

Project Memo

Modelling of spreading of SIBX from mine activity in Førdefjorden

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ABSTRACT

Four scenarios with different set-up for release at 260 m depth of the production chemical Sodium Isobutyl Xanthate (SIBX) have been modelled; S1 with 95 % attached to mine tailings and 5 % dissolved, S2 and S3 with 100 % dissolved, and S4 with 90 % attached to mine tailings and 10 % dissolved. S1 and S3 were modelled with a biodegradation half-life of 25 days, S2 7 days and S4 without biodegradation. The duration of each scenario was 1 year.

This modelling study has shown that the concentration of SIBX in the fjord will depend on the release concentration and it will vary with the local current conditions. The number of grid cells (50x50x10 m) exceeding the PNEC value (3.4 µg/L) varies between 1 and 2 for the scenarios with 100 % dissolved SIBX (S2 and S3). For S1 and S4, there were no grid cells with concentrations above PNEC during the entire simulation period. The maximum concentration for scenarios S1 and S4 is always below PNEC, whereas the maximum concentration for S2 and S3 varies between 1-10 µg/L, with the time-median value in the range 4-5 µg/L. The maximum value only applies to 1-2 grid cells in the entire model domain and is found close to the release depth.



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1 Background

SINTEF has previously performed modelling of spreading of particulates from a planned mine tailings discharge in Førdefjorden¹. In the present memo we investigate the deposition, spreading and dilution of the process chemical Sodium Isobutyl Xanthate, C₅H₉OS₂Na, CAS: 25306-76-5 (SIBX) with different biodegradation rates and different dissolved fractions in the release.

Førdefjorden is a fjord in Vestland county in the western part of Norway (Figure 1.1). It is approximately 40 km long, and the location of the mine, Engjabøneset, is approximately 11 km into the fjord. The depth of the basin where the mine tailing deposit is located is approximately 300 m. Measurements show that the temperature below the thermocline is low, below 10 °C, throughout the year^{2,3}.

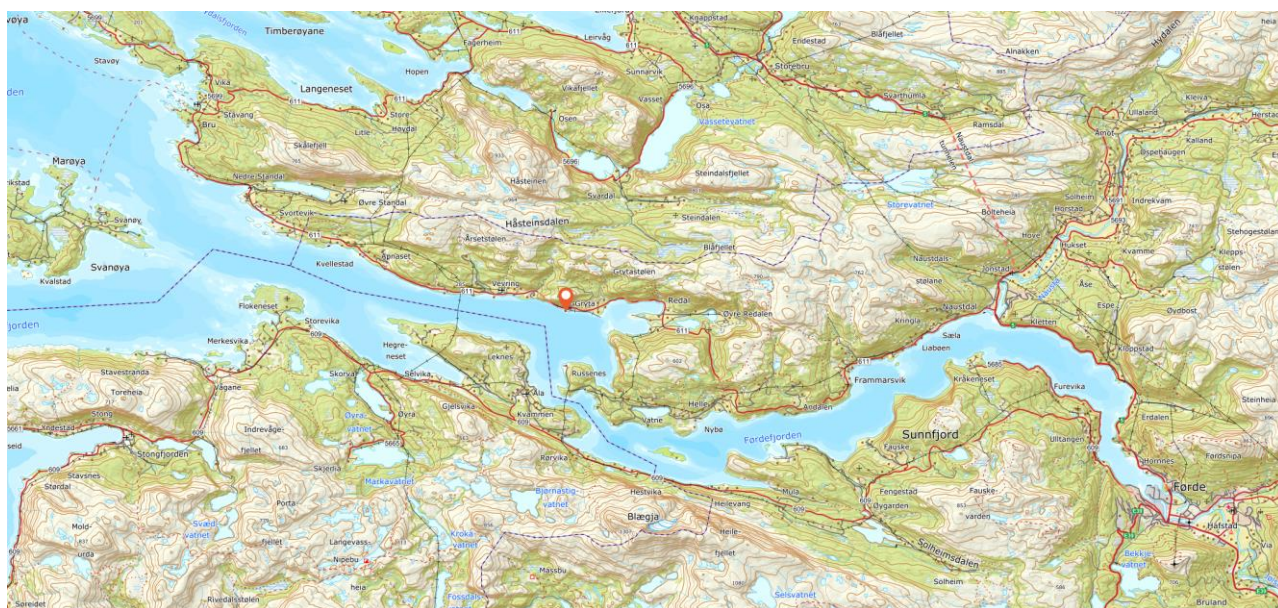


Figure 1.1 Map showing Førdefjorden. The location of the mine for exploration of rutile is marked with a red marker.

2 The DREAM model

In 1996 the Norwegian government issued a White Paper requiring the Norwegian oil industry to reach the goal of a 'zero harmful discharge' for the marine environment by 2005. To achieve this goal the Norwegian oil and gas industry initiated the Zero Discharge Programme for produced water discharges. The 'Zero Discharge Programme' made the oil industry responsible for showing and documenting achievements towards the goal of 'zero harmful discharges'.

In order to quantify and document the potential risk to the marine environment from discharged substances (e.g. as in produced water), SINTEF, together with the Norwegian oil and gas industry, started the development of DREAM (Dose-related Risk and Effects Assessment Model) in 1998. Since 2002, DREAM has been used by all operators on the Norwegian continental shelf as a modelling platform for calculating the Environmental Impact Factor (EIF) for their produced water discharges. The EIF is an indicator of

¹ Nepstad, R. and Rye, H., 2014. *Simuleringer av partikkelspredning i Førdefjorden fra planlagt sjødeponi*. SINTEF report F26318.

² Sundfjord, A. and Bjerkeng, B., 2008. *Strøm, turbiditet og hydrografi i fjordbassenget utenfor Engebø, Førdefjorden*. Rapport, Norsk institutt for vannforskning (NIVA).

³ Alver, M.O., Michelsen, F.A., and Ellingsen, I.H., 2014. *Strømmodellering med SINMOD i Førdefjorden*, SINTEF report F26336.

environmental risk. By reducing the EIF, operators reduce the likelihood of adverse effects occurring as a result of operational discharges.

Later, the DREAM model and the EIF concept were extended to be applied to discharges of particulate matter like drill cuttings and mud as well. During the NYKOS project (2014-2019), the DREAM model was further developed and applied to mine tailings discharges. Today DREAM is used to assess a variety of discharges from different industry, including oil & gas, mining and aquaculture.

The DREAM model uses external input for coastline, bathymetry and environmental data such as currents. For this study, currents modelled by SINMOD have been used. For consistency, the same bathymetry and coastline were used in DREAM as were used in the current modelling.

The DREAM model version 11.0.1 (2019) has been used in this project.

3 SINMOD current data set

The current dataset used in the present modelling was produced with SINMOD in 2014 for the previous modelling of sedimentation and dispersal of mine tailings. The dataset covers Førdefjorden with a horizontal resolution of 53.5 m. The dataset has 68 vertical layers, with higher resolution close to the surface. The dataset is described in SINTEF report F26336⁴.

3.1 Normal current regime

During most of the year the current in the deep part of the fjord inside the submarine tailing deposit area is quite weak. The deep-water circulation in a fjord (defined as below the sill) is much weaker than the estuarine circulation that dominates the layer above the sill (described in Stigebrandt, 1981⁵). Figure 3.1 gives an example of the daily mean current close to the discharge site during the normal current conditions in the deep layers.

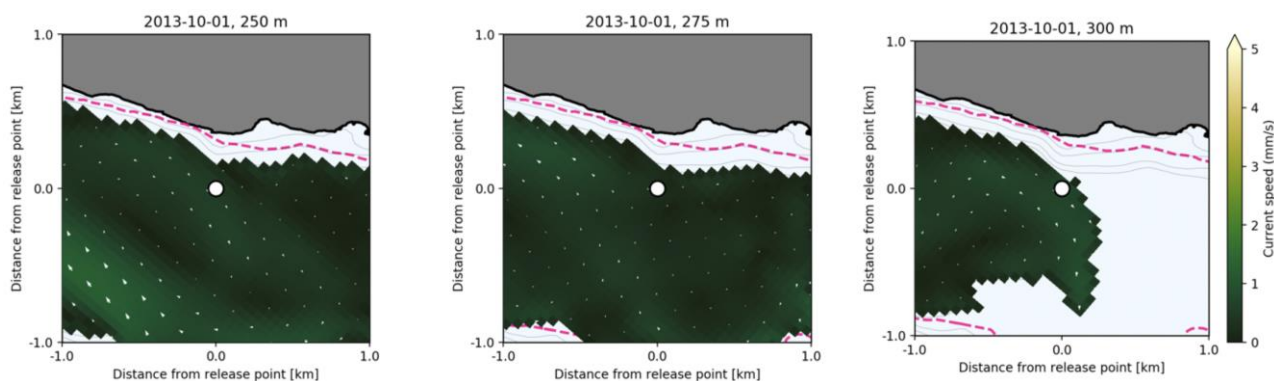


Figure 3.1 Example of daily mean currents at 250, 275 and 300 m depth during the normal current regime.

3.2 Deep-water exchange

When the density of the water residing outside the sill is denser than the water in the basin below the sill, the outside water flows over the sill and replaces the deep water in the basin. During a deep-water renewal, the currents in the deeper parts of the fjord will be stronger than the rest of the year. A description of deep-

⁴ Alver, M.O., Michelsen, F.A., and Ellingsen, I.H., 2014. *Strømmodellering med SINMOD i Førdefjorden*, SINTEF report F26336.

⁵ Stigebrandt, A., 1981. *A mechanism governing the estuarine circulation in deep, strongly stratified fjords*. Estuar. Coast. Shelf Sci. 13, 197-211.

water renewal is found in Gade and Edwards (1980)⁶. For the dataset used in this study, two of these events are identified. The first period is in June/July 2013, and the second in April 2014. Figure 3.2 shows an example of daily mean currents for three layers on June 8th 2013 during a deep-water renewal event.

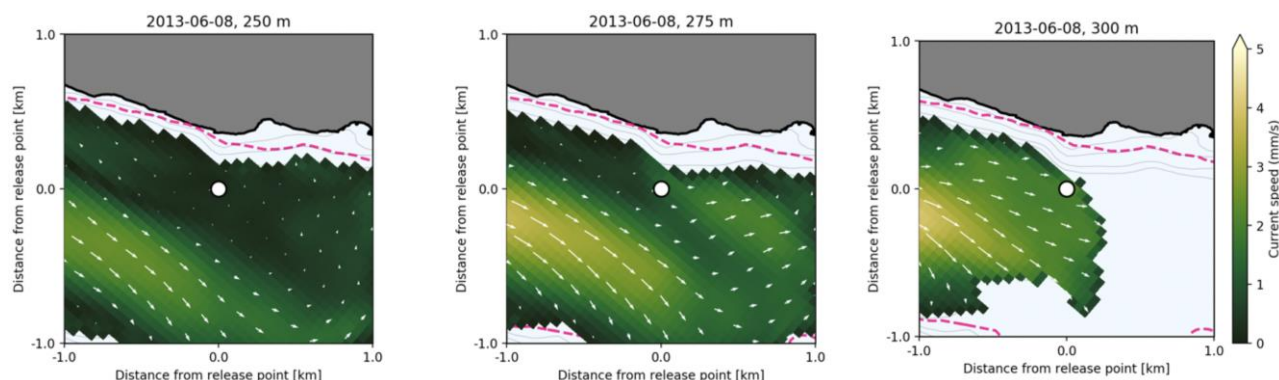


Figure 3.2 Example of daily mean currents at 250, 275 and 300 m depth during a deep-water exchange event.

4 Model setup

4.1 Model and discharge parameters

DREAM was set up to run for one calendar year, starting May 1st 2013. A horizontal resolution of 50 m and a vertical resolution of 10 m was used. The model parameters are displayed in Table 4.1. The parameters of the discharge are given in Table 4.2, these values are based on information provided by the client. The total discharge rate for this set of simulations was reduced to 2 818.5 tonnes/hour compared to the 6 099 tonnes/hour which was used in the previous modelling project. The discharge rate of particulate material was reduced from 8.72 % to 5.16 %, corresponding to 145.5 tonnes/hour.

Table 4.3 gives the particle size distribution of the mine tailings used as input to the model, provided by the client. The particle size distribution has been updated since the 2014 model runs (see report by DNV GL⁷). The main differences are in the larger size bins, as displayed in Figure 4.1.

Table 4.1 Model input parameters.

Parameter	Unit	Value	Comments
Simulation duration	Days	365	Start May 1 st 2013
Model timestep	Minutes	10	
Model output timestep	Hours	3	
Numerical particles used	-	75 000	Use 2 000 particles per timestep
Horizontal diffusivity	m ² /s	0.1	Governs horizontal turbulent mixing on smaller scales than resolved by the ocean model setup.
Vertical diffusivity	m ² /s	0.001	Governs vertical turbulent mixing.
Grid dimensions	m	50 x 50 x 10	

⁶ Gade H.G., Edwards A., 1980. *Deep Water Renewal in Fjords*. In: Freeland H.J., Farmer D.M., Levings C.D. (eds) *Fjord Oceanography*. NATO Conference Series (IV Marine Sciences), vol 4. Springer, Boston, MA002E.

⁷ Endresen, Ø., Glette, T., Volan, C., 2014. *Strømforhold og partikkelspredning i Førdefjorden*- DNV GL report 2014-1244.

Table 4.2 Parameters for the discharge, used as model input.

Parameter	Unit	Value	Comments
Discharge pipe direction	degree	180	Angle from north: 0 = north, 180 = south
Discharge pipe angle	degree	90	Angle from vertical: 0 = upwards, 180 = downwards
Inner diameter of discharge pipe	m	0.49	
Total discharge rate	tonnes/hour	2 818.5	Particulates, fresh water and sea water.
Discharge rate particulate matter	tonnes/hour	145.5	Only mine tailings particulates.
Temperature of discharge	°C	7.7	
Salinity of discharge	g/L	34.7	
Density (particle phase)	tonnes/m ³	3.45	

Table 4.3 Particle sized distribution of the mine tailings.

Upper limit of particle size (µm)	Fraction (%)
15	0
19	0.8
27	0.8
34	1.4
42	1.5
60	5.5
85	8
132	22
150	30.7
180	9.2
212	9.9
224	1
250	0.1
300	0.1
355	1.2
425	4.2
500	3.6
SUM	100

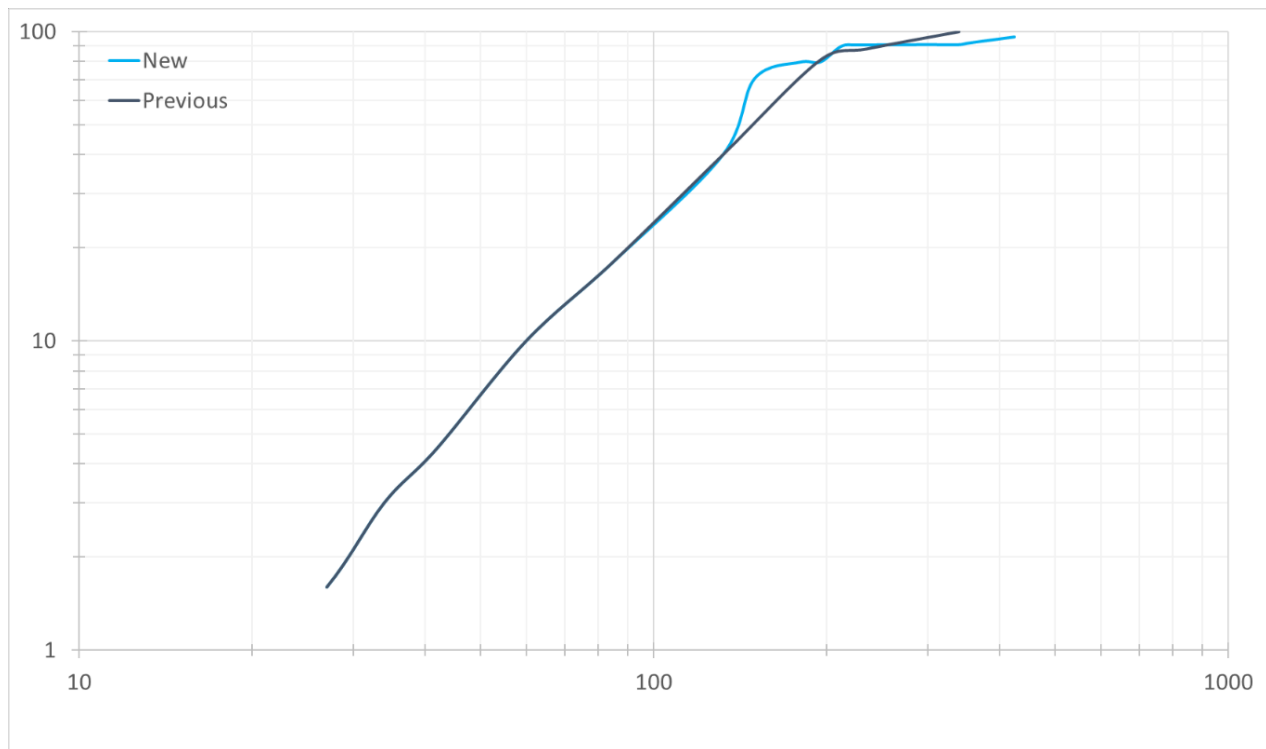


Figure 4.1 Particle size curve (accumulated).

4.2 Discharge site

The position of the discharge site is shown in Figure 3.1, marked by the white square. The outline of the submarine tailing deposit is marked with a pink dashed line. Table 4.4 gives the exact position of the discharge, as well as the discharge depth and the water depth at the location.

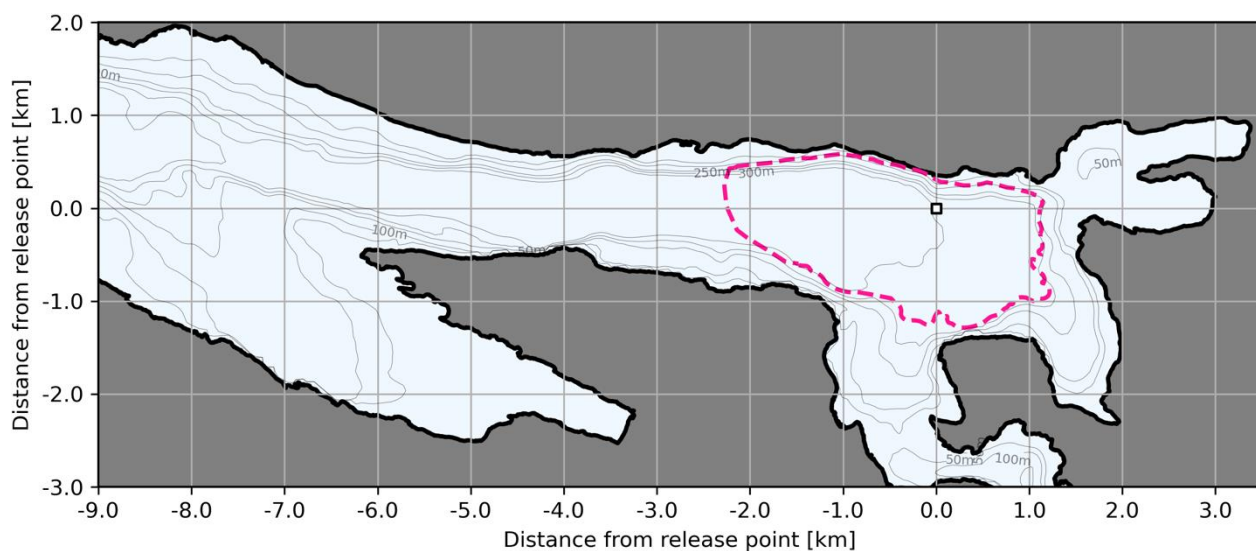


Figure 4.2 Map showing the extent of the model domain used in the simulations. The discharge position is marked with the white square, and the pink dashed line marks the outline of the regulated submarine tailing deposit. The water depth at the discharge location is 298 m.

Table 4.4 Position and water depth for the discharge point.

	Discharge point, U1
Latitude	61° 29.0941' N
Longitude	5° 26.4569' E
Water depth	298 m
Discharge depth	260 m

4.3 Discharge of the production chemical SIBX

The production chemical SIBX has a known structure and is described in a memo prepared by DNV GL⁸. There are some uncertainties regarding the environmental properties, such as attachment to the mine tailings and biodegradation. Due to these uncertainties, four different scenarios were modelled in order to cover different worst-case discharges:

- Scenario S1 and S4, where SIBX is both attached to the mine tailings and dissolved in the water phase of the release. Different fraction attached to the mine tailings, and different degradation rates for dissolved SIBX are evaluated.
- Scenario S2 and S3, where SIBX is fully dissolved in the water phase of the release, evaluating different degradation rates.

Table 4.5 gives a more detailed overview of the different scenarios. The main chemical characteristics for SIBX are given in Table 4.6, which also lists the Predicted No Effect Concentration (PNEC) value, provided by the client.

Table 4.5 Overview of the model input for the different simulations with SIBX. For scenario S4, 90 % of the SIBX was attached to the mine tailings. The concentration values refer to the discharge pipe outlet, which is the initial (input) values for the model simulations.

Scenario	SIBX half-life at 10°C	Dissolved SIBX	SIBX attached to mine tailings	Concentration of dissolved SIBX	Concentration of attached SIBX
S1	25 days	5 %	95 %	4.3 µg/L (ppb)	80.7 µg/L (ppb)
S2	7 days	100 %	0	85 µg/L (ppb)	0 µg/L (ppb)
S3	25 days	100 %	0	85 µg/L (ppb)	0 µg/L (ppb)
S4	No biodegradation	10 %	90 %	8.5 µg/L (ppb)	76.5 µg/L (ppb)

Table 4.6 Additional chemical characteristics of the production chemical SIBX.

Parameter	Unit	Value
Density	tonnes/m ³	0.65 at 20 °C (ECHA)
Solubility	ppm	662.6 - 573 000 ppm at 0 - 35 °C and pH 7 – 10 (ECHA)
Vapour pressure	atm	0 - 0 Pa at 25 °C (ECHA)
PNEC	µg/L ppm	3.4 0.0034

⁸ Sverdrup, L., 2020. Dokumentasjon for miljøegenskaper til stoffet SIBX, sammendrag. DNV-GL memo Nrutile 1006-2020.

5 Results

The results for the nearfield plume are presented in section 5.1. The sediment footprint of SIBX attached to the mine tailings (scenario S4) is given in section 5.2, whereas the fate of the dissolved fraction of SIBX from the same setup (scenario S4) is presented in section 5.3. Section 5.4 gives a comparison between the four different scenarios modelled with different fractions and biodegradation rates of dissolved SIBX.

5.1 Nearfield plume

The mine tailings are discharged through a pipe with inner diameter of 0.49 m. When the mine tailings and water mixture flow through the opening, the density of the release is larger than that of the surrounding sea water, and the nearfield plume descends. The mine tailings continue to fall until they hit the seabed, as illustrated in Figure 5.1. During this phase, ambient water is entrained into the tailings plume, causing it to expand and dilute. When the discharge hits the seabed, the mine tailings will be transported by the continuation of the plume flow along the sea floor and either settle in the vicinity, or they may be transported away from the discharge site by the ambient current. Further transport mainly applies to the finer fractions of the tailings, and the dissolved SIBX, which has no inherent settling speed. The pipe opening is located approximately 38 m above the seabed. The plume with the mine tailings uses 83 seconds to reach the seabed, as shown in Figure 5.2 (left panel). In the present simulations the plume always reached the seabed, and the far-field spreading of particulates therefore started from this depth. The expansion factor of the plume in this case reaches 70 at the bottom (meaning a dilution of 70 times from the pipe outlet to the seabed), as shown in Figure 5.2 (right panel).

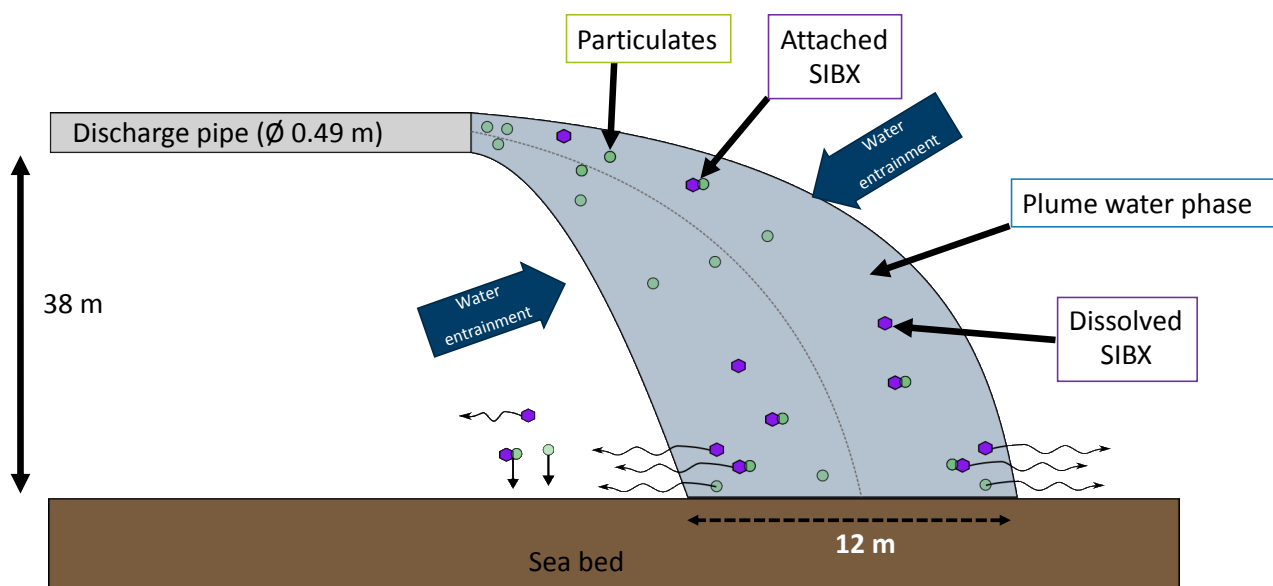


Figure 5.1 Illustration of the nearfield plume model. The mine tailings (particulates, particle-attached SIBX and dissolved SIBX) mixed with water in the pipe are discharged horizontally. The discharge continues to move horizontally before it loses momentum and starts to sink due to the density being greater than the ambient water. When sinking towards the bottom, ambient water is being mixed into the plume. This leads to an expansion of the plume, and the discharge is thus being diluted on the way to the seabed. When hitting the seabed, the larger particle sizes of the mine tailing settles, and the finer particles may escape the plume and transported away from the discharge site with the bottom current generated by the plume and the ambient current.

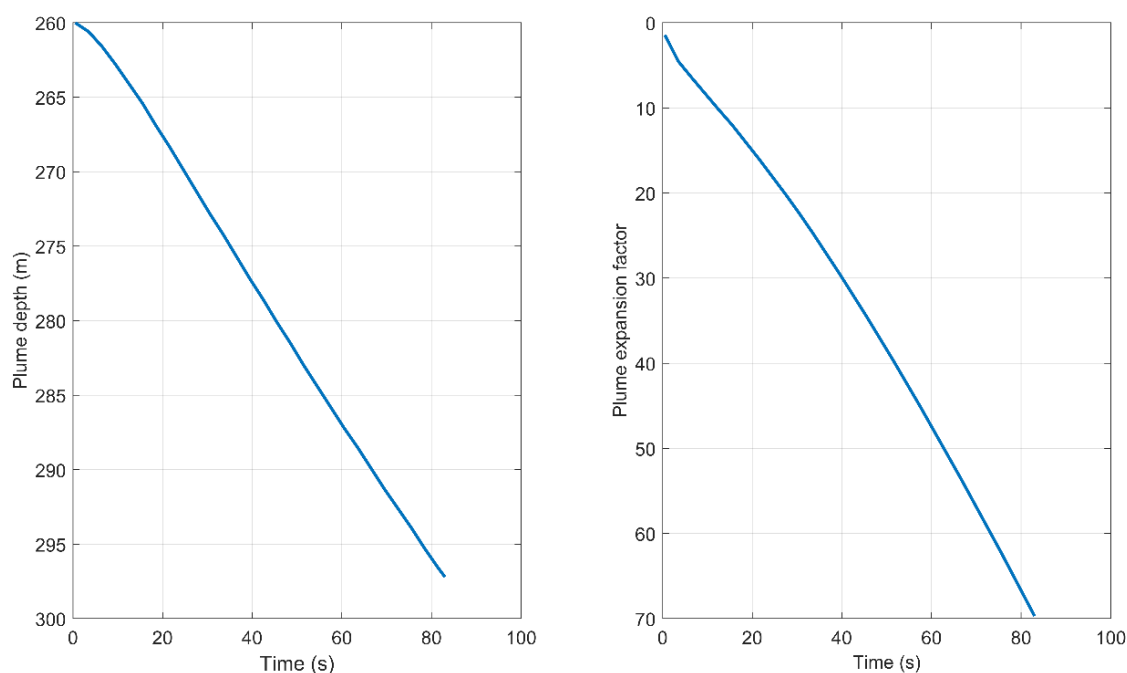


Figure 5.2 Plume depth (left panel) and plume expansion factor (right panel) as a function of time. The plume uses 83 seconds to reach the seabed, and the corresponding expansion factor at the seabed is 70 (meaning that the discharged mine tailings have been diluted with a factor 70).

5.2 Sediment footprint of SIBX with 90 % attached to the mine tailings and no biodegradation (Scenario S4)

After the plume phase, particulates in the model far-field phase will settle with a speed determined from their size and density, which is given as input (see model setup section). When they reach the sea floor, their mass will be transferred to the sediment compartment in the model, resulting in a cumulative build-up over the simulation period. Sedimentation will vary with time and location, depending on the currents and vertical mixing. SIBX attached to the mine tailings, will remain attached when the mine tailings settle on the bottom. The model tracks SIBX in the sediment as total deposited mass per square meter ($\mu\text{g}/\text{m}^2$). In the present model simulations, additional sediment dynamics such as mixing with natural sediment by bioturbation was not included.

Figure 5.3 shows the concentration of deposited SIBX after one year. This applies to the 90 % fraction attached to the mine tailings. The attached concentration of SIBX was $76.5 \mu\text{g}/\text{L}$. The highest concentrations of SIBX in the sediment is found close to the release site. The area with higher concentrations than $1 \mu\text{g}/\text{m}^2$ is within the submarine tailing deposit except for a small area in the south-eastern part of the submarine tailing deposit. The area with concentrations higher than $5 \mu\text{g}/\text{m}^2$ is within the submarine tailing deposit after one year of release. Please note that no biodegradation was used for SIBX in the sediment for this scenario.

The time series of the mass balance for SIBX attached to the mine tailings are shown in Figure 5.4. After one year of release, approximately 2 000 kg of SIBX has been released as attached to mine tailings. Nearly all the SIBX in this scenario has been deposited on the bottom together with the tailings. Only a small fraction (< 1 kg) of SIBX leaves the model domain together with the finest particles. The lower right panel of Figure 5.4 shows that this occurs during two different periods, and coincides with the deep-water exchange in June 2013 and April 2014.

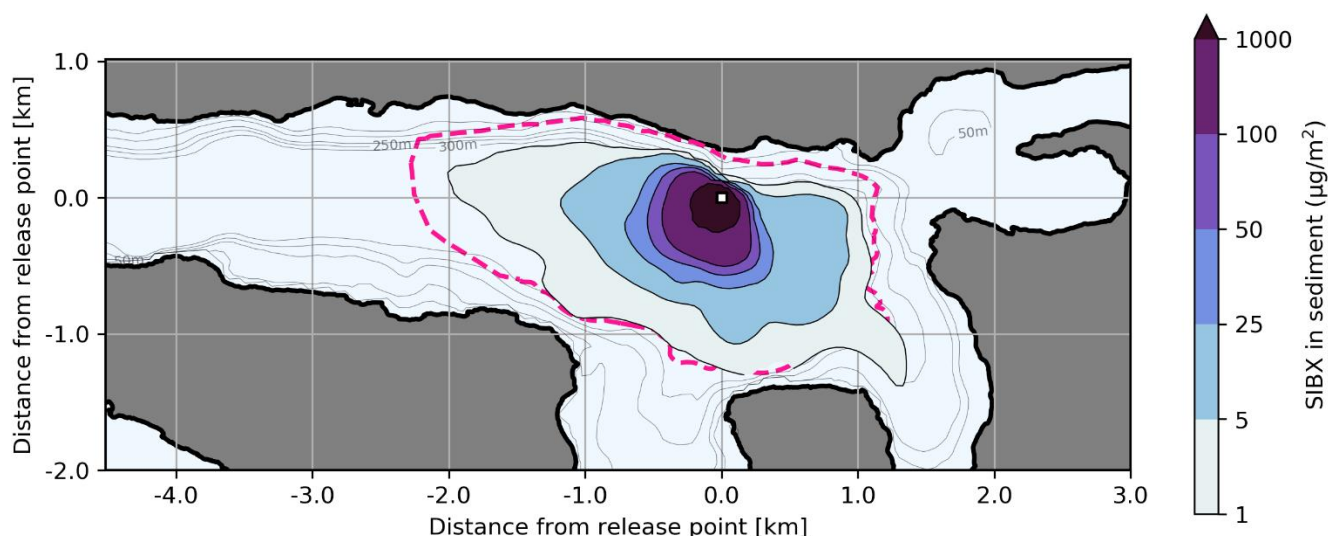


Figure 5.3 SIBX-concentration ($\mu\text{g}/\text{m}^2$) in the sediment after one year of release for the 90 % SIBX fraction attached to the mine tailings. The discharge position marked with the white square, and the pink dashed line marks the outline of the submarine tailing deposit.

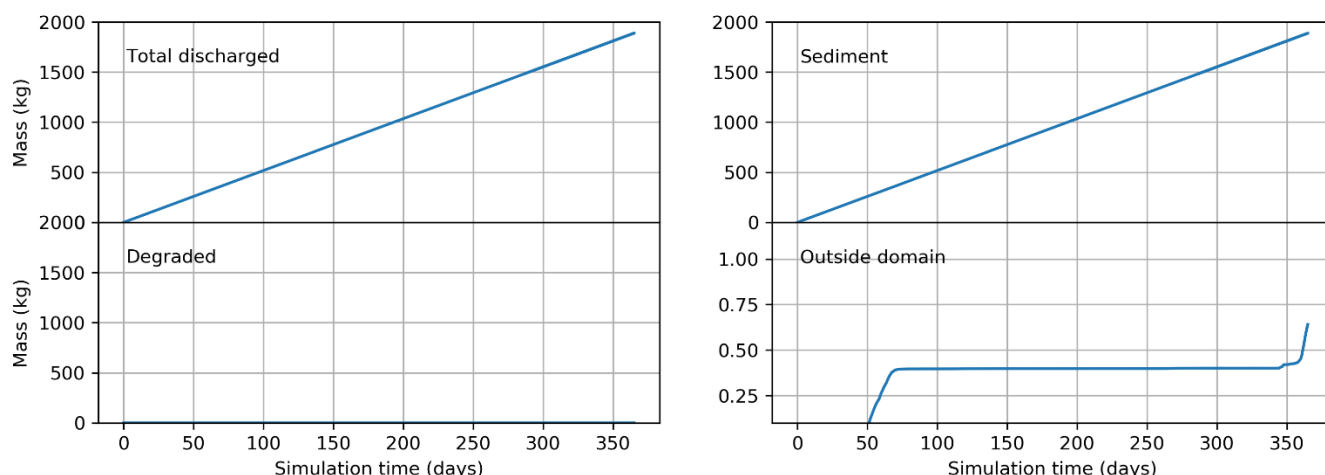


Figure 5.4 Time series of the mass balance for SIBX attached to the mine tailings, Scenario 4. The upper left panel shows the total accumulated discharged SIBX mass over the one-year modelling period. The upper right panel gives the time series of SIBX deposited in the sediment. The lower left panel shows the biodegraded SIBX, which is set to 0 in this case. The lower right panel gives the mass of SIBX attached to mine tailings that leaves the model domain. As the figure show, the mass leaving the domain is less than 1 kg during the modelling period. The SIBX leaving the model area is probably attached to the finest particles, and the figure show that these particles leave the model domain during two periods that corresponds to the deep-water exchange in June 2013 and April 2014.

5.3 Concentration of dissolved SIBX with 10 % dissolved and no biodegradation (Scenario S4)

The dissolved fraction of SIBX will follow the release in the plume phase. Within the plume itself, SIBX will be diluted together with the particulate part of the discharge. The initial concentration of dissolved SIBX for this scenario is $8.5 \mu\text{g}/\text{L}$. The dilution of SIBX within the plume is shown in Figure 5.5. The figure show that

the SIBX concentration is quickly diluted to below the PNEC value (3.4 µg/L), however note that this does not include SIBX present outside the plume phase.

Figure 5.6 shows the time series of maximum concentration of SIBX in the whole model domain, calculated on the concentration grid (cell size 50x50x10 m). The 24-hours mean value has first been calculated before the 96-hours trend line has been plotted. The figure shows that the maximum concentration of SIBX is always below the PNEC during the one-year simulation period.

The mass balance of the dissolved SIBX is shown in Figure 5.7 (not the particle attached SIBX). The left panel shows the total mass, whereas the right panel shows the relative mass (relative to amount discharged at the given time). The figure shows that most of the SIBX will leave the model domain at a relatively steady rate, except during the two deep-water exchanges in June/July 2013 and April 2014. This means that SIBX does not appear to accumulate in the fjord over time but will leave the fjord (model domain) at dilute concentrations and variable rate depending on the prevailing circulation patterns.

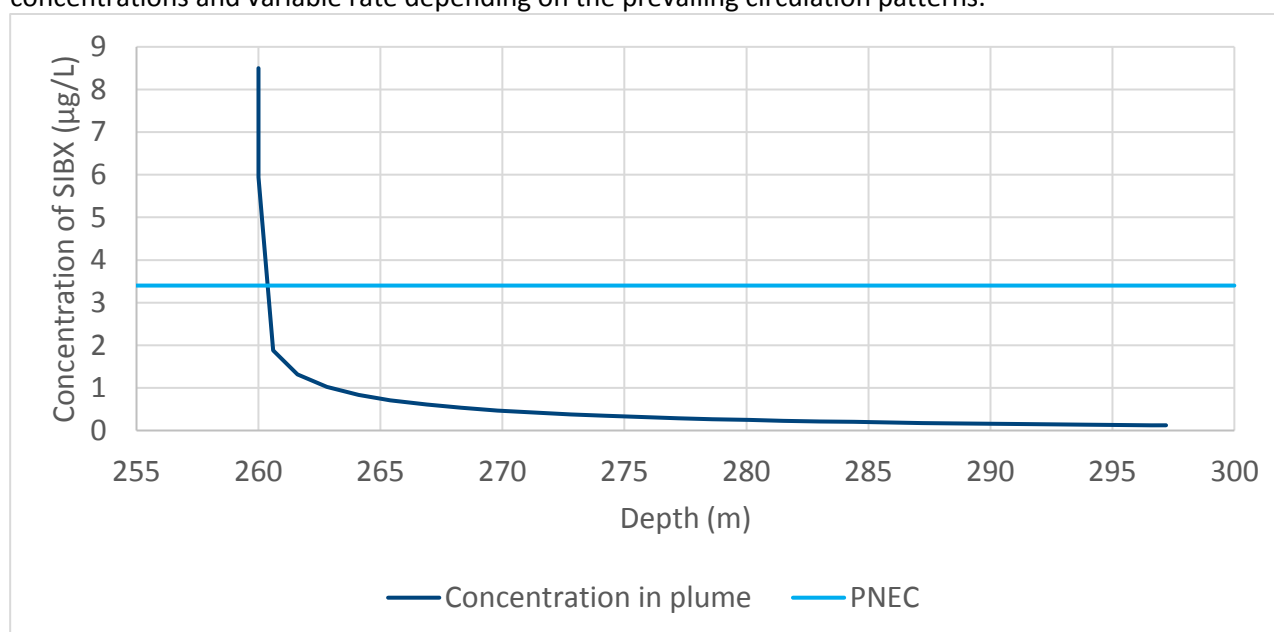


Figure 5.5 Dilution of SIBX in the plume phase. The dark blue line gives the concentration of SIBX within the plume as it sinks from the release point at 260 m to the seabed at nearly 300 m. The light blue line marks the PNEC (3.4 µg/L). Note that ambient water with SIBX is not presented in this figure, only the fate of SIBX within the nearfield plume itself.

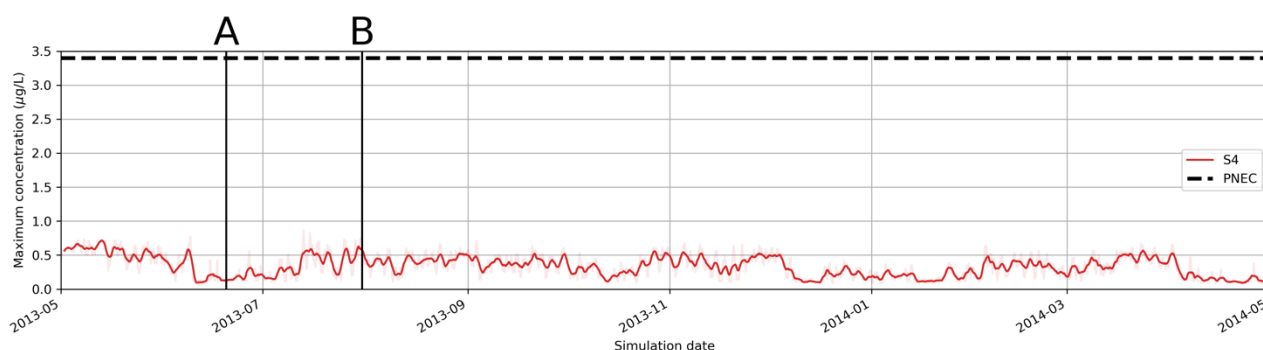


Figure 5.6 Maximum concentration of dissolved SIBX during the one-year simulation period for scenario S4. A 24-hours rolling mean has been applied, then the maximum concentration in any grid cells has been

identified. The plotted lines show the 96-hours trendline for the maximum concentration for the scenario. The black dashed line denotes the PNEC.

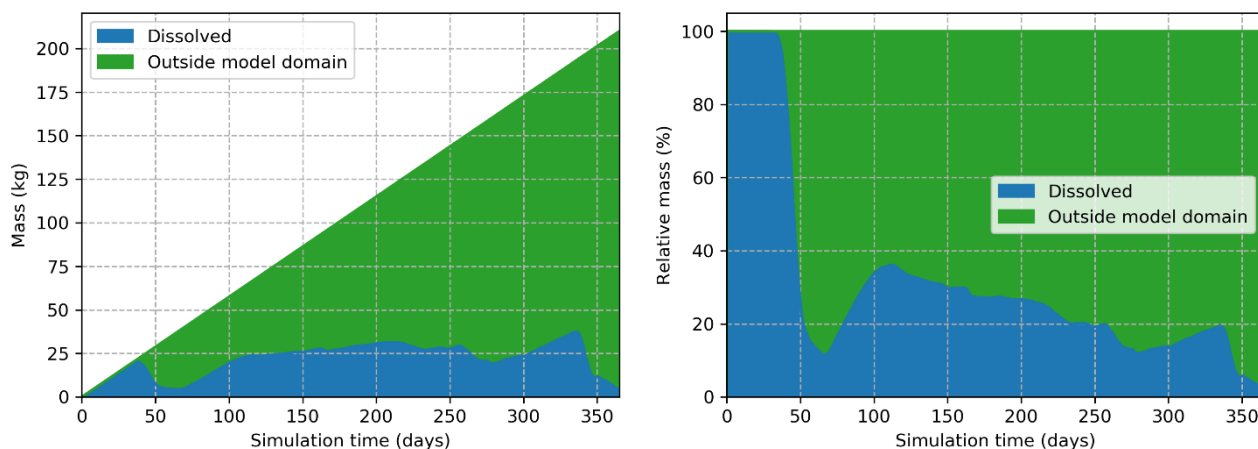


Figure 5.7 Time series of SIBX mass balance. The blue area shows dissolved SIBX within the model domain, and the green area denoted SIBX that has been transported out of the model area by the ambient current. The left panel shows the time series as total released SIBX mass, and the left panel shows the relative mass (%). In the left panel, the sum of the two compartments equals the total amount of discharged (dissolved, not including the particle-attached) SIBX at a given time.

5.4 Comparison of dissolved SIBX concentrations for scenarios S1-S4

Four different scenarios with dissolved SIBX have been modelled. The different scenarios are described in Table 4.5 and Table 5.1. Scenarios S2 and S3 are considered as two worst-case scenarios where none of the discharged SIBX is attached to mine tailings. The difference between the two scenarios is the half-life used. S2 has a half life of 7 days, whereas S3 has a half-life of 25 days. For scenarios S1 and S4, the dissolved fraction of SIBX was 5 and 10 %, respectively. S4 was modelled as a worst-case scenario with respect to biodegradation (no biodegradation).

Table 5.1 Overview of the model input for the different simulations with focus on the dissolved SIBX.

Scenario	SIBX half-life at 10°C	Dissolved SIBX	Concentration of dissolved SIBX at pipe outlet
S1	25 days	5 %	4.3 µg/L (ppb)
S2	7 days	100 %	85 µg/L (ppb)
S3	25 days	100 %	85 µg/L (ppb)
S4	No biodegradation	10 %	8.5 µg/L (ppb)

The time series for each of the four scenarios showing the number of grid cells with concentration exceeding PNEC are shown in Figure 5.8. One grid cell equals a volume of 25 000 m³. There is no grid cell with concentrations higher than PNEC for scenarios S1 and S4, whereas the number of grid cells exceeding PNEC varies between 1 and 2 for S2 and S3.

The maximum concentrations for all four scenarios are shown in Figure 5.9 and Figure 5.10. For Figure 5.9, a 24-hours rolling mean has been applied to the time series before the 96-hour trendline has been plotted as a time series. Figure 5.10 shows the same data as the previous figure, only as a boxplot illustrating the range of the data (boxes are 25-95 percentile). The mean value for each scenario is also given. The figures show that the maximum concentration for scenarios S1 and S4 is always below PNEC, whereas the maximum concentration for S2 and S3 varies between 1-10 µg/L, with the time-median value in the range 4-5 µg/L.

Note that this only applies to 1-2 grid cells in the entire model domain (ref Figure 5.8). We can also observe that the maximum value in scenario S2 can exceed the S3 value, which is not expected based on the higher biodegradation rate in S2, but this is related to numerical fluctuations, which are most pronounced in the maximum values, but less so in other concentration statistics (see next paragraph). The vertical lines in Figure 5.9 denotes the two dates that have been selected for a closer inspection (later in this section).

Figure 5.11 shows the 99.99 percentile for the same data plotted in Figure 5.9. This figure shows that 99.99 % of all the grid cells in the total model domain has value lower than plotted in the figure, whereas only 0.01 % (approximately 20 grid cells) may have a higher value. The figure shows that the 99.99 percentile is always below PNEC for all four scenarios. Here we see that values for scenario S2 is generally below those for scenario S3, as expected.

Time series of the mass balance for dissolved SIBX for scenarios S1-S4 are shown in Figure 5.12. The figure shows that the SIBX leaving the model area mainly leave during two periods that corresponds to the deep-water exchange in June 2013 and April 2014 (mainly S1, S2 and S4). For S3, the mass of SIBX leaving the model domain is larger between the two deep-water exchange episodes than for the other scenarios, which is reasonable, since this scenario has 100% of SIBX not attached to particles, and longer SIBX half-life compared to S2.

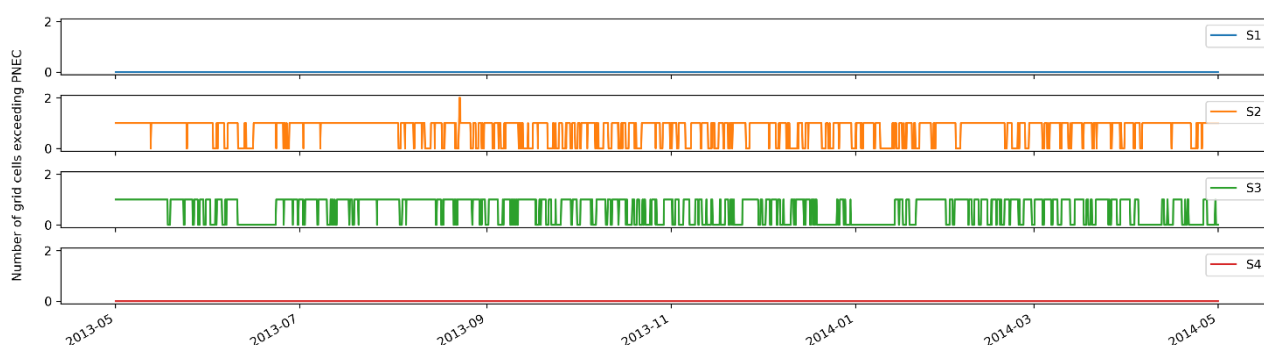


Figure 5.8 Number of grid cells with concentration above the PNEC-value of 3.4 µg/L for the four scenarios (S1 in the upper panel, S2, second, S3 third and S4 lowest panel). The volume in one grid cell equals 50 x 50 x 10 m = 25 000 m³. For scenarios 1 and 4 there is never any grid cells with concentration exceeding the PNEC. For scenarios 2 and 3 there are at any time not more than 1-2 grid cells exceeding PNEC. A 24-hour rolling mean has been applied to the concentration grid before these time series were calculated.

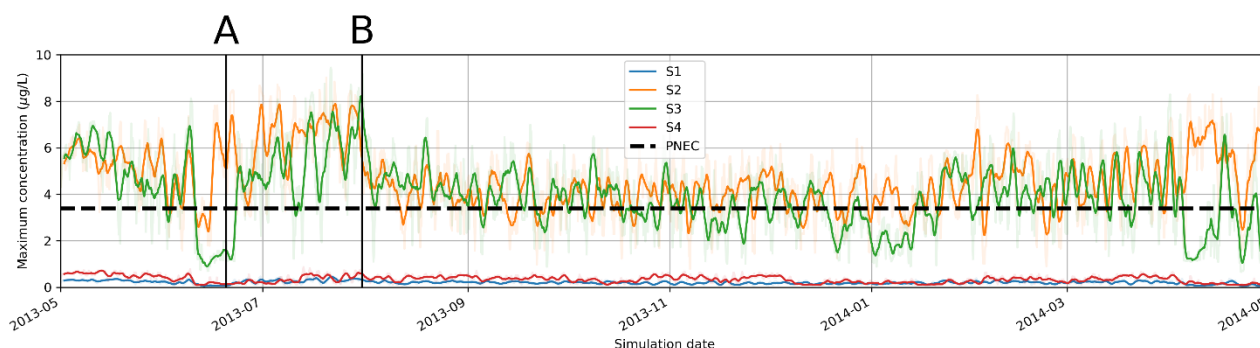


Figure 5.9 Maximum concentration of dissolved SIBX during the one-year simulation period for scenarios S1 – S4. A 24-hours rolling mean has been applied, then the maximum concentration in any grid cells has been identified. The plotted lines show the 96-hours trendline for the maximum concentration for each scenario. The maximum concentration for scenarios S1 and S4 is always below PNEC, whereas the maximum

concentration for S2 and S3 varies between 1-10 $\mu\text{g/L}$. Note that this only applies to 1-2 grid cells in the entire model domain (ref. Figure 5.8 and Figure 5.13). The vertical lines marked "A" and "B" refers to the times used for detailed comparison between the scenarios.

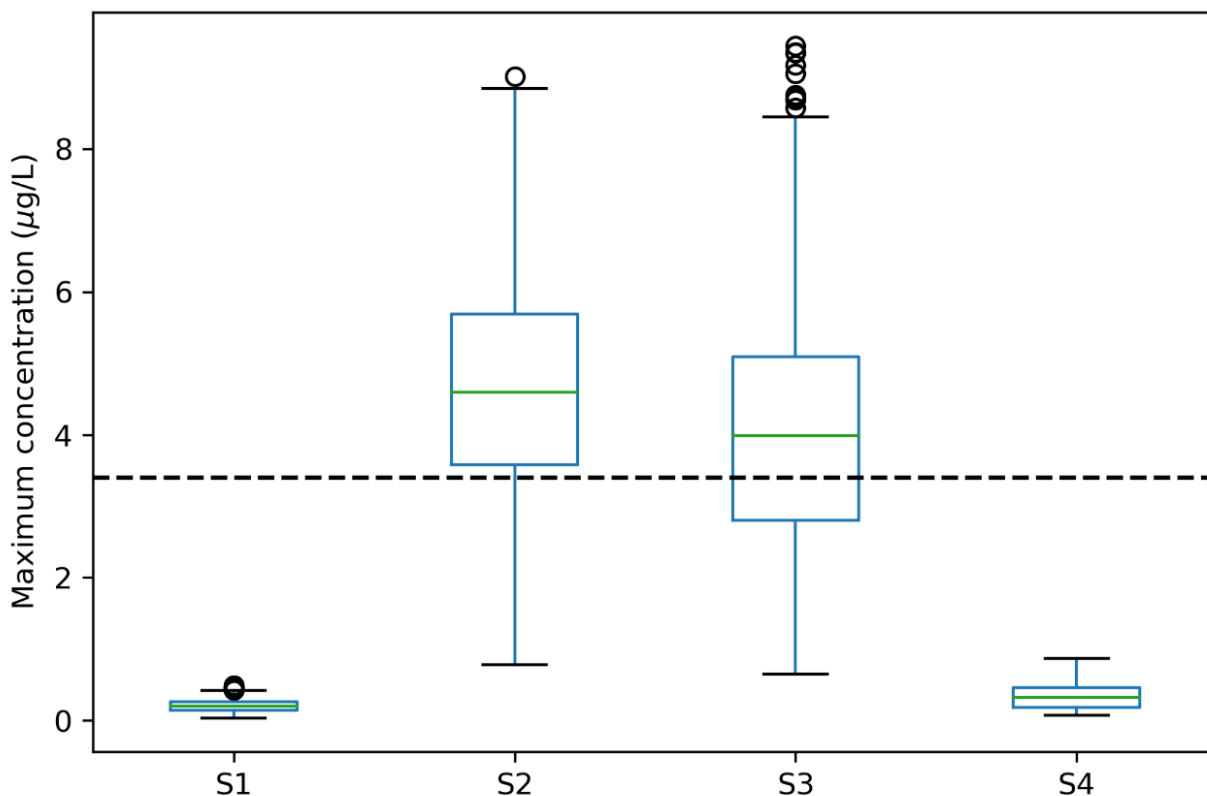


Figure 5.10 Maximum concentration of dissolved SIBX during the one-year simulation period for scenarios S1 – S4. This figure shows the same data as in Figure 5.9, but as a distribution boxplot, which illustrates the range of the data (boxes are 25-95 percentile), and median value (green lines). The maximum concentration for scenarios S1 and S4 is always below PNEC, whereas the maximum concentration for S2 and S3 varies between 1-10 $\mu\text{g/L}$, with the time-median value in the range 4-5 $\mu\text{g/L}$. Note that this only applies to 1-2 grid cells in the entire model domain (ref. Figure 5.8 and Figure 5.13).

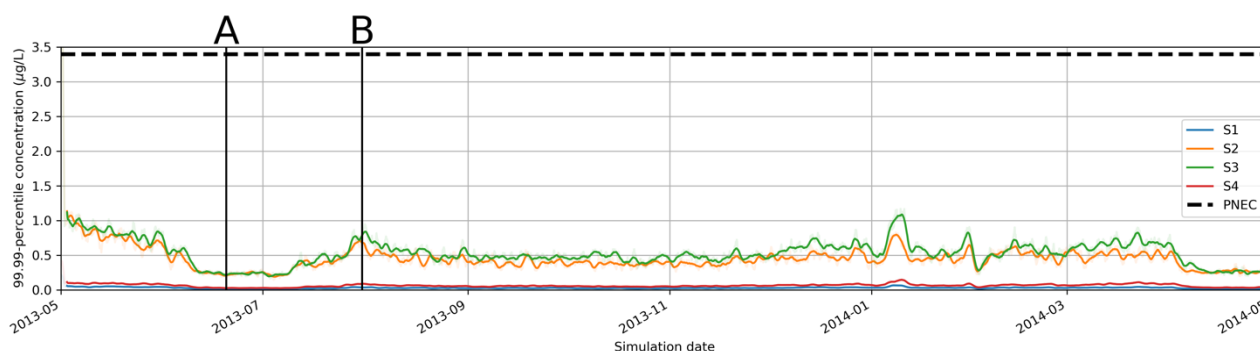


Figure 5.11 99.99-percentile concentration of dissolved SIBX during the one-year simulation period for scenarios S1 – S4. This means that 99.99% of model grid cells have concentrations lower than the values shown here, while 0.01% of grid cells (approximately 20 grid cells) may exceed these values. A 24-hours rolling mean has been applied, then the percentile concentration over all grid cells has been identified. The plotted lines show the 96-hours trendline for the maximum concentration for each scenario. The values concentration

for all scenarios is always below. The vertical lines marked "A" and "B" refers to the times used for detailed comparison between the scenarios.

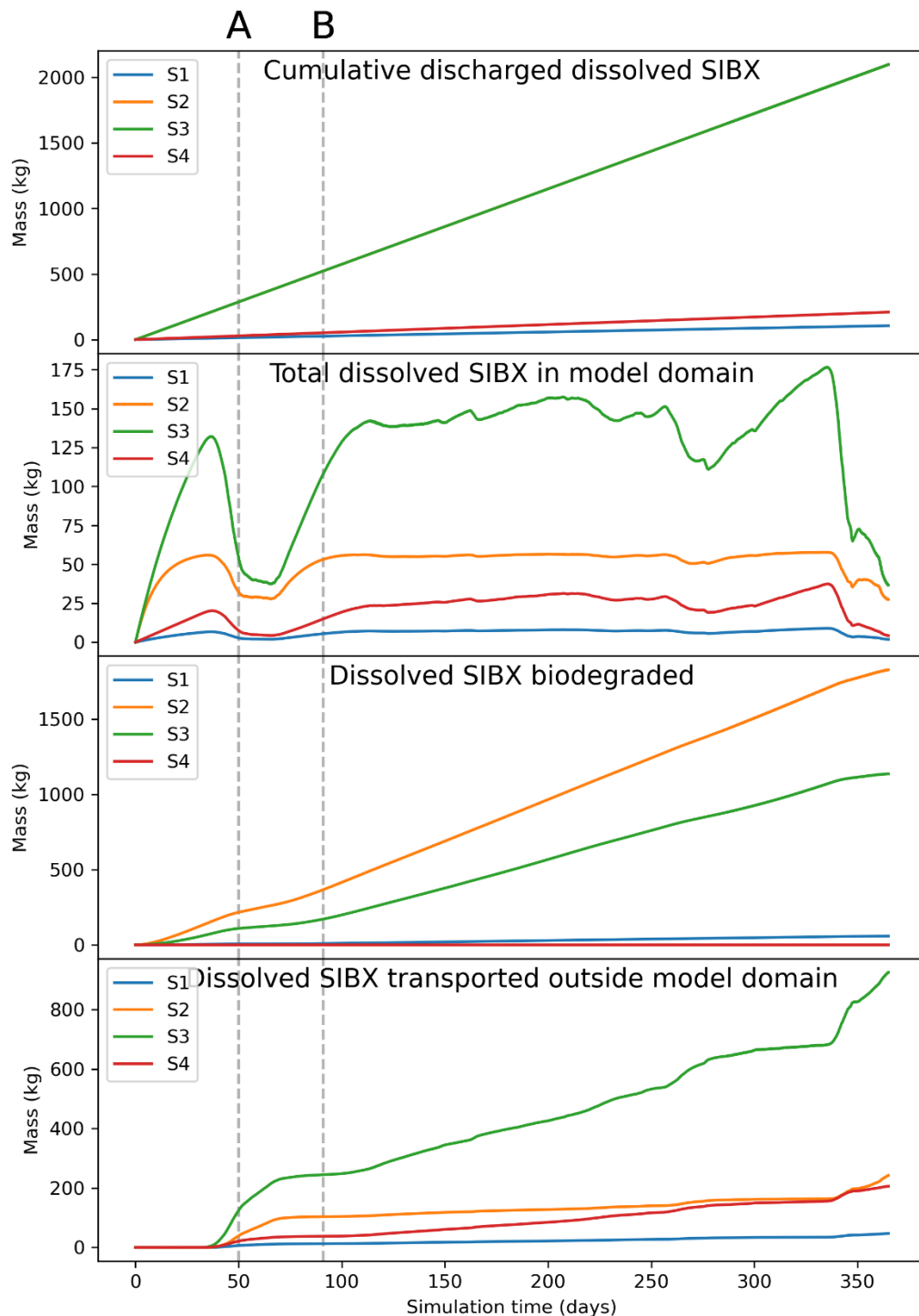


Figure 5.12 Time series of the mass balance for dissolved SIBX for scenarios S1-S4. The upper panel shows the total accumulated discharged SIBX mass over the one-year modelling period. The second panel gives the time series of dissolved SIBX in the water column. The third panel shows the biodegraded SIBX. The lower panel gives the mass of SIBX that leaves the model domain. The figure shows that the SIBX leaving the model area mainly leave during two periods that corresponds to the deep-water exchange in June 2013 and April 2014

(mainly S1, S2 and S4). For S3, the mass of SIBX leaving the model domain is larger between the two deep-water exchange episodes than for the other scenarios.

Two dates, 30th of June and 31st of July 2013 have been chosen as two examples for further study. These two dates are marked with "A" and "B" in Figure 5.9. The basis for choosing these dates, were that the maximum concentration on 30th of June was low in scenario S3, and highest on 31st of July.

Figure 5.13 gives the cumulative distribution of 24-hour mean SIBX concentrations for all four scenarios for the two chosen dates. The maximum concentration for each scenario is marked by an "x" in the same colour as the distribution line. The vertical coloured lines mark the 99.99 percentile, and the vertical black line is the PNEC value. Table 5.2 gives the median, 99 percentile, 99.99 percentile and the maximum values for all four scenarios for the two chosen dates.

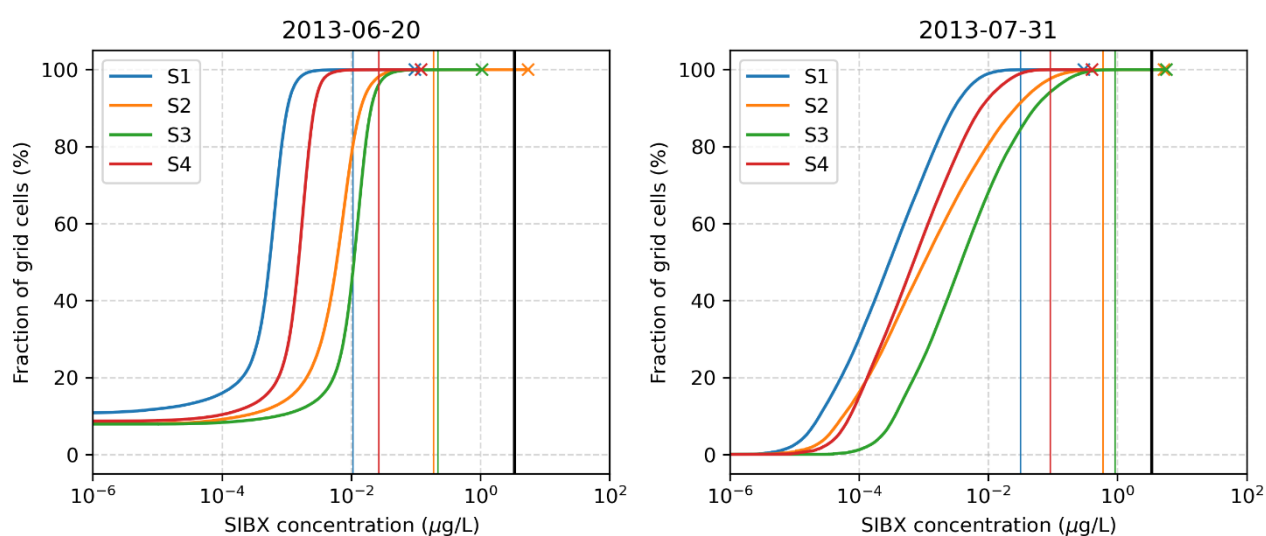


Figure 5.13 Cumulative distribution of dissolved 24 hour mean SIBX concentrations for all model grid cells, days "A" (left panel) and "B" (right panel), scenarios S1 – S4. Maximum concentration values are indicated by the "x" markers. The vertical coloured lines indicate 99.99% concentration values (99.99% of grid cells have concentrations less than this value). The PNEC is indicated by the vertical black line. Generally, scenario S3 has the highest concentration values at any given grid cell fraction (percentile), followed by S2, S4 and S1.

Table 5.2 Dissolved SIBX concentration value statistics for days "A" and "B" (24 hour mean values), taken over all grid cells in the model domain. These correspond to Figure 5.11.

Day	Scenario	Median	P99	P99.99	Maximum
2013-06-20	S1	0.0005	0.0020	0.0105	0.0969
	S2	0.0060	0.0327	0.1867	5.4952
	S3	0.0110	0.0403	0.2169	1.0531
	S4	0.0015	0.0048	0.0264	0.1200
2013-07-31	S1	0.0003	0.0102	0.0315	0.2984
	S2	0.0010	0.1476	0.5912	5.1961
	S3	0.0038	0.2681	0.9117	5.7312
	S4	0.0007	0.0318	0.0910	0.3979

Maps showing the 24 hour-mean, depth-maximum concentrations for two different days ("A" and "B") are given in Figure 5.14. The results for the 20th June (time "A") are shown to the left and the results for 31st July (time "B") are to the right. The figure shows that the maximum concentration on day "A" this day did not exceed the lower figure threshold of 0.3 $\mu\text{g/L}$ for any of the four scenarios. For day "B", the maximum concentration for S1 and S4 did not exceed 0.3 $\mu\text{g/L}$, whereas a larger area inside the submarine tailing deposit with concentrations in the range 0.3-1.0 $\mu\text{g/L}$ is found for S2 and S3. The concentrations are higher for S3 than for S2 (as expected). The corresponding cross-fjord maximum for each scenario is shown in Figure 5.15. The highest concentrations are found for S2 and S3 during day "B", close to the fjord bottom, where the discharge plume terminates.

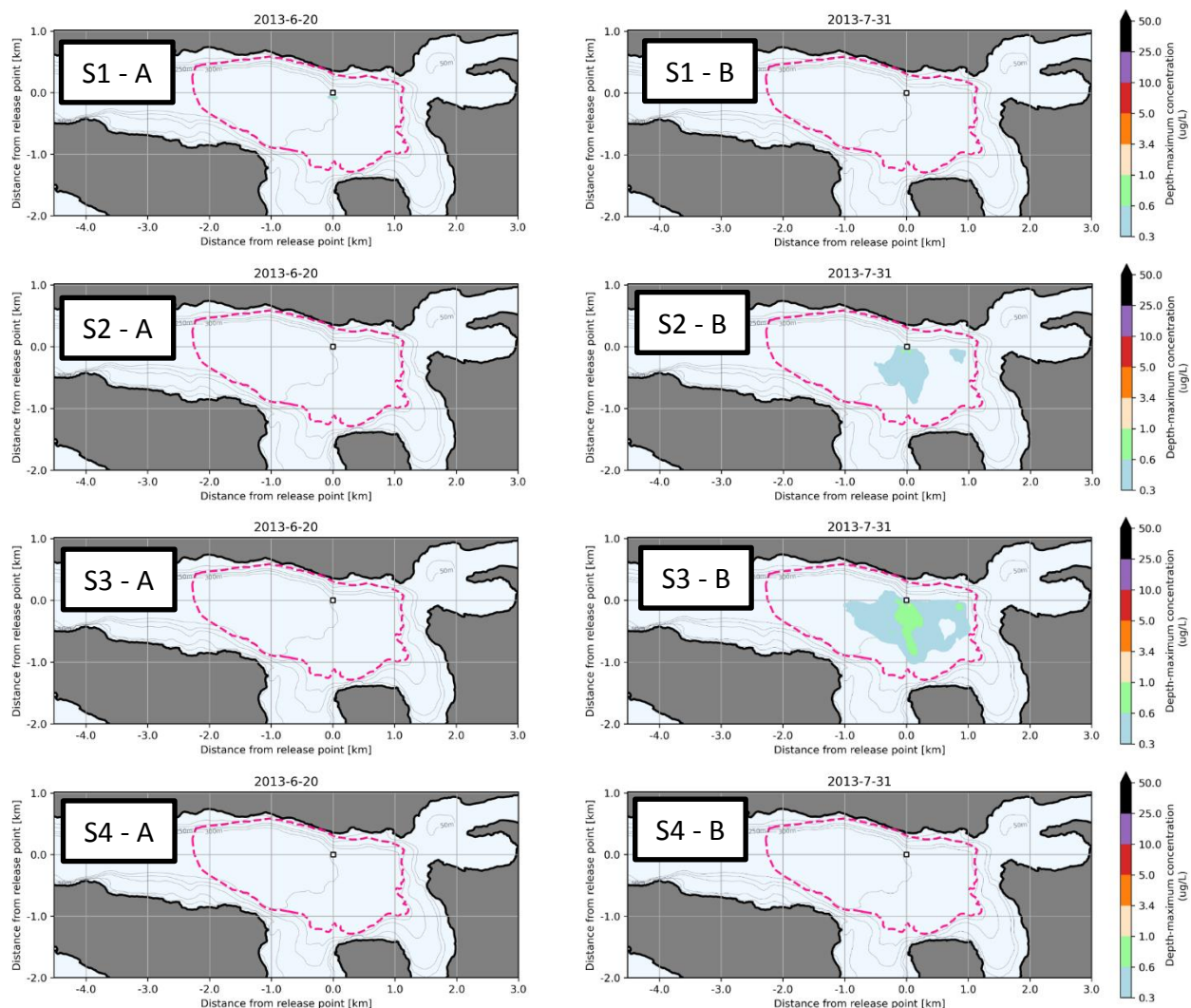


Figure 5.14 24-hour-mean depth-maximum concentration at time "A" (left), and time "B" (right) for the four scenarios. The discharge position marked with the white square, and the pink dashed line marks the outline of the submarine tailing deposit. Values below 0.3 $\mu\text{g/L}$ are not shown here.

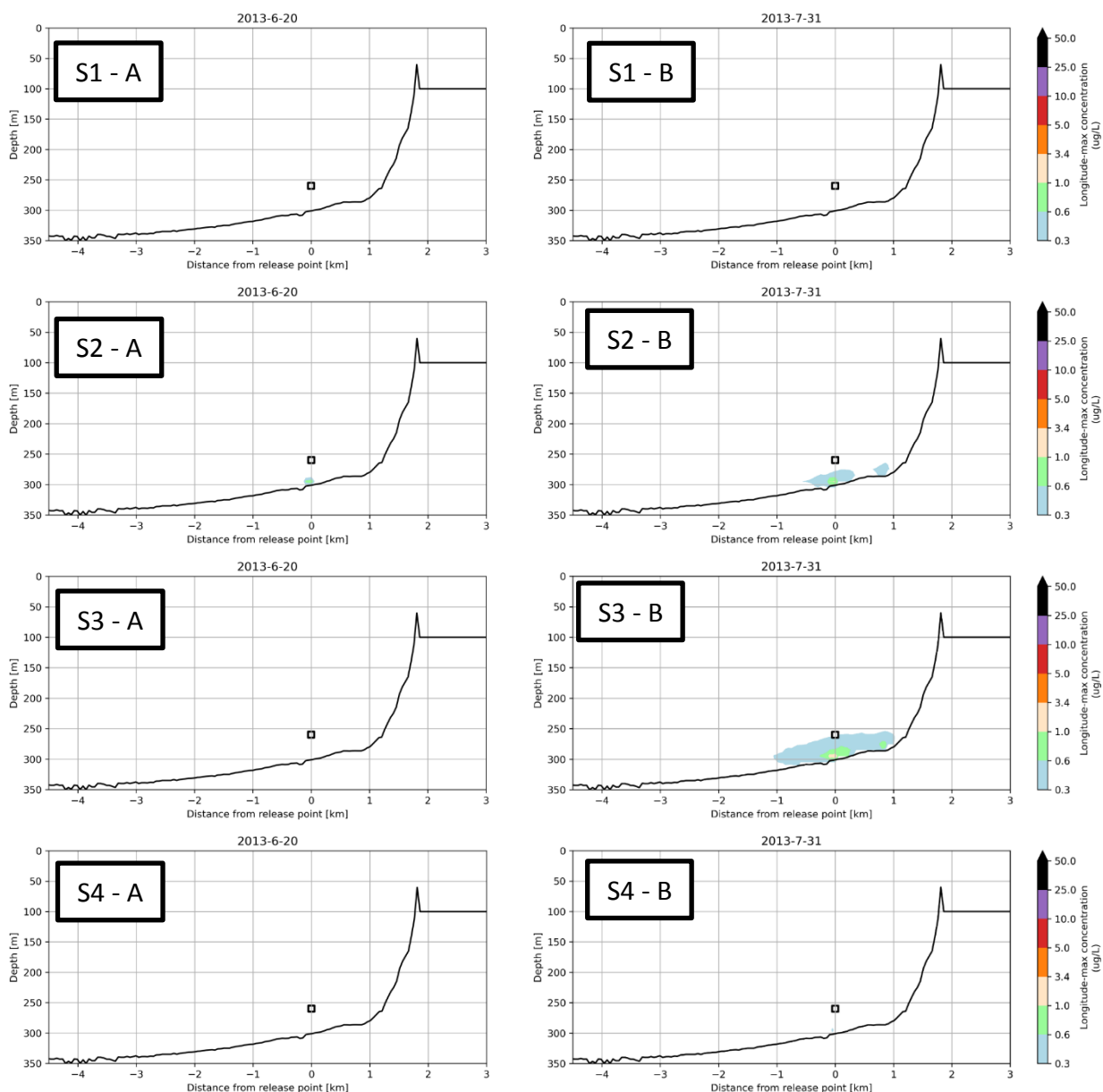


Figure 5.15 24-hour-mean cross-fjord maximum concentration at time "A" (left), and time "B" (right) for the four scenarios. The discharge position marked with the white. Values below $0.3 \mu\text{g/L}$ are not shown here.

6 Summary and conclusion

Four scenarios with different set-up for release of the production chemical SIBX have been modelled: S1 with 95 % attached to mine tailings and 5 % dissolved, S2 and S3 with 100 % dissolved, and S4 with 90 % attached to mine tailings and 10 % dissolved. S1 and S3 were modelled with a biodegradation half-life of 25 days, S2 7 days and S4 without biodegradation.

This modelling study has shown that the concentration of SIBX in the fjord will depend on the release concentration and it will vary with the local current conditions. The number of grid cells exceeding the PNEC value (3.4 µg/L) varies between 1 and 2 for the scenarios with 100 % dissolved SIBX (S2 and S3). For S1 and S4, there were no grid cells with concentrations above PNEC during the entire simulation period. The maximum concentration for scenarios S1 and S4 is always below PNEC, whereas the maximum concentration for S2 and S3 varies between 1-10 µg/L, with the time-median value in the range 4-5 µg/L. The maximum value only applies to 1-2 grid cells in the entire model domain.

The results show that the maximum concentrations for scenarios S2 and S3 are quite similar, and that the biodegradation rate does not seem to influence these results (Figure 5.8 and Figure 5.9). However, when studying the total mass of dissolved SIBX in the fjord, the scenario with the highest biodegradation rate (S2) will have a lower fraction of dissolved SIBX than scenario S3 (Figure 5.12). This can also be seen for the daily mean concentration shown in Figure 5.14, where the extent of dissolved SIBX is much less for S3 than for S2.