CARMU Investigation Report 01/2023

Contractor: Nauru Ocean Resources Inc.

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Acronyms

CARMU	Compliance Assurance and Regulatory Management Unit
CCZ	Clarion Clipperton Zone
CSCT	Collector system component test
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EMMP	Environmental Management and Monitoring Plan
HSE	Health safety and environment
ISA	International Seabed Authority
ISO	International Organization for Standardization
LTC	Legal and Technical Commission
MARPOL	The International Convention for Prevention of Pollution from Ships
MTO	Man-Technology-Organisation
NORI	Nauru Ocean Resources Inc.
OEMMR	Office of Environmental Management and Mineral Resources

I. Introduction and executive summary

1. The present report is a supplementary to CARMU's Inspection Report 01/2023 (INSP/2023/NRU/001) ('the Inspection Report') which reported on the inspection of a collector system component test (CSCT) by Nauru Ocean Resources Inc. (NORI). As noted at paragraph 89 to 103 of that report, CARMU was notified on 28 October 2022 that a temporary overflow of water had occurred on 12 October 2022 during the production ramp-up sequence of the CSCT. CARMU's initial inspection indicated no risk of serious harm to the marine environment as a result of the overflow event, but a reduced robustness in NORI's applied risk management process, leading to an observation in the inspection report (paragraph 99, Inspection Report).

2. On 25 January 2023, CARMU informed the Secretary-General that, notwithstanding the initial inspection results, it would continue its investigation into the overflow event by evaluating evidence collected during and after the on-board visit with a view to determining any possible residual impact on the marine environment resulting from the event. The present report presents the results of that investigation.

3. Based on internal and external assessments, supported by external scientific expert reviews (see Annex 3), the investigation concludes that the overflow event did not cause serious harm to the marine environment. In addition to the two observations included in the Inspection Report, it is recommended that the Contractor conduct an engineering review of the air lift system, its technical operation, and supervision, to identify any areas for improvement of the air lift riser process to learn from the event on 12 October 2022 and to avoid a similar event in future nodule collection operations. A report from the review should be shared with ISA by 30 June 2023.

II. Objective, scope, and methodology

4. The objectives of this investigation were to:

a) delineate the full development and range of the overflow event, including actual and potential consequences and any harm caused directly or indirectly to people, material, or the environment.

b) perform a causal assessment to identify the root cause of the event and to verify that the full potential of the event and its effects were managed satisfactorily by on board operators.

5. The investigation undertaken by CARMU comprised a preliminary assessment of the potential threat of serious harm to the marine environment based on the information shared by the Contractor, complemented by a two-tier external assessment of the potential environmental impacts. The latter was performed firstly by external independent consultants using data from the overflow site, and a review of the assessment (second tier) by different scientific experts.

6. CARMU also undertook an analysis to attempt to identify causal factors contributing to the event to identify the man-technology-organisation (MTO) interactions.

7. This approach is based on best industry practices from the oil and gas industry and has enabled CARMU to organise the investigation based on internationally recognised tools.

III. Overflow event on the *Hidden Gem*

8. As reported in section VI of the Inspection Report, on 28 October 2022, CARMU was informed verbally by the operator that, on 12 October 2022 during the production ramp-up sequence on the *Hidden Gem*, a temporary overflow of water occurred. The overflow was identified and reported to the vessel Master immediately. According to the Contractor, due to the dynamic behaviour of the airlift riser when first switched on, there was a surge in the volume of water flow which exceeded the buffer capacity of the cyclone separator at the top of the riser. As a result, the cyclone experienced an overflow of seawater which contained sediment and fragments of nodules.

At the time of the event the Contractor had eight crew members (riser operators and engineers) in the control room and one watchman by the cyclone. The vessel bridge was manned by two Deck Officers operating the dynamic positioning system, supervised by the Master.

9. CARMU was informed that, following the event, which occurred sporadically over a period of hours, engineering modifications were made to the cyclone separator frame to extend the height of the cyclone. The mitigation measures proved effective, and no recurrence was observed during subsequent test runs.

10. CARMU was informed that the event was classed as minor, based on an internal assessment by the Contractor against MARPOL requirements. It was the Contractor's assessment, in light of the estimated discharge volumes and contents, that the event had no potential to cause serious harm to the marine environment. Nevertheless, CARMU requested the Contractor to provide additional information on the scope, duration and management of the event, and met with NORI representatives in Kingston on 3 November 2022.

11. At CARMU's request, NORI submitted a written report on the event on 4 November 2022 (attached as Annex 1). In that report, the Contractor stated that the event was a temporary overflow of seawater with minor impact on the environment.

12. Based on the initial information provided by NORI on 4 November 2022, the preliminary assessment by the Office of Environmental Monitoring and Mineral Resources (OEMMR) of the ISA Secretariat was that the overflow was dominated by bottom seawater and minor sediment material and did not pose a risk of harm to the marine environment.

Figure 1 Event site with cyclone and dewatering screen (source: NORI)

13. Notwithstanding, CARMU decided to include the event in the scope of the upcoming vessel visit on 18 November to obtain more information about the circumstances of the event and to verify that the full potential of the event was managed satisfactorily by on-board operators, and that the mitigating measures had functioned as intended to prevent reoccurrence.

14. On board the *Hidden Gem* on 18 November 2022, NORI presented its estimate that between 48-72 cubic metres of seawater with a sediment concentration of approximately 5kg per 100 litres went overboard during the event which occurred intermittently during a production test run over a period of eight hours (attached as Annex 2). NORI informed the Investigation Team verbally that it had observed the discharge visually at the time of the event and noted that the surface water appearance returned to normal conditions after 60 minutes.

Based on the presentation, the Investigation Team understood that the Contractor had assessed the overflow as minor and that the evaluations carried out by NORI had been conducted against requirements from The International Convention for the Prevention of Pollution from Ships (MARPOL).

15. The Inspection Team noted a lack of detail in the PowerPoint presentation about the event that indicated a reduced robustness in NORI's applied risk management process. The presentation did not clearly demonstrate how a risk-based approach had been applied to manage the overflow event or how internal risk procedures and tools had been applied. (See Annex 5 of the Inspection Report, (INSP/2023/NRU/001))

16. Follow-up questions revealed that NORI did not follow its own risk management procedure during the post-event assessment of the event. The on-board team did not conduct a documented assessment with relevant resources included in the assessment activity. Reference is made to the Project HSE Plan with Allseas document number *eq-916cm-100-c-c-002*. No written evidence of the assessment can be produced.

17. The Inspection Team found that the riser handling process on board the Hidden Gem included technical barriers to shut off the flow through the riser and to monitor the flow and pressure in the riser column. There was additionally a valve on the hose connecting the flow outlet from the riser to the cyclone.

18. The Inspection Team considered that the absence of a structured process could have affected the accuracy of NORI's estimates of the quantity of seawater going overboard and the sediment concentration in the spilled seawater.

19. An observation into the reduced validity of the applied risk management process was communicated to the vessel Master and to NORI's Head of Offshore Campaigns during the close-out meeting on the *Hidden Gem* on 18 November 2022 (see observation at paragraph 101 of the Inspection Report (INSP/2023/NRU/001)).

Figure 2 Event site with cyclone and dewatering screen (source: ISA Secretariat)

IV. Assessment of potential consequences and risk of serious harm to the marine environment

20. Following the on-board inspection, and after notifying the Secretary-General that further investigations would be conducted, CARMU contracted an external consultant to perform an independent analysis of the overflow event in order to provide a comprehensive assessment of the resulting plume and total volume of ocean water impacted by the overflow. The expert selected was Professor Thomas Peacock of *atdepth LLC*; the *atdepth* team is recognized internationally for its world-leading scientific research on sediment plumes in the entire water column from seabed to mid-water and surface waters, as evidenced by several recent peer-reviewed and invited papers on the basis of best scientific practice.

21. The consultant, through his analysis, provided a scientific modelling approach on current best scientific practice for an estimate of the overflow behaviour and relevant physical processes that control the resulting plume. The consultant submitted a preliminary analytical assessment of the discharge conditions to CARMU on 13 February 2023 and on 28 February 2023 submitted a more comprehensive analytical assessment that incorporated the use of adequate analytical modelling tools to obtain a more accurate estimate.

22. In the model, *atdepth* created 27 scientifically plausible scenarios for each modelling approach, based on the available data collected by CARMU. CARMU also requested the consultant to choose the best fit scenario approach for the low environmental threshold option[1] and to provide proper calculated values for this scenario.

23. The consultant assessed that the resulting plume would have stayed in the turbulent surface layer and would have reached natural sediment concentration at the pycnocline (limit of the surface water layer mass). Based on this assessment, it can be concluded with a reasonable degree of confidence that the plume did not leave the surface water layer above the pycnocline (area of turbulent mixing) and that upon leaving this uppermost surface water layer, the particle concentration was at the natural sedimentation level, sinking to the seabed according to the natural sedimentation process.

24. Following best scientific practice, CARMU then contacted five international experts with scientific expertise, evidenced by relevant scientific publications, in CCZ PMN occurrences, plume modelling, oceanography, seabed minerals and CCZ biology and sedimentation processes to conduct a scientific peer review of *atdepth's* modelling results and provide an assessment of the potential impact on the marine environment of the plume created by the overflow event.

25. The reviewers were provided with all information pertaining to *atdepth's* scientific expertise, and all concurred with the consultant's scientific and modelling approach. The reviewers agreed on the mathematical model and results and concluded that this overflow event was limited in volume, extent and time and did not cause nor have the potential to cause serious harm to the environment. However, *atdepth* and the external scientific reviewers all noted the paucity of real time onsite data during the overflow event.[2] The final report by *atdepth LLC*, together with the reviews, are included in Annex 3.

[1] Natural lowest sedimentation rate in the CCZ (0.01 mg/l)

[2] Following best scientific practice of independent reviews, the ISA Secretariat did not compensate the experts for this task. All five experts signed a non-disclosure agreement (NDA) with the ISA Secretariat.

V. Causal factors

26. The second part of the investigation focused on identifying direct causes and root causes for the event. This included investigating and mapping work site management, competency, information flow, safety culture, human-machine interface at the overflow site, design of and access to equipment, personal protective equipment (PPE), manning planning, and organising of tasks and processes, risk management and work procedures.

27. A simplified Ishikawa causal (fishbone) diagram[3] was developed by the Investigation Team to visualise and analyse causal factors[4] by creating a logic diagram of the event. A qualitative root case analysis based on expert assessment and consensus has been used to identify relationships between variables to provide insight into causality and operational behaviour of the affected process. Causes emerged by analysis have been grouped in three categories (MTO) to identify and classify sources of variation.

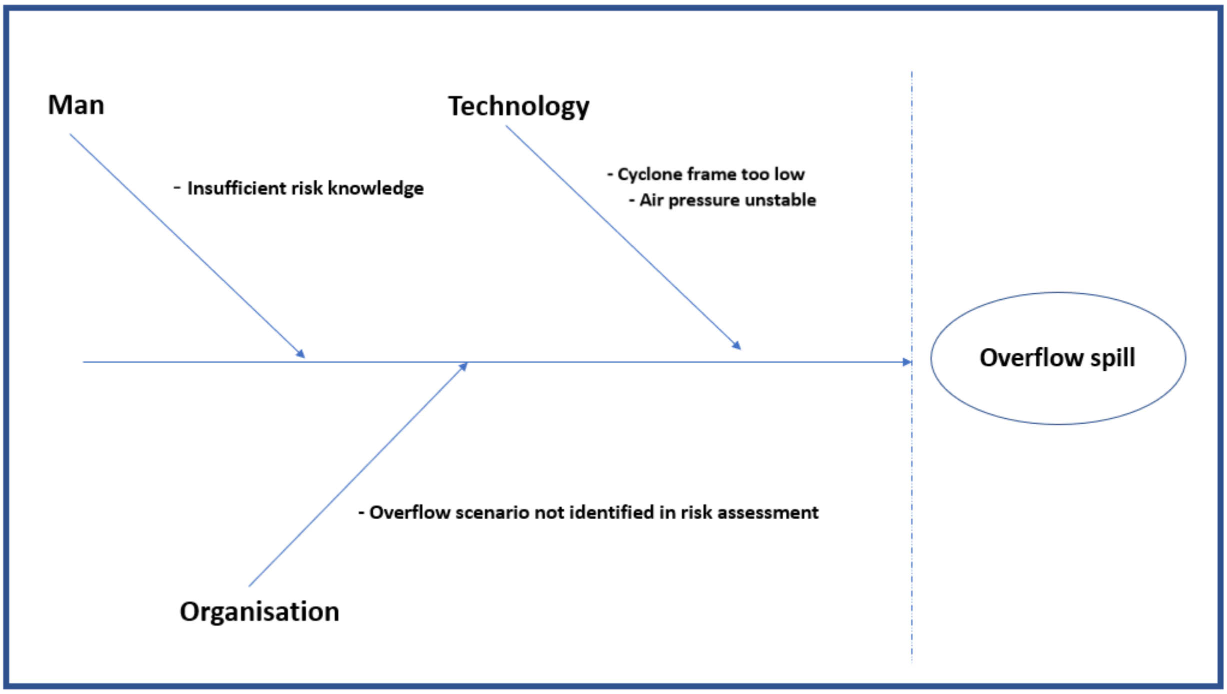


Figure 3 Overflow event causal diagram (Source: ISA Secretariat)

28. It results from the investigation that the Contractor did not identify seawater overflow as a major risk during the pre-cruise risk assessment. Consequently, this risk was not included in its project risk register, and the project crew did not prepare or train to manage this risk. This contributed to an insufficient risk awareness regarding a potential overflow event and had a negative effect on both organisational robustness and personnel performance.

29. The buffer capacity of the cyclone separator at the top of the riser was not constructed to handle the unexpected surge in the volume of water flow. The overflow event indicates that the modelling of the lifting process left out considerations of potential capacity volumes and resulting overflow.

[3] The Ishikawa diagram is a simplified fault tree analysis (FTA) and a graphic tool used to explore the causes of system level failures. It can be described as a top-down approach to identify root causes that enable system-level failures and is well suited to support investigations into unplanned events.

[4] A causal factor can be defined as any major unplanned, unintended contributor to an unplanned event (a negative event or undesirable condition), that if eliminated would have either prevented the occurrence of the event or reduced its severity or frequency.

Combined with the insufficient risk awareness, the lack of a thorough modelling process allowed reduced robustness in the technical design of the cyclone.

30. The CSCT Inspection report dated 20 February 2023 considers that NORI's risk management lacked the expected robustness. Decision-making, incident management and execution were not rooted in a robust risk-based assessment, and Contractor personnel on board the Hidden Gem did not fully apply internally established risk management tools and procedures during the event.

VI. Conclusions and recommendations

31. The investigation did not identify any non-compliances.

32. Based on both completed internal and external assessments, supported by external scientific expert reviews, the investigation concludes that the overflow did not cause serious harm to the marine environment.

Additional recommendations

33. In addition to the two observations recorded in the inspection report, it is recommended that the Contractor conduct an engineering review of the air lift system, its technical operation, and supervision, to identify any areas for improvement of the air lift riser process to learn from the event on 12 October 2022 and to avoid a similar overflow in future nodule collection operations. A report from the review should be shared with ISA by 30 June 2023.

34. It is also recommended that the Contractor conduct a review of the current monitoring programme to verify the programme' s suitability with regards to capturing operational data. The investigation and subsequent follow up suggests that existing sensors and monitoring devices did not provide sufficient information with their current configuration and application. More effective use of available monitoring equipment on board the Hidden Gem could have produced a more accurate calculation of the volumes of water overboard and sediment concentration in the spilled seawater. No accurate flow rate could be produced. No water sampling was made during the normalization phase of the surface waters appearance and no photographs were taken during the surface plume dispersion process.

35. The investigation into the consequences of the event was constrained by the paucity of real time onsite data available to CARMU and consequently the expert consultants. The consequence of this lack of data was that the expert consultant had to model multiple plausible scenarios to fully understand the range of possibilities arising from the event.

36. The Contractor is also reminded of the importance of reporting any unforeseen or unexpected event promptly to ISA through CARMU. Whilst the overflow event was not an incident that caused or was likely to cause serious harm to the marine environment, nevertheless the Contractor should, and could, have notified ISA of the event and the action taken to control it, within a much shorter time frame. In fact, ISA was not notified until 16 days after the event. It is suggested that the Contractor could reasonably have notified ISA within 24-48 hours. Nevertheless, it is accepted that, as noted in the report, the event was managed satisfactorily by on-board operators and appropriate mitigation measures implemented to prevent any re-occurrence.

VII. References and resources

Refer to section VIII of the Inspection Report 01/2023 (INSP/2023/NRU/001).

Annex 1: NORI event report (water discharge letter)

NORI
NAURU OCEAN RESOURCES INC.

4th November 2022

Oystein Larsen
International Seabed Authority
14 – 20 Port Royal Street
Kingston, Jamaica

Dear Oystein,

As requested, please find attached a brief overview of the temporary overflow of water.

On 12 October, 2022 during the production ramp-up sequence, a temporary overflow of water occurred. Due to the dynamic behavior of the airlift riser when first switched on, there was a surge in the volume of water flow which briefly exceeded the buffer capacity of the cyclone separator at the top of the riser. As a result, the cyclone experienced a minor overflow of water which contained some sediment and fragments of nodules. This occurred intermittently during a 7-8 hour test run, with the overflowing water landing on the deck of the vessel and eventually flowing overboard.

When safe to do so the test run was stopped. NORI and AllSeas conducted an assessment to determine if the minor overflow had the potential to cause serious harm to the marine environment. Based on the information provided on the estimated discharge volumes and contents, NORI and AllSeas concluded that this incident did not have the potential to cause serious harm and was, therefore, not a reportable incident. An assessment was conducted on how to prevent an overflow reoccurring on future runs. Based on this assessment, modifications were made to the cyclone. Testing was conducted and the implemented modifications to the cyclone separator proved effective. There have been no further overflows during subsequent test runs.

A more detailed report will be submitted to the ISA as part of the NORI Collector Test Campaign Report.

Sincerely,

Gerard Barron

Gerard Barron
NORI

c.c.
Francillia Akubor, Acting CEO, Nauru Seabed Authority

Eigigu Hardware Store Building
Denig District

Facebook: @NauruOceanResources

Annex 2: Discharge summary memo from NORI

1.0 INTRODUCTION

This memorandum provides a summary of the event of overflowing water from the separator cyclone and subsequent unplanned partial discharge of entrained processing water from the vessel Hidden Gem during the execution of the Pilot Mining test on the 12th of October in the NORI D Contract Area. It also outlines the post event assessment process performed.

2.0 OVERVIEW OF THE EVENT

Due to the unexpected dynamic behaviour of the airlift riser during the execution of the production ramp-up test (STR1.2), the system experienced intermittent surges in the volume of the slurry flow. These surges exceeded the designed buffer capacity of the cyclone feeding the separator deck. As a result, the cyclone experienced intermittent overflows of processing water containing sediment and fragments of nodules.

The overflow was discharged onto the deck of the Hidden Gem and eventually over the side to the surface waters. (see Figure 2, 3 and 4). The intermittent overflow was observed periodically for the duration of the 8-hour test run that was being conducted at the time. Photographs were taken during and after the event to ensure a record of the overflow.

Once the team determined it was safe to do so, the test run was stopped. Immediately after the test was stopped an assessment was performed to determine how to prevent an overflow from reoccurring.

Based on this assessment, modifications were made to the cyclone. Testing was conducted and the implemented modifications to the cyclone proved effective.

An additional assessment was conducted to determine if the minor overflow had caused, was causing or posed a threat of serious harm to the marine environment. Details of this assessment are covered in the next section.

3.0 ASSESSMENT OF THE EVENT

Immediately after the event, information was gathered on the estimated volume and contents of the discharge.

The volume of unplanned discharge to the surface waters was calculated to be 100-150 litres/min, containing ~5kg per 100 liter of sediment. The estimated volumes were based on visual observations from the offshore personnel and based on volumes of sediment recovered during the production test.

Total estimated volume of discharge water = 48-72m3
Total estimated volume of sediment discharge = 2.4-3.6Te

The discharge was observed visually and it was noted that the surface waters appearance returned to normal conditions in less than one hour after the event.

After the event, and at our earliest opportunity, an assessment was performed to determine if the event caused, was causing or posed a threat of serious harm to the marine environment and any necessary reporting requirements pursuant to the rules, regulations and procedures of the Authority. The assessment of the event's impact was performed by offshore and onshore management teams from NORI, TMC, Allseas and DHI.

Several meetings were conducted on the 12th & 13th October.

NORI concluded that the event did not cause, was not causing and did not pose a threat of serious harm to the marine environment on the basis of the following facts:

- The volumes of discharged water and sediment were very small and significantly less than permitted as part of the NORI Collector Test EIS, which clearly demonstrated that, at the scale of a collector test, there was no threat of serious harm to the marine environment from the discharge. For reference the approximate sediment spills included in the Collector Test EIS is 259Te for the mid water discharge and 4015Te from the PCV at the seabed.
- The sediment and nodule fragments discharged are non-Hazardous and originated from the seabed.

As there was no threat of serious harm to the marine environment, NORI determined that formal reporting to the ISA pursuant to Regulation 33 of the Regulations on Prospecting and Exploration for Polymetallic Nodules in the Area was not required. Although formal reporting was not required, in the interests of transparency, NORI chose to notify the ISA of the event and a commitment was made to provide a report of the event as part of NORI's annual report.

In addition to an assessment under applicable ISA rules, regulations and procedures, Allseas offshore and onshore management teams reviewed the event to determine the classification of the event against their internal procedures and polices (Allseas Safety Management System and HSE Plan (EQ-916AH-010-Q-E-001)[1]. The conclusions of Allseas assessment was that the event was not a recordable environmental incident because the contents of the discharge were non-hazardous materials that originated from the seabed.

Allseas and NORI also verified that the discharge event did not contravene the International Convention for Prevention of Pollution from Ships (MARPOL) regulations. The review confirmed that the discharge event did not breach MARPOL regulations.

4.0 MITIGATION MEASURES

Following the assessment, mitigation measures were implemented to extend the height of the cyclone and construct an overflow bypass directly onto the separator deck. These measures successfully prevented any unanticipated overflows from the cyclone on subsequent test runs, and no further unplanned discharges occurred throughout the remaining collector test operations.

For reference, 6 photographs are added to visualise and clarify the issue and the remedial actions taken.

REFERENCE PHOTOGRAPHS

Figure 1: Cyclone feeder in normal operations

[1] The HSE plan was shared with the Secretariat as part of the Hidden Gem mobilization audit.

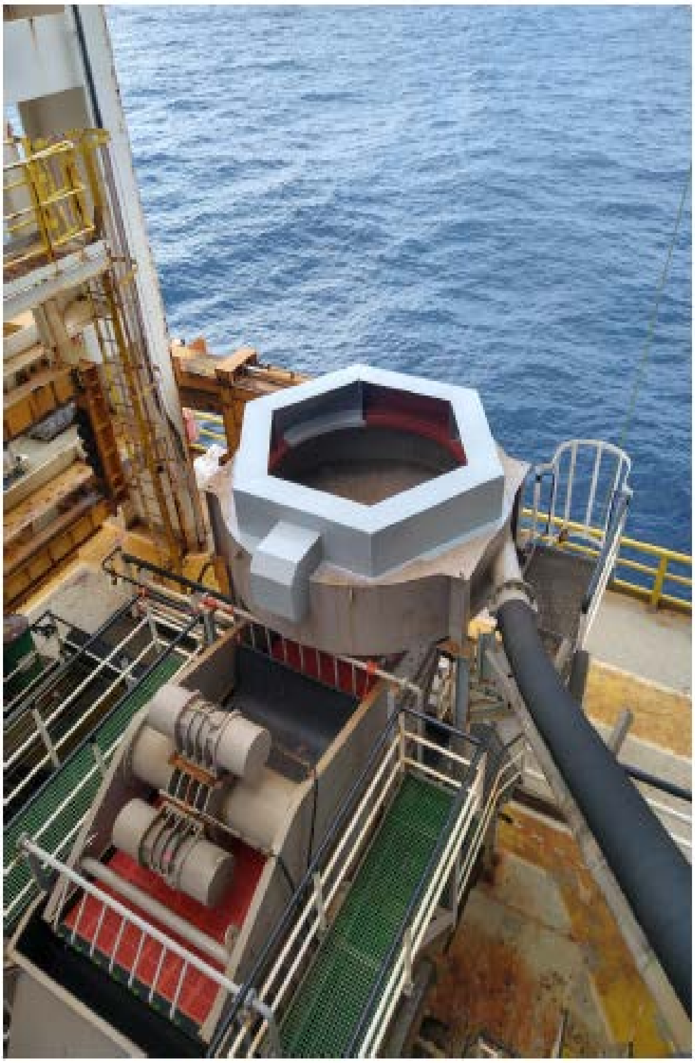
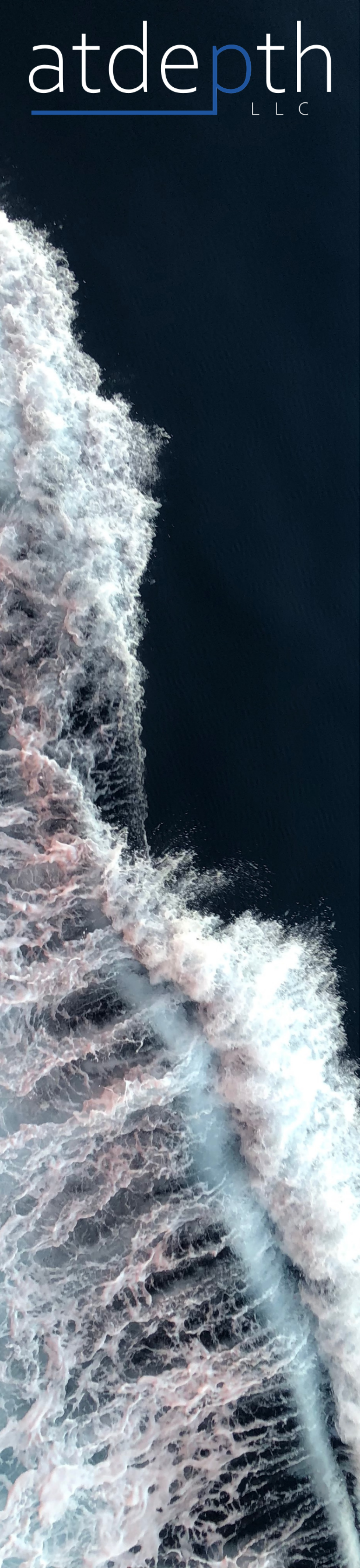


Figure 6 : Modifications to the cyclone feeder – increased height and overflow bypass onto the separator deck.

Annex 3: External Report and Reviews

1. Report by *atdepth* LLC
2. Review by Davide Bonaldo
3. Confidential Review
4. Review by Andrea Koschinsky
5. Review by Gary J. Massoth
6. Review by Tetsuro Urabe



Sediment-laden water spill during NORI technical trials:

Advanced assessment

Author: atdepth LLC

Project: atdepth-ISA 2023

Date: February 28, 2023

atdepth-ISA-R02

Contents

Executive Summary

Findings

- An unplanned partial discharge of entrained processing water from the vessel Hidden Gem to the sea surface took place following an overflow of water from the separator cyclone during the execution of the Pilot Mining test (production ramp-up test STR1.2), on the 12th of October in the Nori D field.
- Limited data is available that pertains to the properties of the discharge. According to the facilitated information, the duration of the spill was approximately 8 hours, with a discharge volume flux of 100-150 l/min and a sediment concentration of 50 g/l. How these values were obtained is not known to *atdepth*.
- Based on available data, and based on assumptions for unavailable data, we have defined a series of possible scenarios within the range of likely values for the parameters of interest.
- The scenarios should not be understood as a comprehensive list of all possible combination of parameters, rather as a representative set of possible combinations.
- Based on the discharge conditions, we identify the relevant physical processes to select the right modeling tools to assess the spill.
- We have used established analytical tools to model the near-field evolution of the sediment plume resulting from the discharge in the buoyancy-driven phase.
- We then produced an order-of-magnitude estimate of the far-field extent of the plume using plume physics knowledge. These estimates include the time required for the discharged plume to dilute down to a threshold concentration, the distance from the discharge where the concentration reduces below this threshold, the maximum vertical extent of the plume, and the total volume of ambient water that ever exceeded the threshold.
- In this report, we further produced a refined estimate of the far-field extent of the plume using a more advanced semi-analytical model that accounts for the key physical processes affecting plumes of this nature.
- This modeling approach was used to estimate the extent metrics above, as well as a fifth extent metric that was unavailable to the basic assessment tool of the previous report: The maximum instantaneous volume of fluid in excess of the threshold.
- We applied the near-field and far-field modeling approaches to the aforementioned spill scenarios, and estimated the aforementioned extent metrics for three different threshold concentrations.
- The advanced modeling approach confirms the validity of the preliminary estimates produced in the initial report, but provides refined estimates and highlights the key processes that affected the plume following the near-field buoyancy-driven phase
- The advanced model shows that plume dilution was controlled by vertical turbulent mixing above the pycnocline, with the plume resurfacing several hundreds of meters away from the discharge points in several of the scenarios considered.
- It also shows that below the pycnocline, plume dilution was controlled by differential settling, with the particle settling velocity distribution playing the critical role there.

- The key extent metrics are reported in figure 5, with variability resulting from different scenarios being considered. For each metric and scenario, three different sediment concentration thresholds are considered.
- We report the minimum, maximum, and median values for the lowest threshold in the table below:

Table 1: Summary of extent metrics for the lowest concentration threshold (0.01 mg/l).

Metric	Minimum	Maximum	Median
Time to dilute below threshold (days)	0.141	9.158	1.425
Distance reached (km)	2.43	45.18	15.15
Plume height reached (m)	27.40	155.68	69.33
Total volume to ever exceed threshold (km^3)	0.034	0.36	0.15
Maximum instantaneous volume above threshold (km^3)	0.010	0.338	0.130

Illustrative scenario

Several scenarios were considered to account for uncertainty in the data available from the spill event. Given that the extent metrics calculated for scenario 1.5 (see table 5) closely match the median values, it is used to illustrate the extent metrics calculated[1]. For this scenario, and for the lowest of the three suspended sediment concentration thresholds considered (0.01 mg/l), the extent metrics are

- Time required for the plume to become diluted below a concentration threshold: 1.4 days
- Distance travelled by the plume over that time: 14.8 km
- Maximum height reached by the plume: 78 m
- Total volume of fluid where the concentration was ever exceeded: 0.16 km^3
- Maximum instantaneous volume of fluid to have been reached above the threshold: 0.14 km^3

Visualization of a vertical slice through the core of the plume is shown below at different times. The plume is transported in the direction of the background current, diluting as a result of the combined effect of vertical turbulent diffusion above the pycnocline and differential settling below.

[1] Scenario 1.5 should not be understood at being the most likely scenario to have occurred. It is only used for illustrative purposes and no scenario can be assumed to be more representative than the others.

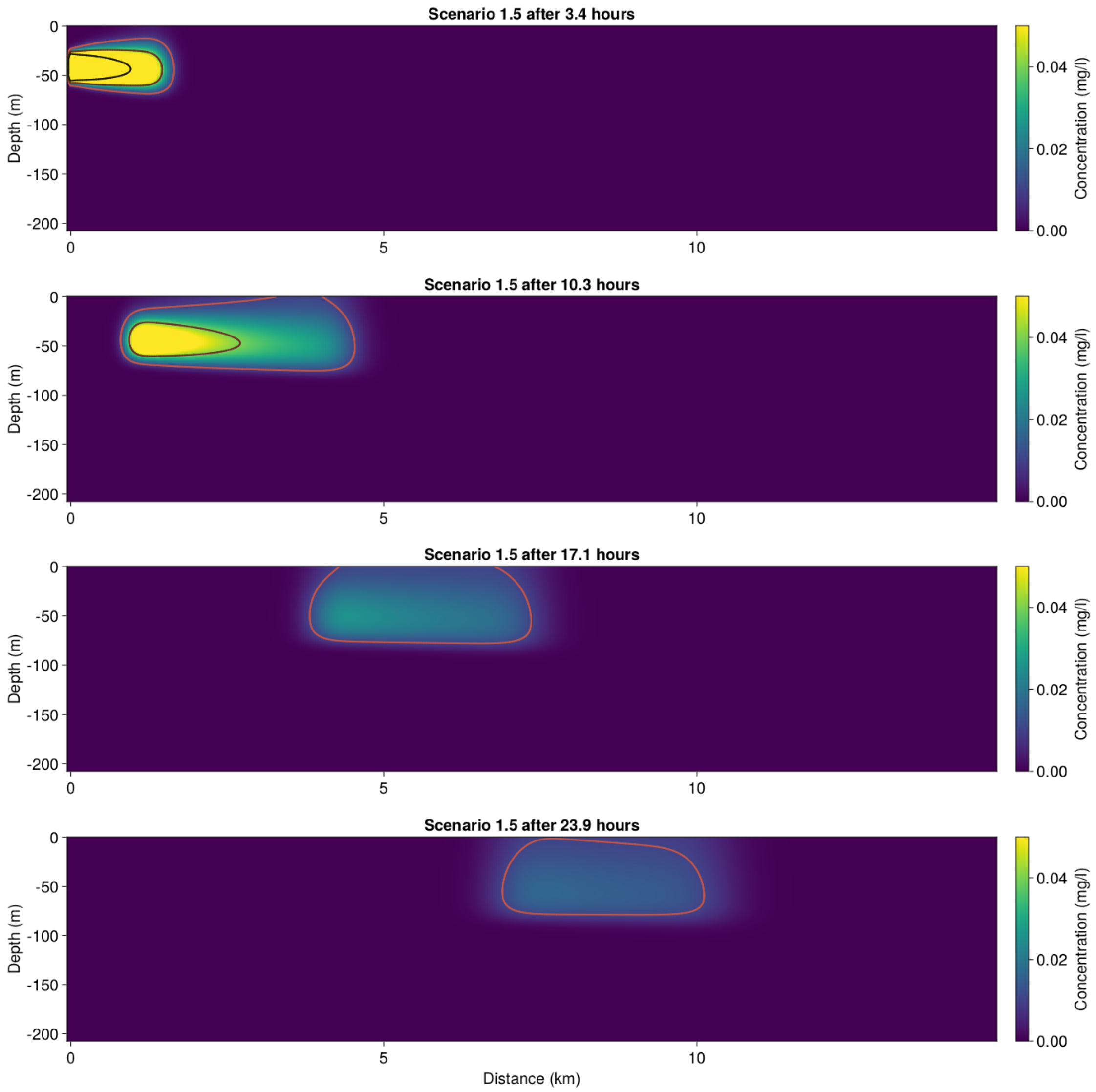


Figure 1: Pseudocolor plot (heatmap) of the suspended sediment concentration along a vertical slice through the center of the plume, calculated for scenario 1.5 at different times.

1 Background

The International Seabed Authority (ISA) was notified by contractor NORI that during their technical trials and activities in their license area in the Clarion Clipperton Zone (CCZ) there was an accidental spill of sediment-laden sewater containing nodule fragments from the M/V Hidden Gem to the ocean surface. On October 12, 2022, during the trials of the riser system onboard M/V Hidden Gem, an overflow of water, sediment and nodule fragments occurred during the production ramp-up sequence. The overflow was related to the dynamic behavior of the airlift riser system; a surge in the volume flux exceeded the buffer capacity of the cyclone separator installed at the top of the riser. The cyclone separator experienced an overflow of lifted seawater from the depth of operation, including seabed sediments and nodule fragments that was directly discharge to the ocean surface.

2 Goals of the study

This study aims to estimate the extent of the sediment plume discharged to the ocean as a result of the overflow. The plume is defined as the volume of water affected at any time by a sediment concentration above a certain threshold level. Given the high level of uncertainty and the limited information available about the spill (see section 3), a number of assumptions are required to conduct the study and different scenarios are studied (see section 4).

It is important to note that the goal of the study is not to evaluate the environmental impact of the spill on the environment, but to evaluate the spatial and temporal extent of the resulting plume for various background concentration thresholds published in the literature.

3 Available information for the study

There is limited information about the spill. All the information available is presented in this section and used as a basis for the study. The information was facilitated to *atdepth* by the ISA. Below, there is a literal copy of the written communication shared by the ISA, and made available for the purpose of this study as a PowerPoint file.

Other relevant sources of information for this study are NORI's Environmental Impact Statement (EIS) submitted to the ISA in March 2022 (Revision V20) and available online on The Metals Company website (https://metals.co/nori/), as well as relevant academic publications in scientific journals.

Start of ISA's facilitated information:

Partial Discharge Overview

EVENT DESCRIPTION:

Overflowing water from the separator cyclone and subsequent unplanned partial discharge of entrained processing water from the vessel Hidden Gem to the sea surface.

WHEN:

During the execution of the Pilot Mining test (production ramp-up test STR1.2), on the 12th of October in the Nori D field.

Cause: unexpected dynamic behaviour of the airlift riser, the system experienced intermittent surges in the volume of the slurry flow. These surges exceeded the designed buffer capacity of the cyclone feeding the separator deck. As a result, the cyclone experienced intermittent overflows of processing water containing sediment and fragments of nodules.

FURTHER DETAILS OF EVENT:

The overflow was discharged onto the deck of the vessel and eventually over the side to the surface waters. This unplanned discharge did not contain any hazardous substances and was limited in volume (<5% of the total flow). The intermittent overflow was observed periodically for the duration of the 8-hour test run that was being conducted at the time. The volume of unplanned discharge to the surface waters was calculated to be 100-150 litres/min, containing 5kg per 100liter (equating to the disposal of the residual sediment from 1-2 sampling box cores per hour).

During the operation Allseas was made aware by the representative of NORI that the approved Environmental Management and Monitoring Program (EMMP) did not allow for any discharge of processing water to the surface waters. Based on this information an intervention meeting was held, where it was decided that at the first safe and practicable opportunity – modifications would be made to the cyclone feeder, to prevent further unplanned overflow on subsequent tests.

CORRECTIVE ACTIONS:

Mitigation measures were implemented to extend the height of the cyclone and construct an overflow bypass directly onto the separator deck. These measures successfully prevented any unanticipated overflows from the cyclone on subsequent test runs, and no further unplanned discharges occurred throughout the remaining collector test operations.

End of ISA's facilitated information

The information included five pictures: (i) the cyclone under normal operation, (ii) a top and (iii) side view the cyclone at a given instant during the overflow incident, (iv) a view of the discharge over the side of the vessel at a given instant during the overflow incident, and (v) a view of the plume from the derrick tower (>100m high from the sea level).

At a later communication, *atdepth* was notified by the ISA that "the ocean surface waters returned to normal conditions in less than one hour after the event".

3.1 Information used in the study

Out of the information facilitated by the ISA (see section 3), the following items are relevant to this study:

- Duration of the test (and spill): 8 hours
- Discharge volume flux: 100-150 l/min
- Sediment concentration: 50 g/l

In the information facilitated by the ISA, there is mention of fragments of nodules also being discharged. However, it is unclear whether the 50g/l of concentration include or not the fragments of nodules. Also, it is not specified how the 50g/l concentration and the 100-150l/min volume flux was determined.

4 Assumptions

The assessment of the spill requires the definition of some assumptions given the scarce quantitative information available. In this section we include all the relevant assumptions considered for the study. In some cases, given the uncertainty around some of the input parameters, we consider multiple scenarios covering a certain range of values.

4.1 Discharge conditions

The discharge is considered to be continuous throughout the 8 hours of duration of the test, with a volume flux of 150 l/min (0.0025m^3/s) and a sediment concentration of 50 g/l for the base scenario, which corresponds to a sediment mass flux of 0.125 kg/s. In order to account for the uncertainty with respect to the data facilitated by the ISA [2], we consider two additional scenarios: (i) a high volume flux and high concentration, and (ii) a low volume flux and low concentration one, which have values 50% higher than the baseline scenario (i.e. 0.0037 m^3/s and 75 g/l) and 50% lower than the baseline scenario (i.e. 0.0013 m^3/s and 25 g/l), respectively. At the impingement point at the ocean surface, the spill source is assumed to have a diameter of 0.25 m, with a top-hat axisymmetric velocity and sediment concentration profiles. The discharge conditions considered for the study are summarized in Table 2.

Table 2: Discharge conditions considered in the study for the low volume flux and low concentration (Low), baseline, and high volume flux and high concentration (High) scenarios.

Parameter	**Low**	**Baseline**	**High**
Duration (hours)	8	8	8
Volume flux (m^3/s)	0.0013	0.0025	0.0037
Total volume flux discharge (m^3)	37	72	107
Sediment concentration (g/l)	25	50	75
Sediment mass flux (kg/s)	0.0325	0.125	0.2775
Total sediment mass discharged (kg)	936	3600	7992
Source diameter at ocean surface (m)	0.25	0.25	0.25
Source velocity profile		top-hat axisymmetric	
Source sediment concentration profile		top-hat axisymmetric	

[2] there is no description of the data sources and methodologies applied to estimate the discharge conditions and no level of uncertainty is provided

4.2 Sediment properties

There are two relevant sediment properties for the purpose of this study: the sediment grain density and the sediment settling velocity distribution (SVD). According to NORI's Environmental Impact Statement (EIS) available online (submitted to the ISA on March 2022, Revision: V20), the sediment grain density is assumed to be 2500 kg/m^3. To the best of our knowledge, the sediment grain density presented in NORI's EIS was not measured or at least the measured values and procedures were not included in the EIS. Sediment grain densities between 2500 and 2600 kg/m^3 have been reported in other areas of the Clarion Clipperton Zone (CCZ) (e.g. Global Sea Mineral Resources reported measured sediment grain densities between 2480 and 2600 kg/m^3 in the EIS submitted to the ISA on April 2018).

NORI's EIS does not present any information related to the SVD, and it presents limited sediment particle size data. The EIS indicates the average particle size (11 $\pm$ 3 μm) and a range of percentages of weight below certain sieve sizes, but does not provide the complete Particle Size Distribution (PSD) information.The vertical spreading, and resulting dilution, of sediment plumes discharged in the water column is primarily controlled by differential settling [Ouillon et al., 2022b], and so the PSD and SVD play a critical role in determining the extent of plumes. In this study, we assume a PSD with a normal distribution with a mean value of 11 μm and a standard deviation of 5 μm (see Table 3). Because of the lack of SVD data, the PSD is then used to compute the SVD assuming Stokes' settling velocity, although it is noted that, generally, sediment particles do not settle at Stokes' velocity because of their non-spherical complex shapes.

As it will be discussed in section 6 and was observed by Muñoz-Royo et al. [2021], flocculation processes due to the cohesivity of the sediment particles does not have an order one effect on a midwater plume behavior and extent. Therefore, the effect of flocculation is not considered in this study.

Table 3: Sediment properties considered in the study.

Parameter	Value
Grain density (kg/m^3)	2500
Mean particle size (μm)	11
Particle size distribution	Gaussian
Particle side distribution standard deviation (μm)	5
Settling velocity	Stokes

4.3 Nodule fragments

In the facilitated information it is reported that nodule fragments were also part of the spill. However, no information or estimates regarding the size or mass flux of such fragments were provided. It is also likely that, apart from the fragments, nodule fines were also present in the discharged water.

The larger nodule fragments (from a few mm to cm-scale fragments) behave as inertial solid bodies and, therefore, they fall inertially to the seabed with velocities likely on the order of a few cm/s or more. Assuming a settling velocity of 20 cm/s, it would take a nodule fragment about six hours to reach the seabed. Assuming a uniform current velocity of 5cm/s throughout the water column, the fragments would reach the seabed about 1km away (horizontally) from the discharge point.

On the other hand, the nodule fines (from a few microns and up to hundreds of microns) present the same behavior as the sediment particles and are controlled by advection (transport by ocean current), turbulent diffusion and settling processes and are treated as sediment.

4.4 Ocean conditions

For the purpose of the study, the following parameters are required to characterize the ocean conditions during the spill:

- Near-surface ocean current velocity
- Ocean stratification
- Surface mixed layer turbulence levels
- Ocean interior turbulence levels

No information or data about the physical oceanography conditions at the time of the incident was provided. As a consequence, we considered the data presented by NORI in the EIS, as well as other data from the area collected by NORI in the past and made available by the ISA for the purpose of this study.

The only mention of measured near-surface current velocities in NORI's EIS is with respect to the measurement of a maximum velocity of 17 cm/s made during one of the baseline campaigns. The area is known to be affected by the North Equatorial Current with surface current velocities reaching up to 20 cm/s as reported both in NORI's and Global Sea Mineral Resources' (GSR) EIS. The contractor BGR reported in their EIS (submitted to the ISA on March 2018) near surface current velocities from ocean reanalysis models of similar magnitude. In this study we therefore consider three different scenarios with ocean currents of 5 cm/s, 12 cm/s, and 20 cm/s.

According to the conductivity and temperature vertical profiles (CTD) presented in NORI's EIS and other available data from the area, the surface mixed layer typically extends between 40 meters and 90 meters deep. In the study we consider three scenarios with mixed layer depths of 40 m, 60 m and 90 m.

Within the mixed layer, the stratification is very weak with low buoyancy frequency values ($N^2 \sim 10^{-5}$ s^{-2}) which results in vertical turbulent diffusivities that are significantly higher than in the ocean interior ($\kappa_z \sim 10^-2$ m^2/s) [e.g. Ozturgut et al., 1978]). In the ocean interior (i.e. below the pycnocline), the buoyancy frequency and the vertical diffusivity are assumed to be $N^2 = 10^{-3}$ s^{-2} and $\kappa_z = 10^{-5}$ m^2/s, respectively. A horizontal diffusivity of $\kappa_x = 1$ m^2/s is considered both for the mixed layer and the ocean interior [e.g. Ozturgut et al., 1978].

4.5 Thresholds

A sediment plume is not well-defined until a sediment concentration threshold is selected. Once a threshold is selected, the plume is defined at a given time as a the ensemble of the fluid parcels (the volume) where the concentration threshold is exceeded. NORI's EIS plume modeling considered a threshold value of sediment concentration of 0.1 mg/l to assess the extent of the plume. Some proposed threshold values for the CCZ in the scientific literature are lower. For instance, van der Grient and Drazen [2022] argue in their study that sediment concentrations between 0.01 mg/l and 0.02 mg/l (equivalent to background values in the CCZ; e.g. Gardner et al. [2018], Burns et al. [1980]) may affect 20% of the species, and sediment

Table 4: Ocean conditions considered in the study.

Parameter	**Value**
Current velocity (cm/s)	$5, 12, 20$
Mixed layer depth (m)	$40, 60, 90$
Mixed layer N^2 (rad^2/s^2)	10^{-5}
Mixed layer vertical diffusivity (m^2/s)	10^{-2}
Mixed layer horizontal diffusivity (m^2/s)	10^{0}
Ocean interior N^2 (rad^2/s^2)	10^{-3}
Ocean interior vertical diffusivity (m^2/s)	10^{-5}
Ocean interior horizontal diffusivity (m^2/s)	10^{0}

concentrations between 0.04 mg/l and 0.08 mg/l may affect 50% of the species. For the purpose of this study we consider three concentration thresholds to define the extent of the plume: 0.01 mg/l, 0.04 mg/l and 0.1 mg/l. We re-emphasize that the goal of this study is not to characterize the environmental impact of the spill, but only to characterize the spatial and temporal extent of the plume with respect to concentration thresholds based on measured background sediment concentrations in the oceanic region of interest.

5 Scenarios

The very limited information available for the study results in a significant level of uncertainty around some of the key input parameters for the study. In order to appropriately represent the levels of uncertainty we analyze a number of scenarios that cover a wider parameter space. Three discharge scenarios are considered (Baseline, Low and High). For each scenario, the current velocity and the depth of the pycnocline are varied between 5, 12 and 20 cm/s, and 40, 60 and 90m, respectively, for a total of 9 combinations per scenario, and 27 cases in total (Table 5).

Table 5: Scenarios considered in the study.

Scenario	Discharge scenario	Current velocity (cm/s)	Pycnocline depth (m)
1.1	Baseline	5	40
1.2	Baseline	5	60
1.3	Baseline	5	90
1.4	Baseline	12	40
1.5	Baseline	12	60
1.6	Baseline	12	90
1.7	Baseline	20	40
1.8	Baseline	20	60
1.9	Baseline	20	90
2.1	Low	5	40
2.2	Low	5	60
2.3	Low	5	90
2.4	Low	12	40
2.5	Low	12	60
2.6	Low	12	90
2.7	Low	20	40
2.8	Low	20	60
2.9	Low	20	90
3.1	High	5	40
3.2	High	5	60
3.3	High	5	90
3.4	High	12	40
3.5	High	12	60
3.6	High	12	90
3.7	High	20	40
3.8	High	20	60
3.9	High	20	90

6 Physical processes

The first step before selecting the appropriate methodology for the study is to identify the relevant physical processes that control the behavior of the spill, as visually summarized in figure 1. For such purpose, we need to evaluate the competing forces at each stage of the spill and the consequent sediment plume. Initially, the spill fluid has a density (ρ_0) that is greater than the ocean water density at the surface (ρ_a), and a vertical momentum due to the mostly vertical velocity of the spilled fluid as it impinges at the ocean surface. The spill encounters a weakly stratified mixed layer with a horizontal current velocity. Given these conditions, the spill will initially behave as a turbulent plume in a cross-flow with non-zero initial momentum [Muñoz-Royo et al., 2021, Rzeznik et al., 2019, Lee and Chu, 2003]. In this initial phase, the plume behavior is mainly controlled by its buoyancy, the ocean stratification, and the turbulent mixing due to shear. Note that the initial impingement of the discharge at the air-water interface is expected to have played no role in the following behavior of the plume. It is nonetheless possible that some initial turbulent mixing immediately following impingement lead to a small fraction of the sediment detaining and being observed at the surface.

Because of a combination of the turbulent mixing and the ocean stratification (i.e. increasing density of the ocean water with depth), the plume eventually reaches the intrusion depth at which it is neutrally buoyant. At that point, the plume behavior is no longer controlled by buoyancy; the particle-laden fluid is now subjected to the advection (i.e. horizontal transport) by ocean currents, turbulent diffusion (i.e. mixing with background ocean water due to the ocean's horizontal and vertical turbulence), and settling of the individual sediment particles. Because of the high turbulence, flocculation is not expected to be a relevant process in this initial buoyancy-driven phase. Additionally, at the end of the buoyancy-driven phase the sediment concentration is, in most cases, sufficiently low and does not result in significant flocculation [Gillard et al., 2019]. In the horizontal plane, the plume is advected by ocean currents and diluted (i.e. mixed with background ocean water) as a result of horizontal diffusion. Because of the slow nature of the horizontal diffusion process in comparison to the advection the plume has a narrow and elongated shape [see Muñoz-Royo et al., 2021, Ouillon et al., 2022b]. In the vertical, differential settling (i.e. the difference in the particle settling velocities between particles) usually dominates versus the usually weak vertical diffusivity in the ocean [Ouillon et al., 2022b]. Although, in this case and because of the presence of the mixed layer, vertical turbulence may play a more relevant role there than in the ocean interior. This will be explored in the follow-up in-depth assessment.

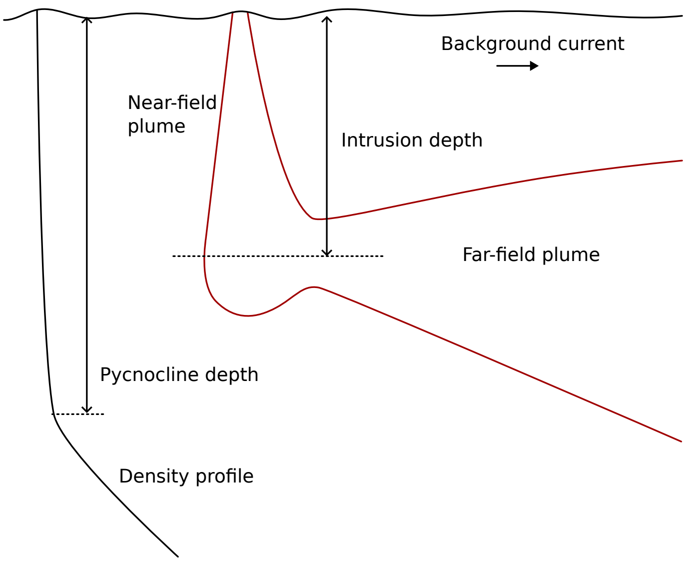


Figure 2: Sketch of the plume generated by the spill.

The mixing processes continuously dilute the plume as it is transported by ocean currents until the defined sediment threshold levels are reached. After that, the individual sediment particles will continue to be transported, but the concentration will be below the threshold.

7 Methodology

7.1 Near-field assessment of buoyancy-driven phase

In Section 6, we identified two relevant stages of the plume: (i) the initial buoyancy-driven phase, and (ii) the advection-diffusion-settling phase. Because of the very different forces and physical processes involved, each phase needs to make use of a different model.

For the buoyancy driven phase, we use a turbulent plume model that takes into consideration the effects of a background cross-flow. The model is described by Rzeznik et al. [2019], and was applied and validated by Muñoz-Royo et al. [2021] in a midwater plume experiment using actual sediment from the CCZ. The model first solves the zone of flow establishment using the approach developed by Henderson-Sellers [1983], in which the plume velocity and concentration profile evolves from the initial top-hat profile to a Gaussian profile. After the zone of flow establishment, the model is based on the classic and widely applied model by Morton et al. [1956] for turbulent plumes, but taking into consideration the effects of the ocean background currents and the vertically variable ocean stratification on the plume. The main goal of the buoyancy-driven phase model in this study is to determine the intrusion depth of the plume.

7.2 Advanced semi-analytical assessment of far-field plume extent

In this advanced semi-analytical assessment, the advection-diffusion-settling transport equation is solved following the approach of Ouillon et al. [2022a], with several improvements. First, it is important to note that there are several fundamental reasons why such an approach is more adapted to assessing the key extent metrics than traditional ocean-scale numerical simulations. The near-field model predicts intrusion depths of a few tens of meters, generally above the pycnocline. Because of the range of particle settling velocities, this suggests that fast-settling particles crossed through the pycnocline at some point in time following intrusion[3], while slow settling particles will have remained above the pycnocline. Thus, it should be expected that above the pycnocline, where turbulent mixing is strong, vertical transport processes were diffusion-driven, while below the pycnocline, where turbulent mixing is minimal, vertical transport processes were settling-driven. As such, not only is it imperative that the modeling approach includes a highly-resolved particle settling velocity distribution, something that is impractical in the context of ocean-scale models, but also that the modeling approach captures with great accuracy the role of vertical diffusion.

This problem is particularly challenging for traditional ocean-scale models as very sharp gradients due to the extremely low vertical turbulent diffusion experienced below the pycnocline needs to be resolved without introducing numerical diffusion, all while maintaining solver stability in the diffusion-driven regime above the pycnocline. In the present, this is tackled by solving the vertical transport problem numerically using a conservative, fully-implicit in time, second-order in space discretization scheme for diffusion terms, and an implicit Crank-Nicolson implicit in time, upwind advection discretization scheme for the settling term. This method guarantees mass conservation despite the very sharp gradient of the vertical diffusivity term at the pycnocline, and is highly stable. As the advection-diffusion-settling problem is solved in the direction of advection assuming no significant dispersion at the scales of interest [see Ouillon et al., 2022a], the horizontal solution can be trivially obtained analytically. This means that only the vertical one-dimensional in space diffusion-settling problem needs to be solved, and a large number of grid cells can be used. In the following, we use $N_z = 1000$ vertical levels, which achieves full convergence with grid resolution (i.e. further refining the grid would produce the same results). Because the numerical problem was reduced from three to one dimensions, we can also consider a highly resolved settling velocity distribution. In the following, the particle size distribution (section 4.2) is discretized using $N_p = 200$ different particle sizes, as shown in figure 3.

Unlike the simple model employed in the preliminary assessment (see appendix A), the ad-

[3] Note that because the density difference between the particles and the ambient fluid is very large, there will not have been a significant changes to the settling velocity of the particles as they crossed through the pycnocline

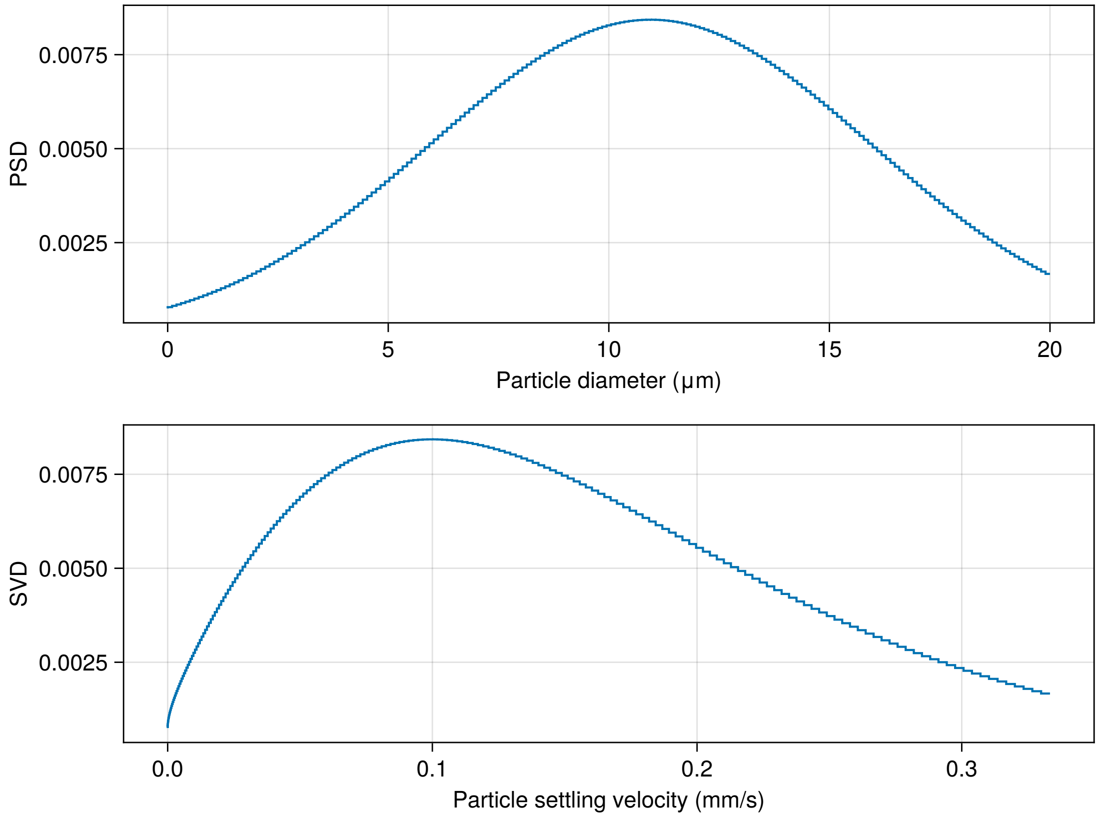


Figure 3: Discretized particle size distribution (PSD) and particle settling velocity distribution (SVD) with the $N_p = 200$ different particle sizes being used in the advanced model. The model solves the advection-diffusion problem for each of the 200 concentration fields associated with each of the particle sizes, and combines the solutions to obtain the total concentration of suspended sediment.

vanced semi-analytical model accounts for the spatial distribution of the sediment following intrusion. Here, it is assumed that following intrusion, the sediment was distributed along a Gaussian profile in both the vertical direction and following Muñoz-Royo et al. [2021], Peacock and Ouillon [2023], the height of the plume (taken here as 2σ where σ is the standard deviation of the initial Gaussian profile) was equal to 40% of the intrusion depth. Unlike the simple model, the advanced model also accounts for changes in the vertical turbulent diffusivity between the mixed layer above the pycnocline and the stratified interior ocean below. The turbulent diffusivities used are detailed in section 4.4, and the vertical profiles of turbulent diffusivity $\kappa_z(z)$ is defined as

$$\kappa(z) = \frac{1}{2}(\kappa_0 - \kappa_1)\left(1 + \tanh\left(\frac{z + H_p}{\delta}\right)\right) + \kappa_1,$$

where z is the vertical position with $z = 0$ defining the surface, $\kappa_0 = 10^{-5}$ m^2/s is the mixed layer vertical diffusivity, $\kappa_1 = 10^{-2}$ m^2/s is the ocean interior vertical diffusivity, H_p is the pycnocline depth (see table 5), and $\delta = 10$ m is used to define the transition between the mixed layer and the interior at the pycnocline.

7.3 Extent metrics of interest

As discussed above, plumes are generally described at any given time as the instantaneous volume of fluid where a certain concentration threshold is exceeded. As such, the extent of a plume cannot be discussed without first defining a concentration threshold of interest. Then, several metrics exist that can provide insight into the spatial and temporal extent of the plume, and we refer to Ouillon et al. [2022b] for a comprehensive discussion. Herein will be presented five key extent metrics:

- The time required for the plume to become diluted below a concentration threshold,
- The distance travelled by the plume over that time,
- The maximum height (i.e. vertical extent) reached by the plume in the far field,
- The total volume of fluid where the concentration was ever exceeded,
- The maximum instantaneous volume of fluid where the concentration is ever exceeded.

The distinction between the total volume of fluid where the concentration was ever exceeded and the maximum instantaneous volume of fluid where the concentration is exceeded is an important one. The former identifies the total volume of fluid that, over the course of the evolution of the plume, will have at some point contained a concentration of sediment in excess of the identified threshold. This is calculated as in Ouillon et al. [2022b] by integrating in time the volume flux of fluid across the maximum vertical cross-sectional area of the plume where the threshold concentration is exceeded, over the duration of the spill event. The maximum instantaneous volume of fluid where the concentration is exceeded identifies the volume of fluid where the concentration exceeds the chosen threshold, taking a snapshot at the point in time when this volume reaches a maximum. This metric could not be calculated using the preliminary assessment methodology, but it can be calculated using the present advanced methodology. This is done by solving the advection-diffusion-settling equations in order to obtain a spatio-temporally resolved description of the plume, and directly computing at a given time the volume of water where the concentration threshold of interest is exceeded.

8 Plume estimates

8.1 Buoyancy-driven phase

The results from the buoyancy-driven phase model are presented in the form of a boxplot (figure 4), where the color box represents values between the 25th and 75th percentile, and the horizontal bar represents the median value. Note that the results presented are estimates and the boxplots are understood to represent a likely range for the possible values of interest. The results indicate an intrusion depth between 23 m and 72 m for all the considered scenarios. As expected, the lowest intrusion depth is reached for scenario 2.7, i.e. the Low discharge scenario with the strongest background current and the thinnest mixed layer (or smallest pycnocline depth). The highest intrusion depth is reached for scenario 3.3, i.e. the High discharge scenario with the weakest background current and the thickest mixed layer. The sediment concentration at the end of the near-field buoyancy-driven phase, i.e. immediately prior to intrusion is also shown in figure 4.

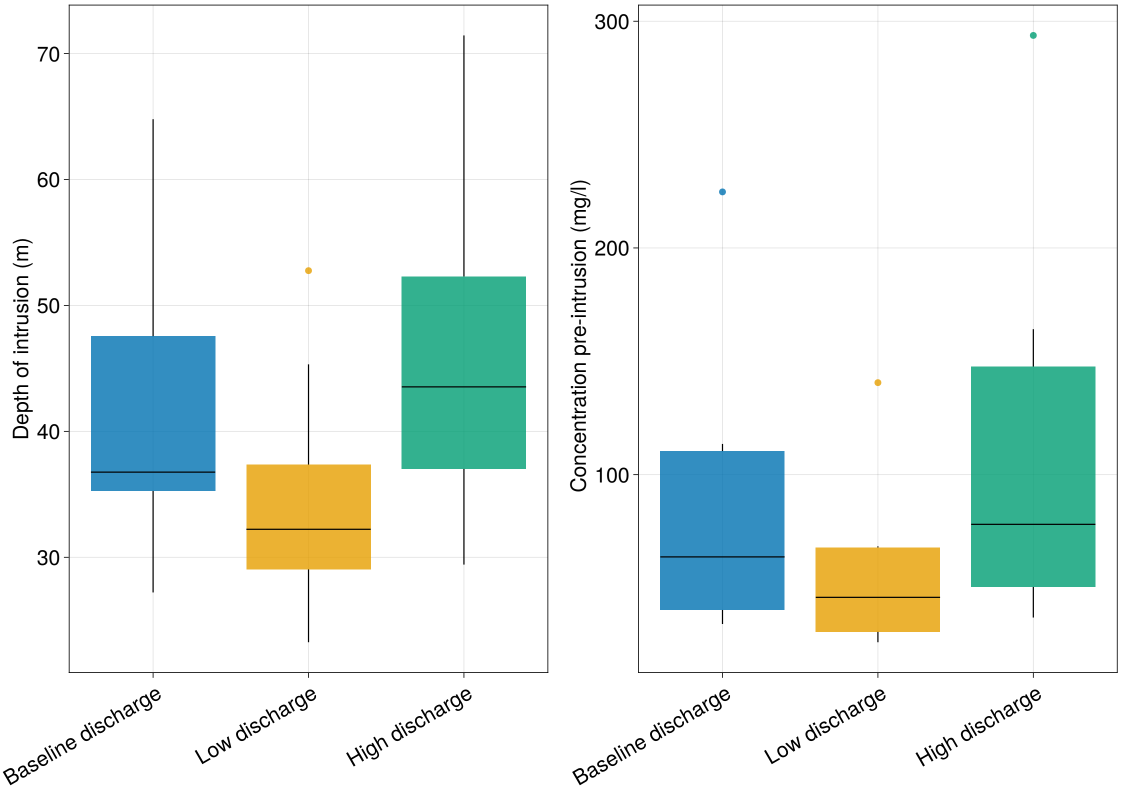


Figure 4: Results of the near-field model for the three discharge scenarios considered. (left) Depth of intrusion (m) and (right) concentration of the plume immediately prior to intrusion (mg/l). The results are presented in the form of a boxplot to account for the parametric uncertainty (see section 4), where the color box represents values between the 25th and 75th percentile, and the horizontal bar represents the median value. Note that the results presented are estimates and the boxplots are understood to represent a likely range for the possible values of interest.

8.2 Advanced assessment of passive transport phase

The methodology described in section 7.2 is used to estimate the time required for the spill plume in the passive transport phase to become diluted down to the threshold concentrations discussed in section 4.5, i.e. 0.01 mg/l (low threshold), 0.04 mg/l (medium threshold) and 0.1 mg/l (high threshold). All 27 scenarios are considered for each threshold. The advanced estimates of the time required to reach the threshold, the distance travelled by the plume after that time, the maximum plume height, the maximum volume of water to ever exceed the concentration threshold, and the maximum instantaneous volume of water above the threshold, are reported in figure 5, again as boxplots. This time, the variability in the results for the 3 scenarios and 9 parameter combinations are all combined into one boxplot for each concentration threshold.

First, we find good consistency between the advanced estimates and the preliminary estimates (see appendix A) based on simple physical arguments, with the extent metrics found using the advanced methodology being slightly smaller than those found using the preliminary methodology. Interestingly, the total volume to ever exceed the threshold is only marginally larger than the maximum instantaneous volume above threshold at the lowest threshold. This is purely coincidental and only holds true for the particular duration of the spill (8h), spill conditions, and threshold. At higher thresholds, the total volume to ever exceed threshold is, from a relative perspective, much larger than the maximum instantaneous volume above threshold. We recall from Ouillon et al. [2022a] that the total volume to ever exceed threshold increases linearly with the duration of the spill while the maximum instantaneous volume above threshold eventually reaches a steady-state asymptotic value.

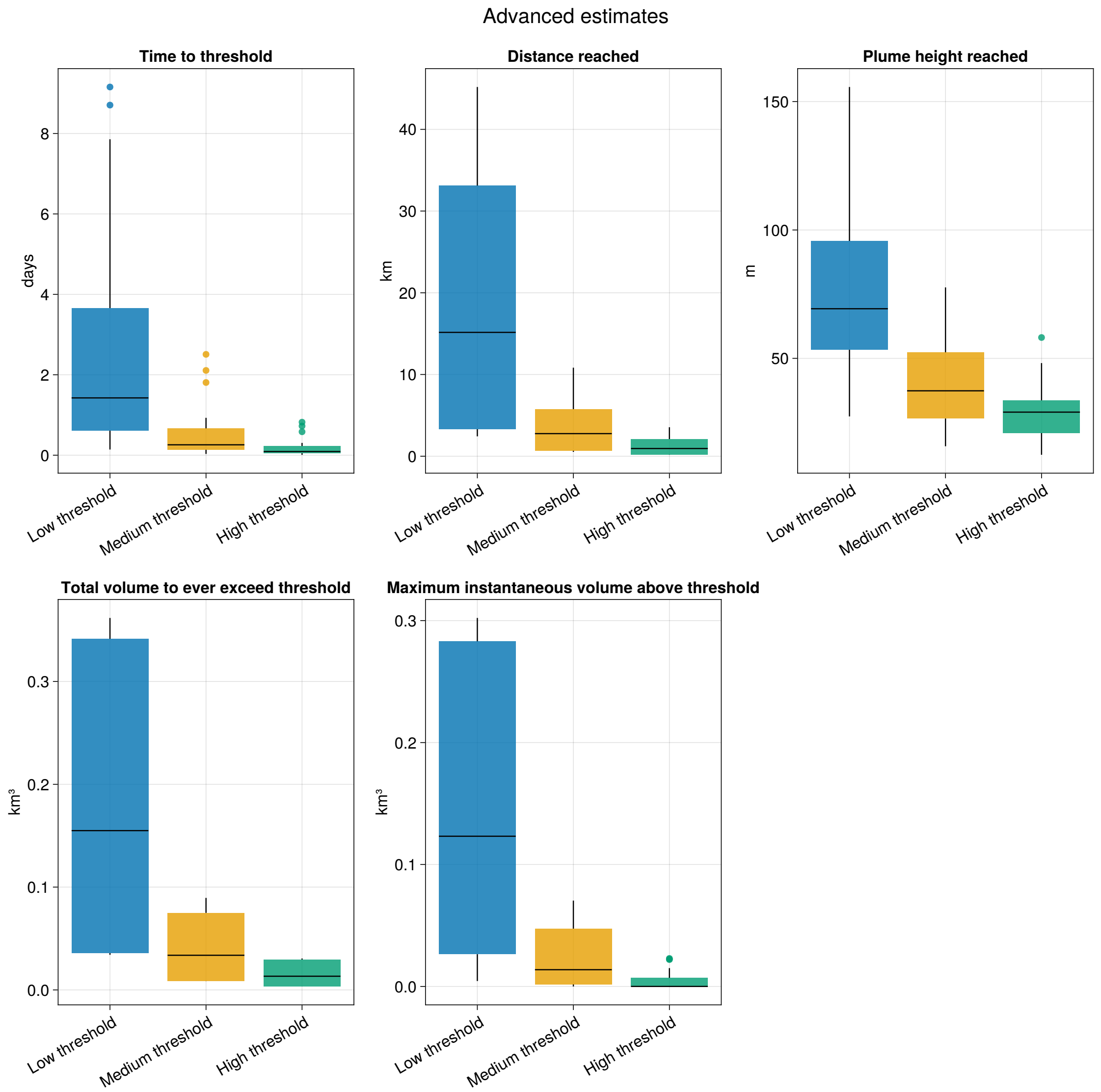


Figure 5: Advanced estimate of key far-field extent metrics using the preliminary advanced assessment method described in section 7.2.

The complete results are listed in section B for all three thresholds and every scenario. To provide a qualitative visual of the plume, heatmaps of the sediment concentration along a vertical slice through the center-line of the plume are shown at different times and for every scenario in appendix C. Note that for better readability, the sediment concentration in the color scale is clipped. The contours of the three concentration thresholds are superimposed. Note that the times at which the plume is shown and the horizontal axis (distance) is different for each scenario, again to improve readability of the results.

9 Conclusions

- High levels of uncertainty regarding key physical parameters, and lack of available information regarding the methodologies used to measure the available data justify a scenario-based approach in which combinations of parameters over a likely range are considered.
- The near-field modeling of the buoyancy-driven phase shows that the plume will have reached depths of over 20m in all scenarios considered prior to intruding horizontally and becoming passively advected by background currents.
- At a later communication to *atdepth*, it was added that "the ocean surface waters returned to normal conditions in less than one hour after the event". However, sediment visible at the surface would have resulted from turbulent mixing processes due to the plume impingement at the surface, but do not represent the bulk of the sediment, which, as stated above, will have descended in the buoyancy-driven plume down to depths of tens of meters. Additionally, sediment concentrations around or below mg/l are not perceptible to the naked eye.
- As it was anticipated in the preliminary analysis, the advanced modeling results show that vertical turbulent diffusion in the mixed layer allowed for slow-settling particles to reach the surface after some time for some of the scenarios (see appendix C), but this re-surfacing took place hundreds of meters away from the surface vessel at concentrations of a few mg/l or less, thus not perceptible to the human eye.
- In all scenarios, but to varying degrees, it is seen that both differential settling and vertical turbulent diffusion above the pycnocline, along with horizontal turbulent diffusion, all contributed on first order to the dilution of the plume generated during the spill. This confirms the importance of using a modeling approach that accurately captures all processes, and explains the differences between the results herein and the preliminary estimates presented in the report "Sediment-laden water spill during NORI technical trials: Preliminary analytical assessment".
- The values of the extent metrics discussed herein are estimates of the extent of the plume, and not the impact of the plume. They should not be understood as exact nor be interpreted as representative of the final environmental impact and potential harm that resulted from the spill incident of interest.

A Preliminary assessment of far-field plume

This appendix includes the far-field plume preliminary assessment methodology and obtained results that were used in the Preliminary Assessment conducted for the ISA.

A.1 Methodology

For the purpose of this preliminary analysis, the passive ocean-transport phase of the plume following intrusion is simplified such that only advection is considered in the direction of the background current, only horizontal diffusion is considered in the direction normal to the background current, and only stretching by differential settling is considered in the vertical direction. These simplifications are justified by the physics of plumes in the passive transport phase. Indeed, it was shown [Ouillon et al., 2022b] that the dilution of passively transported plumes in the midwater column is dominated by vertical stretching imparted by differential settling, with vertical turbulent diffusion being negligible. Similarly, turbulent diffusion can be neglected in the direction of the background current, as transport is dominated by advection.

In this preliminary assessment, the goal is to estimate the time required for the plume, in the passive-transport phase, to become diluted down to a certain threshold concentration (section 4.5). In the passive transport phase, the plume concentration can be estimated after a certain evolution time t as the mass flux of sediment divided by the volume flux of water occupied by the plume. This can be simply expressed as $\bar{c}(t) \approx \frac{\dot{m}}{UA(t)}$, where $\dot{m}$ is the mass flux of sediment discharged (which is the same as the mass flux of the spill because mass is conserved), U is the background current velocity and $\bar{c}(t)$ and $A(t)$ are the approximate plume concentration and vertical surface area of the plume after time t of evolution. In this preliminary analysis, the concentration is assumed homogeneous and the area of the plume is assumed to be a simple function of vertical stretching due to differential particle settling, and horizontal stretching due to turbulent diffusion. In the follow-up in-depth review, the full advection-diffusion-settling equation for the plume will be solved, also accounting for the initial vertical and horizontal distribution of sediment following intrusion. For now, it is assumed that $A(t) \approx \sqrt{4\kappa_h t}\Delta V t$, where $\sqrt{4\kappa_x t}$ approximates the horizontal spread of the plume with a background turbulent diffusivity κ_x, and $\Delta V t$ approximates the vertical stretching resulting from the difference in settling speed ΔV between the fastest and the slowest settling particles. Following section 4.4, we assume a turbulent diffusivity $\kappa_x = 1$ m^2/s. Following 4.2, we assume that ΔV is the difference in particle settling velocity between particles with diameters $\bar{d} \pm \sigma$ where $\bar{d} = 11\mu m$ is the mean particle diameter and $\sigma = 5\mu m$ is the standard deviation. Applying Stokes law, we find that $\Delta V \approx 0.24$ mm/s.

A.2 Preliminary plume extent estimates

The methodology described in section A.1 is used to estimate the time required for the spill plume in the passive transport phase to become diluted down to the threshold concentrations discussed in section 4.5, i.e. 0.01 mg/l (low threshold), 0.04 mg/l (medium threshold) and 0.1 mg/l (high threshold). All 27 scenarios are considered for each threshold. The first order estimates of the time required to reach the threshold, the distance travelled by the plume after that time, the maximum plume height, and the maximum volume of water to ever exceed the concentration threshold are reported in figure 6, again as boxplots. This time, the variability in the results for the 3 scenarios and 9 parameter combinations are all combined into one boxplot for each concentration threshold.

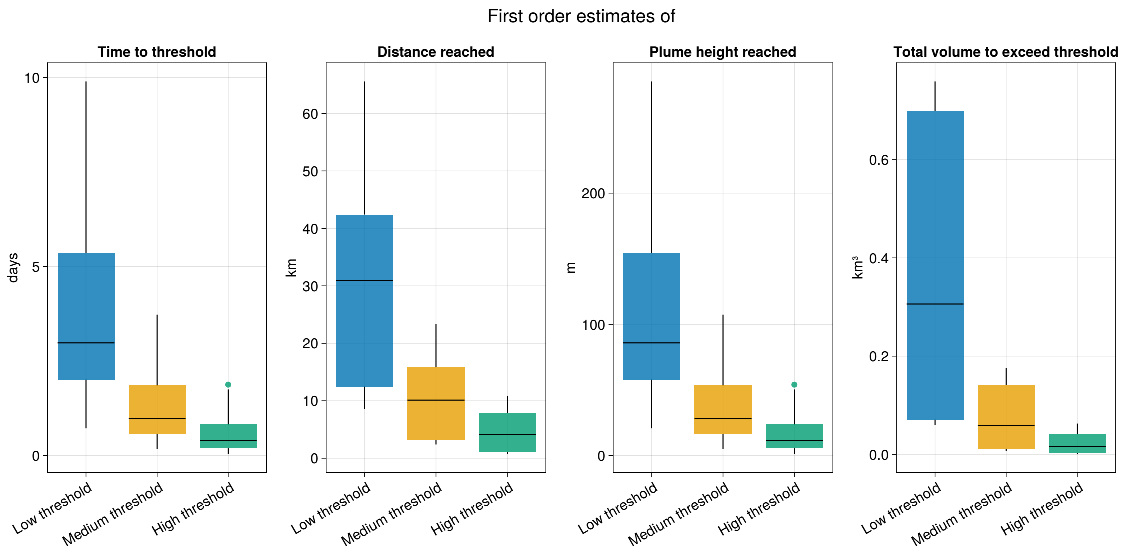


Figure 6: First order estimate of key far-field extent metrics using the described preliminary assessment method.

B Results per scenario

Nomenclature:

- T Time to threshold (days)
- L Distance reached (km)
- H Plume height reached (m)
- V1 Total volume to ever exceed threshold (km^3)
- V2 Maximum instantaneous volume above threshold (km^3)

Table 6: Low threshold (0.01 mg/l)

Scenario	T (days)	L (km)	H (m)	V1 (km^3)	V2 (km^3)
1.1	4.66	20.12	85.93	0.155	0.130
1.2	4.11	17.75	101.71	0.160	0.132
1.3	3.51	15.15	111.67	0.150	0.122
1.4	1.81	18.74	64.35	0.162	0.146
1.5	1.42	14.77	78.05	0.158	0.140
1.6	1.05	10.89	75.55	0.140	0.127
1.7	0.93	16.05	53.97	0.161	0.149
1.8	0.70	12.15	59.78	0.146	0.130
1.9	0.60	10.39	57.70	0.136	0.120
2.1	0.96	4.14	57.70	0.041	0.033
2.2	0.80	3.44	52.72	0.045	0.029
2.3	0.62	2.68	57.29	0.035	0.028
2.4	0.31	3.16	34.87	0.036	0.023
2.5	0.26	2.67	36.53	0.035	0.019
2.6	0.24	2.50	36.95	0.034	0.017
2.7	0.16	2.82	27.40	0.035	0.012
2.8	0.15	2.53	28.23	0.034	0.011
2.9	0.14	2.43	28.23	0.034	0.010
3.1	9.16	39.56	120.39	0.321	0.274
3.2	8.71	37.62	134.50	0.338	0.285
3.3	7.86	33.95	155.68	0.345	0.283
3.4	4.36	45.18	82.61	0.345	0.306
3.5	3.81	39.48	97.56	0.358	0.319
3.6	3.11	32.22	115.41	0.359	0.323
3.7	2.56	44.20	69.33	0.356	0.335
3.8	2.06	35.56	83.03	0.362	0.338
3.9	1.51	26.16	93.82	0.348	0.323

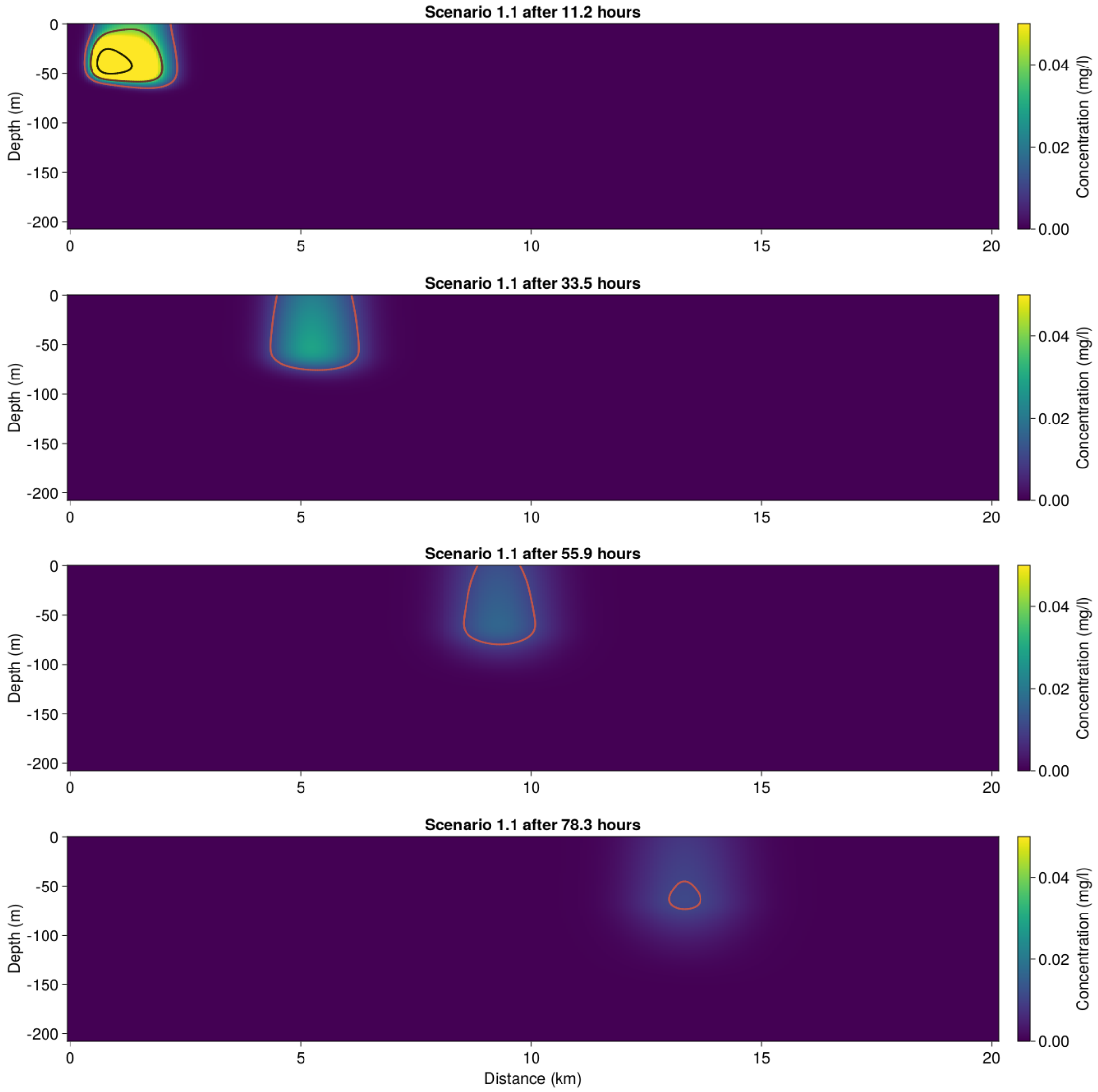
Table 7: Medium threshold (0.04 mg/l)

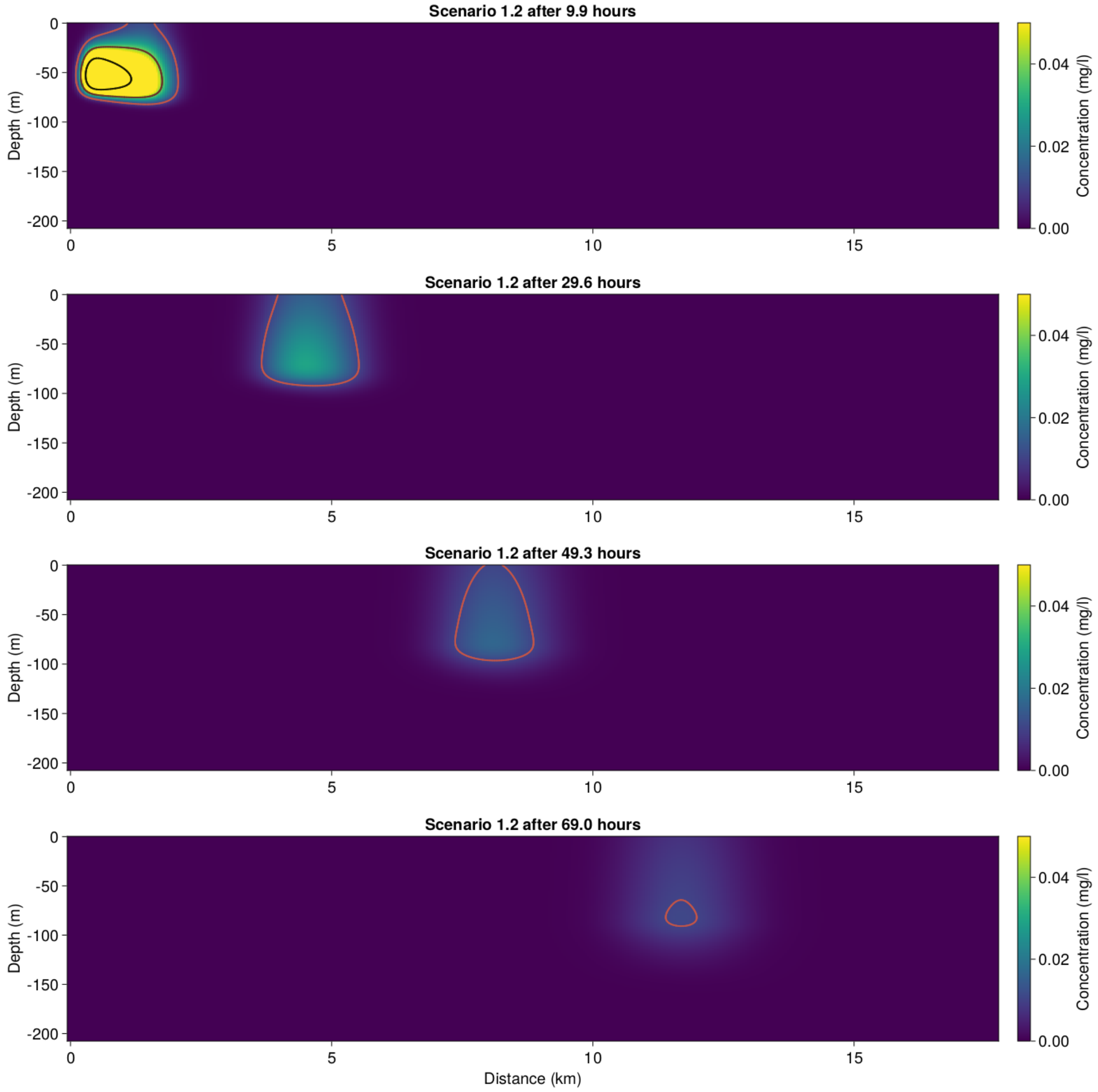
Scenario	T (days)	L (kms)	H (m)	V1 (km^3)	V2 (km^3)
1.1	0.9289	4.01	54.38	0.0369	0.02977
1.2	0.7959	3.44	50.23	0.0340	0.02813
1.3	0.6400	2.76	56.46	0.0343	0.02730
1.4	0.3052	3.16	33.21	0.0337	0.02120
1.5	0.2580	2.67	35.70	0.0337	0.01841
1.6	0.2249	2.33	37.36	0.0330	0.01581
1.7	0.1634	2.82	26.57	0.0335	0.01138
1.8	0.1409	2.43	28.64	0.0332	0.00997
1.9	0.1356	2.34	28.64	0.0329	0.00939
2.1	0.1821	0.79	26.57	0.0087	0.00324
2.2	0.1575	0.68	33.21	0.0087	0.00284
2.3	0.1356	0.59	38.19	0.0086	0.00240
2.4	0.0637	0.66	19.10	0.0086	0.00117
2.5	0.0551	0.57	23.66	0.0086	0.00102
2.6	0.0551	0.57	24.91	0.0085	0.00098
2.7	0.0353	0.61	15.78	0.0085	0.00066
2.8	0.0332	0.57	18.27	0.0085	0.00059
2.9	0.0311	0.54	18.68	0.0085	0.00058
3.1	2.5078	10.83	73.06	0.0895	0.07372
3.2	2.1078	9.11	77.63	0.0810	0.06628
3.3	1.8078	7.81	75.55	0.0763	0.06654
3.4	0.8210	8.51	56.45	0.0859	0.07463
3.5	0.6813	7.06	50.23	0.0760	0.06653
3.6	0.5297	5.49	54.38	0.0747	0.06244
3.7	0.4235	7.32	39.44	0.0770	0.06137
3.8	0.3484	6.02	40.68	0.0752	0.05288
3.9	0.3052	5.27	41.93	0.0734	0.04740

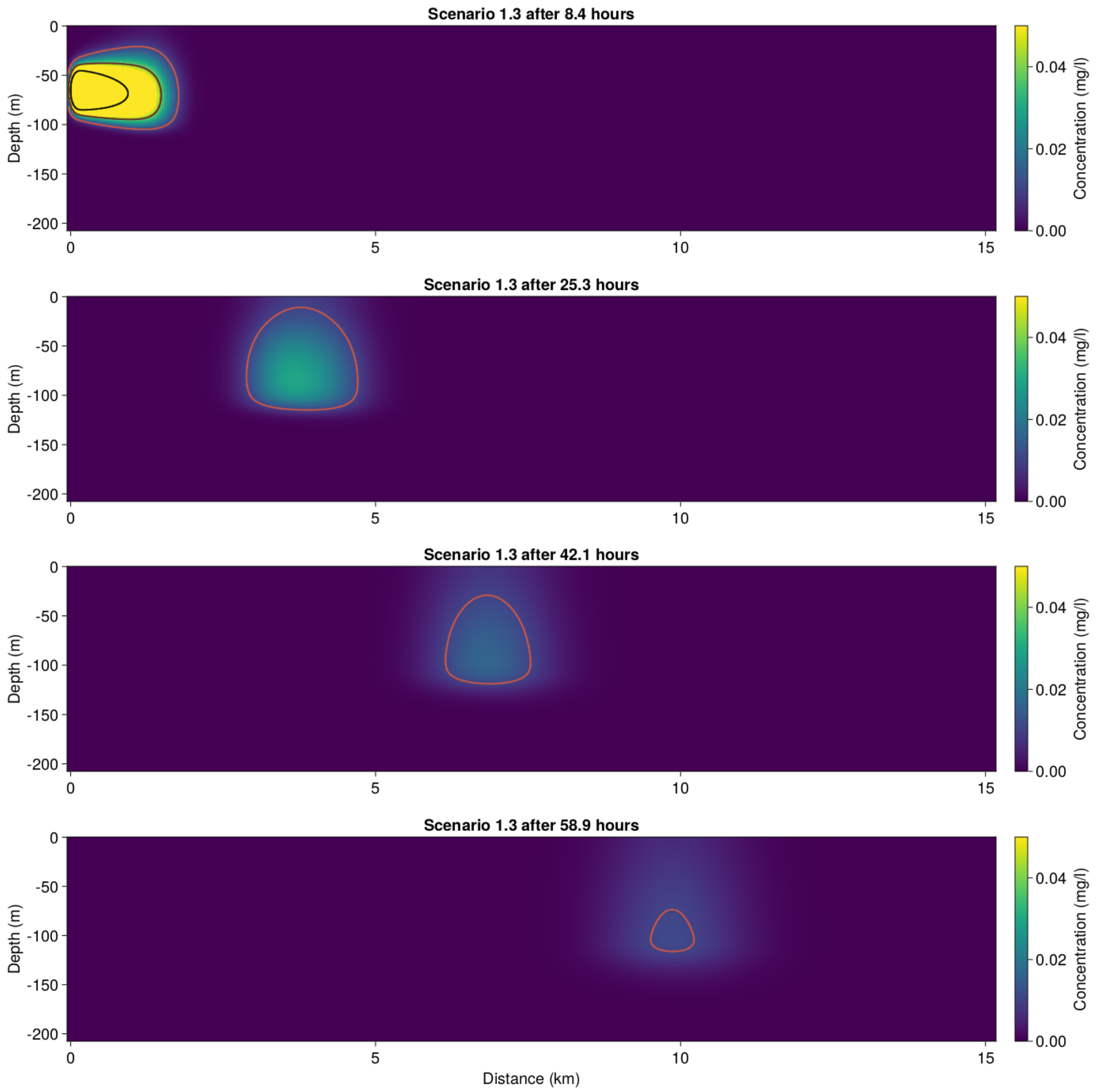
Table 8: High threshold (0.1 mg/l)

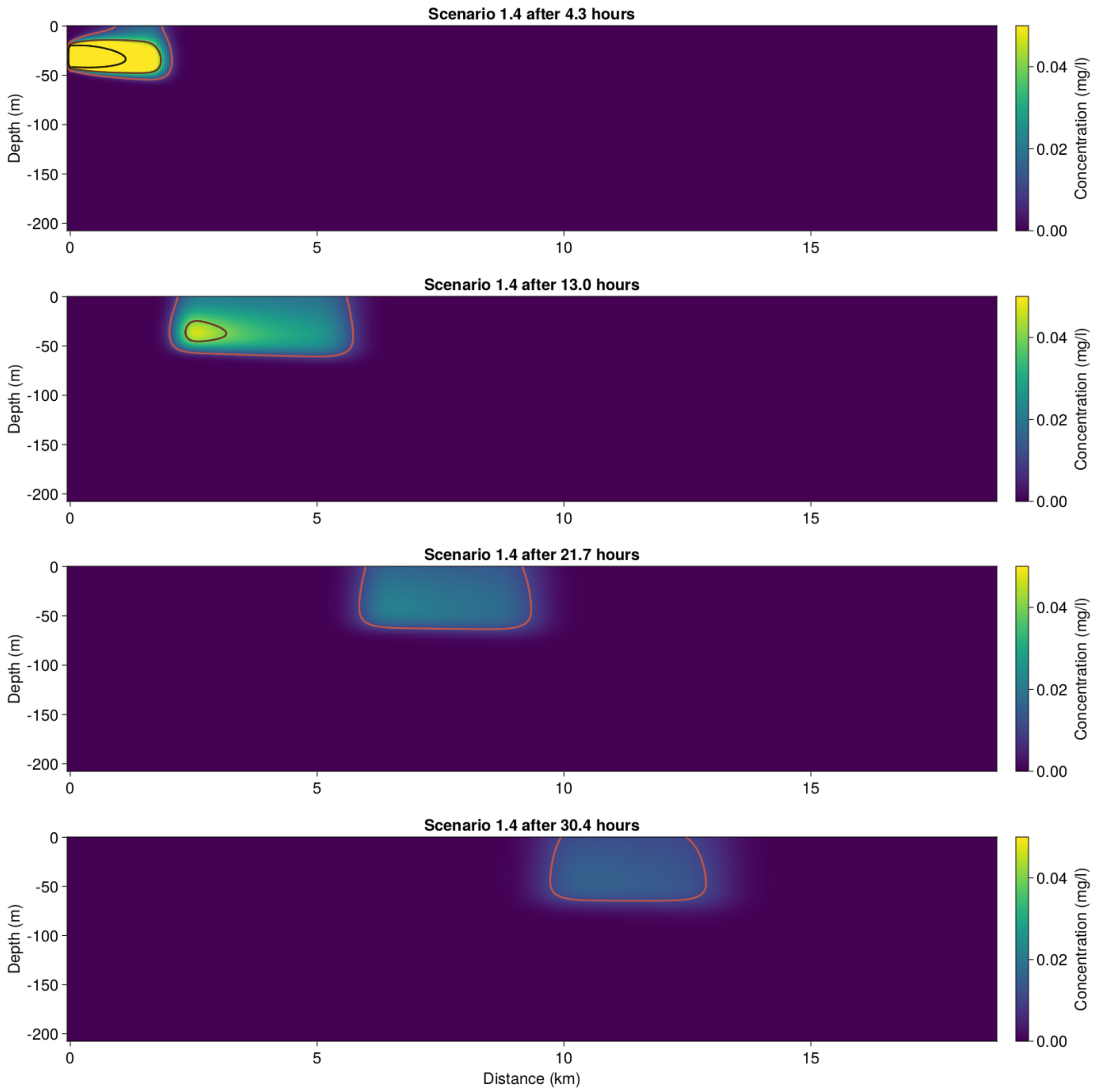
Scenario	T (days)	L (kms)	H (m)	V1 (km^3)	V2 (km^3)
1.1	0.305	1.32	31.55	0.01337	0.007941
1.2	0.267	1.15	38.61	0.01348	0.007367
1.3	0.217	0.94	48.16	0.01344	0.006124
1.4	0.107	1.11	22.83	0.01331	0.003021
1.5	0.091	0.94	29.06	0.01331	0.002587
1.6	0.084	0.87	31.97	0.01316	0.002310
1.7	0.058	1.00	18.68	0.01321	0.001651
1.8	0.052	0.90	23.66	0.01320	0.001439
1.9	0.050	0.86	23.66	0.01313	0.001384
2.1	0.064	0.28	22.00	0.00344	0.000447
2.2	0.052	0.23	28.23	0.00345	0.000364
2.3	0.045	0.19	31.97	0.00343	0.000307
2.4	0.022	0.22	15.78	0.00342	0.000160
2.5	0.018	0.19	18.68	0.00342	0.000133
2.6	0.018	0.19	19.93	0.00340	0.000124
2.7	0.012	0.20	12.45	0.00340	0.000089
2.8	0.010	0.18	14.11	0.00339	0.000075
2.9	0.010	0.18	14.11	0.00338	0.000074
3.1	0.820	3.55	45.66	0.03057	0.025002
3.2	0.725	3.13	47.33	0.03003	0.024451
3.3	0.582	2.52	58.12	0.03045	0.024019
3.4	0.267	2.77	30.72	0.02980	0.016838
3.5	0.233	2.41	35.29	0.02996	0.014822
3.6	0.196	2.03	40.68	0.02945	0.012335
3.7	0.146	2.53	24.91	0.02967	0.009080
3.8	0.126	2.17	29.06	0.02958	0.007882
3.9	0.116	2.01	31.55	0.02926	0.007211

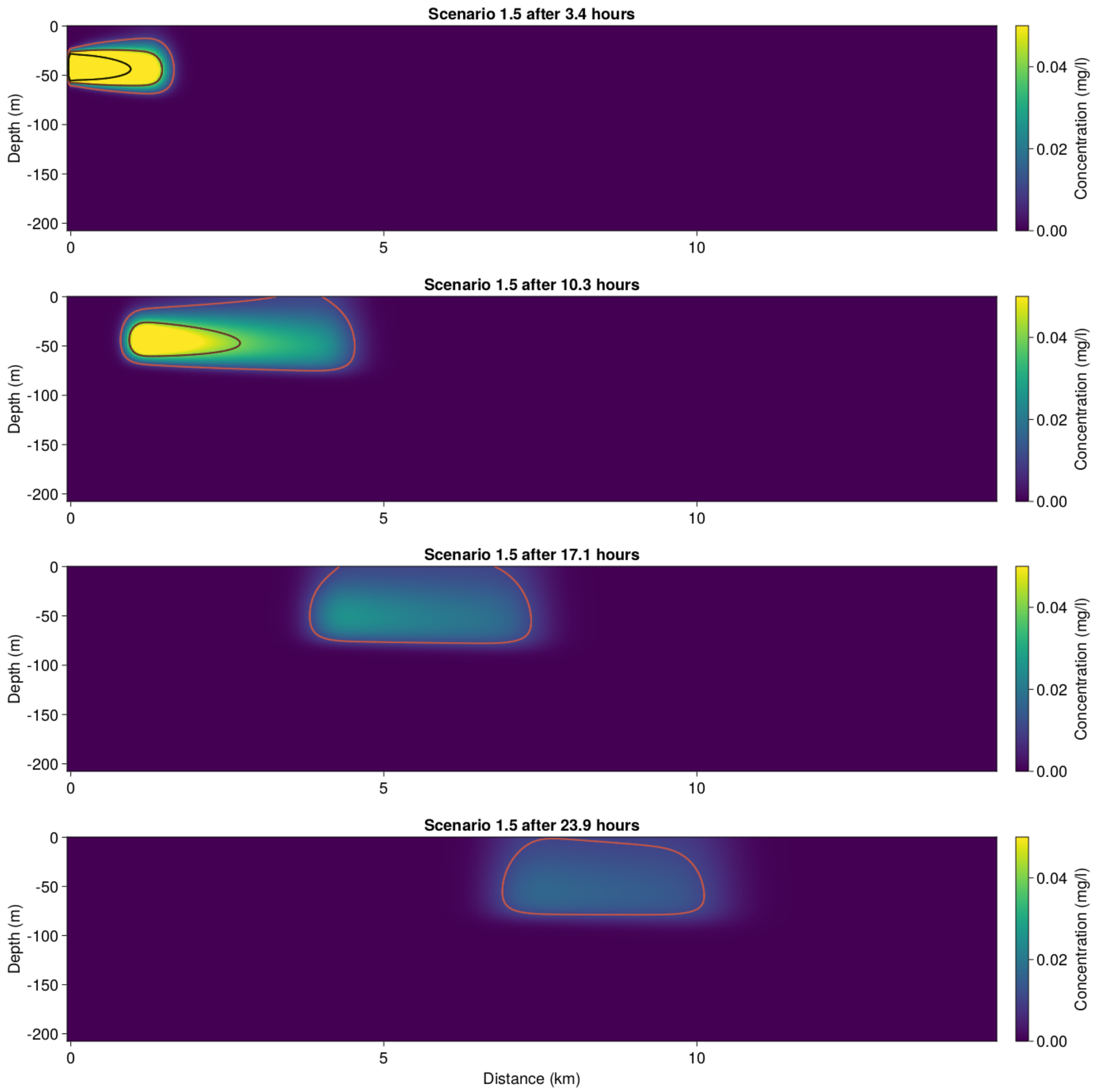
C Heatmaps

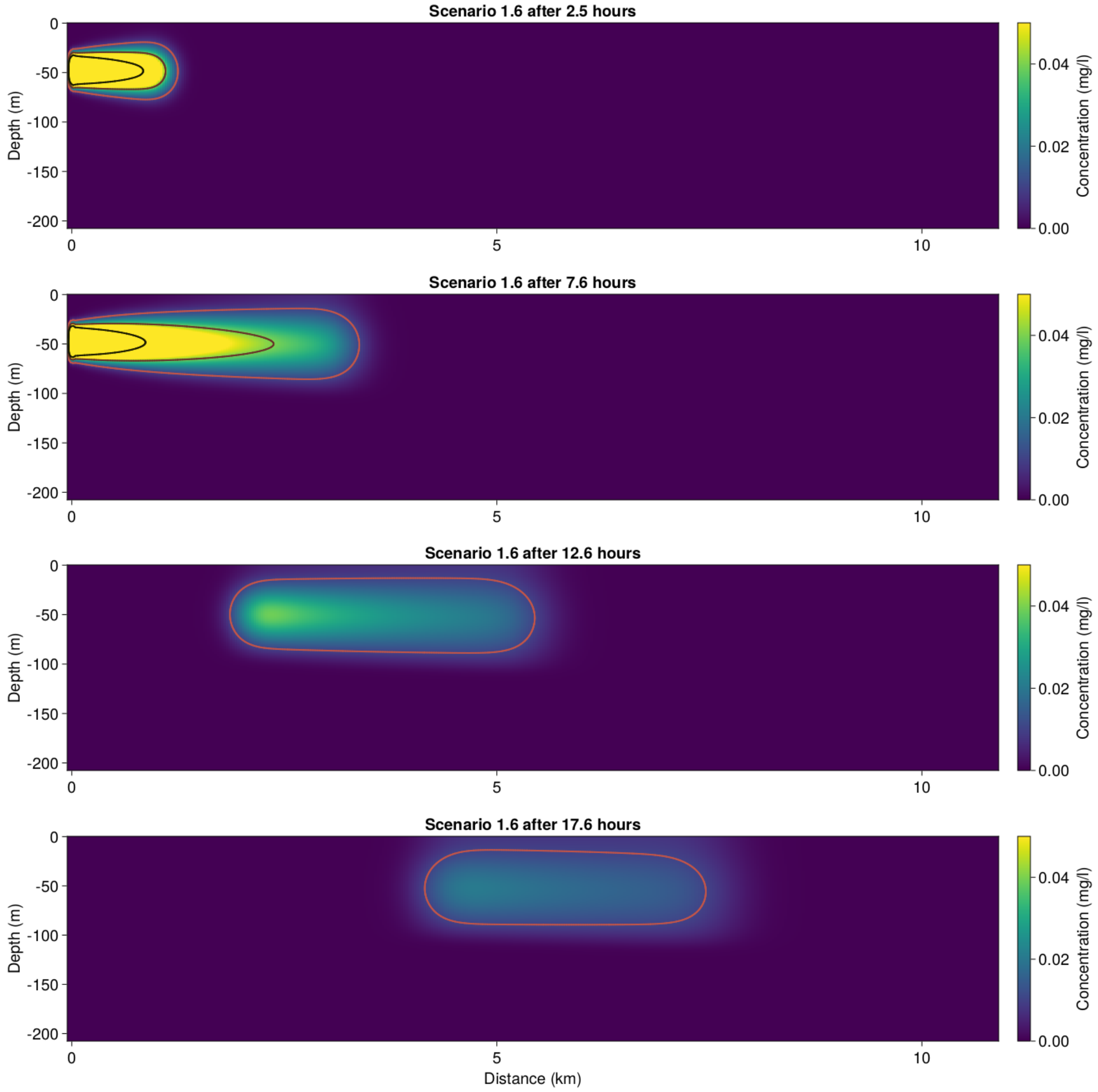

Scenario 1.1 after 11.2 hours
Scenario 1.1 after 33.5 hours
Scenario 1.1 after 55.9 hours
Scenario 1.1 after 78.3 hours
Depth (m)
0
-50
-100
-150
-200
0
5
10
15
20
Distance (km)
Concentration (mg/l)
0.00
0.02
0.04


Scenario 1.2 after 9.9 hours
Scenario 1.2 after 29.6 hours
Scenario 1.2 after 49.3 hours
Scenario 1.2 after 69.0 hours
Depth (m)
0
-50
-100
-150
-200
0
5
10
15
Distance (km)
Concentration (mg/l)
0.00
0.02
0.04

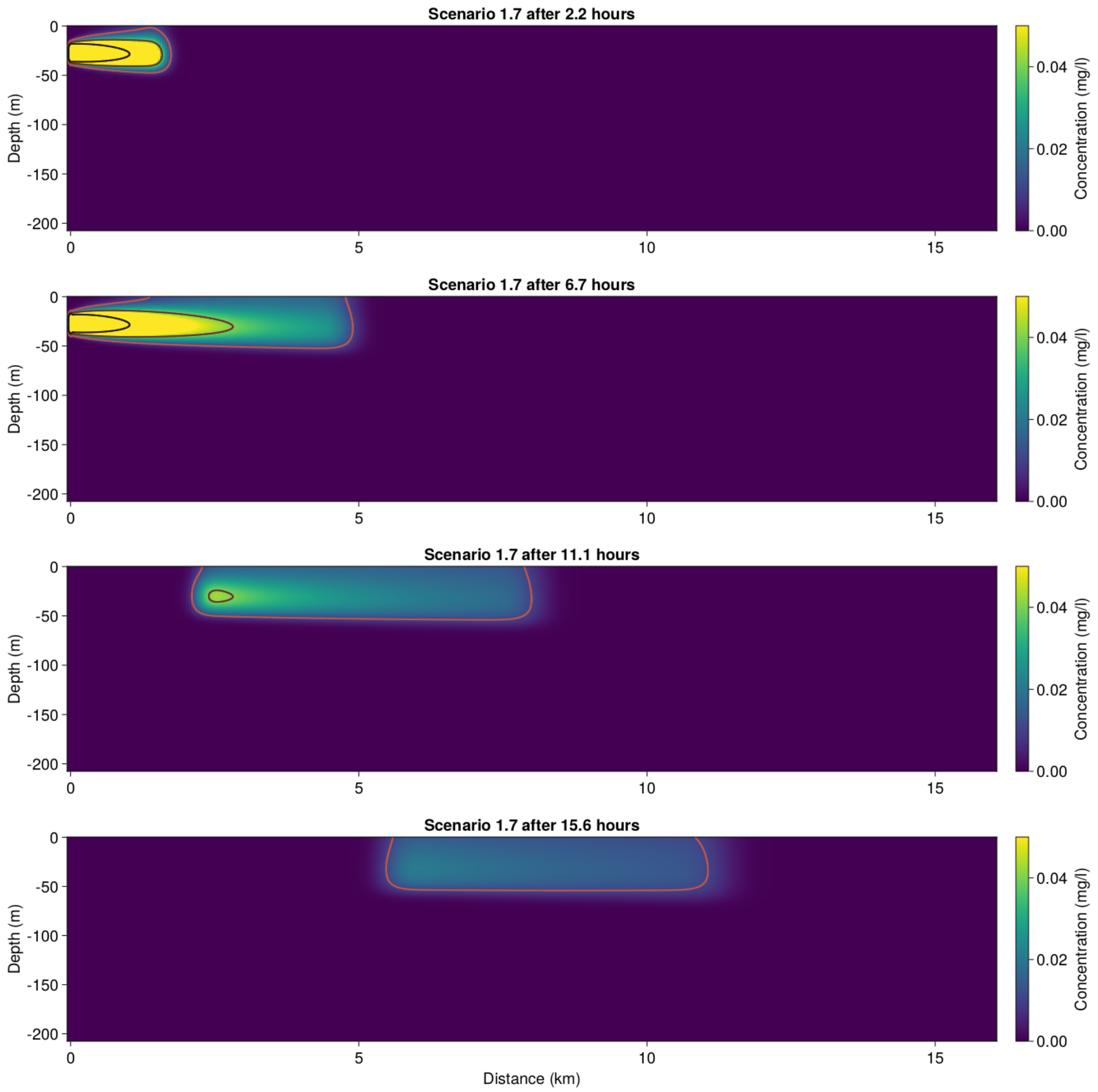

Scenario 1.3 after 8.4 hours
Scenario 1.3 after 25.3 hours
Scenario 1.3 after 42.1 hours
Scenario 1.3 after 58.9 hours
Depth (m)
0
-50
-100
-150
-200
0
5
10
15
Distance (km)
Concentration (mg/l)
0.00
0.02
0.04

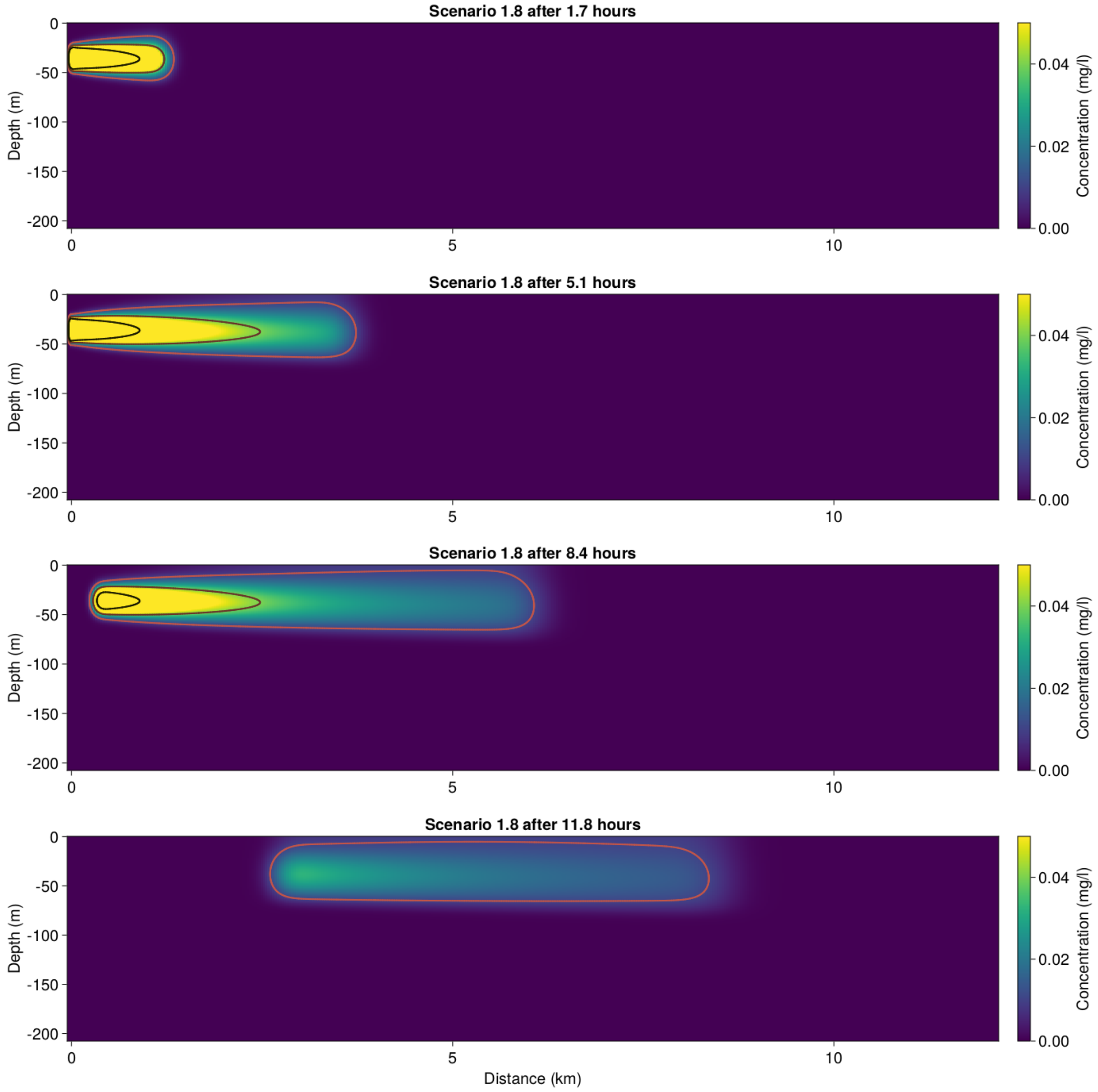

Scenario 1.4 after 4.3 hours
Scenario 1.4 after 13.0 hours
Scenario 1.4 after 21.7 hours
Scenario 1.4 after 30.4 hours
Depth (m)
0
-50
-100
-150
-200
0
5
10
15
Distance (km)
Concentration (mg/l)
0.00
0.02
0.04

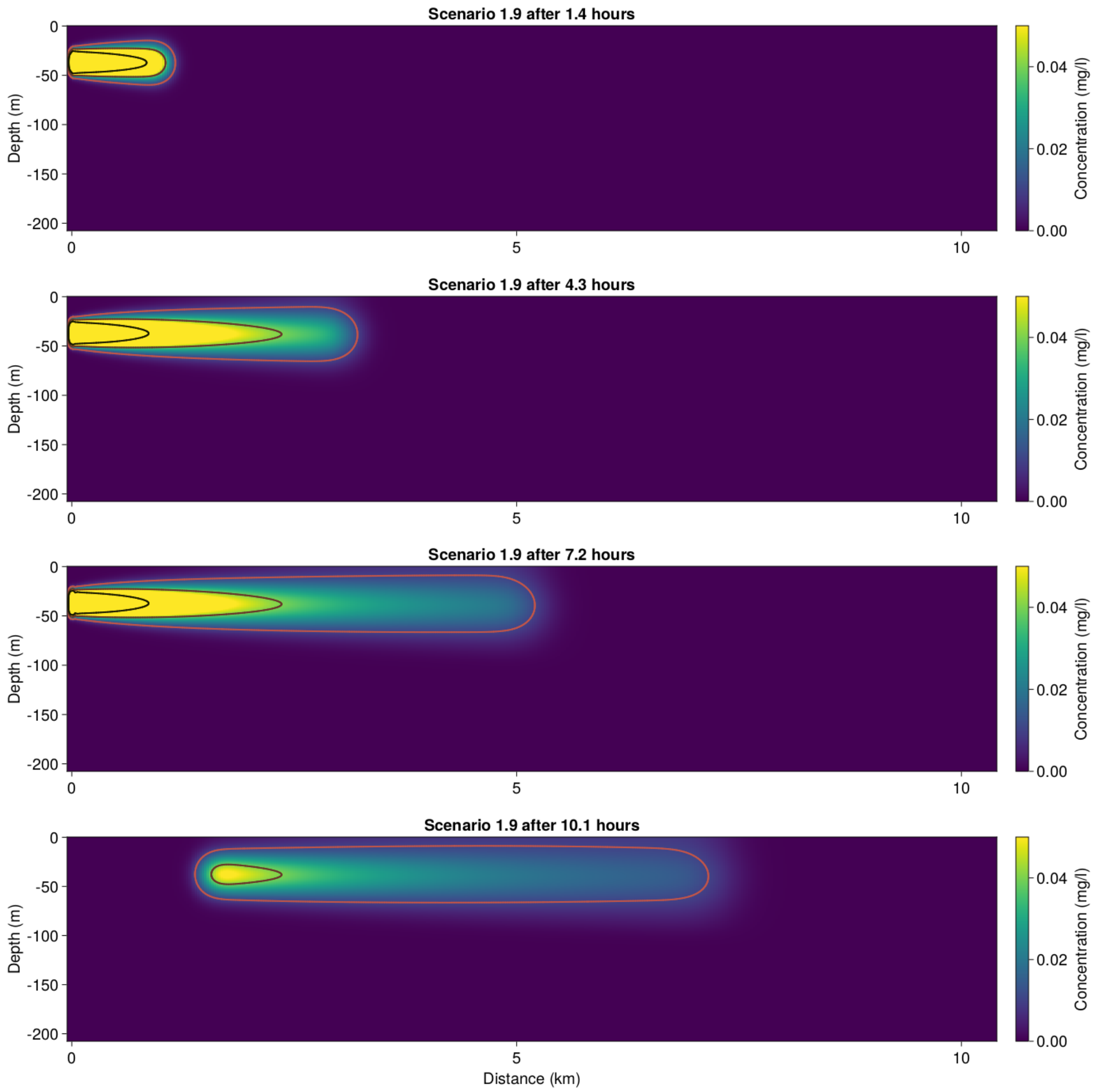

Scenario 1.5 after 3.4 hours
Scenario 1.5 after 10.3 hours
Scenario 1.5 after 17.1 hours
Scenario 1.5 after 23.9 hours
Depth (m)
0
-50
-100
-150
-200
0
5
10
Distance (km)
Concentration (mg/l)
0.00
0.02
0.04

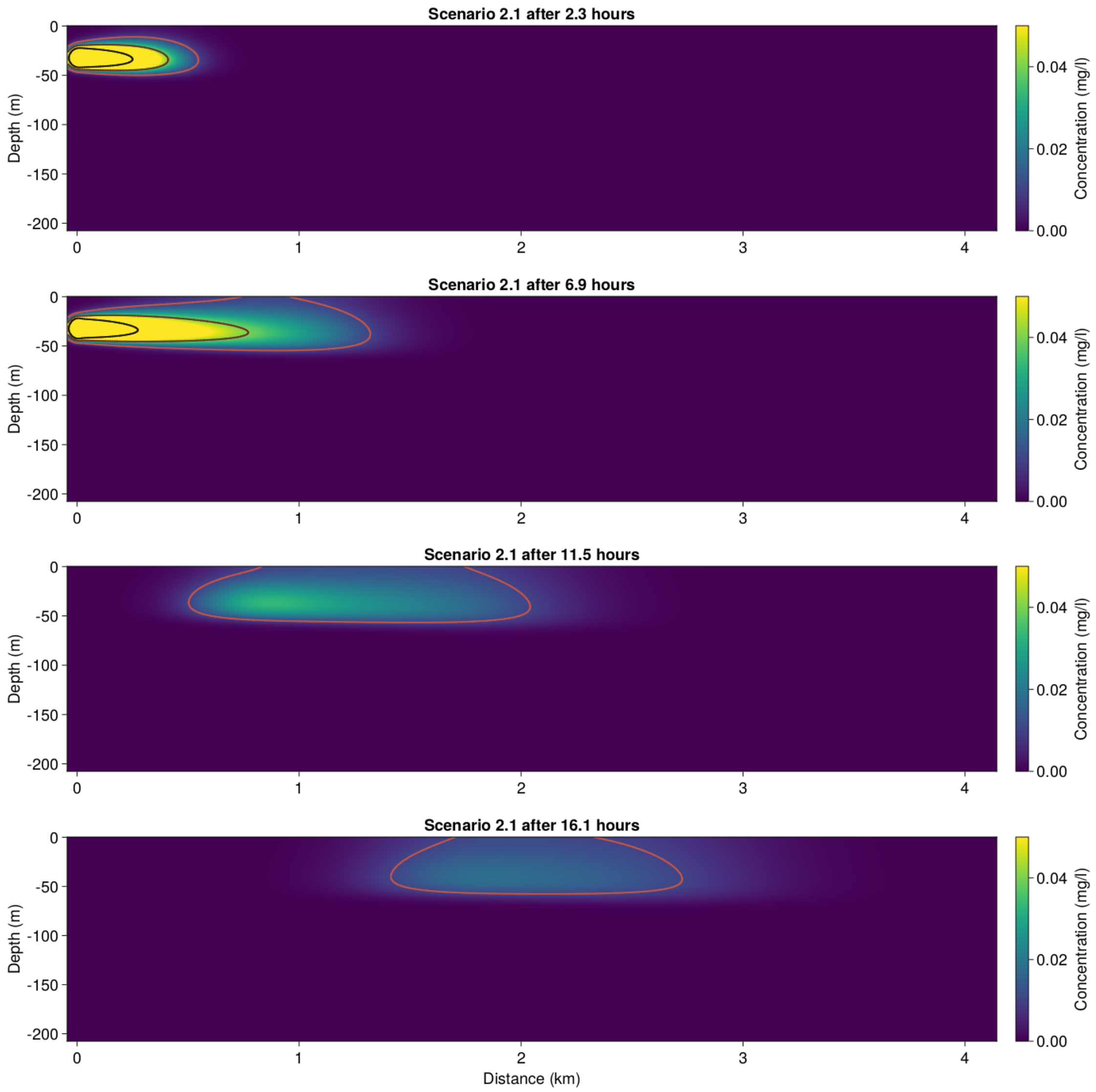


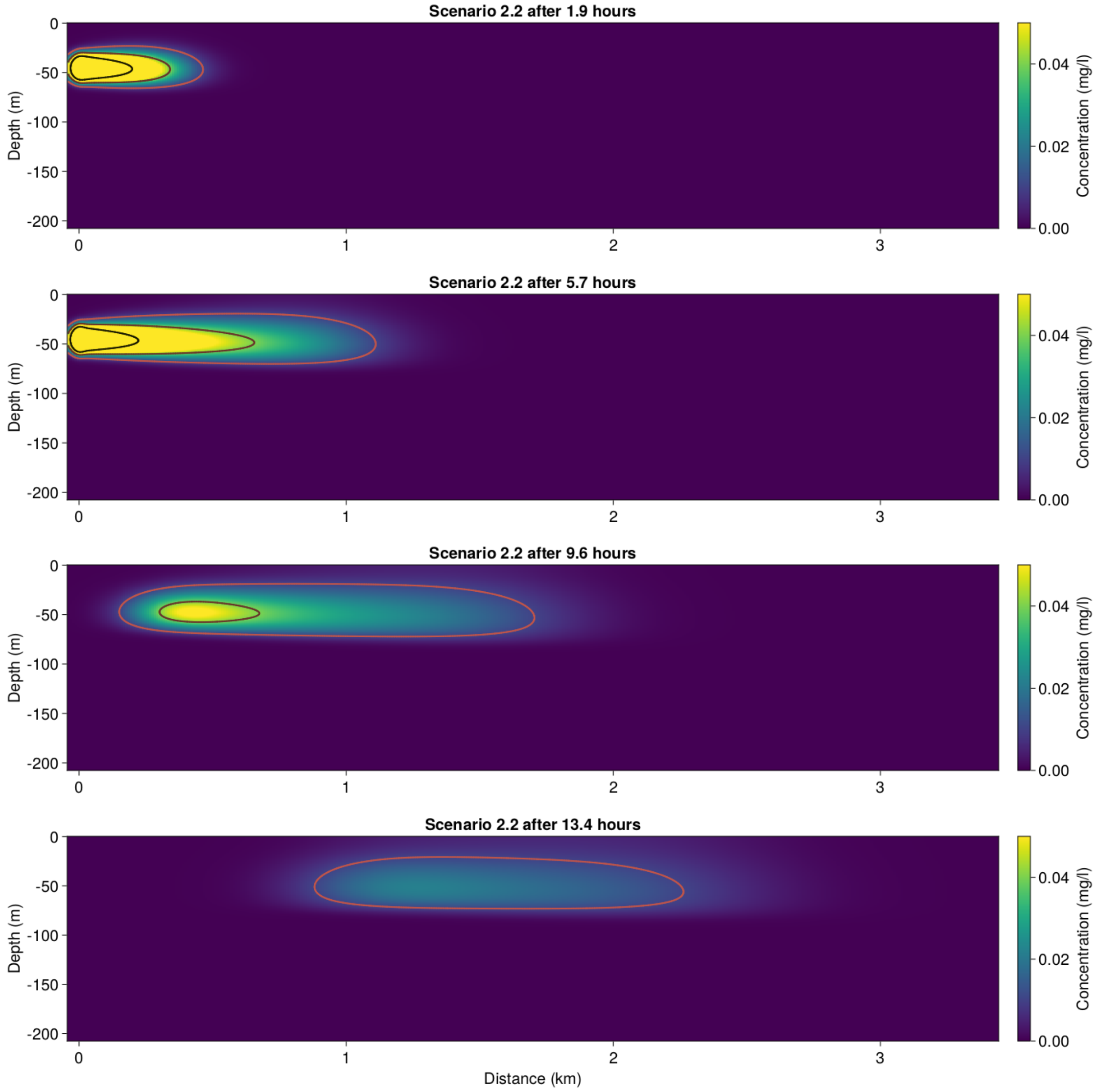
Scenario 1.6 after 2.5 hours
Scenario 1.6 after 7.6 hours
Scenario 1.6 after 12.6 hours
Scenario 1.6 after 17.6 hours
Depth (m)
0
-50
-100
-150
-200
0
5
10
Distance (km)
Concentration (mg/l)
0.04
0.02
0.00

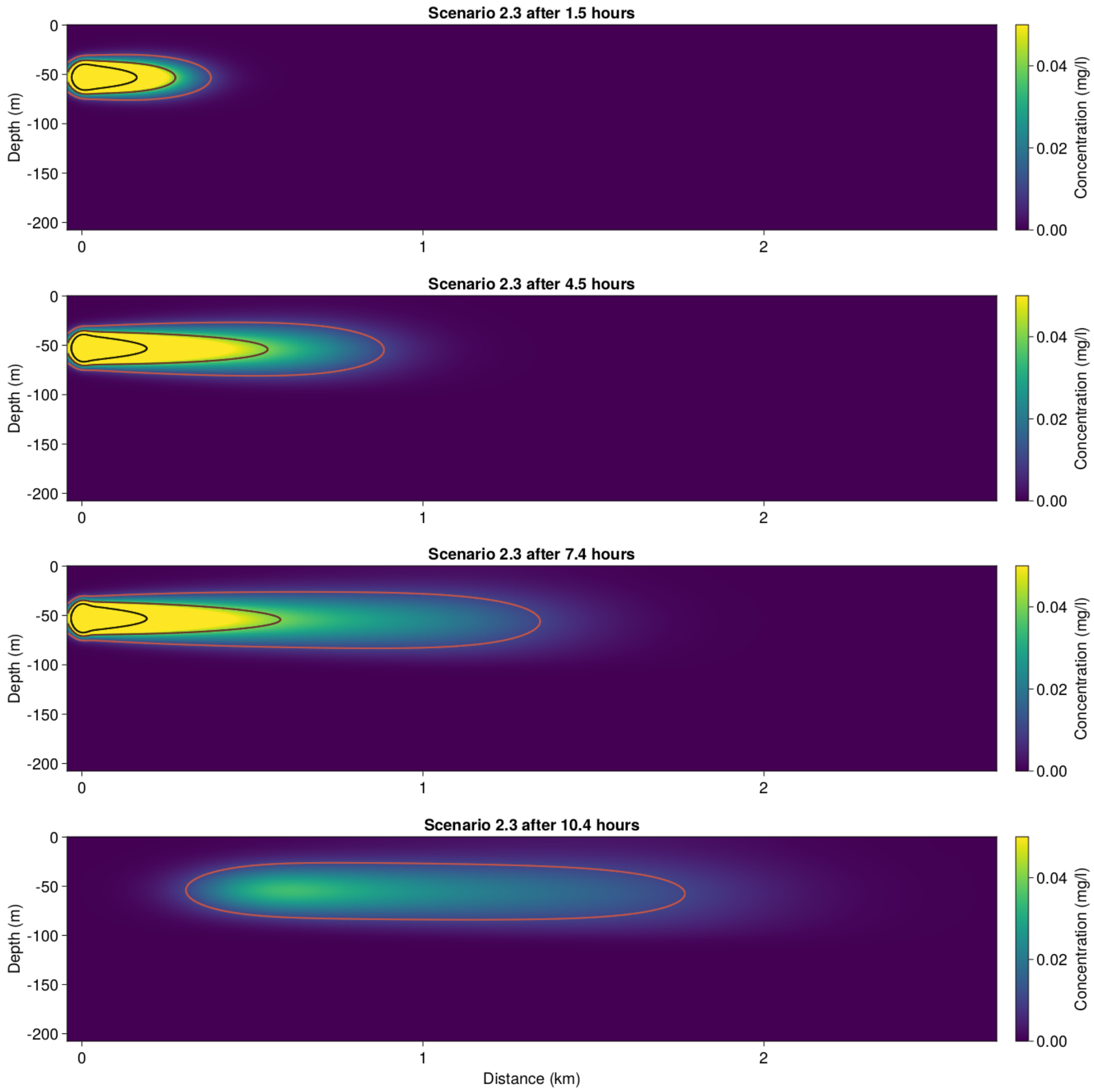

Scenario 1.7 after 2.2 hours
Scenario 1.7 after 6.7 hours
Scenario 1.7 after 11.1 hours
Scenario 1.7 after 15.6 hours
Depth (m)
0
-50
-100
-150
-200
0
5
10
15
Distance (km)
Concentration (mg/l)
0.04
0.02
0.00

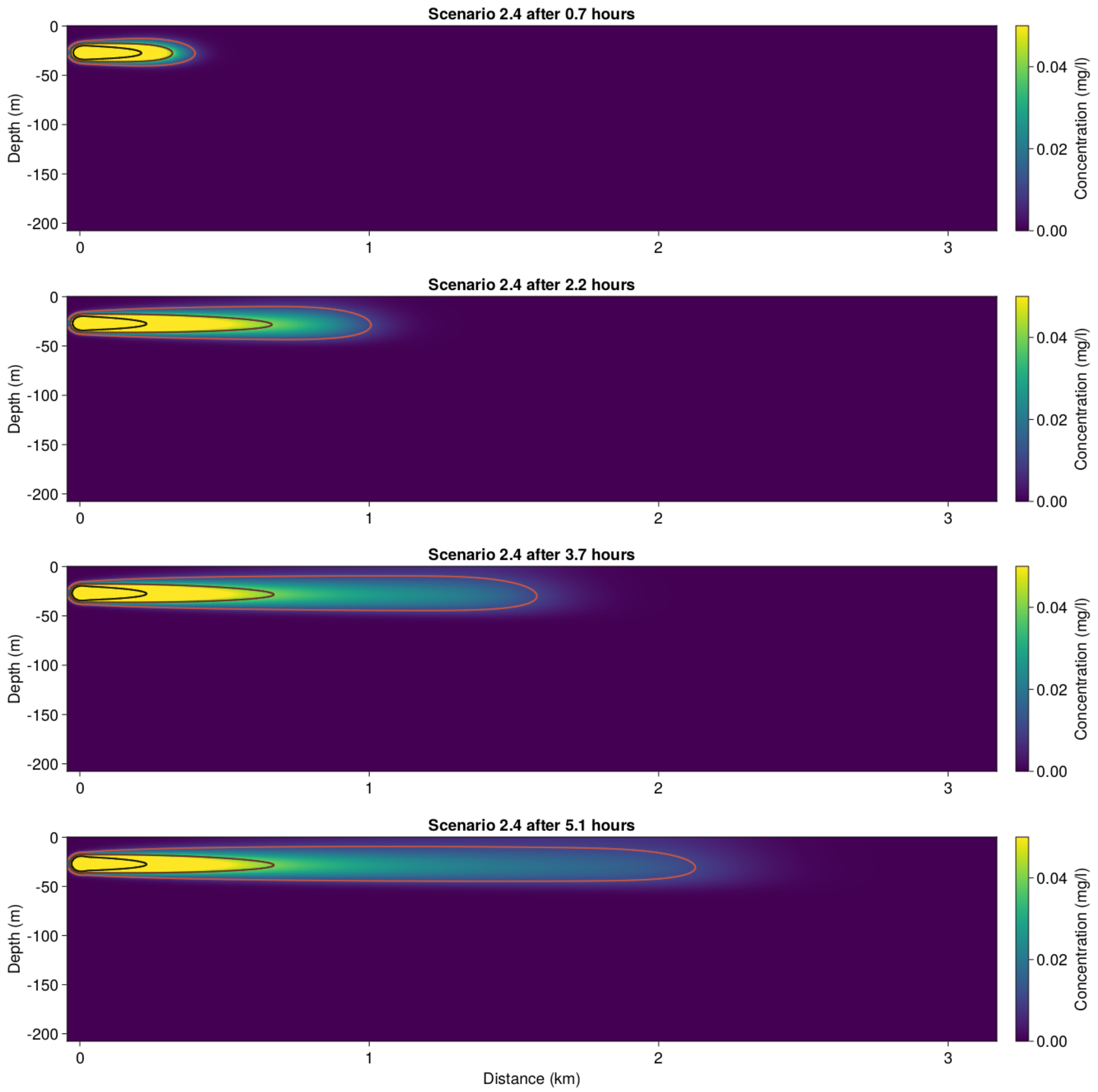

Scenario 1.8 after 1.7 hours
Scenario 1.8 after 5.1 hours
Scenario 1.8 after 8.4 hours
Scenario 1.8 after 11.8 hours
Depth (m)
0
-50
-100
-150
-200
0
5
10
Distance (km)
Concentration (mg/l)
0.04
0.02
0.00

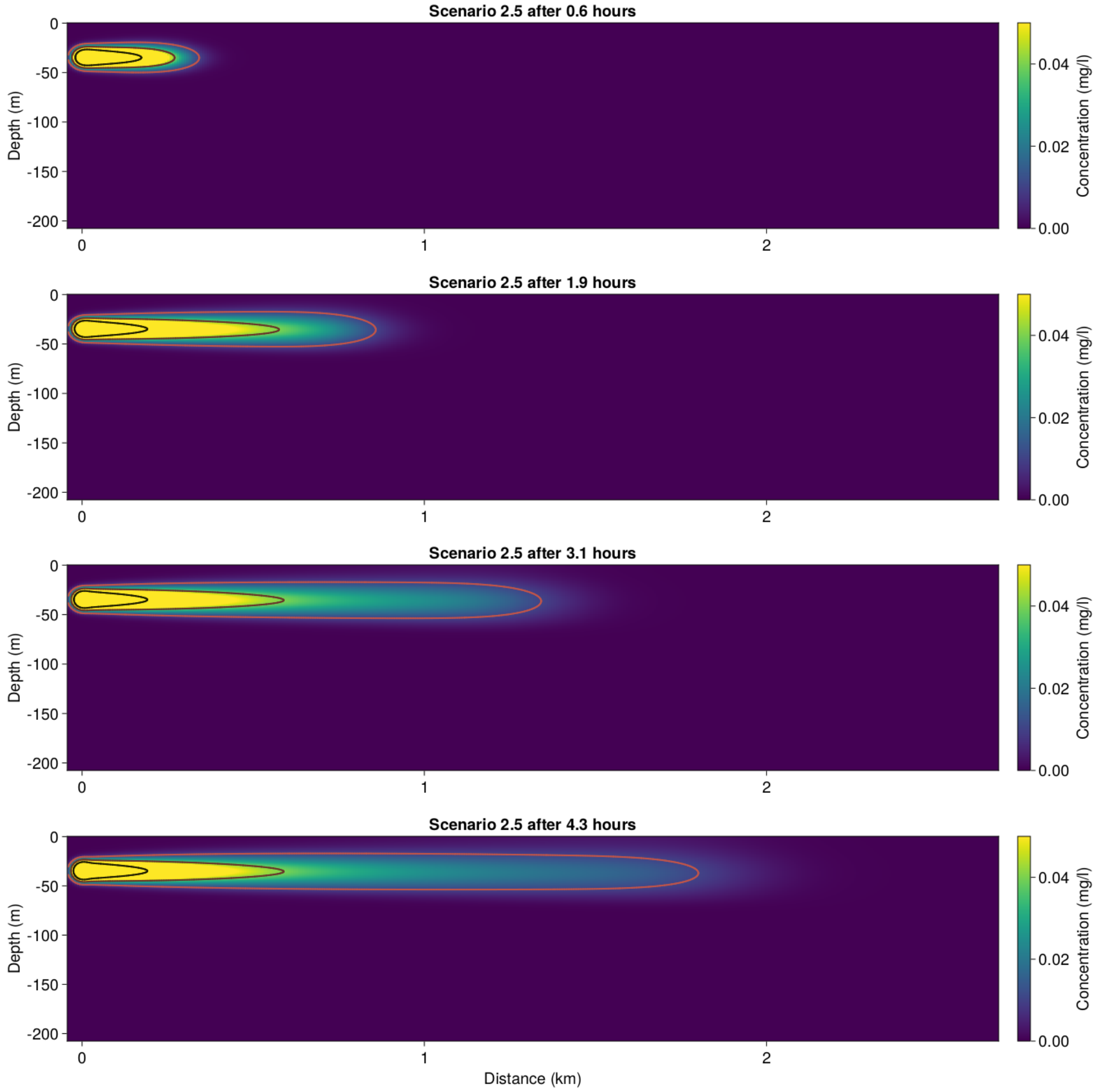

Scenario 1.9 after 1.4 hours
Scenario 1.9 after 4.3 hours
Scenario 1.9 after 7.2 hours
Scenario 1.9 after 10.1 hours
Depth (m)
0
-50
-100
-150
-200
0
5
10
Distance (km)
Concentration (mg/l)
0.04
0.02
0.00


Scenario 2.1 after 2.3 hours
Scenario 2.1 after 6.9 hours
Scenario 2.1 after 11.5 hours
Scenario 2.1 after 16.1 hours
Depth (m)
0
-50
-100
-150
-200
Distance (km)
0
1
2
3
4
Concentration (mg/l)
0.00
0.02
0.04

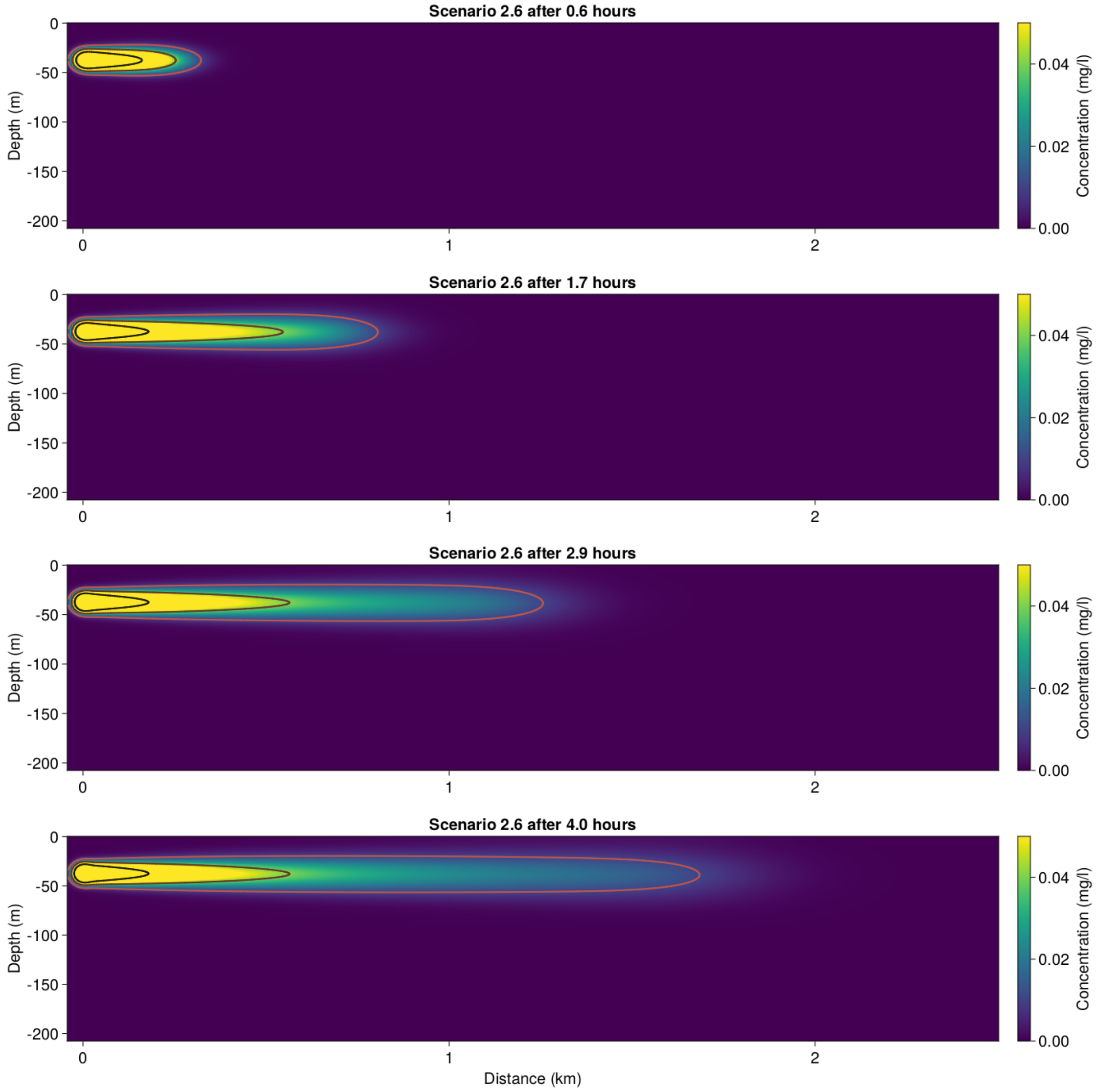

Scenario 2.2 after 1.9 hours
Scenario 2.2 after 5.7 hours
Scenario 2.2 after 9.6 hours
Scenario 2.2 after 13.4 hours
Depth (m)
0
-50
-100
-150
-200
0
1
2
3
Distance (km)
Concentration (mg/l)
0.04
0.02
0.00

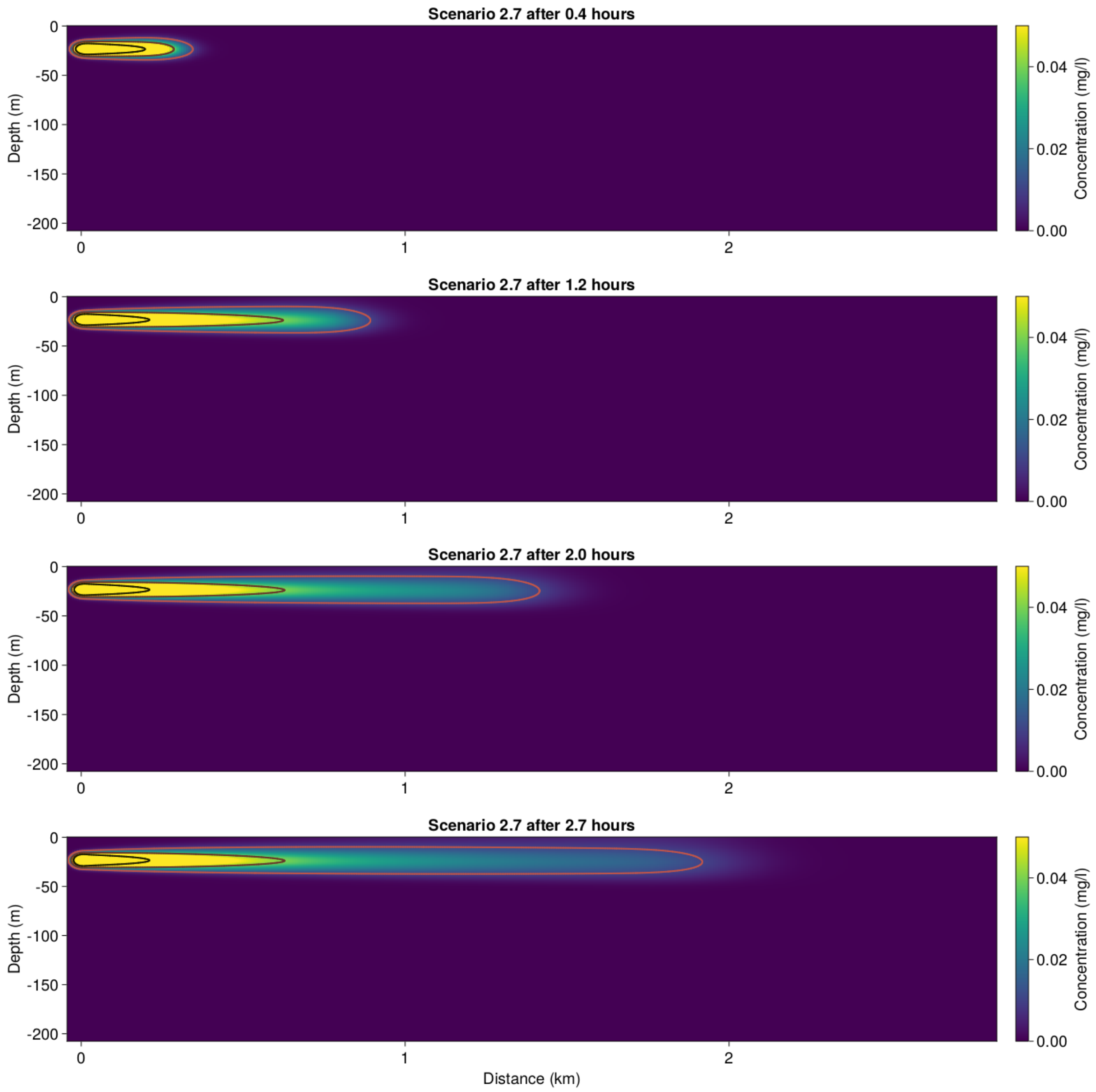

Scenario 2.3 after 1.5 hours
Scenario 2.3 after 4.5 hours
Scenario 2.3 after 7.4 hours
Scenario 2.3 after 10.4 hours
Depth (m)
0
-50
-100
-150
-200
0
1
2
Distance (km)
Concentration (mg/l)
0.04
0.02
0.00

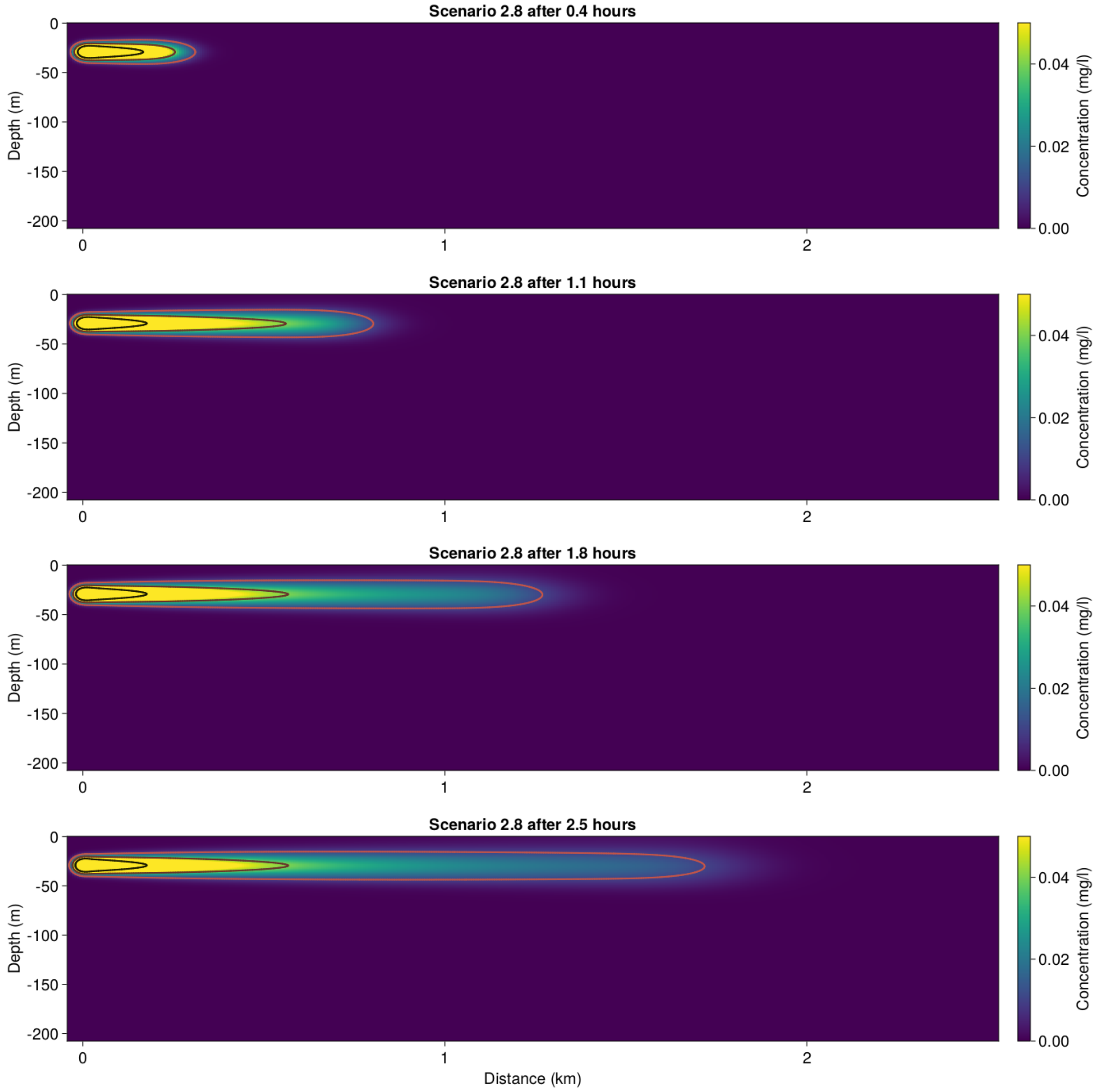

Scenario 2.4 after 0.7 hours
Scenario 2.4 after 2.2 hours
Scenario 2.4 after 3.7 hours
Scenario 2.4 after 5.1 hours
Depth (m)
0
-50
-100
-150
-200
0
1
2
3
Distance (km)
Concentration (mg/l)
0.00
0.02
0.04

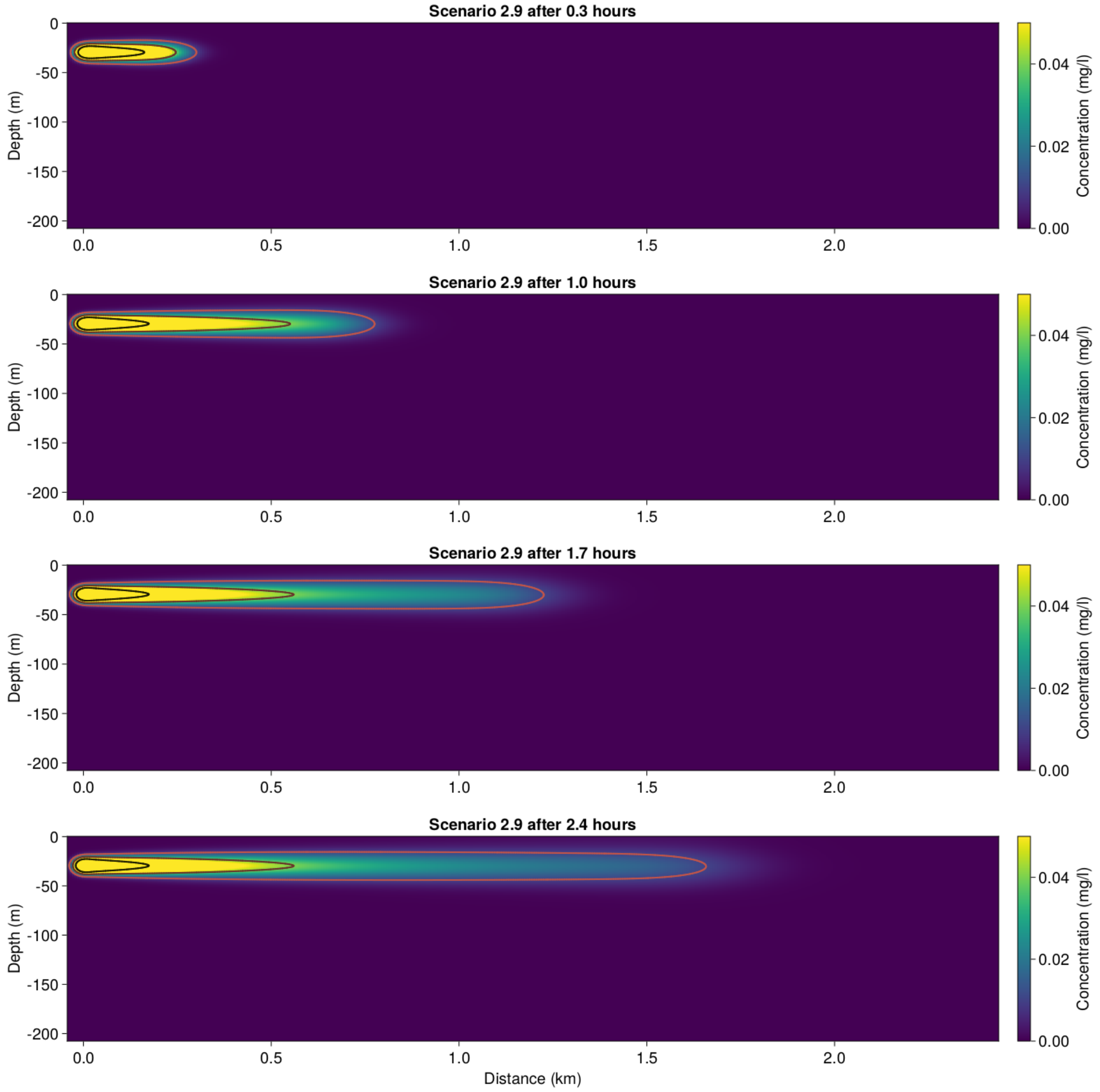


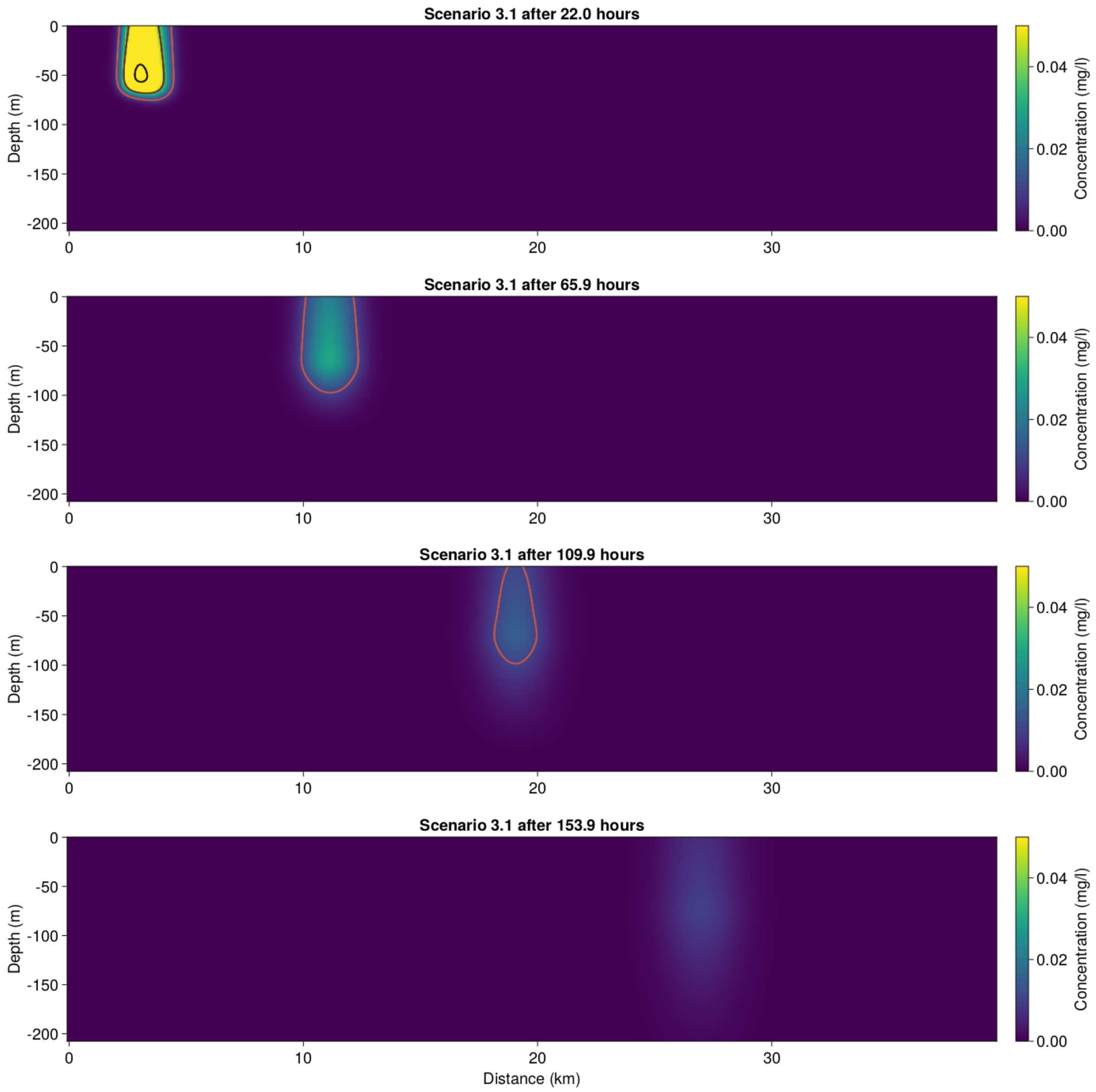
Scenario 2.5 after 0.6 hours
Scenario 2.5 after 1.9 hours
Scenario 2.5 after 3.1 hours
Scenario 2.5 after 4.3 hours
Depth (m)
0
-50
-100
-150
-200
Distance (km)
0
1
2
Concentration (mg/l)
0.04
0.02
0.00


Scenario 2.6 after 0.6 hours
Scenario 2.6 after 1.7 hours
Scenario 2.6 after 2.9 hours
Scenario 2.6 after 4.0 hours
Depth (m)
0
-50
-100
-150
-200
0
1
2
Distance (km)
Concentration (mg/l)
0.04
0.02
0.00

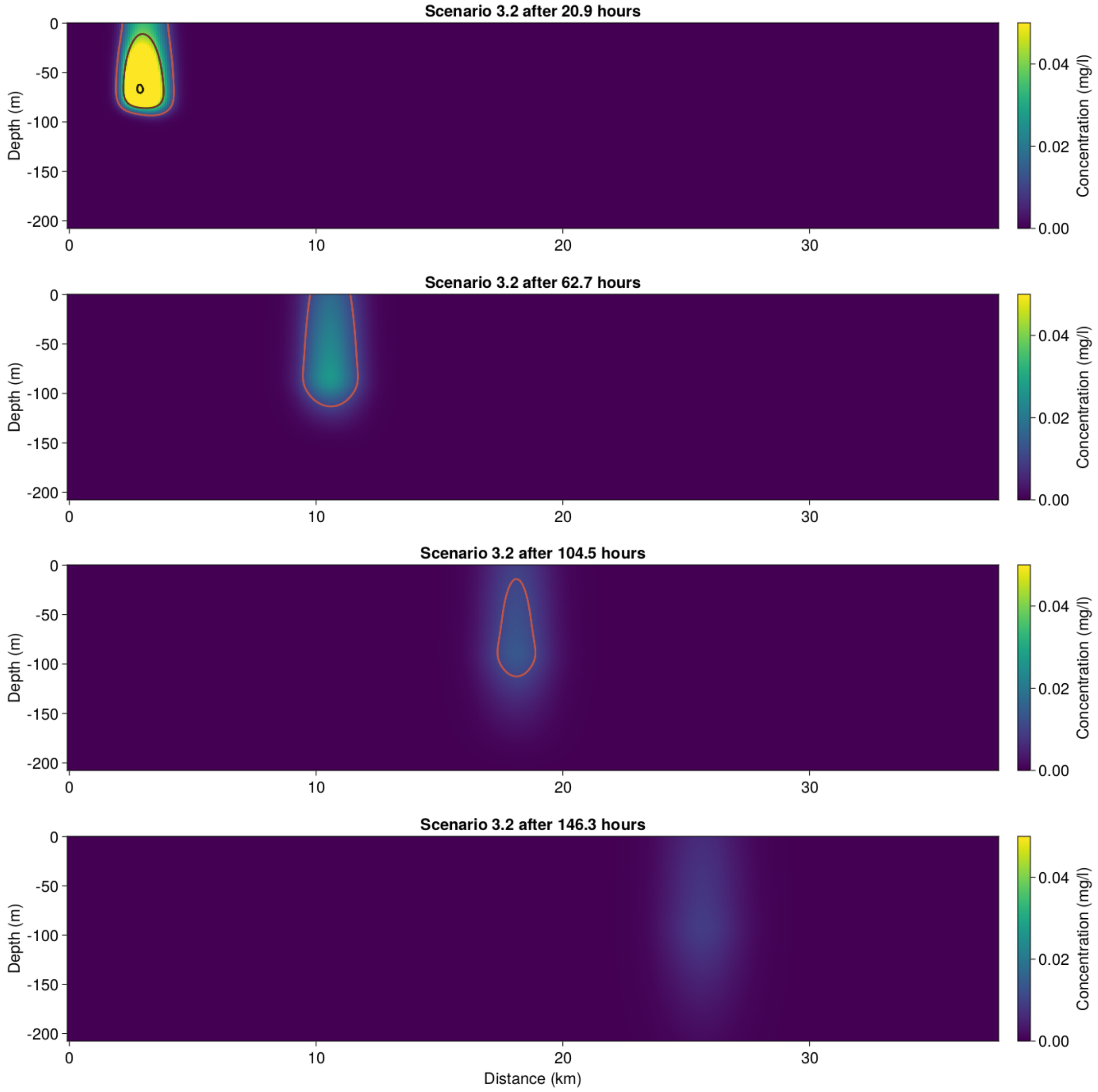

Scenario 2.7 after 0.4 hours
Scenario 2.7 after 1.2 hours
Scenario 2.7 after 2.0 hours
Scenario 2.7 after 2.7 hours
Depth (m)
0
-50
-100
-150
-200
Distance (km)
0
1
2
Concentration (mg/l)
0.00
0.02
0.04


Scenario 2.8 after 0.4 hours
Scenario 2.8 after 1.1 hours
Scenario 2.8 after 1.8 hours
Scenario 2.8 after 2.5 hours
Depth (m)
0
-50
-100
-150
-200
0
1
2
Distance (km)
Concentration (mg/l)
0.00
0.02
0.04

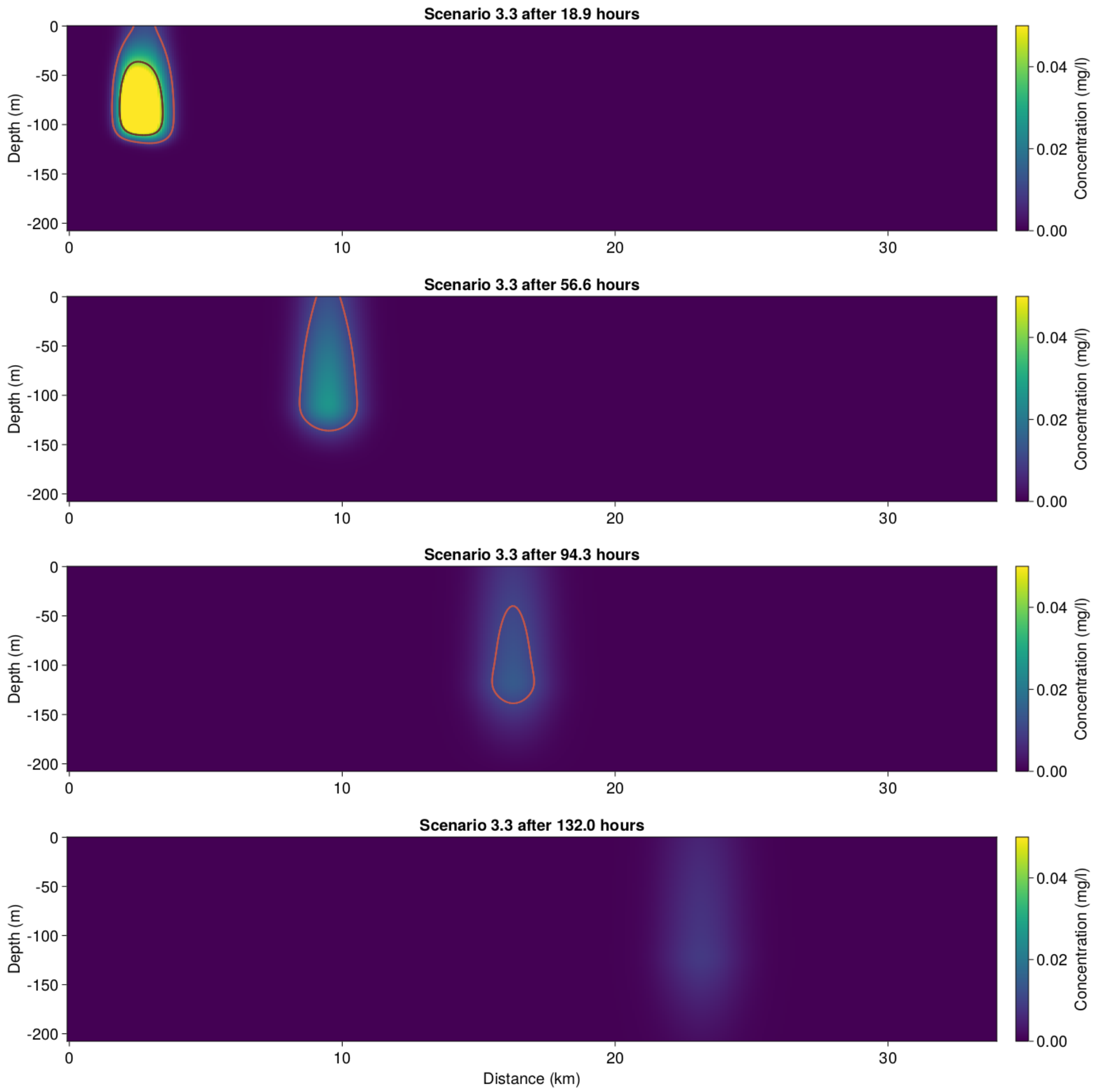

Scenario 2.9 after 0.3 hours
Scenario 2.9 after 1.0 hours
Scenario 2.9 after 1.7 hours
Scenario 2.9 after 2.4 hours
Depth (m)
0
-50
-100
-150
-200
0.0
0.5
1.0
1.5
2.0
Distance (km)
Concentration (mg/l)
0.04
0.02
0.00

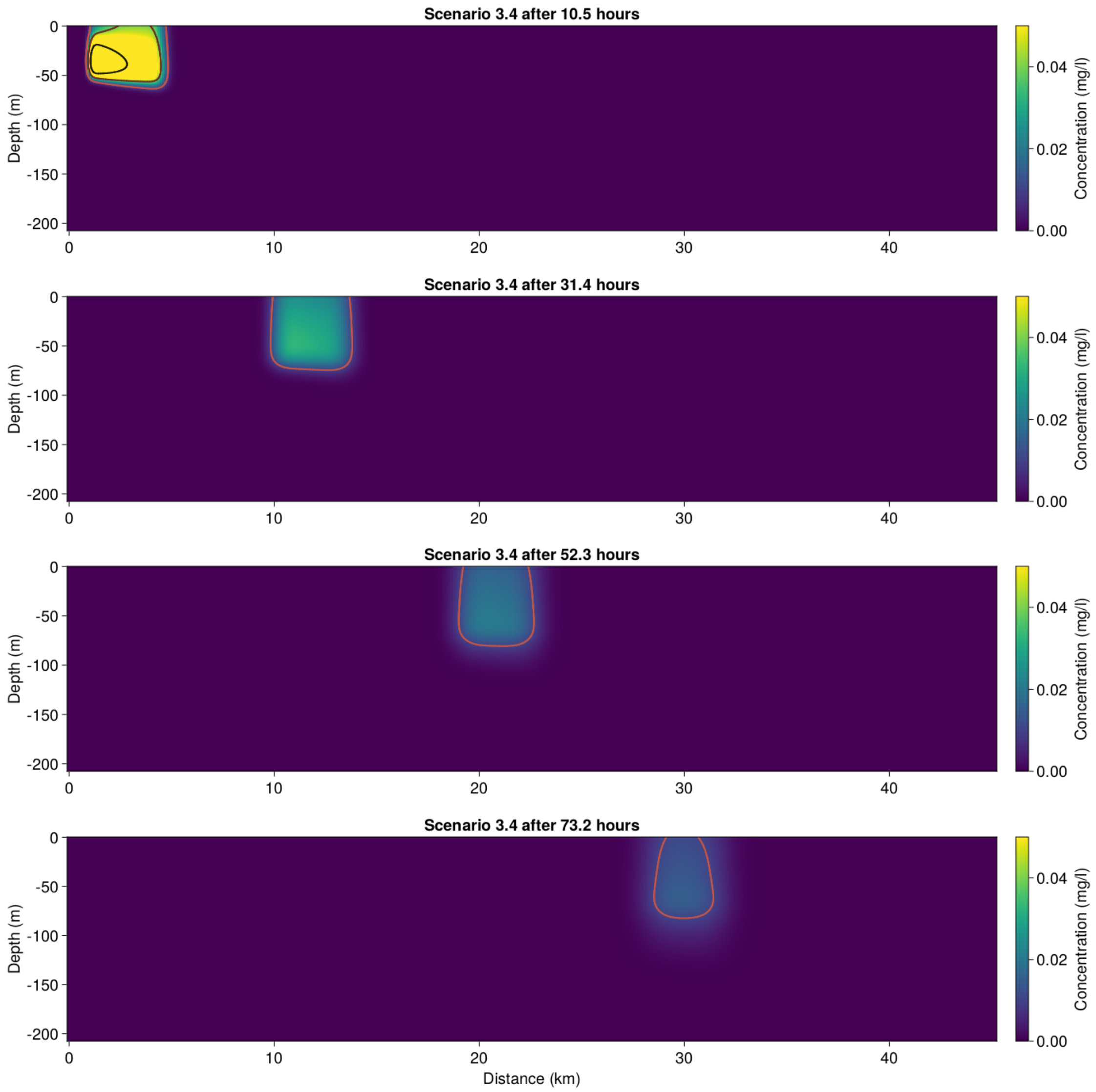


Scenario 3.1 after 22.0 hours
Scenario 3.1 after 65.9 hours
Scenario 3.1 after 109.9 hours
Scenario 3.1 after 153.9 hours
Depth (m)
0
-50
-100
-150
-200
0
10
20
30
Distance (km)
Concentration (mg/l)
0.04
0.02
0.00

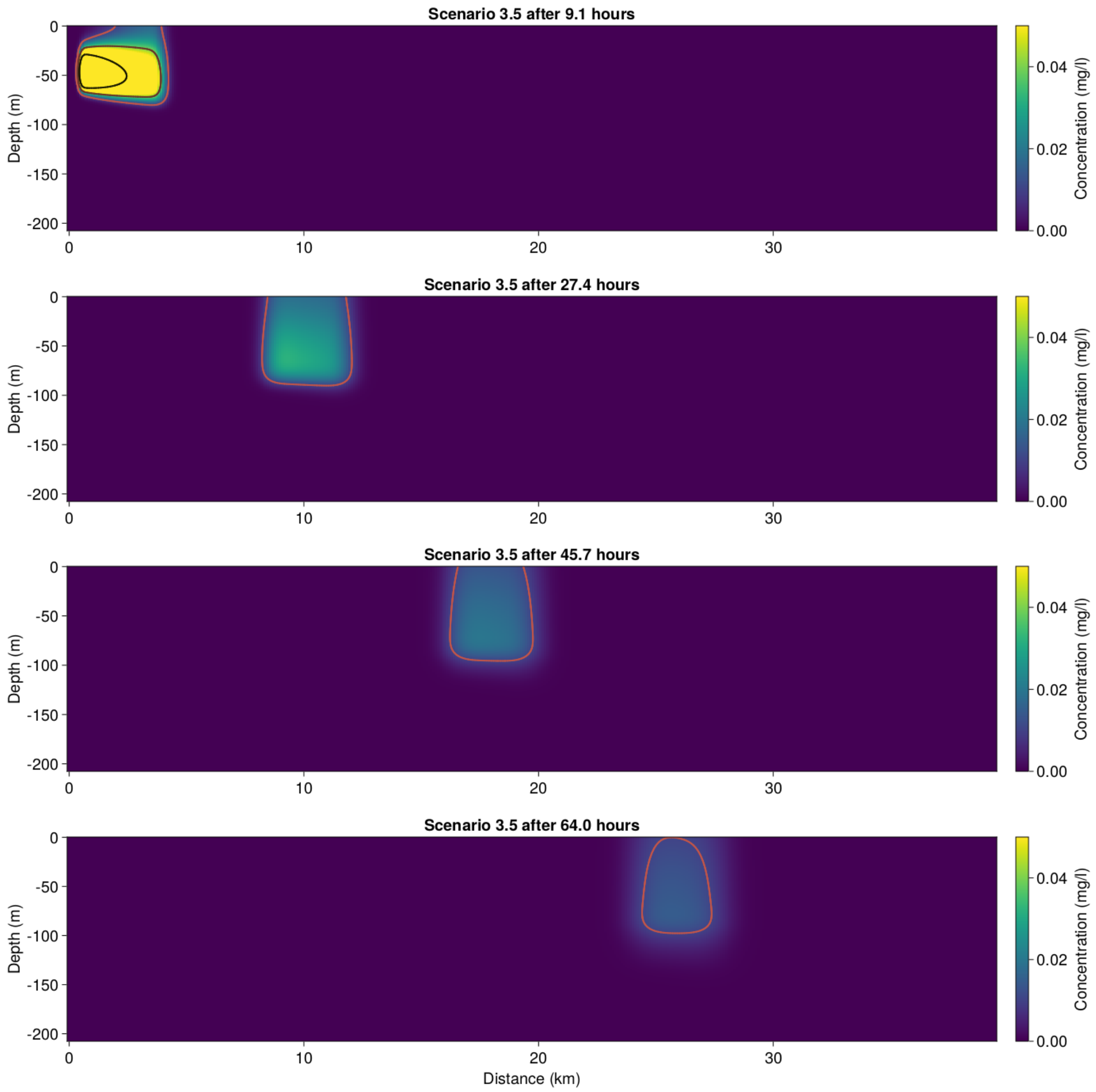


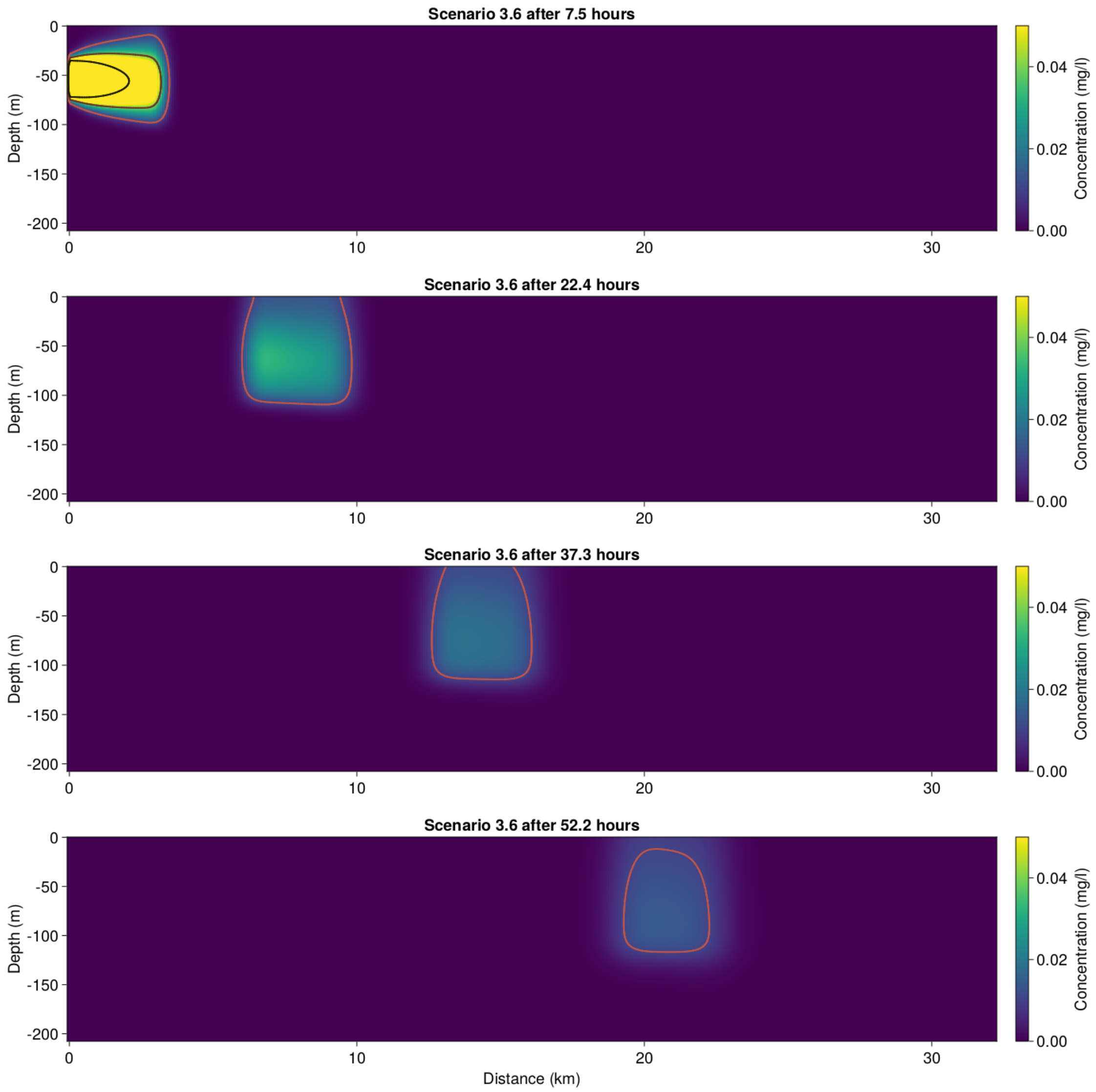
Scenario 3.2 after 20.9 hours
Scenario 3.2 after 62.7 hours
Scenario 3.2 after 104.5 hours
Scenario 3.2 after 146.3 hours
Depth (m)
0
-50
-100
-150
-200
0
10
20
30
Distance (km)
Concentration (mg/l)
0.04
0.02
0.00

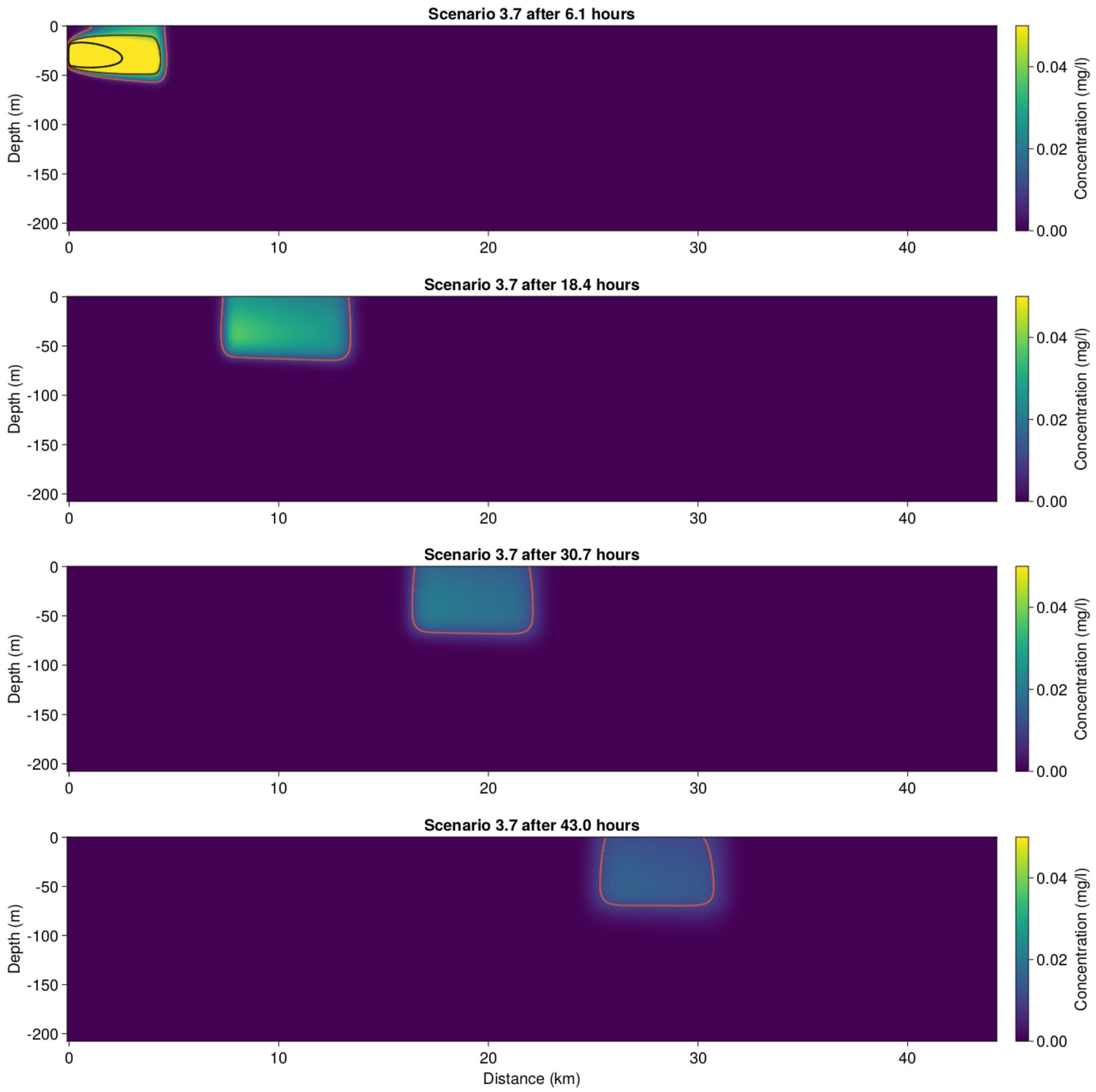

Scenario 3.3 after 18.9 hours
Scenario 3.3 after 56.6 hours
Scenario 3.3 after 94.3 hours
Scenario 3.3 after 132.0 hours
Depth (m)
0
-50
-100
-150
-200
0
10
20
30
Distance (km)
Concentration (mg/l)
0.00
0.02
0.04



Scenario 3.4 after 10.5 hours
Scenario 3.4 after 31.4 hours
Scenario 3.4 after 52.3 hours
Scenario 3.4 after 73.2 hours
Depth (m)
0
-50
-100
-150
-200
0
10
20
30
40
Distance (km)
Concentration (mg/l)
0.00
0.02
0.04

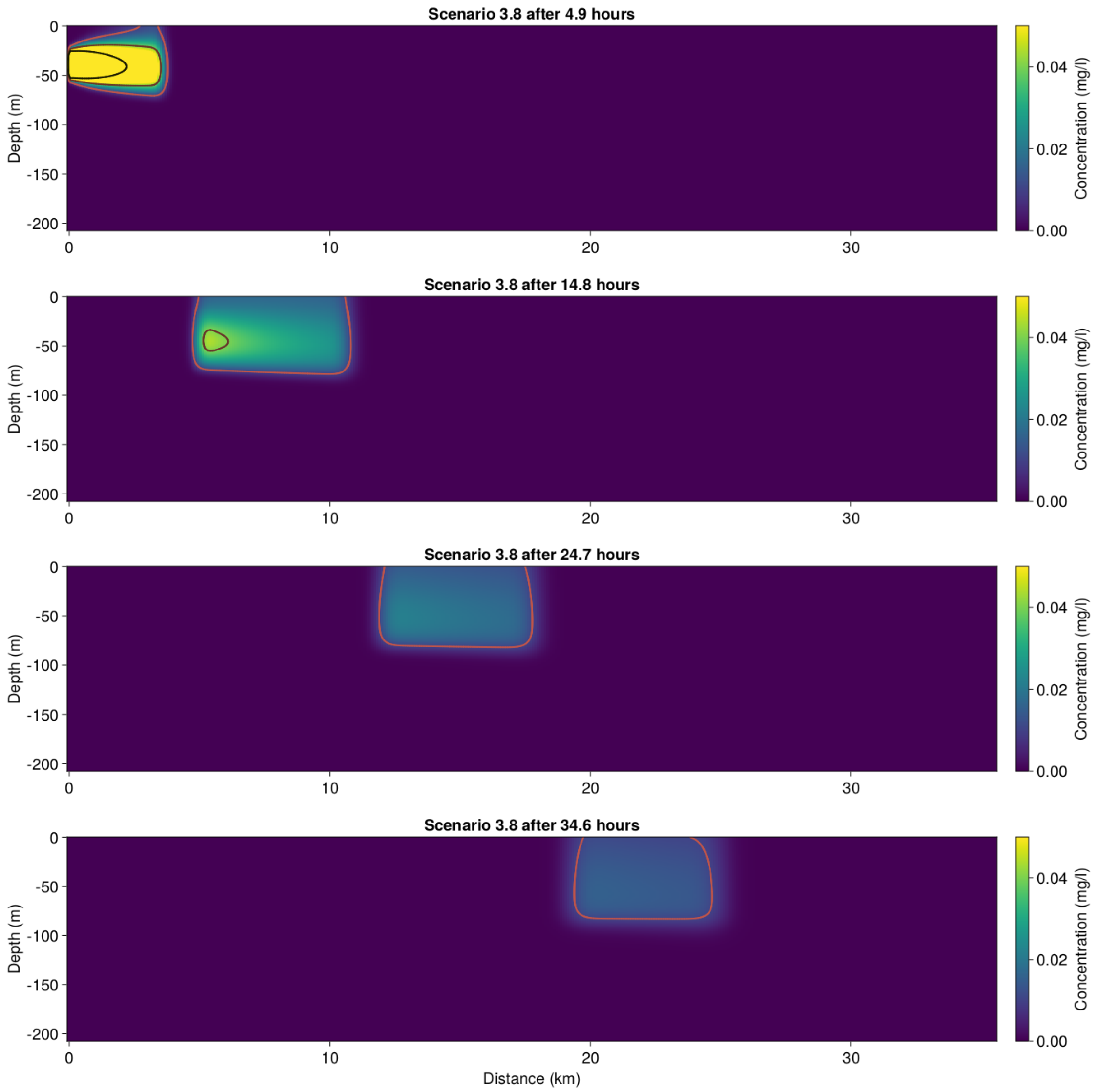

Scenario 3.5 after 9.1 hours
Scenario 3.5 after 27.4 hours
Scenario 3.5 after 45.7 hours
Scenario 3.5 after 64.0 hours
Depth (m)
0
-50
-100
-150
-200
0
10
20
30
Distance (km)
Concentration (mg/l)
0.00
0.02
0.04


Scenario 3.6 after 7.5 hours
Scenario 3.6 after 22.4 hours
Scenario 3.6 after 37.3 hours
Scenario 3.6 after 52.2 hours
Depth (m)
0
-50
-100
-150
-200
0
10
20
30
Distance (km)
Concentration (mg/l)
0.00
0.02
0.04

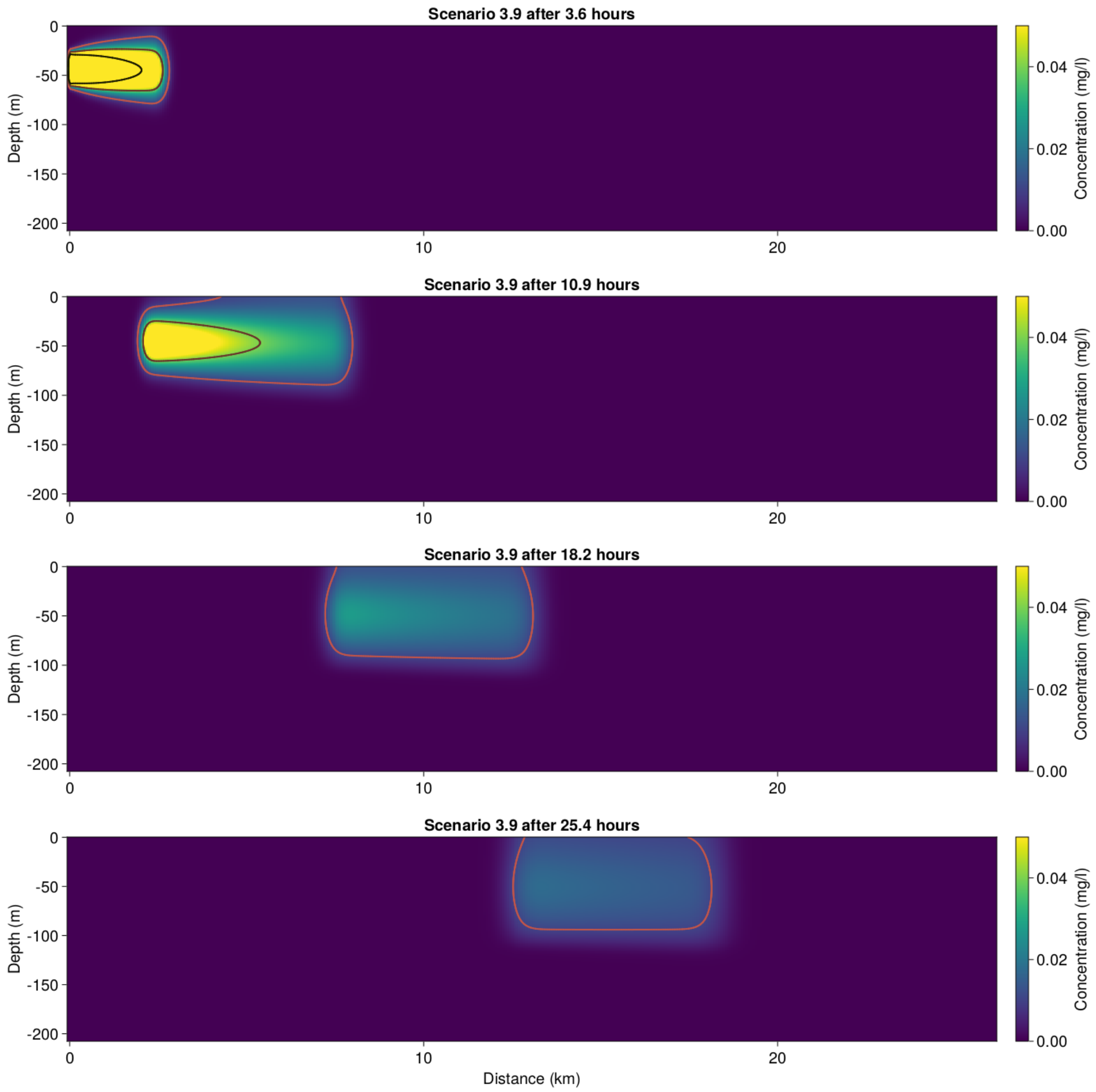


Scenario 3.7 after 6.1 hours
Scenario 3.7 after 18.4 hours
Scenario 3.7 after 30.7 hours
Scenario 3.7 after 43.0 hours
Depth (m)
0
-50
-100
-150
-200
0
10
20
30
40
Distance (km)
Concentration (mg/l)
0.00
0.02
0.04

atdepth LLC



Scenario 3.8 after 4.9 hours
Scenario 3.8 after 14.8 hours
Scenario 3.8 after 24.7 hours
Scenario 3.8 after 34.6 hours
Depth (m)
0
-50
-100
-150
-200
0
10
20
30
Distance (km)
Concentration (mg/l)
0.04
0.02
0.00


Scenario 3.9 after 3.6 hours
Scenario 3.9 after 10.9 hours
Scenario 3.9 after 18.2 hours
Scenario 3.9 after 25.4 hours
Depth (m)
0
-50
-100
-150
-200
0
10
20
Distance (km)
Concentration (mg/l)
0.04
0.02
0.00

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CNR ISMAR
ISTITUTO DI SCIENZE MARINE

Venice, March 29th, 2023

Subject: Comments on *Sediment-laden water spill during NORI technical trials: Advanced assessment*

To whom it may concern,

I have carefully read the document on *Sediment-laden water spill during NORI technical trials: Advanced assessment.* The report describes the modelling analysis carried out to estimate the main features of the evolution of a plume resulting from an accidental spill occurred during a mining test at sea. The report is very clear in describing the methodological approach followed in the assessment and, not less important, in distinguishing what falls within the scope of the analysis (that is, the characterization of the possible extent of the plume) from the aspects that remain unaddressed (namely, the impacts of the plume and the potential harm resulting from the spill incident). Although some details have to be retrieved from the cited literature, the document provides sufficient information to understand fairly clearly the validity and the possible limitations of the results obtained.

The study relies on the use of two models, describing respectively the initial buoyancy-driven phase (near-field assessment) and the subsequent turbulent propagation of the plume under the effect of a background flow. While introducing some significant simplifications in the description of the processes, this approach should enable a high-resolution description of the plume dynamics, whose typically sharp gradients and comparatively small spatial scales are generally poorly addressed by traditional ocean models. The plume is characterised by five metrics, computed considering reference concentration thresholds discussed in the literature over a reasonably conservative range. The two models use a relatively small set of parameters, and the uncertainty about the ocean state at the moment of the incident has been tackled by carrying out several simulations exploring different values of the parameters identified "as a representative set of possible combinations". Nonetheless, although certainly realistic, the values considered seem only loosely addressing a characterisation of the real meteo-marine conditions (namely, wind, waves, 3D-current field), and it seems strange that no better information was available from some model reanalysis. As they are defined, it is difficult to see how the considered parameters compare against the real in-situ values and against the statistics for that site.

If I were to propose any further investigation, I would definitely suggest to improve the characterization of the ocean conditions. One possibility, and maybe the most consistent with the methodology undertaken up to now, would be to re-run the plume models having estimated the values of the parameters based on realistic data from ocean model hindcast or reanalysis. Another step towards a more realistic oceanographic background description, this time following a complementary approach, could be to investigate the plume dispersion by means of a non-hydrostatic ocean model (e.g. MIT-GCM), maybe pushed to very high resolutions, possibly renouncing the full description of the grain size spectrum and considering instead only two or three representative diameters. Anyway, this is probably beyond the scope of the present study.

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Although declaredly out of the reach of the present study, a comment on the potential effect of the abrupt increase of suspended sediment concentration can be drawn based on the concentrations resulting from the simulations and the impacts, described in the literature, associated with the different concentration values. In particular, van der Grient and Drazen (2022), when estimating the effect of mining sediment plumes on deep-sea communities, in the absence of extensive information on the specific biological dynamics, on the relevance of the exposure time, and on the cumulative effect of other stressors related to the mining activities (such as underwater noise), recommend to consider as a threshold for the acute plume impacts "very close to the natural background" concentration values, which for the site should be on the order of 0.01 mg/l (that is, the lowest threshold considered in the study). Based on this and on the model results, it could be reasonable to focus the research for possible impacts on the marine communities, if any, within approximately 40 km from the incident site, considering that up to approximately 0.35 km^3 could have ever (which means, considering also very small exposure times) experienced concentration values above the desired threshold.

It was my pleasure to review this document and I remain at your disposal for any further interaction. Also, I agree to disclose my identity.

Best Regards

Davide Bonaldo

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Confidential Reviewer

I was provide with the copy of the AtDepth LLC model report of the extent of the plume. A video of the spill taken from the mining ship was found on greenpeace.org, though this offered little actual information. Based on this information, you have asked me to evaluate if this spill did not cause "serious environmental harm" as stated earlier by the ISA and "to evaluate the potential environmental impact." My brief assessment is in two parts – evaluation of the model and evaluation of potential environmental impact.

Evaluation of the model.

1) The plume model is based on very little data. The estimated flow rate of 100-150 l/min seems really low. TMC's EIS suggested flow rates of 0.1 m3/s or 6000 l/min for the full operation and videos online of the overflow off the deck during the spill shows spouts of water from multiple scuppers (greenpeace.org). The modeling does create scenarios of both higher and lower flow rates (and sediment concentrations) that can partially account for what were likely ballpark estimates of the spill conditions.

2) Given the limited data provided, AtDepth LLC took a solid approach in evaluating multiple scenarios to determine the plume extent and duration resulting from the TMC/AllSeas spill. I am not a physical modeler but their approach is based on peer reviewed approaches published in the scientific literature (Munoz-Royo et al 2021, Ouillon et al 2022).

3) The plume modeling suggests that the spill may have ranged from 0.14 to 9 days in duration and extended 2.5 to 45km effecting a volume of water of 0.01 to 0.34 km3. These results were largely confined from the mixed layer (top 60m or so) to the euphotic zone (top 150m or so). These dimensions are for a return to background concentration of about 0.01 mg/l in these exceptionally clear open ocean waters.

4) Even with the parameters presented the spill is NOT comparable to a couple of boxcores and associated sediment washing, as indicated by the ISA in their request for this assessment. It typically takes 200-400l of cold seawater to process a scientific 0.25 m2 boxcore (Glover et al 2016). This process typically takes a few hours. For the spill, there was discharge of 100-150 l per minute for 8 hours or about 60,000 l of water. One box core (0.5x0.5x0.4 m) is about 250kg of sediment and perhaps 2 boxcores would be done in one day at any location. Based on the provided flow and concentration, this spill was about 3,000 kg of sediment in 8 hours, 6-12x more than 1-2 boxcores in a day.

Evaluation of environmental impact

Based on potential sediment thresholds of aquatic animals from mostly coastal and even freshwater environments and extrapolation to open ocean and deep-sea species, up to 20% of species might have been negatively affected within the resulting plume and 50% where concentrations exceeded 0.04 mg/l (Van der Grient and Drazen 2022). The plume likely did not extend into the mesopelagic but the vertical migration behavior of pelagic animals in this part of the ocean is very strong

(Perelman et al 2021) so that during the night the mesopelagic migrants may also have been affected. We can only speculate about such responses because studies of sediment plumes are largely confined to nearshore waters in the contexts of harbor dredging and in some cases oil drilling. There was no time to search comprehensively for open ocean precedents for this type of accident but quick searches revealed none. Despite this lack of information, the relatively short duration (few days) suggests a rather transient impact. Further, the spatial extent of the plume is relatively small, perhaps a few kilometers (though up to 45km if distributed in a current-elongated narrow path), minimizing any impacts.

In summary, it is unlikely that this sediment spill caused any serious environmental harm.

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International Seabed Authority ISA
Kingston,
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Bremen, 15th March, 2023

To Whom It May Concern:

Evaluation of a spill incident during 'test mining' and its plume modelling

I have read the Advanced Assessment report of atdepth LLC "Sediment-laden water spill during NORI technical trials" with much interest; although I am not a modeler and my understanding of the used methodology is very limited, the report is written in a way that it is easy to follow the rationale for having selected certain boundary conditions for the different modeling scenarios. The group of T. Peacock is highly acknowledged or their work in the field of modeling oceanographic processes including sediment plume behavior and I trust that they have used the best possible approach. However, considering the limited availability of data that are needed as input parameters for the model, and that were not available from NORI, many assumptions had to be made, which is clearly a limiting factor for assessing the environmental impact of the different scenarios. Considering that in each of the settings of the model the distribution of the sediment plume is limited to the upper turbulent layer and the amount of discharged material is relatively small, as it was a test trial and an event that lasted only 8 hours, it can readily be assumed that the environmental impact of this spill incident has been rather limited in space and time and no serious environmental harm related to this event is to be expected. The magnitude of this event is likely comparable to impacts caused during research activities with box core or TV grab sampling of sediment or other muddy material that is discharged from the surface of the vessel.

Nevertheless, this event demonstrates that the technology used by NORI still bears imponderables and risks of failure which apparently were unexpected; if such spills would happen on a larger scale during industrial mining activities, the sensitive photic surface layer could be severely negatively impacted by the interaction of organisms with the particles or the reduction of light penetration; while a significant release of toxic metals is unlikely in the oxic water column including the surface layer, when sinking through the oxygen minimum zone partial reduction of manganese oxides and associated metals or desorption could increase dissolved metal concentrations.

Furthermore, the scarcity of data made available by NORI for the modeling approach of the impact demonstrates that there should be more focus on continuously collecting all types of data during the activities that would be necessary to make a proper environmental impact assessment. It may be useful for the ISA to clearly define the type of data (with suggestions for methods of data collection, such as sensors) that need to be collected and made available if necessary.

With kind regards,

Professor of Geoscience
Department of Physics and Earth Sciences

16 March 2023

Dr. Ulrich Schwarz-Schampera
International Seabed Authority
Jamaica

Dear Ulrich,

I have now studied the atdepth Advanced Assessment of 28 February.

Consistent with my previous email to you in response to your overview of the situation, I find the now more broadly defined values and ranges of variables used in the modelling exercises to be reasonable. Despite the paucity of real time onsite data, the authors have carefully selected values from the regional oceanographic and ocean modelling literature seemingly appropriate to the case at hand. By breaking down the dispersion problem into buoyancy driven and passive transport phases they have constrained plume dispersion in an elegant and robust fashion. From a modelling perspective, I have no quarrel with the atdepth findings regarding post-discharge plume behavior. That said, my only caveat is that all modelling results are predicated on the unsubstantiated values for flow and particle concentration at the point of discharge. To the extent that these values are acceptable, I suggest the report findings are also acceptable.

Regarding potential environmental harm, which is beyond the scope of the Assessment by atdepth, it is my feeling is that due to the very limited spatial extent and ephemeral lifetime of the ‘detectable plume’, no serious deleterious effects should impact the surface ocean at the test site.

Based on a web search of Professor Peacock and the Environmental Dynamics Laboratory, their academic credentials and a publication track record clearly justify authorship of your requested assessment.

Although I am not a numerical plume modeler, I have co-authored four peer-reviewed publications with J.W. Lavelle, a recognized leader regarding modelling submarine hydrothermal plumes and the processes that occur within them during dispersion. Additionally, I have authored numerous publications describing the detection and dimensions of dispersing hydrothermal plumes.

Most Respectfully,
Gary J. Massoth
Oceanographer

Dr. Ulrich Schwarz-Schampera
INTERNATIONAL SEABED AUTHORITY
14-20 Port Royal Street, Kingston, Jamaica

Dear Dr. Ulrich Schwarz-Schampera,

I would like to point out two issues regarding the report by **atdepth LLC** (2023). The first point relates to the technical aspects of the report. While the report is very thorough and excellent, I must say that it is not appropriate to use as a reference in a real case.

Second, I would like to point out another important issue in terms of preventing the recurrence of such accidents. The lack of on-site monitoring of the leaks (their volume estimates and environmental impact) is what makes it difficult to properly determine the real impact of this accident. The calculations are based on the assumption that the amount of leakage is not very large as reported by NORI, so the impact of any of the scenarios in the numerical experiments appears to be small. However, the problem is that it is not possible to know exactly what it was.

1. Technical point:

Under conditions where the physical environment at the point of discharged sediment plume is not clear, 27 scenarios are assumed within the range of possible parameter values, and each case is discussed in detail, mainly through numerical experiments. However, the following issues may be raised.

When attempting to model a shipboard spill incident, it is appropriate to consider the source of the discharged sediment plume as a point source from the ocean side, and its spread should be tracked in a three dimensional space. In particular, the three-dimensional model is essential when considering the effects of rotating currents such as near-inertial currents, which are thought to predominate in the mixed layer, as described below. Although not explicitly stated in this report, the present calculations appear to have been performed in the vertical two-dimensional plane. At the very least, quantitative discussion is needed regarding the possible differences that might occur when considering this problem in the two-dimensional plane and in the three-dimensional space.

Although the advection effect by the North Equatorial Current in the ocean surface layer is taken into account, the existence of near-inertial currents excited by wind-stress fluctuations that should prevail in the surface mixed layer is not taken into account at all. Considering the latitude of the target area to be ~15°N, this near-inertial currents would have a rotation period of ~ 46 hours (i.e., reversal in one day). It is necessary to estimate the spread of the discharged sediment plume at each instant of time, taking into account the co-existence of this rotating inertial currents in the three dimensional model mentioned above.

2. Lack of monitoring:

There is no question that test mining, even if it is a small-scale operation, should be conducted with due consideration for the environment. Experiments should not only verify whether ore can be lifted efficiently and inexpensively, but also the technology that can estimate the environmental impact of actual mining operations. If there is an operational guideline how to minimize the environmental impact in the event of unexpected accident, the situation would have been less serious.

When Japan's JOGMEC conducted ore-lifting experiment of polymetallic sulfides at the Okinawa Trough, all the riser fluid was collected in a barge without being returned to the sea. Although such an operation is not possible this time because of the large amount of ore mined, it would have been possible not to dump the overflow of particle-laden fluid to the surface of the ocean. Several technologies have also been developed to measure the environmental impact of a leakage accident on site at low cost (e.g. ISO 23734 Ship and marine technology - Marine environment impact assessment - Onboard bioassay to monitor seawater quality using delayed fluorescence of microalgae.)

3. Conclusions:

As is properly stated in the conclusions of atdepth LLC (2023), *"the values of the extent metrics discussed herein are estimates of the extent of the plume, and not the impact of the plume. They should not be understood as exact nor be interpreted as representative of the final environmental impact and potential harm that resulted from the spill incident of interest."*

Although I have no knowledge of the conditions under which this test mining was permitted, the lessons learned from this accident should be used to require additional considerations to the enterprises which may conduct similar experiments in the future. To that end, I hope that this accident will be properly verified from various points of views.

I hope this report will be of some help to you in your considerations.

23, March, 2023

Tetsuro Urabe (signed)
Professor Emeritus, The University of Tokyo