temperature in intake layer for design 16, Approach A

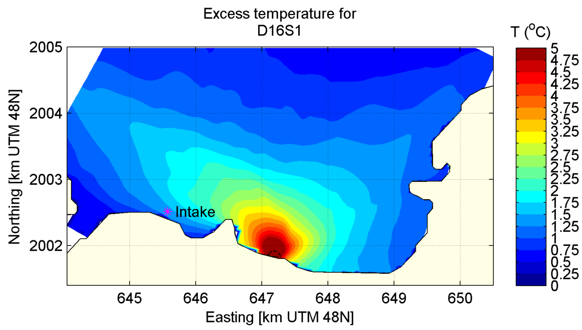


Figure 5.18: Maximum excess temperature in intake layer for design 16, Approach B

Design choice based on Approach B

Table 5.11 shows the results of the 18 designs valued by the criteria of Section 3.2. Because the included near-field model resulted in lower excess temperatures at the outfall, the environmental criteria is met for all diffuser designs. For the open surface outfall, the maximum excess temperature is too high to meet the first criteria. Similar to the observation based on Approach A, the second criteria is met for all designs expect for the design with an open intake and open outfall.

From the remaining design options, design 1-7 and 10-15, the cheapest option is selected to be the 'best' design. Based on the capital costs this would be design 10. This is a diffuser design at 1250 meter from the coast in combination with a open surface outfall. The lifetime recirculation cost of this design is $1.191.000.

Table 5.11: Results Approach B, with 'best' scenario marked in yellow

Design	Outfall	Intake	Criteria 1: Environmental	Criteria 2: Maximum excess temperature	CAPEX	Recirculation costs (lifetime)
1	Diffuser	Submerged	yes	yes	$ 7.500.000	$ 1.089.000
2	Diffuser	Submerged	yes	yes	$ 7.845.000	$ 1.003.000
3	Diffuser	Submerged	yes	yes	$ 8.190.000	$ 914.000
4	Diffuser	Submerged	yes	yes	$ 8.535.000	$ 831.000
5	Diffuser	Submerged	yes	yes	$ 8.880.000	$ 792.000
6	Diffuser	Submerged	yes	yes	$ 9.225.000	$ 706.000
7	Open	Submerged	no	yes	$ 5.125.000	$ 1.058.000
8	Open	Submerged	no	yes	$ 5.125.000	$ 961.000
9	Open	Submerged	no	yes	$ 5.125.000	$ 940.000
10	Diffuser	Open	yes	yes	$ 4.375.000	$ 1.191.000
11	Diffuser	Open	yes	yes	$ 4.720.000	$ 1.114.000
12	Diffuser	Open	yes	yes	$ 5.065.000	$ 1.007.000
13	Diffuser	Open	yes	yes	$ 5.410.000	$ 892.000
14	Diffuser	Open	yes	yes	$ 5.755.000	$ 785.000
15	Diffuser	Open	yes	yes	$ 6.100.000	$ 708.000
16	Open	Open	no	no	$ 2.000.000	$ 1.562.000
17	Open	Open	no	no	$ 2.000.000	$ 1.450.000
18	Open	Open	no	no	$ 2.000.000	$ 1.309.000

Differences between the final results

The main difference between the two chosen designs is the 40% larger pipe length and the depth of the diffuser outfall. These differences results in:

- The design chosen by Approach A is $1.035 million more expensive in capital costs, an expenditure increase of 23%. This is because Approach A values designs as unfit, environmental criteria are not met, were these designs turn out to be fit by Approach B.
- The difference in intake temperature can be seen in Figure 5.19. The difference in intake temperature is small. Nonetheless, the design chosen based on Approach B will be $299.000 more expensive when it comes to recirculation costs, with an assumed 25 year lifetime of the plant.

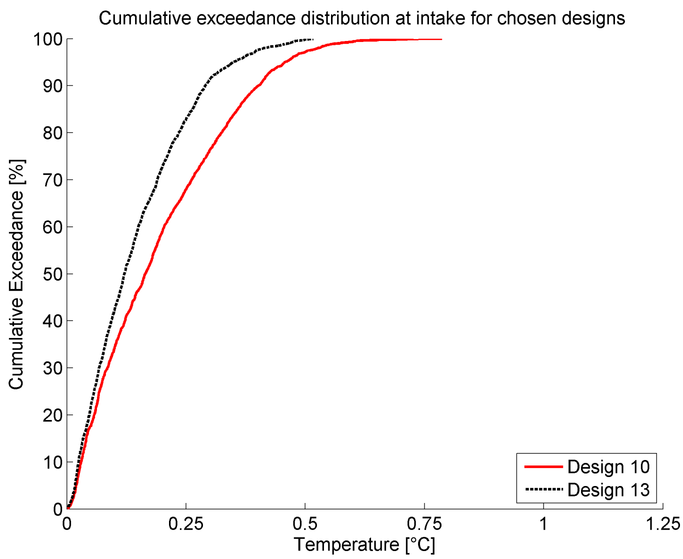


Figure 5.19: Difference in yearly excess intake temperature for the proposed design, as assessed based on Approach B

CHAPTER 6

Discussion

The potential added value for an intake and outfall design was investigated in this research. A common practice model (Approach A) was compared with a state-of-the-art model (Approach B). Several assumptions needed to be made to allow for a feasible study. Nevertheless, these assumptions could affect the outcome of the study and therefore the sensitivity of these assumptions is discussed below. This chapter gives a discussion on the operational cost assessment, intake/outfall configuration, the model approaches and the case study aspects.

6.1 Operational costs assessment

There are many uncertain parameters included in the costs assessment used in this study such as; the present and future energy prices, inflation rates and the gross load of the power plant. The assumed Gross Load and Energy price are linear related to the recirculation costs. The assessed recirculation costs are therefore very sensitive to these parameters. For example, the largest coal power plant in the world consist of 10×550MW power units, whereas the power plant in this study case produces only 10% of this amount (Kable, 2016). A quick evaluation showed that from a 4.5 times larger power plant than used in this study, the recirculation costs would start to influence the selection process. This would also result in a lower added-value for Approach B in terms of recirculation costs.

The costs assessment was based on the relation found by Tramel (2000) between the net unit heat rate and the intake temperature found by the models. However, Tramel (2000) only investigated the net unit heat rate for power units between 100 and 230 MW. Most new built power plant consists of units of at least 500MW. Therefore, it would be interesting to investigate what the net unit heat rate would be for such large power units and the effect on the recirculation costs.

Furthermore, Tramel (2000) investigated the difference in condenser efficiency for a temperature difference between $18°C$ and $22°C$. However, it would be relevant to research whether the relation found by Tramel (2000) is still valid for higher ambient temperatures. In addition, the assumed energy price could highly fluctuate during the lifetime of the power plant. A higher energy price is expected to make Approach B less beneficial because the difference between the two approaches is getting lower. Moreover, Supasri et al. (2013) stated that the net heat rate of the condenser is not only related to the intake temperature but also to other parameters such as the flow magnitude and pressure rates in the condenser. Therefore, the net unit heat rate can differ per power plant for the same intake temperature.

However, the differences found in recirculation costs are low in this study. Therefore, the above mentioned aspects are expected to have a small effect on the conclusion of this study.

Nevertheless, as was introduced in chapter 2, the operational costs consist of much more factors, e.g. pumping costs, than just the recirculation costs. Therefore, the assumption to assessment the operational costs just by the recirculation costs is simplistic. The different final designs as chosen in Section 5.3 might therefore result in other conclusions in terms of the operational costs when the total operational costs are considered. More research is required to fully assess this. But it is expected that the recirculation cost are only a minor part of the total operational costs.

Finally, the capital costs are expected to vary per region. The estimate used in this study showed that there is a difference between the modeling approaches. The variation in regional prices could therefore result in a different magnitude in the added value, but an added value is always expected.

6.2 Intake and outfall configuration

In this case study, Approach A always underestimates the intake temperature in case of a diffuser design. An additional quick assessment was performed to see whether cases exist that Approach A overestimates the modeled intake temperature of Approach B. This was performed by checking the excess temperature at other intake locations than the initial two locations of the framework introduced in Section 3.2. Considering the possible recirculation and effect of the intake temperature on the effluent, this is only an approximation, but suitable for this comparison.

In case of a submerged intake and a diffuser outfall, the intake temperature will always be underestimated by Approach A because the temperature in the lower layers is underestimated by Approach A, also if the intake is located closer to the outfall. Approach A underestimated the lower layers because this model cannot capture the near field plume behavior, resulting in the plume going quicker to the surface than modeled by Approach B.

In case of an open surface intake design with a diffuser outfall, it was found that an intake very close to the outfall would result in Approach A overestimating the modeled intake temperature of Approach B. This will make the design based on Approach B not only more cost-efficient in term of capital cost but also in terms of the recirculation costs. Therefore, the added value of Approach B increases in cases where the intake and outfall are very close to each other.

6.3 Methods and model set-up

The Approach A based model is sensitive to some model input parameters. For example, a large grid size could result in high numerical dilution. Furthermore, the discharge location within the water column has its influence on the estimated initial mixing. Therefore, Approach A will lead to less reliable results because this methods input is more sensitive to choices and assumptions made by the modeler. The use of a near-field model reduces these uncertainties.

Furthermore, Approach A is more sensitive to the assumptions and choices made by the modeller considering the choice in ambient scenarios. For example in this case, the neglected direction in the residual current has a low occurrence time. However, when this would be an often occurring condition, Approach A would be less accurate and the added-value of SBAM would be larger. Therefore, Approach B would lead to more reliable results because the modeller is forced to understand the system better and is therefore expected to make better assumptions. Consider a case in the Middle-East where often a land-sea breeze is forcing the system, the direction of the wind is toward the coast during the day and offshore during the night but this is very site specific. Wrong assumptions in such a system could have large influence on the recirculation. In that case, the added-value of the SBAM method is expected to be higher in the performed study. The advantageously selected scenarios in Approach A caused to minimized the added-value of Approach B. The added value of the near-field model could be even more when the SBAM approach was performed as suggested by de Fockert et al. (2011). The amount of scenarios where reduced in this study because of a large amount of scenarios would result in unfeasible large computation times. Nonetheless, it is assumed that the thorough analysis and selection process results in a better estimation of the ambient scenarios than for the simpler selection method.

A parameter that causes uncertainty in Approach B is the model coupling location. In this study, the indicators for the coupling location, in the post-processing function, were set based on expert judgment. Research is carried out to create a generic guideline for the coupling location. Furthermore, the dynamic coupling is still under development. In this case it was found that in some cases the coupling location was outside the maximum range of 500 meter. This is probably caused by a bug in Delft3D and the repair of this is in development. This bug only occurred less than 10 time steps so it is expected that this would not influence the overall conclusions of this project.

The used models in this study were not calibrated because measurements were not available. However, calibrating the final design option would be very difficult anyway. This study had the objective to investigate to added value of state-of-the-art modeling. Therefore, the physical processes should be accurately and good incorporated in both models. However, tuning the models to the exact ambient conditions of the case area, Vung Ang, is not required to answer the research question because a relative comparison is made. This is valid as long as the forcing is the same and the case is realistic, i.e. magnitudes and combinations of ambient conditions could occur. Due to the fact that validation is not possible, the assumption was made that Approach B gives a more physical correct estimation of the plume behavior. Several studies show that the state-of-the-art approaches result in more accurate system estimation (Bleninger and Morelissen, 2015; de Fockert et al., 2011; Morelissen et al., 2015). Therefore, the assumption is legitimate and the best estimation of the current available options.

6.4 Representativeness of the case study

This study showed that the extension of the far field model with a near field model highly contributes to the added-value of accurate numerical modelling. It is therefore expected that in other cases the near field model is also of added value. The currently investigated case area is suitable and representative to investigate the added-value for other case areas, because the most typical processes that occur in recirculation studies have been taken into account. Furthermore, typical values for the outfall temperature were used. Additionally, the ambient forcing processes in the study all have a similar contribution to the outfall plume and recirculation behaviour. The effect of a few ambient processes on the final conclusion is discussed further in more detail:

The discharge used in this case is considered as large for a diffuser line (Morelissen et al., 2015). It is expected that the overall observations found in this case are valid for cases with smaller discharge as well. However, the effect of the near field on the far field becomes less and the intial mixing processes become less dominated by the near field outfall dynamics. This results in a decreased difference in the near field plume behaviour and consequently a lower added value of Approach B.

In addition, a dominant wind is expected to decrease the added value of Approach B. A strong wind at the water surface is expected to decrease the surface temperature. Because the surface temperature of Approach A is generally larger than estimated by Approach B, the wind has more influence on the plume behaviour modelled by Approach A. The difference in surface temperature between the two approaches is expected to be lower, resulting in a lower added value of Approach B.

The added-value of Approach B would become less in terms of recirculation costs when no river is present in the system, in case of a diffuser design. It is less likely that the plume would be horizontally stratified , a phenomenon that influences both near and far field plume behaviour. This phenomenon is less accurately assessed by Approach A.

The water depth has a large influence on the initial mixing; the process where the largest differences between Approach A and B were found. The beach slope used in the study is gentle. It is expected that in case of a very steep slope, which might result in a diffuser at a large water depth, the added value of Approach B would become more. This can also be seen in the investigated diffusers in this study, see table 5.10 and 5.11.

In general, it is expected that there is always an added-value for using a coupled near-far-field model. However, in case of mild ambient conditions compared to the diffuser characteristics, e.g. the near field plume trajectory and dilution do not vary much, a one-way coupling approach might be sufficiently good.

6.5 Addition model choice considerations

Besides the investigated capital en recirculation costs, the following has to be considered when choosing the model approach:

- Considering the maintenance of both designs, it is expected that the design chosen by Approach B would be cheaper. This is due to the shorter and less deep laying pipelines. Maintenance of a pipeline includes the removal of dirt or biofouling inside the pipes and the inspection of the pipelines on damage. The maintenance costs is difficult to estimate because the costs are related to many indicators such as the pipes diameter, length, depth but also to local labor costs and the required decommissioning time of the plant. However, San Diego County Water Authority (2009) estimated the annual intake and diffuser inspection costs to be $120.000 for a plant in the USA with an outfall pipe length of 2600 meter. A 40% larger pipe length for the 'best' Approach A design compared to the Approach B based design has therefore a significant influence on the maintenance costs of the intake and outfall configuration of a power plant.
- The operational costs of the power plant could increase when pumping is required for the outfall. Pumping is required when gravity is not sufficient to discharge at a certain pressure or to guaranty an certain pressure at the intake. Damon S. Williams Associates (1999) estimated the pumping costs to be $80.000 per year for a sewage plant, inflation since 1999 was accounted for. These costs are mainly the result of the required electricity needed for pumping. Longer pipelines require more pumping and could therefore be more expensive. More research is required to assess this more accurately.
- Design 10 would be easier to build considering the pipe length and depth. Therefore, the labor costs would be lower for the design based on Approach B.
- The model set-up of Approach B was approximately 1.5 as long as for Approach A. Therefore, a study based on Approach B is expected to be more expensive for the client.
- Approach A is not capable of incorporating the characteristics of the diffuser. Therefore, the diffuser design cannot optimized and which is a large disadvantage of Approach A.

CHAPTER 7

Conclusion and recommendations

New modeling approaches have been developed to provide more accurate and comprehensive design information with the goal of a better design of the intake and outfall of a power plant. This study objectively investigated the added value of state-of-the-art recirculation modeling (Approach B) compared to a typical straightforward modeling approach (Approach A) for the optimization of the intake and outfall configuration of a power plant. This chapter will answer the research question as posed in Chapter 1. Hereafter some recommendation for further research are presented.

Approach A: a 3D far field model forced by ambient scenarios that are selected based on common weather conditions, see details in Section 4.1 and 3.1.3 respectively.

Approach B: the far field model of Approach A is dynamically coupled with a near field model, see Section 4.2. In addition, the SBAM method is used to select the ambient scenario, see Section 5.1.1.

7.1 Conclusions

Could the usage of a state-of-the-art recirculation modeling approach result in a better intake and outfall design, compared to a straightforward model approach?

- In terms of **capital costs**, a straightforward approach based design is expected to have larger capital costs because suitable designs are rejected by the straightforward approach which are not rejected by a state-of-the-art model. In this study, Approach A overestimates the surface temperature for a diffuser outfall. Consequentially, environmental criteria are not met resulting in a less advantageous proposed design when using an Approach A based study. In this case, the proposed design based on Approach A resulted in a 40% longer pipeline compared to Approach B. This has several consequences:
  - For this case study, the capital cost for the proposed design would be 1.035 million higher when using Approach A compared to Approach B. This is an increase in capital cost of 23%.
  - The annual maintenance costs will be higher for an Approach A based design. This can be up to 40% difference, which is in the order of tens of thousands dollars per year. The operational costs of the intake and outfall system may increase as well, depending on local characteristics.
  - Additional capital cost, such as labor costs, will be lower for the SotA-approach because a shorter and shallower pipeline is easier and therefore quicker to build.

- The **recirculation costs** computed by a straightforward based model are overly optimistic, in case of a diffuser design. This could result in unforeseen costs for the operator. Furthermore, the safety for example nuclear power plants can be underestimated. It is expected that a change in energy prices, inflation rates, size of the power plant and discharge would not change this conclusion.
- This case study suggested that for an open surface outfall, there is limited added value considering the estimation of the intake temperature. However, this study suggested that a state-of-the-art modeling approach results in more **reliable** model results. First, because it is less influenced by the modelers input, such as the grid size, and secondly because the SBAM-method decreases the risk on wrong assumptions made by the modeler.

7.2 Recommendations for further research

Based on the performed study the following is recommended to investigate further:

- It is recommended to perform more research into the coupling location of the near and far field model. It was found that this is yet not fully performing as desired because the maximum couple location is sometimes not satisfied.
- The possibility in Delft3D to place vertical thin dams should be investigated to be able to model the submerged intake in a more accurate way.
- It would be interesting to investigate the relation between the net heat flux and the intake temperature for larger power units and higher intake temperatures than studied by Tramel (2000).
- Currently, the near field behavior of the plume for an open surface outfall can not yet be estimated as accurately as for the diffuser designs. Therefore, more research is required to develop such a accurate model.

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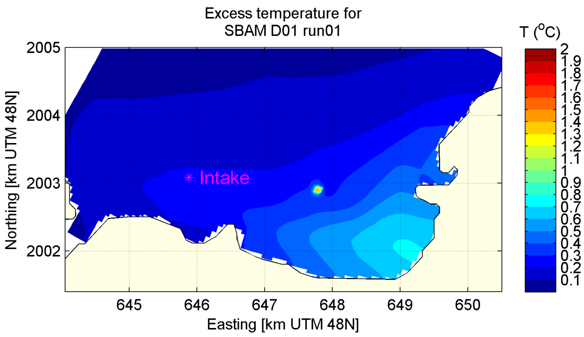
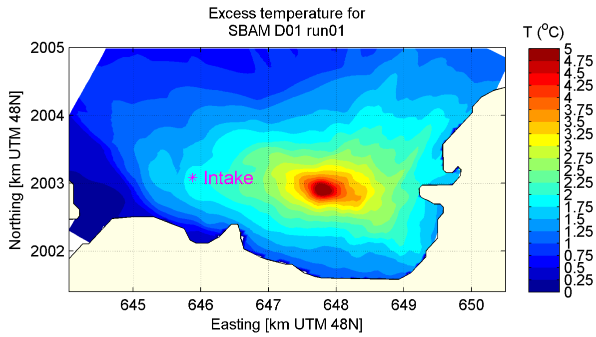
APPENDIX A

Results SBAM

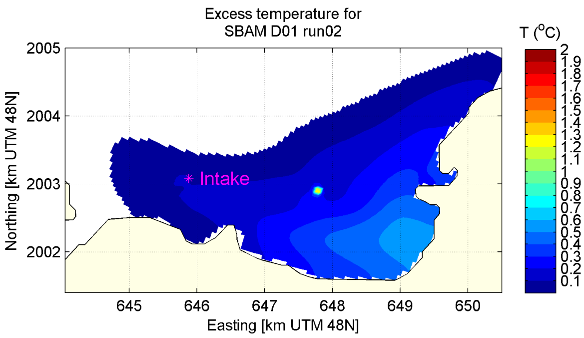
This appendix provides the model outcomes of the SBAM method. Please note the difference in scale for the mean excess temperature in the intake layer compared to the maximum excess temperature in the surface layer.



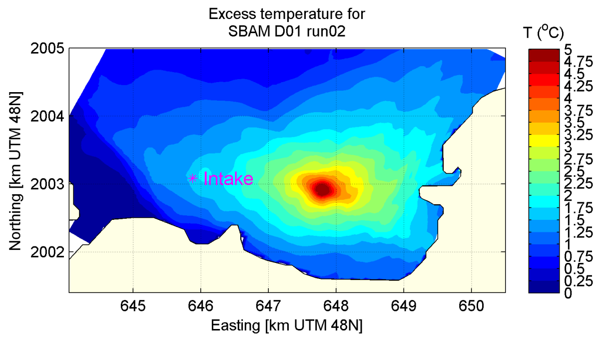
(a) Mean temperature in intake layer, 3cm/s NW residual current



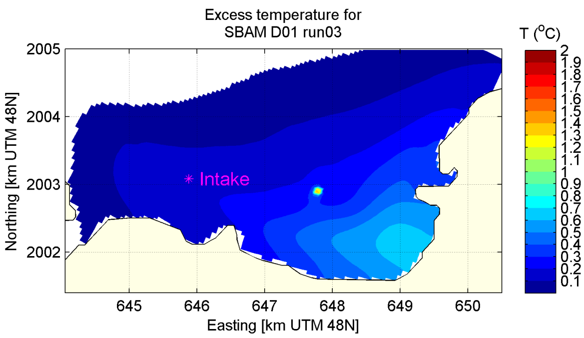
(b) Maximum temperature in surface layer, 3cm/s NW residual current



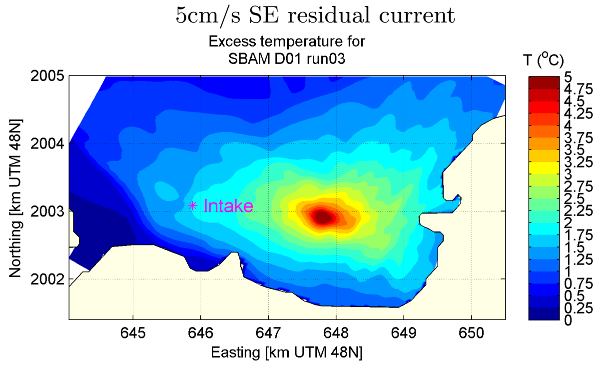
(c) Mean temperature in intake layer, 5cm/s SE residual current



(d) Maximum temperature in surface layer, 5cm/s SE residual current

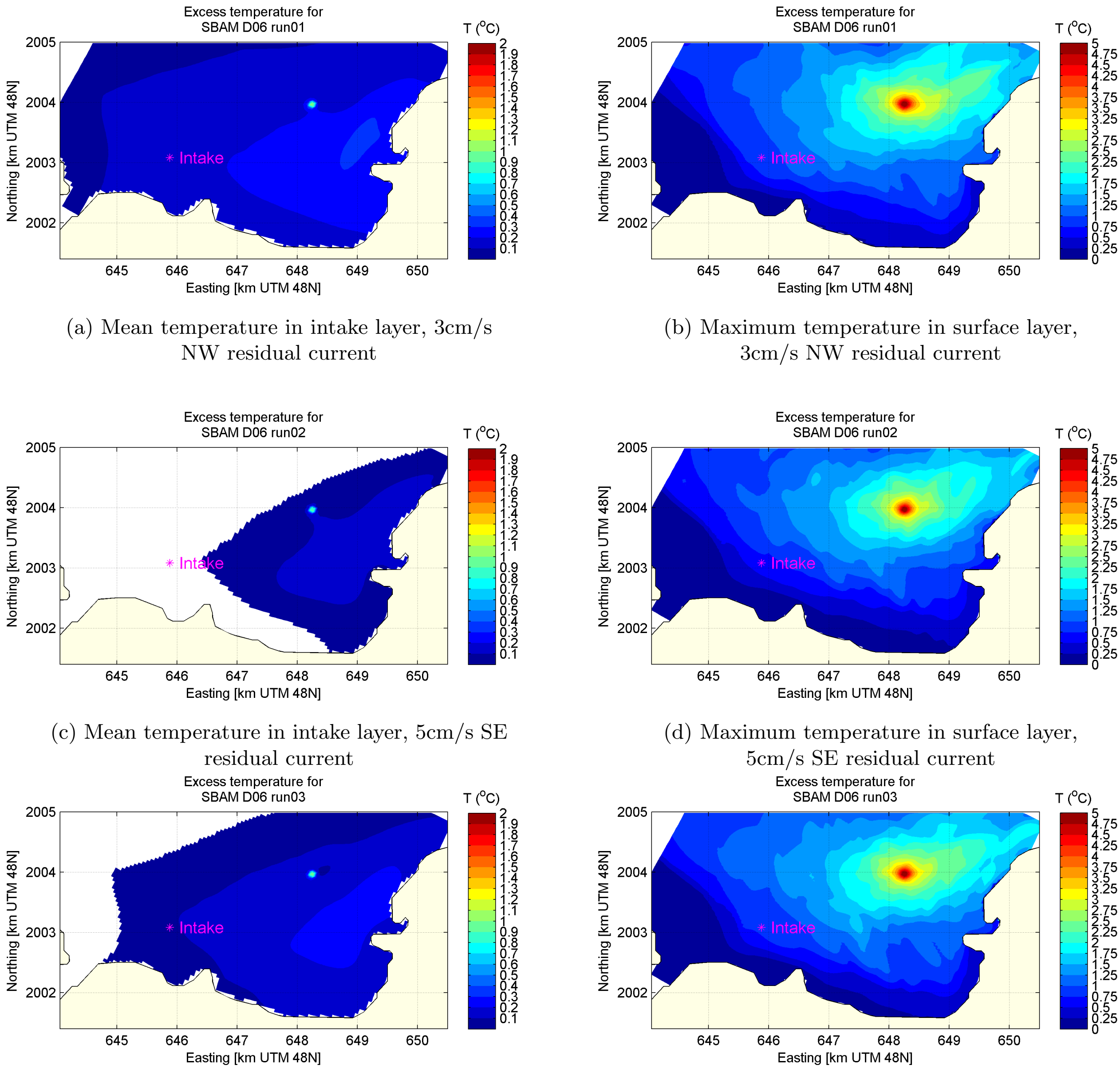


(e) Mean temperature in intake layer, no residual current



(f) Maximum temperature in surface layer, no residual current

Figure A.1: Influence of the residual current on system behavior for design 1. For left pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume. Note the scale differences.



(a) Mean temperature in intake layer, 3cm/s NW residual current

(b) Maximum temperature in surface layer, 3cm/s NW residual current

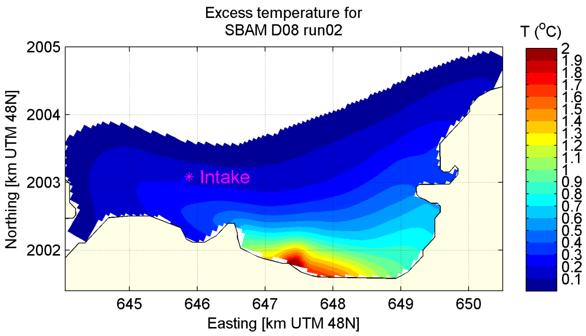
(c) Mean temperature in intake layer, 5cm/s SE residual current

(d) Maximum temperature in surface layer, 5cm/s SE residual current

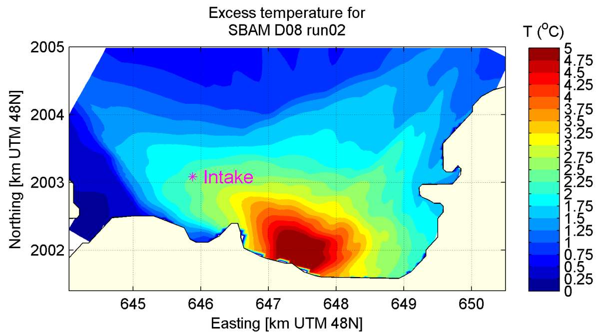
(e) Mean temperature in intake layer, no residual current

(f) Maximum temperature in surface layer, no residual current

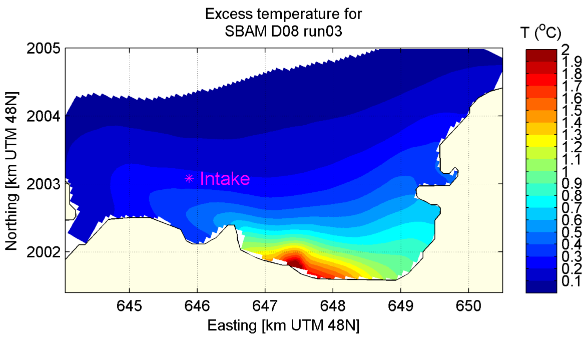
Figure A.2: Influence of the residual current on system behavior for design 6. For left pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume. Note the scale differences.



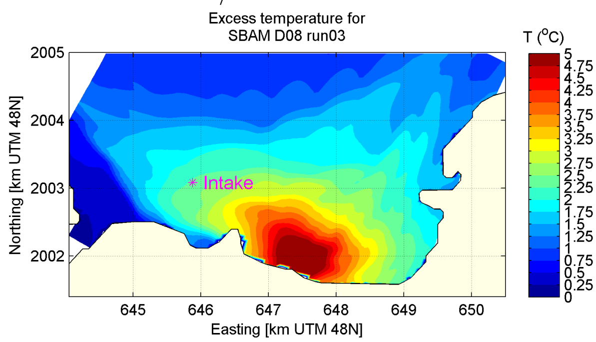
(a) Mean temperature in intake layer, 5cm/s SE residual current



(b) Maximum temperature in surface layer, 5cm/s SE residual current

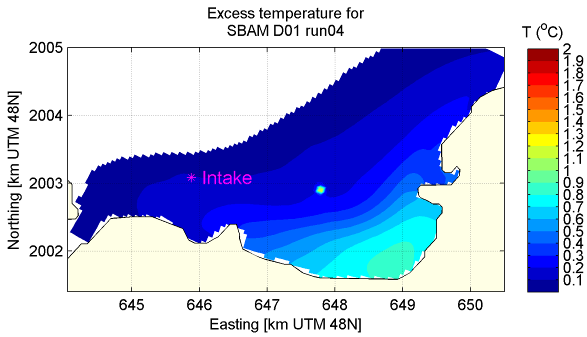


(c) Mean temperature in intake layer, no residual current

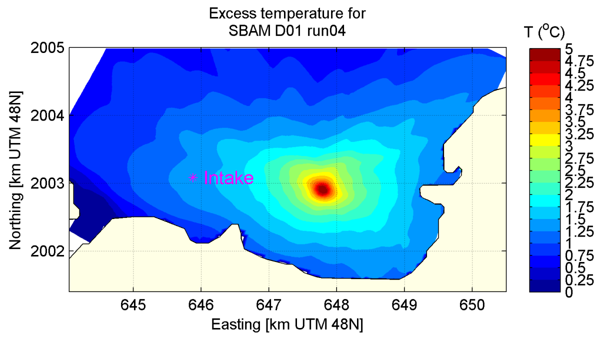


(d) Maximum temperature in surface layer, no residual current

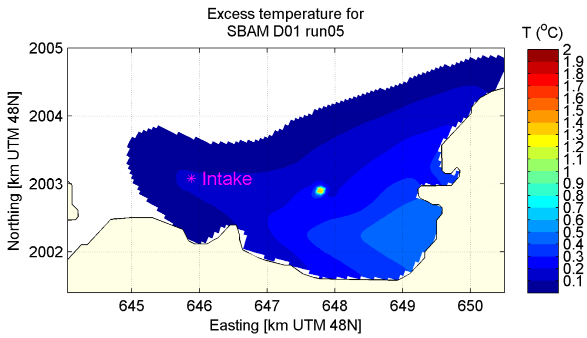
Figure A.3: Influence of the residual current on system behavior for design 8. For left pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume. Note the scale differences.



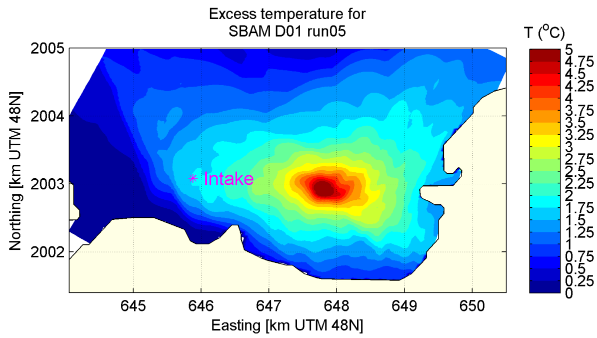
(a) Mean temperature in intake layer, Q=$0m^3/s$



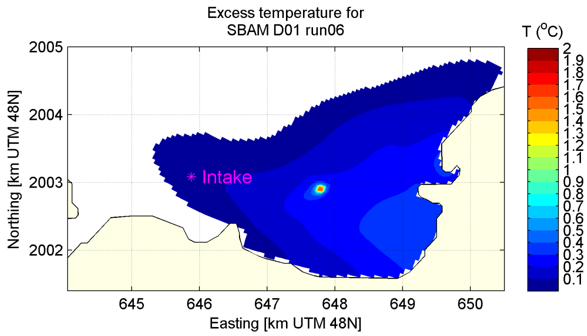
(b) Maximum temperature in surface layer, Q=$0m^3/s$



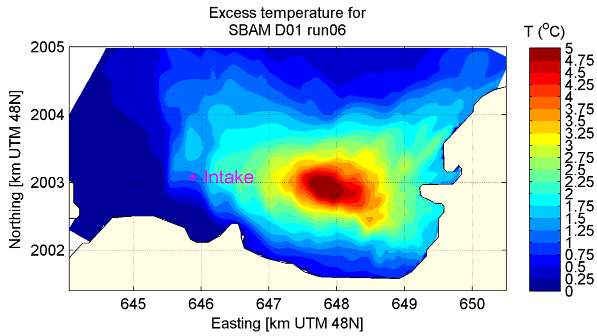
(c) Mean temperature in intake layer, Q=$70m^3/s$



(d) Maximum temperature in surface layer, Q=$70m^3/s$

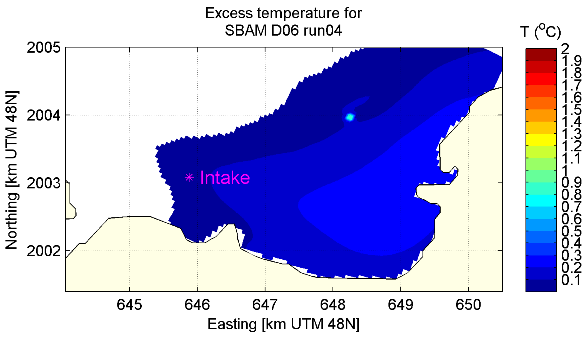


(e) Mean temperature in intake layer, Q=$170m^3/s$

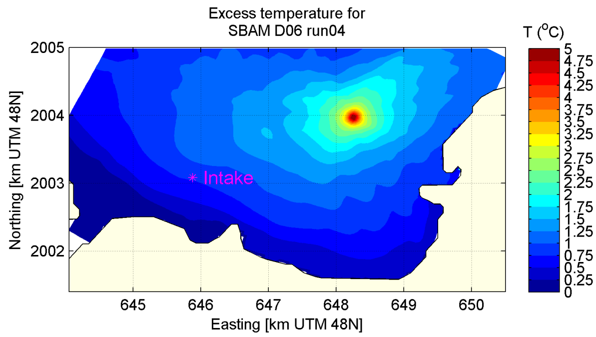


(f) Maximum temperature in surface layer, Q=$170m^3/s$

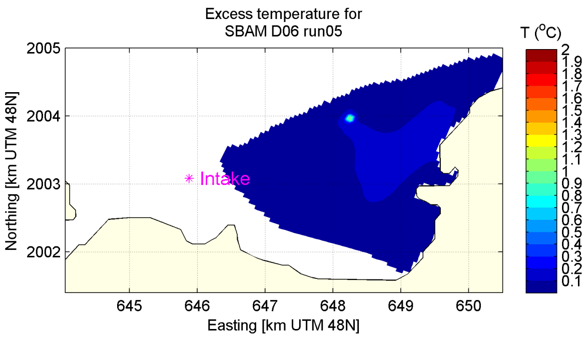
Figure A.4: Influence of the river on system behavior for design 1. For left pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume. Note the scale differences.



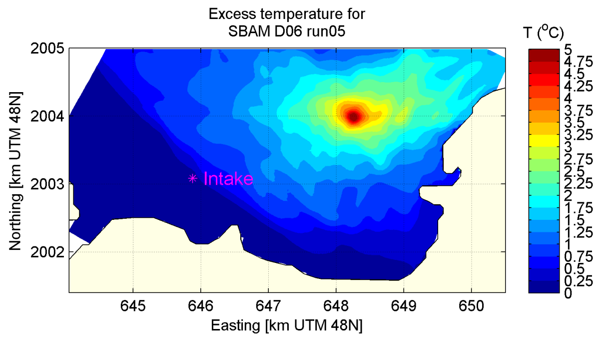
(a) Mean temperature in intake layer, Q=$0m^3/s$



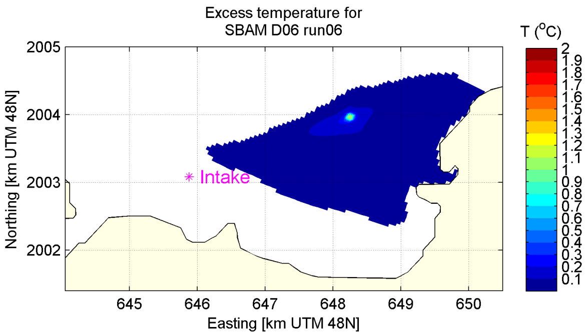
(b) Maximum temperature in surface layer, Q=$0m^3/s$



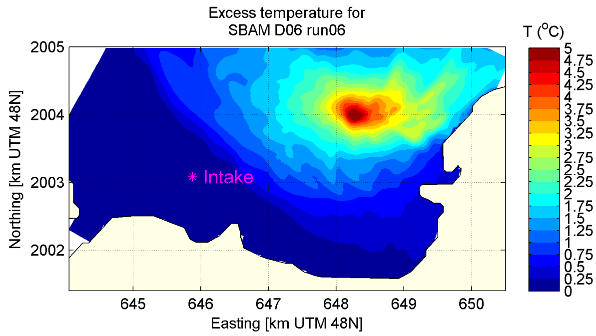
(c) Mean temperature in intake layer, Q=$70m^3/s$



(d) Maximum temperature in surface layer, Q=$70m^3/s$

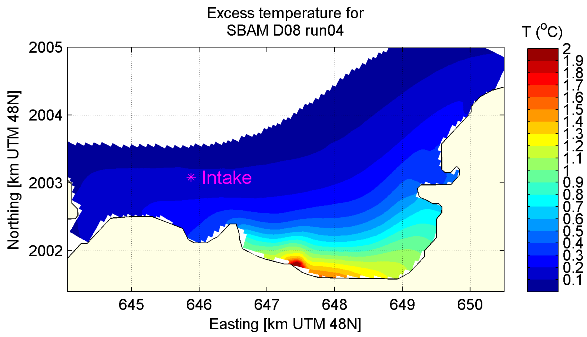


(e) Mean temperature in intake layer, Q=$170m^3/s$

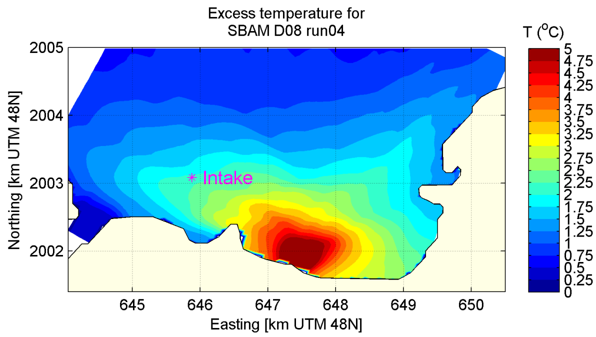


(f) Maximum temperature in surface layer, Q=$170m^3/s$

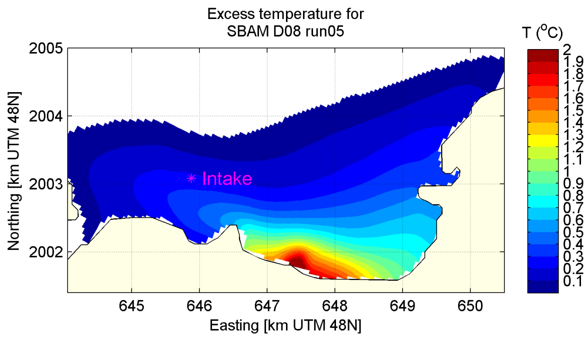
Figure A.5: Influence of the river on system behavior for design 6. For left pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume. Note the scale differences.



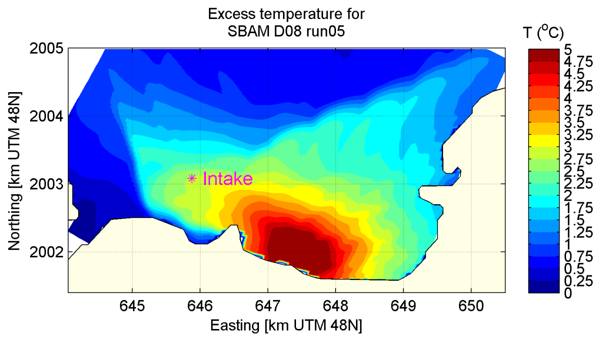
(a) Mean temperature in intake layer, Q=$0m^3/s$



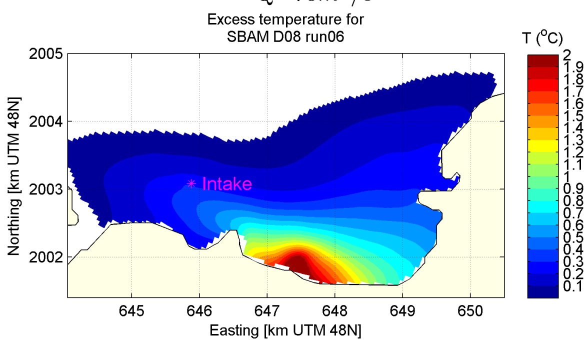
(b) Maximum temperature in surface layer, Q=$0m^3/s$



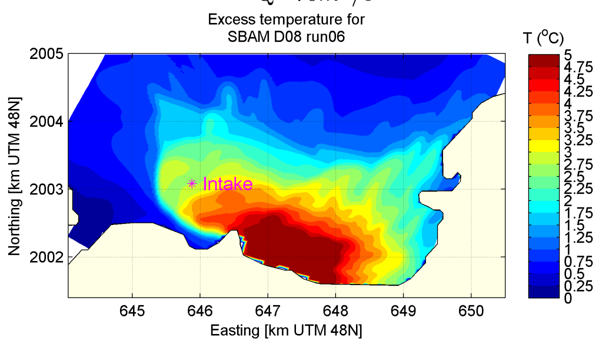
(c) Mean temperature in intake layer, Q=$70m^3/s$



(d) Maximum temperature in surface layer, Q=$70m^3/s$

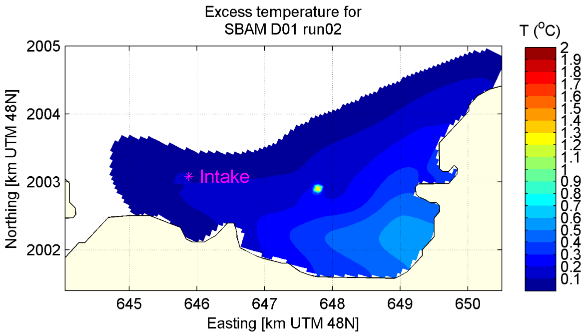


(e) Mean temperature in intake layer, Q=$170m^3/s$

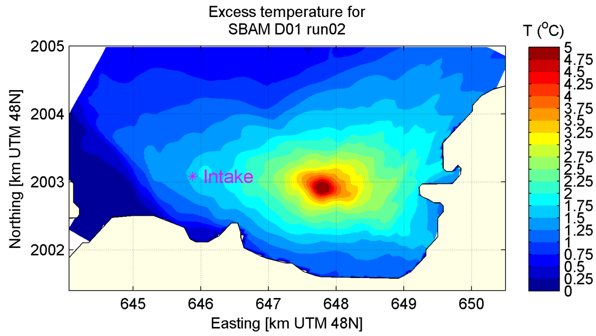


(f) Maximum temperature in surface layer, Q=$170m^3/s$

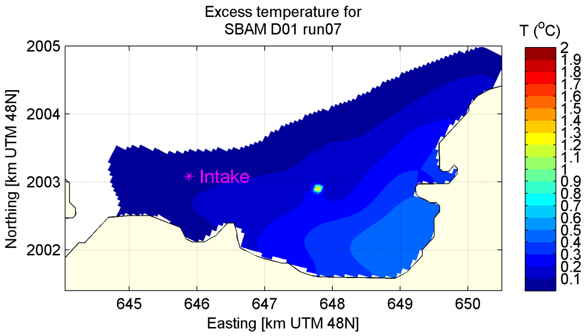
Figure A.6: Influence of the river on system behavior for design 8. For left pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume. Note the scale differences.



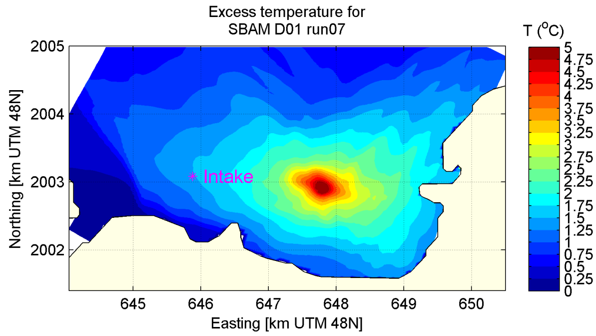
(a) Mean temperature in intake layer, persistent wind



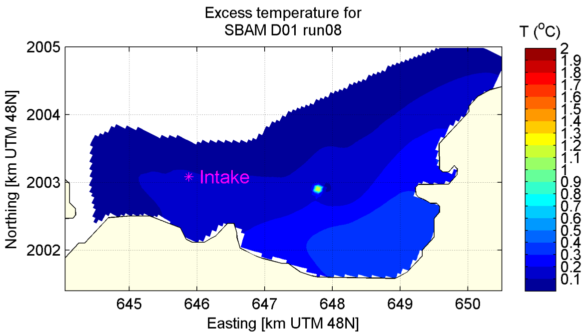
(b) Maximum temperature in surface layer, persistent wind



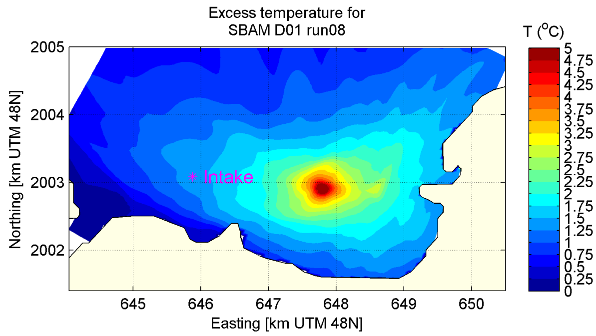
(c) Mean temperature in intake layer, maximum wind



(d) Maximum temperature in surface layer, maximum wind

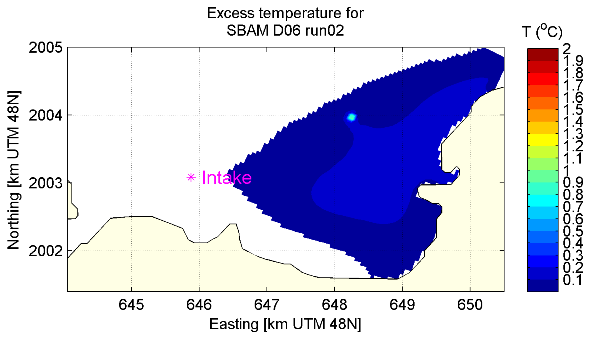


(e) Mean temperature in intake layer, daily varying wind

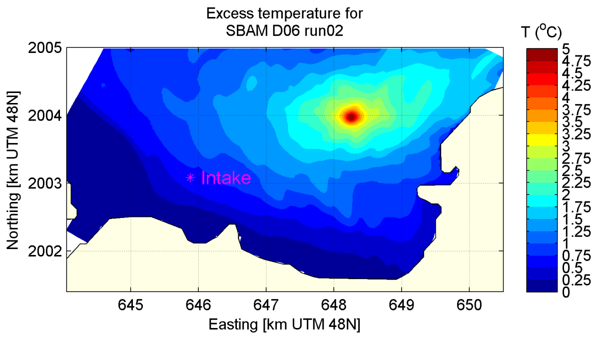


(f) Maximum temperature in surface layer, daily varying wind

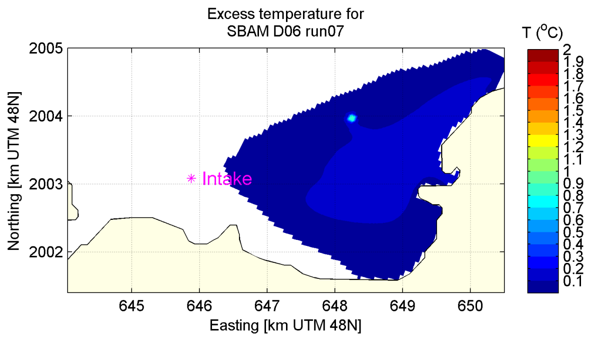
Figure A.7: Influence of the wind on system behavior for design 1. For left pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume. Note the scale differences.



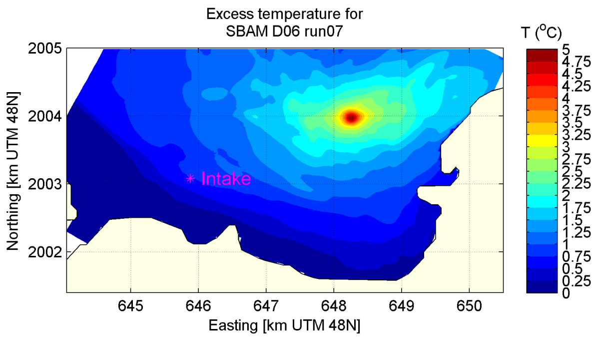
(a) Mean temperature in intake layer, persistent wind



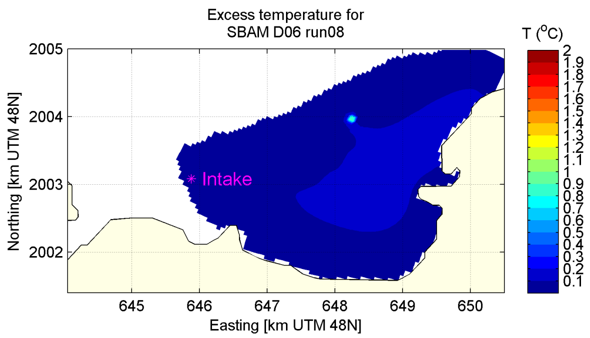
(b) Maximum temperature in surface layer, persistent wind



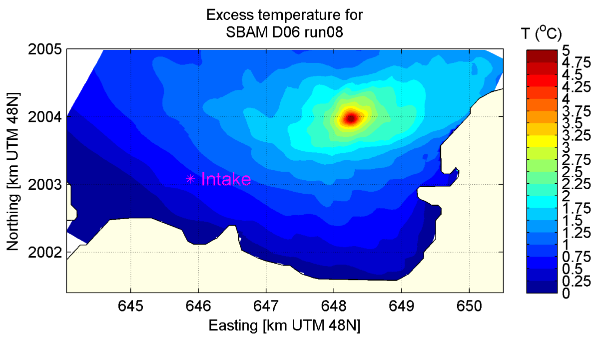
(c) Mean temperature in intake layer, maximum wind



(d) Maximum temperature in surface layer, maximum wind

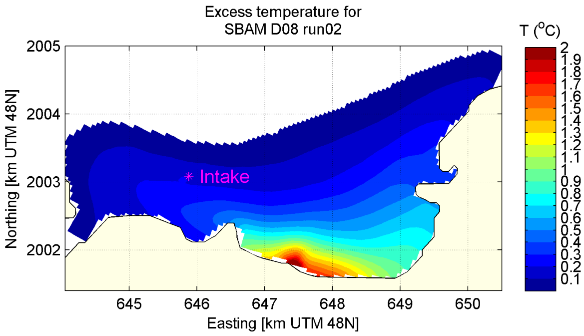


(e) Mean temperature in intake layer, daily varying wind

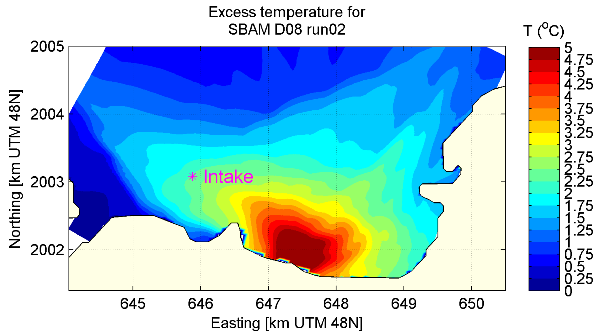


(f) Maximum temperature in surface layer, daily varying wind

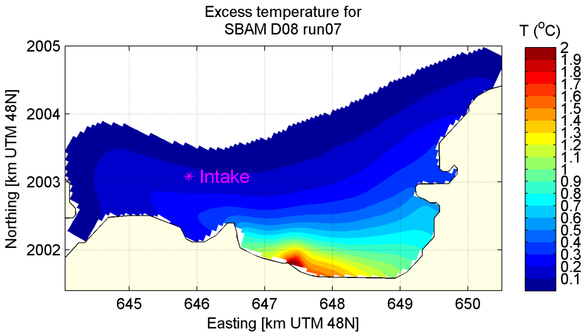
Figure A.8: Influence of the wind on system behavior for design 6. For left pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume. Note the scale differences.



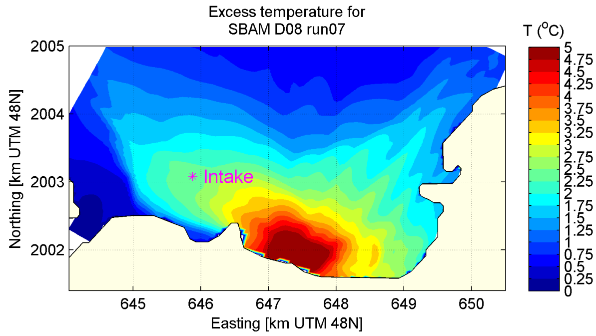
(a) Mean temperature in intake layer, persistent wind



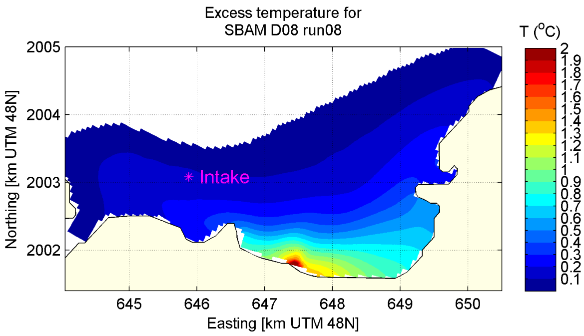
(b) Maximum temperature in surface layer, persistent wind



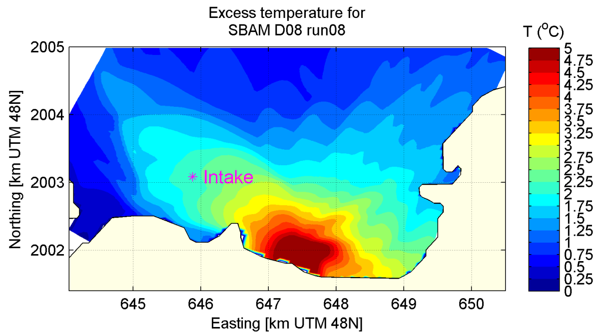
(c) Mean temperature in intake layer, maximum wind



(d) Maximum temperature in surface layer, maximum wind

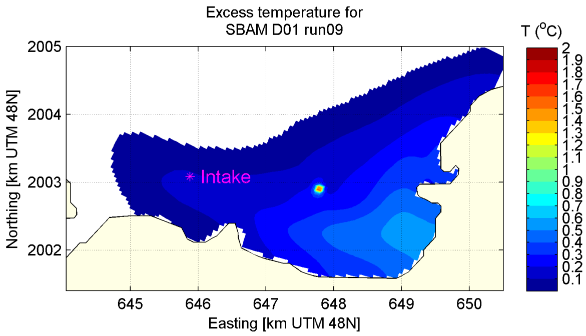


(e) Mean temperature in intake layer, daily varying wind

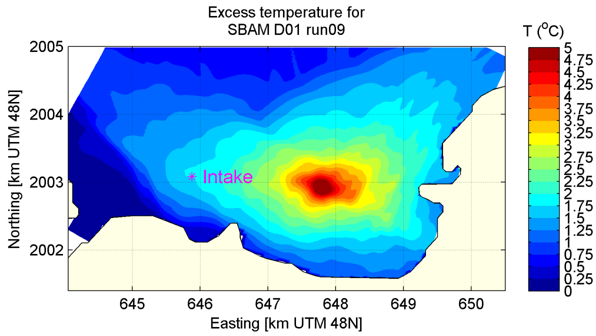


(f) Maximum temperature in surface layer, daily varying wind

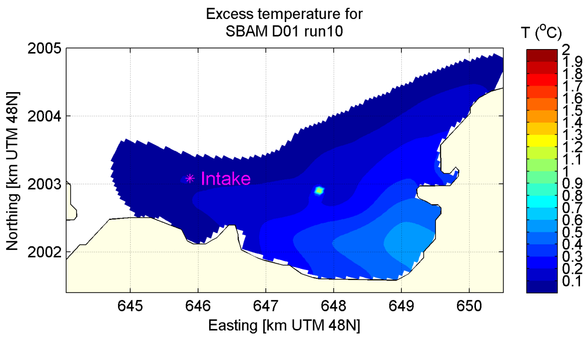
Figure A.9: Influence of the wind on system behavior for design 8. For left pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume. Note the scale differences.



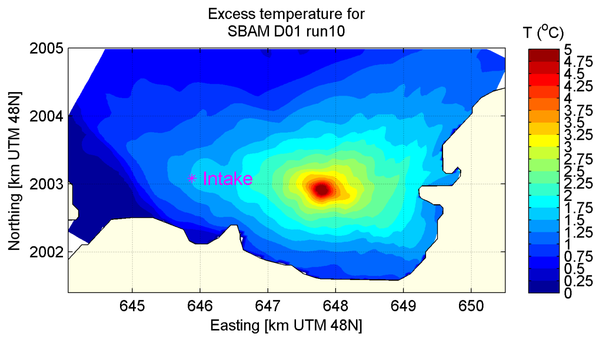
(a) Mean temperature in intake layer, T=16 $^{\circ}C$



(b) Maximum temperature in surface layer, T=16 $^{\circ}C$

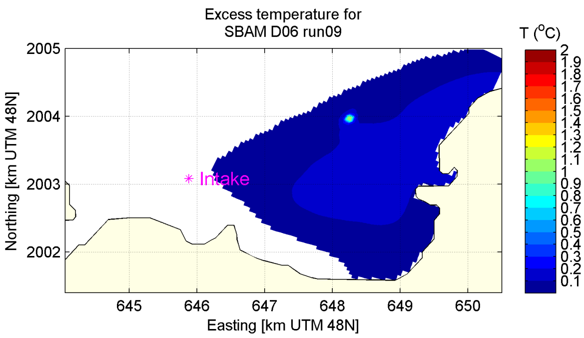


(c) Mean temperature in intake layer, T=33 $^{\circ}C$

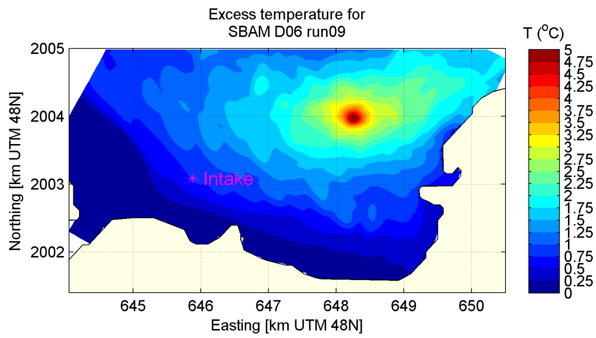


(d) Maximum temperature in surface layer, T=33 $^{\circ}C$

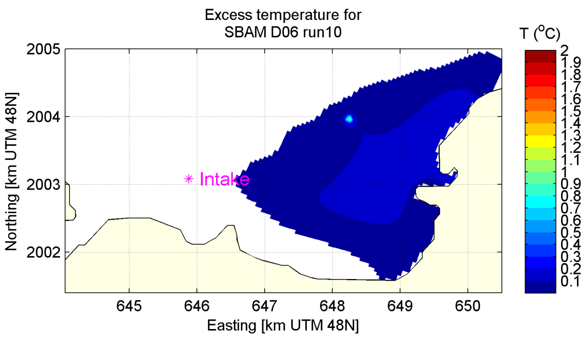
Figure A.10: Influence of the ambient temperature on system behavior for design 1. For left pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume. Note the scale differences.



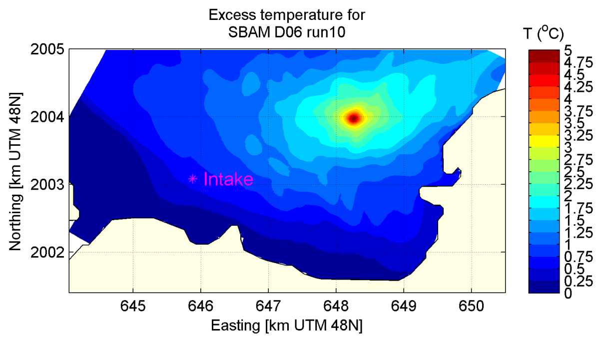
(a) Mean temperature in intake layer, T=16 °C



(b) Maximum temperature in surface layer, T=16 °C

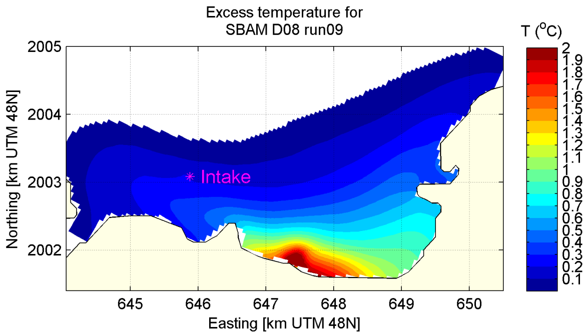


(c) Mean temperature in intake layer, T=33 °C

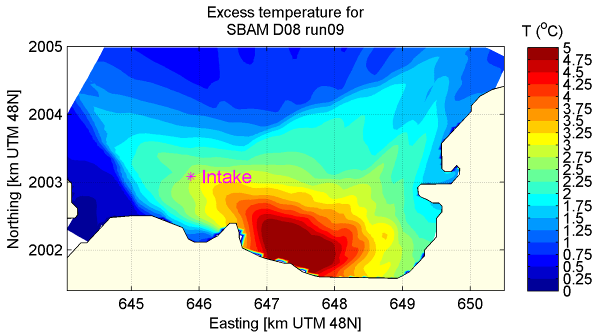


(d) Maximum temperature in surface layer, T=33 °C

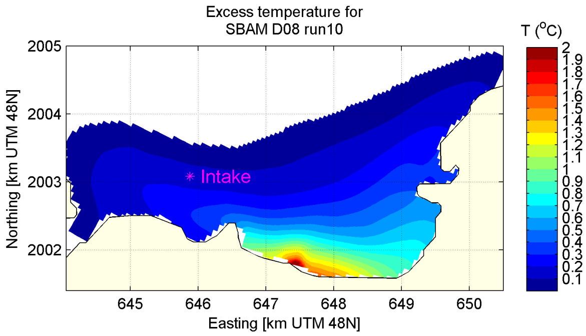
Figure A.11: Influence of the ambient temperature on system behavior for design 6. For left pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume. Note the scale differences.



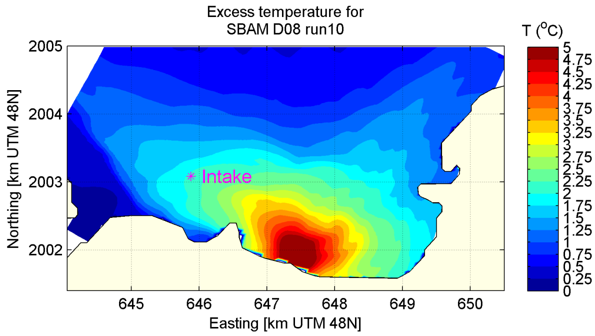
(a) Mean temperature in intake layer, T=16 $^\circ C$



(b) Maximum temperature in surface layer, T=16 $^\circ C$

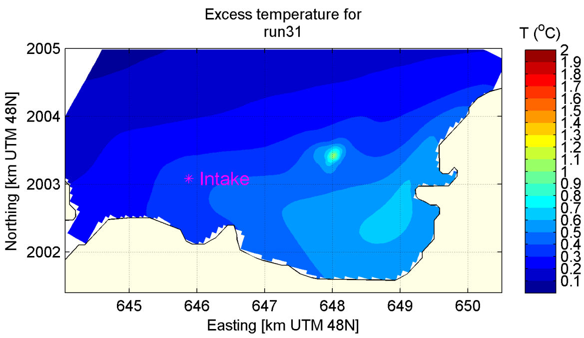


(c) Mean temperature in intake layer, T=33 $^\circ C$

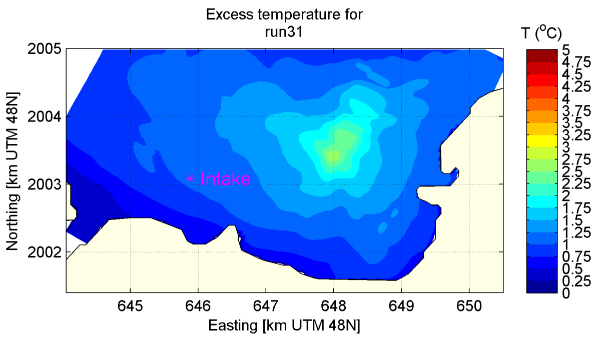


(d) Maximum temperature in surface layer, T=33 $^\circ C$

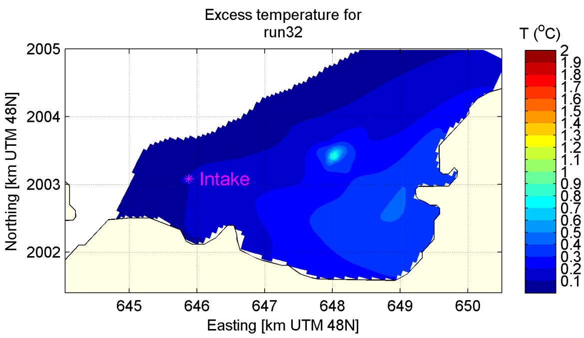
Figure A.12: Influence of the ambient temperature on system behavior for design 8. For left pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume. Note the scale differences.



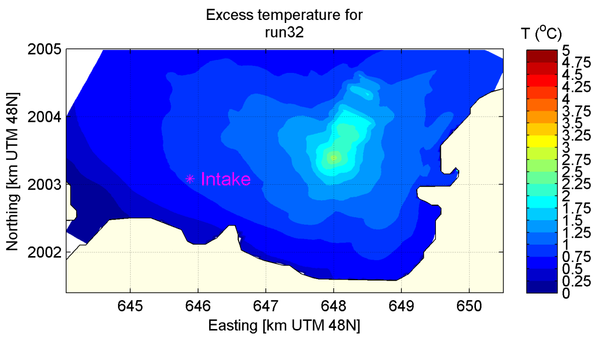
(a) Mean temperature in intake layer, 3cm/s NW current with Q=$0m^3/s$



(b) Maximum temperature in surface layer, 3cm/s NW current with Q=$0m^3/s$



(c) Mean temperature in intake layer, 5cm/s SE current with Q=$0m^3/s$



(d) Maximum temperature in surface layer, 5cm/s SE current with Q=$0m^3/s$

Figure A.13: Interaction between zero river discharge and the residual current. For left pictures, the excess temperatures below 0.05 are marked in white to highlight the extent of the plume. Note the scale differences.