Massachusetts Bay Outfall Treated Effluent Discharge Plume Characteristics from the EPA-supported Near-field Mixing Model

Massachusetts Water Resources Authority
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Summary

The Massachusetts Water Resources Authority (MWRA) manages a sewage system that sends treated effluent through a tunnel about 15 km long for discharge through an outfall in Massachusetts Bay. This report examines the effluent plume behavior in the immediate vicinity of the outfall by utilizing the EPA-supported Cornell Mixing Zone Expert System (CORMIX). The CORMIX analysis showed that the behavior of the effluent strongly depends on the stratification in the project area. In the period October to February, when the temperature and salinity is relatively uniform over depth, the treated effluent is expected to reach the water surface. From March onwards, stratification starts to build up, resulting in the treated effluent being trapped at depth. The plume characteristics for these two periods, under typical hydrodynamic and discharge conditions, are summarized in the table below. The end of the near-field zone, defined as the region where the initial momentum of the jet is dissipated such that the plume dynamics become dominated by the ambient flow, ranges from about 50 to 200 m from the outfall. (Conditions beyond the near-field zone are the focus of simulations using the separate Bays Eutrophication Model, which is not addressed by this report; also, the near-field zone is much smaller than the 10 x 12 km area centered on the outfall referred to as the “nearfield” in the context of MWRA ambient monitoring programs.) The dilution values are the unitless ratio of ambient to effluent volume, which has minimum of 1 where the effluent leaves each outfall diffuser port opening. The table shows flux-averaged (bulk, averaged across the plume cross-section) monthly-mean results at the end of the near-field zone. The plume depth levels are given in meters relative to mean sea level (MSL). Values in parentheses show the expected within-month temporal variations, which are mainly due to variations in ambient flow velocity. The minimum time-varying dilution is 100X (monthly-mean 200X, reduced by 50% due to within-month temporal variations), which can occur at 50 m from the outfall, during stratified conditions. These results are consistent with past observational and modeling studies.

		Characteristics at end of near-field			
Period	**General plume characteristics**	**End of near-field [m]**	**Monthly mean dilution [-]**	**Upper level of the plume [m; MSL]**	**Plume thickness [m]**
October – February (unstratified)	Surfacing / vertical mixing	About 200	350-500X (- 50% to +500%)	Water surface	15-34
March – September (stratified)	Trapped	About 50	200 – 400X (± 50%)	-10 to -20 (± 8)	8-15

1 Introduction

MWRA requested Deltares to examine the effluent plume behavior in the immediate vicinity of its Massachusetts Bay outfall using CORMIX computations. The objective is to assess and describe the near-field behavior of effluent resulting from the MWRA sewage treatment outfall. The behavior (dimensions, dilution rates, etc.) was analyzed for a representative set of ambient conditions (flow, temperature and salinity) that are expected to occur in the vicinity of the outfall.

As input to the near-field assessment, data was required with regard to the characteristics of the effluent, outfall design and ambient conditions. The data that was used in this study is briefly described in Section 2.

The near-field assessment was carried out with the US-EPA-approved CORMIX expert system. CORMIX is developed by MixZon, with different modules for the design and assessment of outfalls and with which a wide range of applications and situations can be assessed. CORMIX is the most used and accepted system worldwide and has been used by Deltares in many studies. The MWRA diffuser geometry cannot be fully represented in CORMIX, which is why the near-field behavior has been assessed for different diffuser schematizations that have subsequently been combined and interpreted with expert judgement. The results for these different schematizations and their applicability are discussed in Section 3.

In Section 4, conclusions are drawn with regard to the expected near-field behavior of the effluent.

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2 Overview of input information

2.1 Diffuser geometry characteristics

The outfall diffuser consists of an outfall tunnel with a length of about 15 km, which transports the treated effluent from the Deer Island Treatment Plant towards the riser caps located on the seabed (Figure 2.1). The 55 riser caps cover a distance of about 2 km at a spacing of about 38m on average. Each riser cap consists of 8 discharge ports, which are distributed uniformly around the circumference of the riser cap. Each port opening is about 1.7 m away from the center of the riser cap. An overview of the most important diffuser geometry characteristics is given in Table 2-1. It is noted that not all ports of the diffuser are open and active.

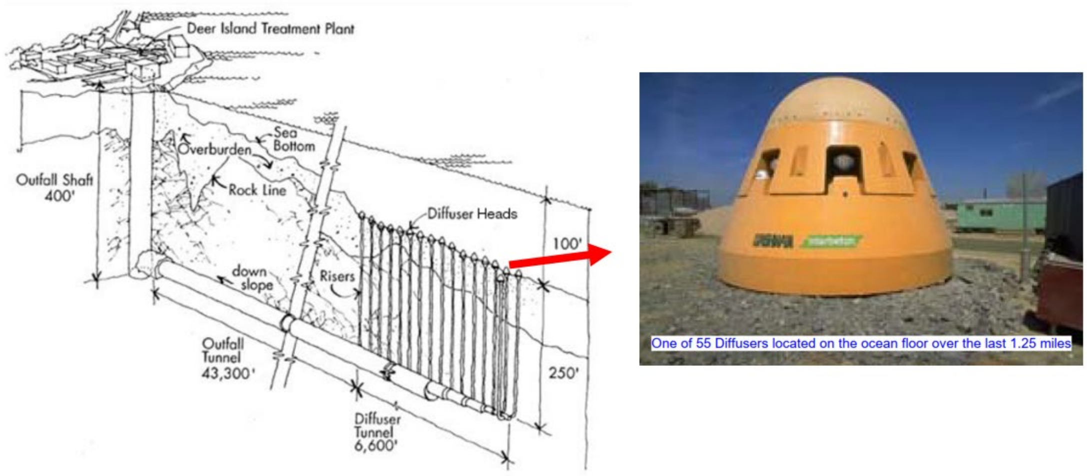

Figure 2.1: left: schematic of the diffuser design, right: photo of a riser cap.

Table 2-1: Diffuser geometry characteristics

Diffuser Characteristic	Description
Number of risers	55
Number of discharge ports	In total 271 ports are active. On average, 4.93 ports are being user per riser cap.
Port diameter	0.203 m
Vertical orientation of the ports	Horizontal
Distance between ports and the local bed	Varies between 0.15 m and 2.9 m. On average 1.2 m.
Distance between neighboring risers	37.6 m on average
Local water depth	Varying from 33 to 35 m

2.2 Effluent characteristics

The discharge through the diffuser varies throughout the year with an average value of about 13.8 m³/s (Figure 2.2). The flow rate is typically lowest in the August/September and highest in March/April. The temperature varies from about 14 °C in winter to about 22 °C in summer. The monthly variation in effluent characteristics is further shown in Table 2-2. The salinity of the effluent is in the range of 0 psu to 2 psu throughout the year (independent of seasonality).

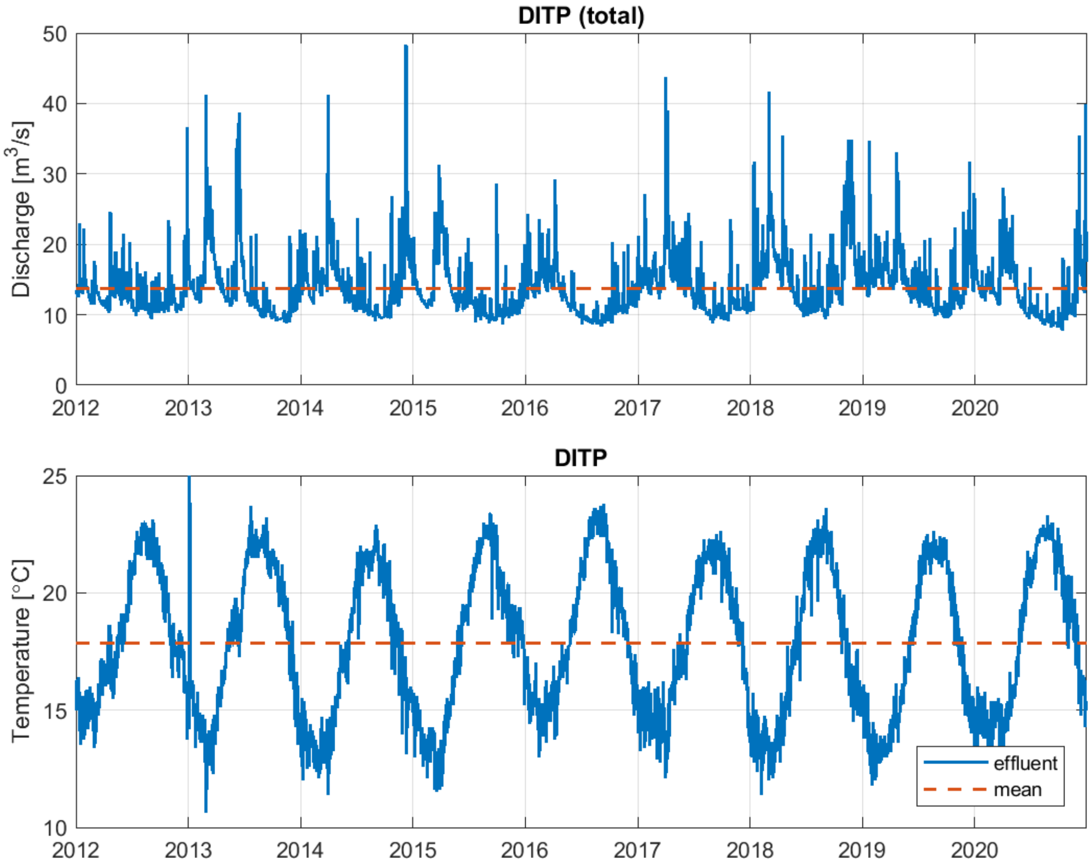

Figure 2.2: Effluent characteristics over time. Upper plot: outfall flow rate, lower plot: temperature of the effluent

Table 2-2: Effluent flow rate and temperature characteristics per month. Based on the period 2012-2020.

	Flow rate effluent [m³/s]			Effluent temperature [°C]		
Month	5-percentile	Average	95-percentile	5-percentile	Average	95-percentile
Jan	12	15	21.4	12.9	14.7	16.2
Feb	11.4	14.9	19.9	12.7	14	15.5
Mar	11.6	16.9	25.5	12.2	14	16.1
Apr	11.2	17.7	28.5	12.9	15	17.1
May	11.3	13.9	18.2	15.2	17	18.7
Jun	10.1	13.5	23.3	17.1	19	20.7
Jul	9.4	11.7	16.4	20	21.3	22.5
Aug	8.9	10.7	14	21.2	22.1	23.2
Sep	8.7	10.5	14.7	20.8	21.9	23
Oct	8.9	11.5	17.3	18.7	20.3	21.7
Nov	9.3	13.3	24.9	16.2	18.3	20.2
Dec	10.4	15.4	24.4	14.3	16.3	18.8

2.3 Ambient conditions

The near-field behavior of the effluent mainly depends on the ambient salinity and temperature profiles in the vicinity of the outfall as well as the ambient flow velocity. These parameters have been extracted from the existing Bays Eutrophication Model (Deltares, 2021) for the year 2016 for a location close to the diffuser. For purposes of the CORMIX modeling, the year 2016 is representative.

The current velocity in the vicinity of the outfall typically varies between 0 to 0.25 m/s.

The average salinity and temperature stratification for the different months is given in Table 2-3. In the period October to March both temperature and salinity are relatively uniform over the water depth. From April onwards a typically linear temperature stratification starts to build up, leading to a relatively strong stratification in July-August, during which a weak thermocline can be observed (temperature stratification concentrated at mid-depth more strongly, rather than a linear profile).

Table 2-3: Average temperature and salinity stratification near the diffuser. Extracted from the BEM for the representative year 2016 (calibration year).

Month	Difference between surface and bed		
	Temperature [°C]	Salinity [psu]	Density [kg/m^3]
Jan	1.4	0.2	0.0
Feb	-0.3	-0.1	-0.1
Mar	0.3	-0.4	-0.4
Apr	1.2	-0.6	-0.6
May	4.3	-0.7	-1.2
Jun	7.4	-0.5	-1.8
Jul	9.9	-0.2	-2.1
Aug	10.1	-0.3	-2.3
Sep	6.3	-0.2	-1.5
Oct	0.6	-0.1	-0.2
Nov	0	0	0.0
Dec	0	0	0.0

3 Near-Field assessment

3.1 Introduction

The objective of the near-field assessment is to assess the initial mixing behavior of the treated effluent in the near-field zone. The near-field zone is the area close to the diffuser where the initial momentum and buoyancy of the jets and plumes dominates over the ambient hydrodynamics[1]. CORMIX simulations are used to assess the effluent for a representative range of effluent and ambient characteristics. The main parameters that were addressed in the near-field assessment are 1) whether the effluent will reach the water surface or becomes trapped at a certain level, 2) how much the effluent will be diluted along the plume trajectory, 3) the dimensions of the plume.

3.1.1 Dilution Factors

Dilution of the effluent plume occurs through entrainment of ambient water into the plume. The reported dilution factors are defined as the factors by which the original effluent concentration is diluted. For example, when the effluent exits the port, the concentration of the effluent is equal to the original concentration, resulting in a dilution factor of 1 (undiluted). For example, when the effluent concentration reduces to 10% of the original concentration, the dilution factor is 10.

CORMIX applies different modules to compute the plume characteristics along the trajectory. For the present outfall system CORMIX typically uses the CorJet module to assess the plume until trapping/surfacing. For this module, CORMIX outputs the centerline dilution (i.e. minimal dilution in the plume cross-section). After trapping/surfacing CORMIX typically uses a boundary layer module, in which a flux-averaged dilution is given. The reported dilution factors in this report typically refer to the end of near-field, which is captured by the boundary layer module. These dilution factors are therefore bulk, flux-averaged dilution factors, unless explicitly referred to as a centerline dilution factor (e.g. Schematization 1).

3.2 Approach and schematization

The MWRA diffuser geometry cannot be fully represented in the limited number of schematization options available in CORMIX. The near-field behavior has therefore been assessed for different diffuser schematizations, each with their own advantages and reservations and subsequently interpreted by means of expert judgement. The schematizations that have been assessed can be summarized as follows:

1. Single port
2. Multiport: 55 risers with 5 port per riser (i.e. the average of functional ports per riser)
3. Multiport: 271 ports uniformly distributed along the entire diffuser length (about 2 km).

The considered schematizations are further explained below. Based on the analysis it is expected that the near-field behavior of the outfall is best represented by Schematization 3, as will be explained below.

In all considered CORMIX schematizations, the effluent is discharged horizontally (vertical angle of 0°).

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[1] The near-field zone, as referred to in this report, is much smaller than the 10 x 12 km area centered on the outfall referred to as the "nearfield" in the context of MWRA monitoring programs.

Schematization 1. Single port schematization

In case of the single port analysis, the effluent from only one discharge port is considered. For single ports a lot of experiments and research studies have been conducted in the past, which increases the accuracy of the single port near-field assessments. This analysis results in a solid understanding of the initial phase of the plume trajectory. However, potential interaction between different individual jets, which can occur in case of the MWRA outfall because it has multiple ports, is not taken into account in single port analysis. Therefore, multiport CORMIX simulations have also been carried out.

Schematization 2. Multiport schematization with 55 risers

For multiport CORMIX simulations different options are available to specify the location of each riser and the orientations of its discharge ports. The option that best represents the actual diffuser geometry is to specify 55 risers with 5 active ports each (i.e. an alternating multiport diffuser with rosette arrangement). To compute the near-field behavior, CORMIX assumes for such a schematization that the 5 individual ports can be represented by one representative port per riser, which discharges in one direction. Therefore, before the effluent exits the ports, CORMIX assumes partial merging of the jets, which is not expected to be fully realistic, since the actual ports are oriented in different directions. These simulations are therefore expected to underestimate the dilution (i.e. entrainment of ambient water into the plume) and to overestimate how far the depth level of trapping is from the seafloor (i.e. too high in the water column) in summer.

Schematization 3. Multiport schematization with 271 ports

In addition to the above described multiport schematization, another multiport schematization was considered in which all active ports (271) are equally distributed along the 2 km long diffuser. The actual near-field behavior is expected to be best represented by means of this CORMIX schematization. The combined effect of the 271 individual ports is taken into account (which was not taken into account in Schematization 1) without exaggerating the plume interaction (as in Schematization 2).

Density profile

The ambient density profile needs to be schematized in CORMIX, meaning that the actual density profile needs to be represented as depth-uniform, a fully linear profile, a block profile or a combination of both a linear and a block profile. For the months October to February a depth-uniform density was used in the abovementioned CORMIX simulations, because of the absence of stratification (see Section 2.3). For the months March to September a fully linear density profile was used. The schematized density profiles in the CORMIX simulations were chosen such that trapping in Schematization 1 occurred at the same level as predicted by CorJet (which has the ability to represent the actual density profiles in more detail but is not able to model the plume behavior after trapping). More information on this approach can be found in Appendix A.

Sensitivity analysis

Sensitivity tests have mainly been carried out using the single port approach. The main focus of the sensitivity analysis was on trapping (whether it would occur or not and at what depth levels) and the dilution at trapping/surfacing of the plume. Given the design of the riser caps, with discharge ports pointing in different directions, no significant jet merging is expected until the point of trapping/surfacing. The single port approach (which does not consider any possible jet merging) is therefore judged to be suitable for assessing the abovementioned items. Consequently, the overall conclusions of the sensitivity analyses are expected to be applicable to the plume behavior in the multiport schematizations as well. The main observations from the sensitivity analyses are described in Section 3.4.

A brief summary of the CORMIX results is given in Section 3.3. A more detailed overview of the results for the three different outfall schematizations is given in Appendix A.

3.3 Brief summary of CORMIX results

The near-field behavior for monthly-averaged conditions (regarding effluent flow rate, temperature, ambient stratification and ambient flow) has been assessed for three different CORMIX schematizations, as described in Section 3.1. In all CORMIX simulations for Schematization 1-3 a vertically uniform co-flowing ambient current is assumed (i.e. the flow is in the same direction as the effluent discharge). In this section only the computed near-field plumes for January and August conditions are shown. The visualizations for the other months are included in Appendix A.

The output from CORMIX (for example, presented in Figures 3-1 to 3-3, described next) deserves a brief initial explanation because it differs fundamentally from that of grid-based model simulations that many readers are likely to be more familiar with. CORMIX simulates conditions only within the near-field mixing zone (recall, this is the area where the plume momentum and buoyancy are the dominant influences on its dynamics—rather than ambient conditions or boundaries, etc). The distance that the near-field mixing zone extends away from the source is determined by CORMIX during the course of its simulation, and no CORMIX output is generated beyond that distance. For the results shown in Figure 3-2, for example, CORMIX determined that the near-field mixing zone extends about 200 m from the source during January and about 46 m from the source during August; CORMIX output is only within those distances of the source, respectively, so the frame for unstratified conditions (left side of figure) shows results across a larger area than the frame for stratified conditions (right side of figure). This aspect of CORMIX output is fundamentally different than the output from grid-based models, for which a similar pair of runs would typically show results extending over the same area.

One other feature of CORMIX results also merits initial explanation. As the plume extends away from the source, the dynamics controlling it change as it evolves under influences of varying relative importance (momentum, buoyancy, ambient flow, boundaries, etc). CORMIX determines what dynamics are applicable throughout this evolution, and applies them. Thus at certain distances from the source, transitions occur from one type of dynamics to another. When such transitions occur over short distances they can be visible in plume plots. Examples include the decrease in plume thickness at a distance of about 36 m in the right panel of Figure 3-2, and the increase in the plume thickness at a distance of about 38 m in the right panel of Figure 3-3.

Schematization 1: Single jet:

Stratified conditions. The single port simulations show that the effluent becomes trapped for periods with a weak to strong stratification (April to September), see Figure 3.1. The effluent becomes trapped at a level of -20 m MSL (Mean Sea Level) in September to -10 m MSL in April. This happens because the plume entrains relatively dense water while moving upwards (because the density of the plume is initially lower than the ambient density, due to a lower salinity). At a certain depth level (the trapping level), the density of the effluent plume is similar to the ambient density, which prevents the effluent from moving further upwards. At the depth level of trapping, the dilution factor (amount of entrained ambient water) is about 100-200 (centerline dilution factor). After trapping, the effluent will be further transported as a boundary layer until it reaches the end-of near-field. The end-of near field is defined as the region where the initial momentum of the jet is dissipated such that the plume dynamics become dominated by the ambient flow. For the present study, the end-of near field was assessed to be located at the point of trapping/surfacing (typically at a horizontal distance of about 50 m from the diffuser). Note that the single port simulations (as for any single port CORMIX simulation) underestimate the possible plume merging and accumulation of effluent in the boundary layer and therefore overestimate the dilution after trapping by an estimated 20%[2].

Unstratified conditions. In the period October to March, the stratification is much weaker or even absent. In this period, the effluent will therefore reach the water surface and will form a plume spreading along the water surface. Since the plume travels over a larger distance, the dilution factors are higher than in the case of trapping (i.e. 400 to 800 at the end of near-field). Again, these dilution factors can be considered higher than applicable, since the accumulation of effluent is underestimated.

Schematization 2: Multiport - 55 risers, 5 ports per riser:

Stratified conditions. The multiport CORMIX simulations with 55 risers (and 5 ports per riser) showed that effluent trapping occurs in the period March – September, which is in line with the single port simulations, see Figure 3.2. As expected, the level of trapping is higher in the water column (-8 m MSL to -1 m MSL) than in the single port simulations and the dilution factors, at the end of near-field (about 50 m from the risers), are lower (60 to 120). Since CORMIX is expected to overestimate the plume interaction in this schematization, these results can be considered to have a dilution lower than applicable and vertical trapping level higher in the water column than applicable.

Unstratified conditions. For the period of October to February, CORMIX predicts the effluent to become vertically mixed after which it will partially re-stratify. The dilution factors are much higher than for the period March to September (about 500-700 at a distance of 200 m).

Schematization 3: Multiport: all active ports uniformly distributed along diffuser length

Stratified conditions. For this schematization, the effluent becomes trapped in the period March to September (Figure 3.3). The vertical level of trapping (-20 m MSL to -10 m MSL) and dilution at the point of trapping is very similar to the single jet computations. The dilution rates at the end of near-field are in between the two abovementioned schematizations (200 to 250).

Unstratified conditions. For the period October to February, the effluent is expected to become vertically mixed at a distance of about 200 m from the outfall with a dilution factor in the range of 350 to 500.

Summary. The actual near-field behavior is expected to be best represented by means of Schematization 3. The combined effect of the 271 individual ports is taken into account, which was not taken into account in Schematization 1, without exaggerating the plume interaction as in Schematization 2.

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[2] The dilution factors for Schematization 1 are expected to be overestimated by about 20% after trapping. The reported/visualized dilution factors have not been corrected for this.

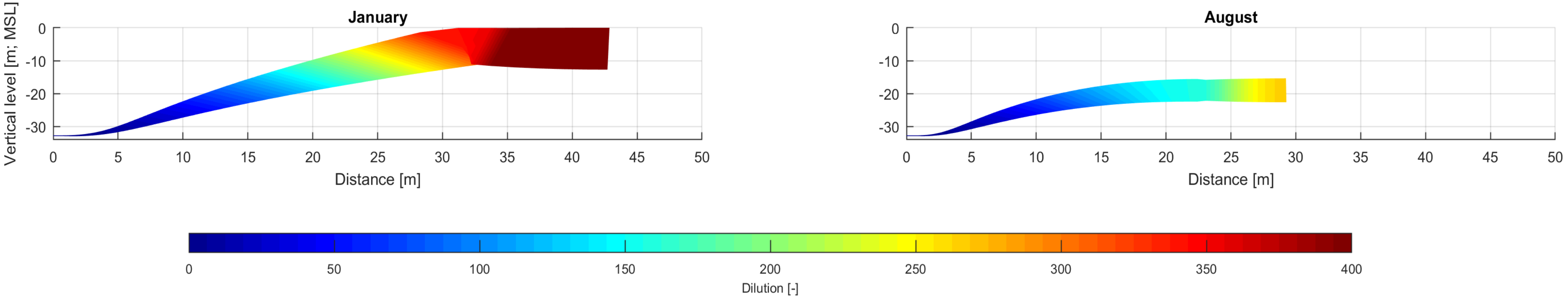

Figure 3.1: Vertical cross section of the near-field plume behavior for average January and August conditions, based on Schematization 1: single port. The colors indicate the near-field dilution factor.

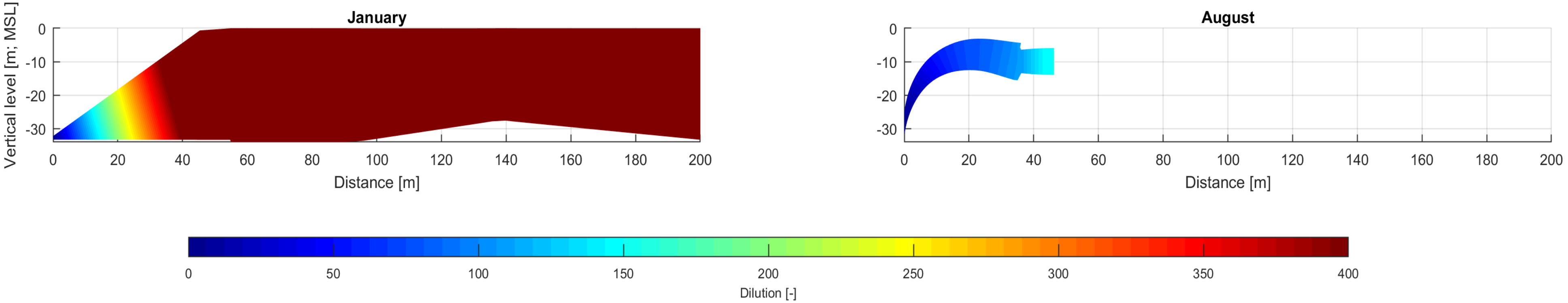

Figure 3.2: Vertical cross section of the near-field plume behavior for average January and August conditions, based on Schematization 2: Multiport – 55 risers, 5 ports per riser. The colors indicate the near-field dilution factor.

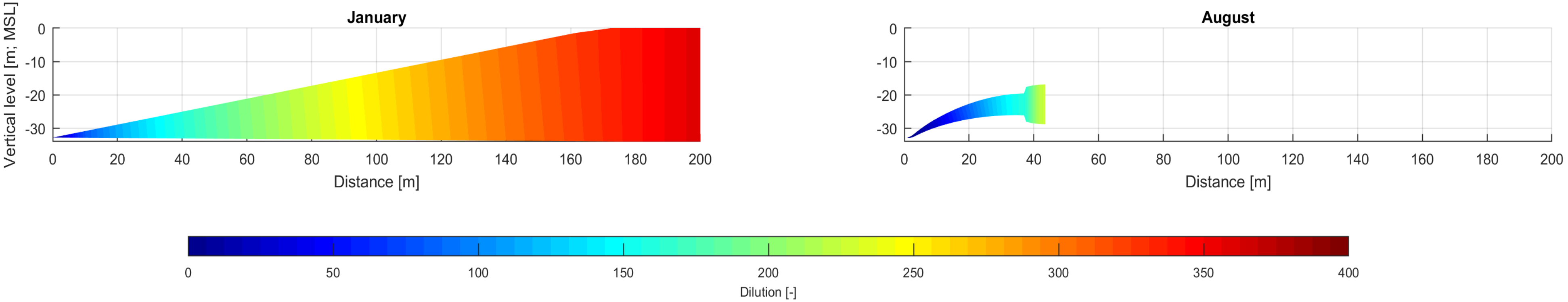

Figure 3.3: Vertical cross section of the near-field plume behavior for average January and August conditions, based on Schematization 3: Multiport – all active ports equally distributed along diffuser length. The colors indicate the near-field dilution factor.

3.4 Sensitivity analyses

This sensitivity analysis of the near-field plume behavior focuses on changes to the results above, which are representative for monthly-mean conditions, that would occur due to within-month temporal variability. Sensitivity has been investigated for the parameters shown in Table 3-1 for January, April and August conditions. It is noted that the variations in density profiles within the months have not been considered in the sensitivity analysis, because the variations within a month are of a lower magnitude than the seasonal variations. The sensitivity of the plume characteristics to the density profiles is therefore well captured by considering the monthly-averaged conditions in the CORMIX simulations for Schematization 1-3 (see Section 3.3).

Table 3-1: Parameters considered in sensitivity simulations

Parameter	Value in Reference simulation	Values in sensitivity simulations
Ambient flow velocity [m/s]	0.1 (co-flowing)	0.05, 0.15 and 0.2 (co-flowing and counter-flowing)
Discharge [m^3/s]	Average (see Table 2-2)	5-percentile and 95-percentile (see Table 2-2)
Effluent temperature [°C]	Average (see Table 2-2)	5-percentile and 95-percentile (see Table 2-2)
Effluent salinity [psu]	0	2
Distance between port and bed [m]	1.2	0.6 and 3

This assessment has shown that the depth level of trapping (if at all) and dilution factor mainly depend on the ambient flow velocity and to a lesser extent to the flow direction (results are shown in Table 3-2). The other parameters only have a limited or negligible influence on the effluent behavior (see Appendix A, Section A.4).

The higher the ambient flow velocity, the larger the dilution and, consequently, the lower in the water column the trapping depth level. When the ambient flow is opposite to the direction of the discharge, the dilution is a bit lower compared to a co-flowing regime. However, it is noted that in reality the discharge ports are pointing in all directions, meaning that in all circumstances some jets will experience a co-flowing current, while the opposing jets may experience a counter-flowing current. The actual combined dilution is therefore expected to be in between the co-flowing and counter-flowing regimes.

It is noted that the actual flow regime is not constant over time. The travel time of the effluent from the discharge port to the end of near-field is in the order of minutes. Given that the ambient flow varies with a timescale in the order of hours, the effluent will experience a relatively steady current. The steady state assumption in the CORMIX computations is therefore applicable.

Furthermore, it is noted that the actual flow profile is not constant over depth (as assumed in the CORMIX simulations). The maximum current velocity in the lower 20 to 30 m of the water column is typically in the range of 0.05 to 0.2 m/s. Only in the upper 5 to 10 m, the current speed occasionally reaches higher speeds (e.g. due to wind events, etc.). In the period of April to September, the plume does not reach this upper layer, so the occasionally increased current speed in this layer will not affect the behavior of the trapped plumes. For January conditions an additional sensitivity simulation was performed in which a current velocity of 0.4 m/s was specified in the upper 10 m (0.2 m/s in the lower part of the water column).

The sensitivity simulations for April (when the ambient stratification is weak) and August (when ambient stratification is relatively strong) have shown that within each month, the depth level of trapping could vary within about 8 m compared to the average depth level of trapping (Table 3-2). This variation in depth level is mainly related to the variation in ambient flow velocity. In the next section these variations are included in a summary of ranges of near-field plume characteristics for all months.

Table 3-2: Observed variation in vertical level and dilution in sensitivity simulations

Months	Variation of depth level of trapping compared to the Reference Simulation (i.e. monthly-averaged conditions)	Variation of dilution compared to the Reference simulation at the point of trapping/surfacing (i.e. about 50 m from the riser caps)
April, August (when the effluent is expected to become trapped)	+/- 8 m	+/- 50%
January	n/a (plume is not being trapped)	-50% to +500%

4 Conclusions regarding expected near-field behavior

Based on an expert interpretation of the near-field assessment with CORMIX, the following conclusions can be drawn:

For the period of March to September:

- The discharged treated effluent becomes trapped in the water column before reaching the water surface in the period April to September. This is supported by all three CORMIX schematizations that have been considered in this study.
- In March the effluent is expected to be on the transition of surfacing and trapping.
- Due to the design of riser caps, with ports pointing in different directions, no significant jet interaction is expected in the initial phase of the effluent plume (until trapping or surfacing). The depth level of trapping is therefore expected to be best represented by Schematizations 1 and 3. For monthly averaged conditions, the trapping level is expected to be about -10 m MSL (March/April) to about -20 m MSL (August/September).
- Within each month, the depth level of trapping could vary by about 8 m compared to the average depth level of trapping, mainly due to variations in ambient flow velocity.
- After trapping, the plume will be further transported as a boundary layer with a typical thickness of about 8 to 15 m.
- The dilution at the end of near-field (about 50 m from the risers) is expected to be best represented by Schematization 3. Depending on the ambient velocity and density profiles, the dilution at the end of near-field is expected to range between 100 to 600.

For the period of October to February

- The discharged treated effluent is expected to reach the water surface in the period October to February, because of the absence of ambient stratification. This is supported by all three CORMIX schematizations that have been considered in this study.
- At a distance of about 200 m from the risers, the effluent is expected to be mixed over the entire (or upper part of the) water column, with a dilution factor of about 175 to 2500.

Table 4-1 shows the flux-averaged (bulk, averaged across the plume cross-section) monthly-mean results at the end of the near-field zone. Values in parentheses show the expected within-month temporal variations, which are mainly due to variations in ambient flow velocity.

These results are consistent with past observational and model studies (e.g. Hunt et al, 2010, Roberts et al., 2011).

Table 4-1 Monthly means of expected plume characteristics per month. MSL = Mean Sea Level.

Month	Trapping level [m MSL]	Characteristics at the end of near-field (50 m for the period Mar – Sep and 200 m for the period Oct - Feb)	
		Monthly mean dilution (within month variability) [-]	Plume thickness [m]
Jan	Surfacing / vertical mixing	350 (- 50% to +500%)	15 - 34
Feb	Surfacing / vertical mixing	350 (- 50% to +500%)	15 - 34
Mar	-10 m MSL (± 8m) (potentially surfacing)	400 (± 50%)	8 - 15
Apr	-15 m MSL (± 8m)	300 (± 50%)	8 - 15
May	-15 m MSL (± 8m)	250 (± 50%)	8 - 15
Jun	-15 m MSL (± 8m)	200 (± 50%)	8 - 15
Jul	-15 m MSL (± 8m)	250 (± 50%)	8 - 15
Aug	- 20 m MSL (± 8m)	250 (± 50%)	8 - 15
Sep	- 20 m MSL (± 8m)	200 (± 50%)	8 - 15
Oct	Surfacing / vertical mixing	500 (- 50% to +500%)	15 - 34
Nov	Surfacing / vertical mixing	400 (- 50% to +500%)	15 – 34
Dec	Surfacing / vertical mixing	350 (- 50% to +500%)	15 - 34

5 References cited

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A Appendix – CORMIX simulation results

A.1 Schematization 1: Single port analysis

This section describes the results of the CORMIX simulations for monthly averaged conditions using a single port schematization. For these simulations a typical ambient velocity of 0.1 m/s is used. The ambient density profile needs to be schematized in CORMIX, meaning that the actual density profile needs to be represented by a fully linear profile, a block profile or a combination of both. To be able to optimize the density profile schematization, the depth level of trapping (if at all) was assessed using CorJet, which is part of CORMIX. CorJet is an integral jet and plume model and is typically used by CORMIX to assess the behavior of the effluent before the jet reaches a boundary (surface or bed) or interacts with neighboring jets. The advantage of using CorJet in a standalone manner is that the density profile can be represented in a bit more detail (specified at up to 10 levels) compared to CORMIX. The schematized density profiles in CORMIX were chosen such that trapping (or surfacing) occurred at the same level as predicted by CorJet. This approach gives the opportunity to also assess the behavior after trapping/surfacing (which cannot be computed by CorJet).

For average conditions in the period April to September, CORMIX predicts that the effluent becomes trapped at a level of -20 m MSL to -10 m MSL (Figure A.1). This happens because the plume entrains relatively dense water while floating upwards (because the density of the plume is initially lower than the ambient density due to a lower salinity and higher temperature). At a certain level (the trapping level), the density of the effluent plume is similar to the ambient density, which prevents the effluent from rising further. After trapping, the effluent will be further transported as a boundary layer until it reaches the end of near-field. Note that the single port simulations underestimate the accumulation of effluent in the boundary layer and therefore overestimate the dilution after trapping by an estimated 20%.

For the period October to February, the effluent is expected to reach the water surface, given the absence of a significant stratification.

The plume behavior in March is a mix between the typical behavior in winter (surfacing) and summer (trapping). According to CORMIX, the plume reaches a so-called ‘terminal rise height’ at about -4 m MSL, which typically indicates that the plume will become trapped. However, in the subsequent CORMIX module (boundary layer), the plume is further transported towards the water surface.

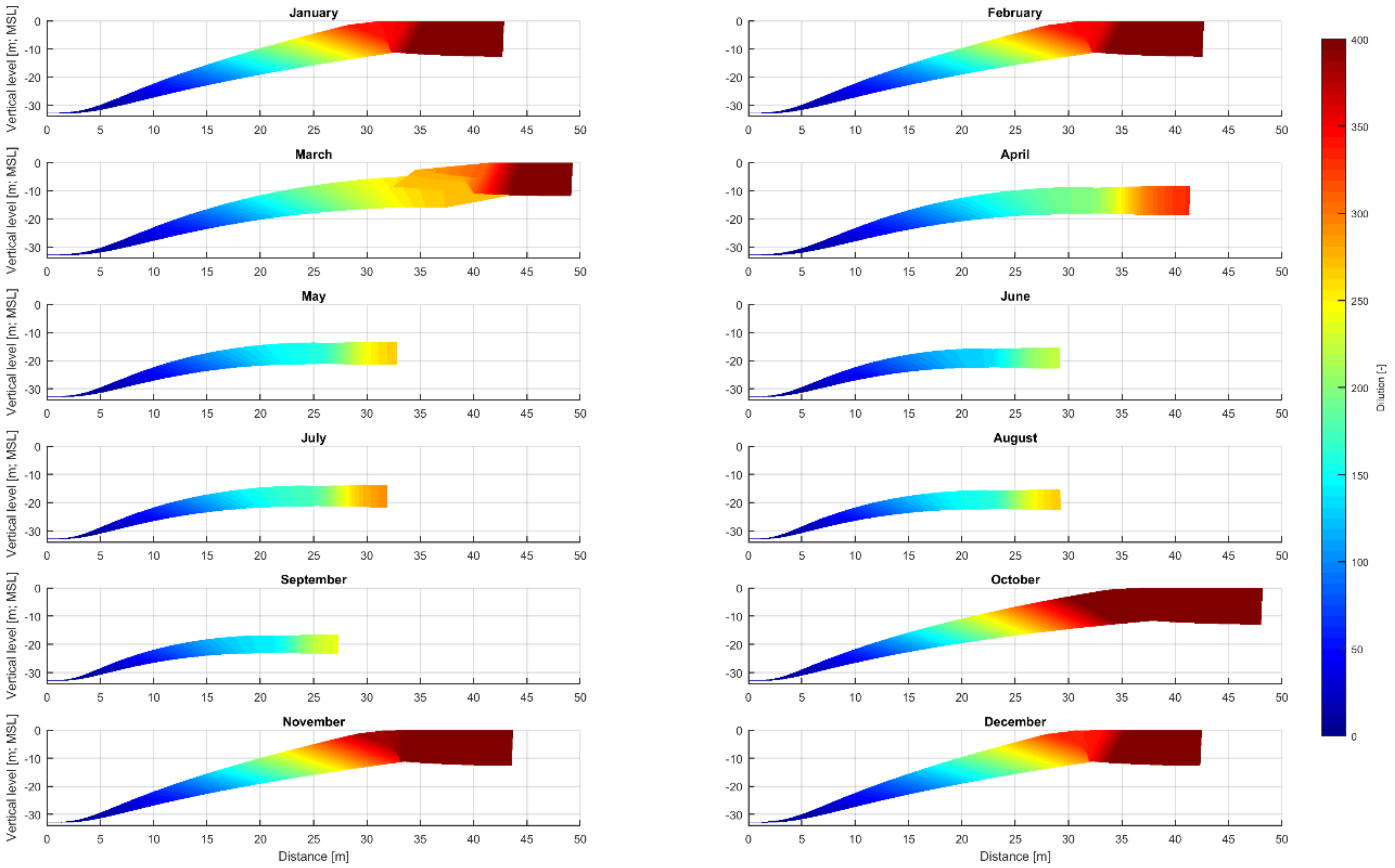

Figure A.1: Vertical cross section of the near-field plume behavior for monthly-averaged conditions, based on a single port schematization. The colors indicate the near-field dilution factor.

A.2 Schematization 2: Multiport - 55 risers with 5 ports per riser

In addition to single jet simulations, multiport CORMIX simulations have also been performed, in which 55 risers were prescribed with 5 ports per riser. The advantage of this schematization compared to the single port schematization is that the accumulation of effluent after trapping/surfacing is better represented. However, as explained in Section 3.1, these simulations are expected to overestimate the interaction of the individual jets, since CORMIX represents the 5 discharge ports per riser by one representative port per riser, which discharges in one direction. These simulation results can therefore be interpreted to have a dilution that is lower than applicable, and vertical trapping level that is higher in the water column than applicable.

The computed plume trajectory and dilution along the trajectory is visualized in Figure A.2.

The treated effluent is expected to become trapped for the period March to September, which is in line with the single port simulations. The trapping depth levels are higher and the dilution factors are lower compared to Section A.1, for the abovementioned reasons.

For the period of October to February, CORMIX predicts the effluent to become vertically mixed after which it will partially re-stratify. The dilution factors are much higher than for the period March to September (about 500-700 at a distance of 200 m).

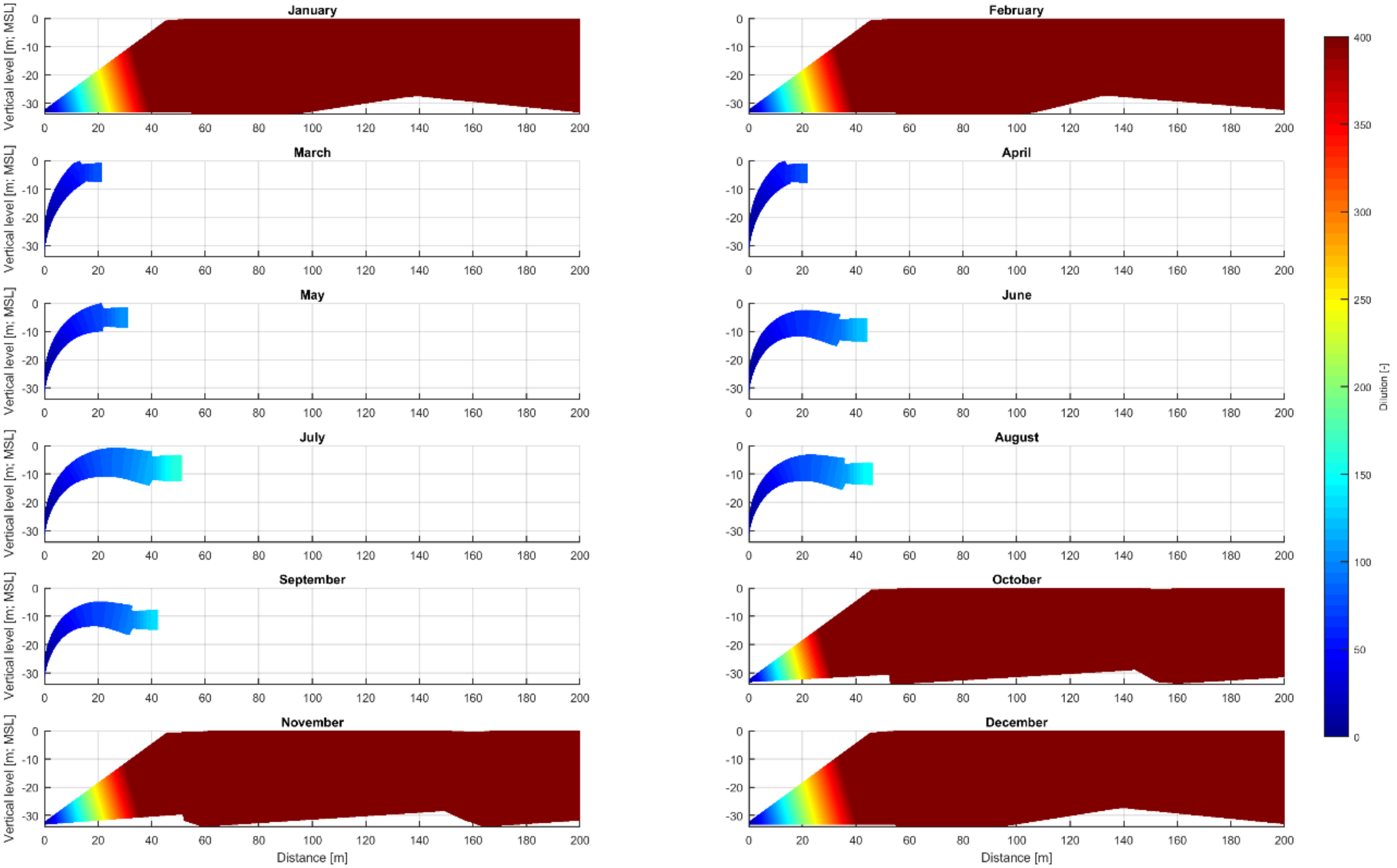

Figure A.2: Vertical cross section of the near-field plume behavior for monthly-averaged conditions, based on schematization 2: Multiport – 55 risers with 5 ports per riser. The colors indicate the near-field dilution factor.

A.3 Schematization 3: Multiport - 271 ports equally distributed along diffuser length

Since Schematization 2 is expected to overestimate the jet interaction, another multiport schematization was considered in which all active ports (271) were distributed along a 2 km long diffuser (the distance covered by the 55 riser caps), resulting in a port spacing of about 7.5 m. By means of this multiport schematization the accumulation of effluent further away from the diffuser can be taken into account (which was not considered in Schematization 1), without assuming (overestimating) jet merging from the start of the plume trajectory.

The computed plume trajectory and dilution along the trajectory is visualized in Figure A.3. The plumes are visualized until trapping (in the summer months) or when the plume becomes vertically mixed (in the winter months).

For the period May to September, the trapping depth level and dilution at the point of trapping is very similar to the single jet computations, because jet interaction is expected to be limited before trapping. After trapping, the plume will be further transported as a boundary layer. The dilution at the end of near-field is in between the other two considered schematizations (180 to 250).

For March and April, the plume behavior deviates from Schematization 1 and 2, because CORMIX expects the individual plumes to merge relatively quickly for these conditions. To test the sensitivity of the plume behavior to the assumed port spacing, additional simulations were carried out in which only 110 ports (2 per riser) were distributed along the diffuser length (see Figure A.4). Note that the total discharge was corrected to ensure a similar discharge per port. With a larger port spacing, the March and April plumes are behaving in a similar way as in Schematization 1 and 2. This is expected to be more realistic, since plume interaction before trapping is not expected to be likely given the design of the riser caps.

For the period October to February, the effluent is expected to become vertically mixed after a distance of about 200 m with a dilution factor in the range of 350 to 500.

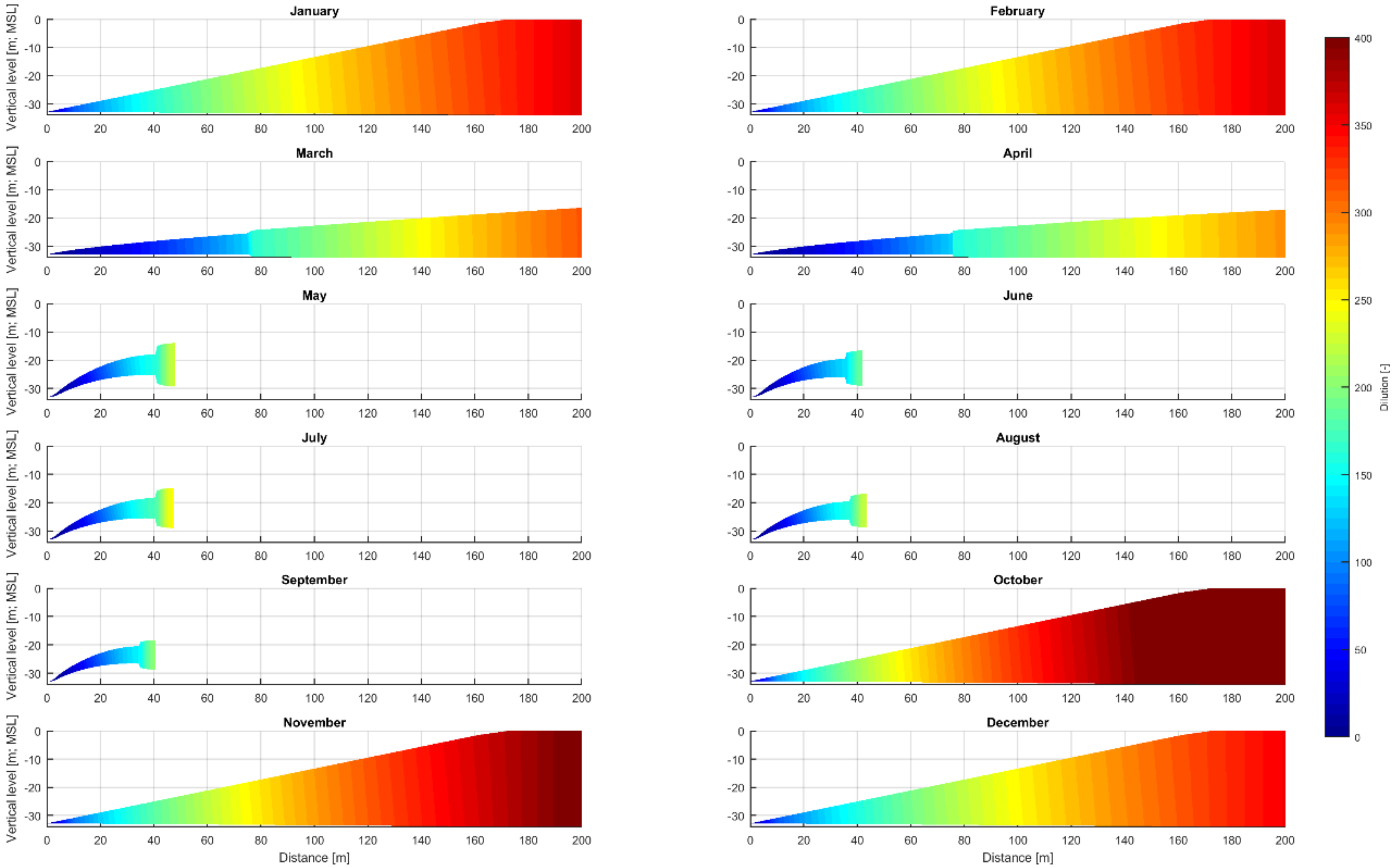

Figure A.3: Vertical cross section of the near-field plume behavior for monthly-averaged conditions, based on schematization 3: Multiport – 271 ports equally distributed along diffuser. The colors indicate the near-field dilution factor.

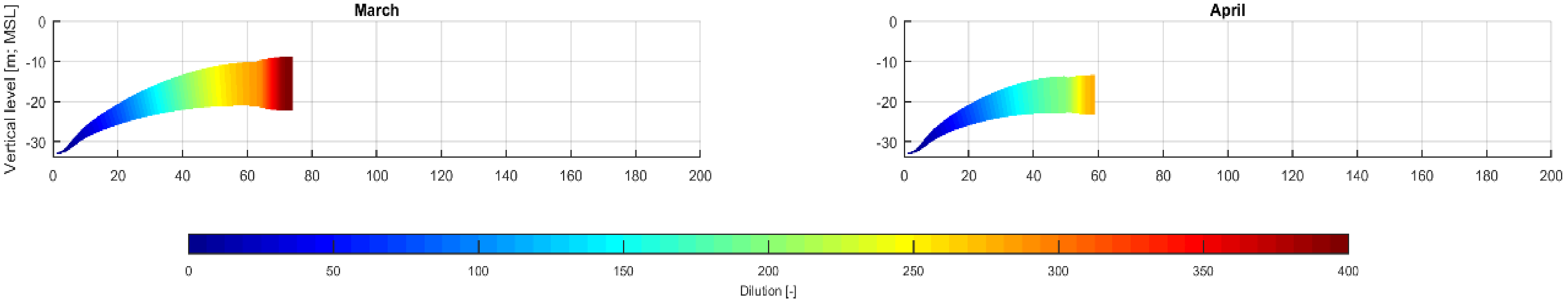

Figure A.4: Vertical cross section of the near-field plume behavior for monthly-averaged conditions for March and April with 110 ports (instead of 271) along the 2km long diffuser. The colors indicate the near-field dilution factor.

A.4 Sensitivity analyses

The sensitivity analyses have been carried out using the CorJet, module, which is part of CORMIX.

The sensitivity analysis in this section is based on August ambient conditions. Table A-1 shows the parameter values that have been used in the Reference Simulation (average August conditions) and in the various sensitivity simulations. The near-field results for all these simulations are shown in Figure A.5. The figure shows that for all tested conditions, the plume is expected to become trapped (plume centerline between -22 m MSL and -13 m MSL) and that the dilution factor at the point of trapping is in the range of 100 – 300.

Based on all sensitivity simulations, it is concluded that the level of trapping (if at all) and dilution factor mainly depends on the ambient flow velocity. The higher the ambient flow velocity, the larger the dilution and the lower the trapping level. The other parameters only have a limited or negligible influence on the effluent behavior.

Table A-1 Parameter values that have been used in the Reference Simulation (average August conditions)

Parameter	Value in Reference simulation	Values in sensitivity simulations
Ambient flow velocity [m/s]	0.1	0.05, 0.15 and 0.2
Discharge [m^3/s]	10.7	8.9 and 14
Effluent temperature [°C]	22.1	21.2 and 23.2
Effluent salinity [psu]	0	2
Distance between port and bed [m]	1.2	0.6 and 3

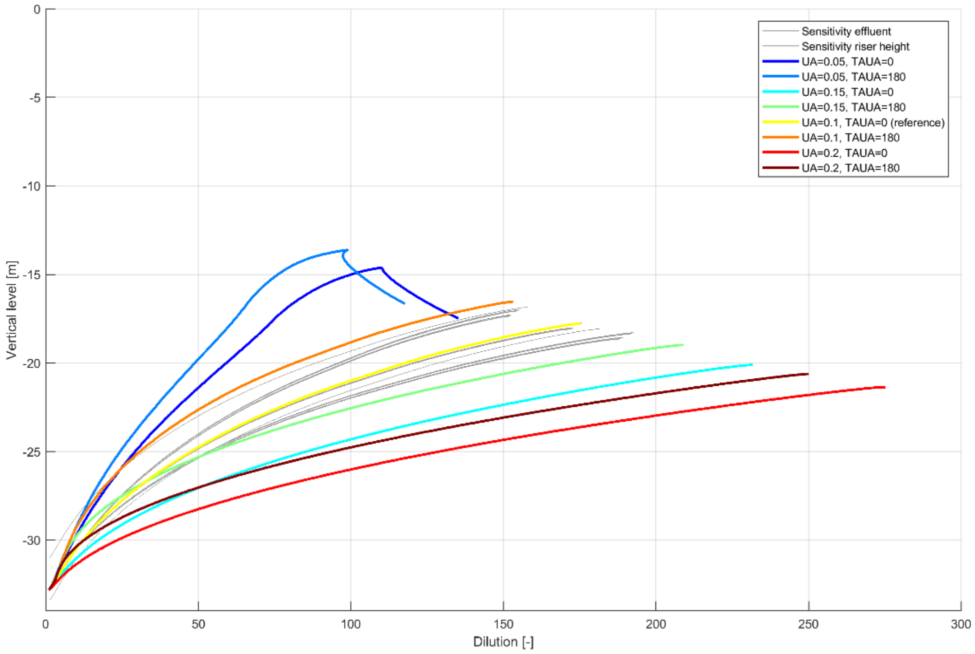

Figure A.5: Relation between dilution factor (horizontal) and depth (vertical) for all August sensitivity simulations that have been performed. Only the results for the simulations with varying ambient flow velocity have been labelled (TAUA = 0: co-flowing, TAUA = 180: counter-flowing). The results for the other (less sensitive) simulations are visualized in gray.

Massachusetts Water Resources Authority
100 First Avenue • Boston, MA 02129
www.mwra.com
617-242-6000