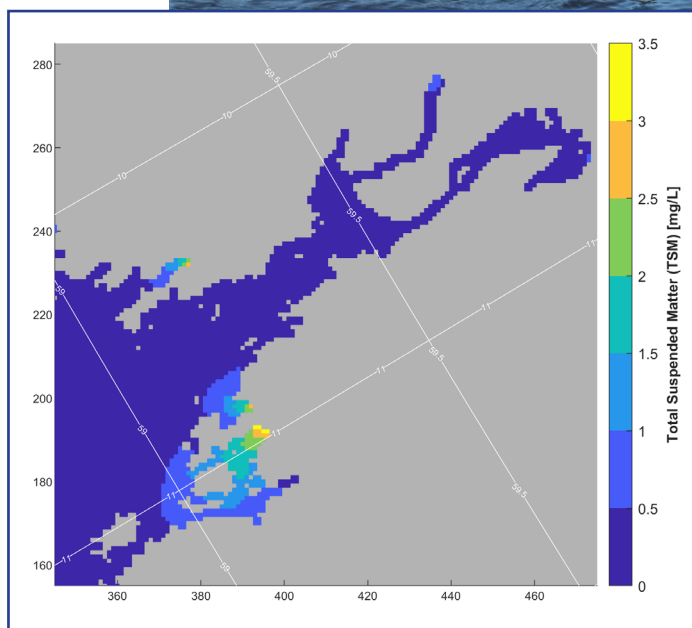
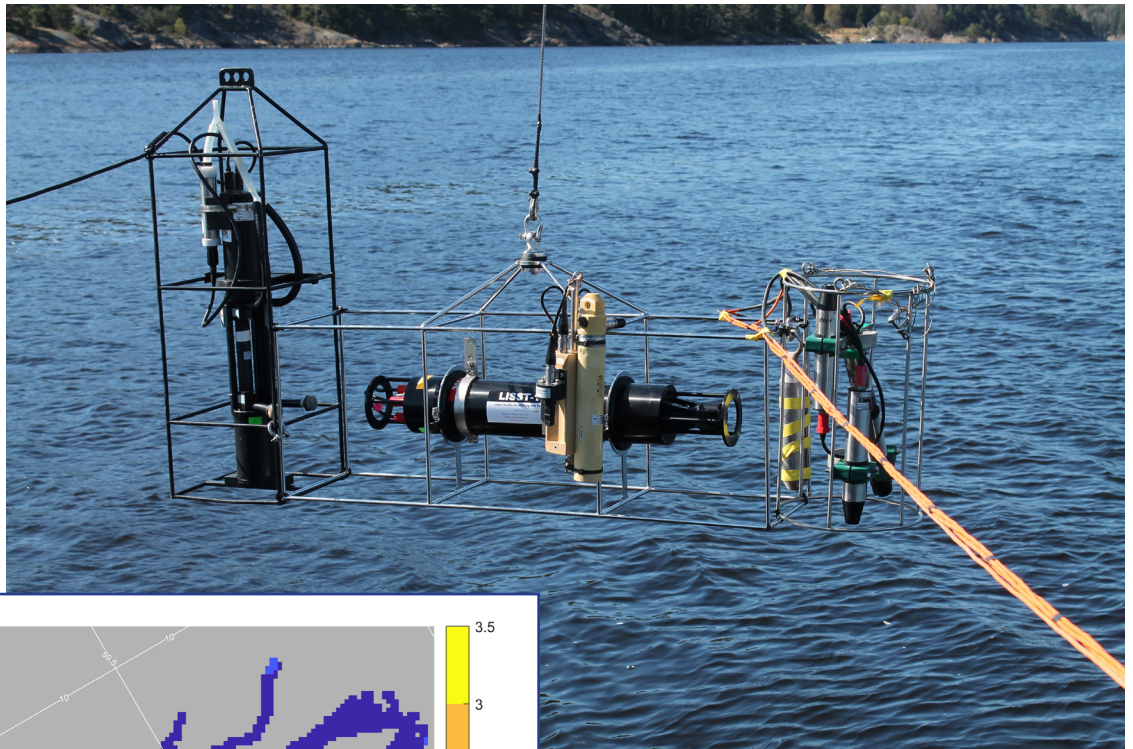


# Potential effects of reduced riverine inorganic particle loading on water quality in the Oslofjord region



# REPORT

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Summary : A model investigation was carried out of the potential impacts of reduced riverine inorganic particle loading in the Oslofjord region. Some significant improvements in water clarity, particularly in the Glomma estuary, were projected by the model for a 100% reduction in inorganic particle loading. This was partly offset by an intensification of phytoplankton blooms, due to more light availability, although this did not strongly impact bottom water dissolved oxygen levels. More focused modelling and observational work is recommended before any large-scale implementation of particle reduction measures, in view of the risks of exacerbating eutrophication and potential harmful algal blooms, and a potential need for concurrent reductions in nutrient loading to minimize these risks.

Four keywords 1. inorganic 2. particles 3. Oslofjord 4. water quality	Fire emneord 1. uorganisk 2. partikler 3. Oslofjord 4. vannkvalitet
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This report is quality assured in accordance with NIVA's quality system and approved by:

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**Potential effects of reduced riverine inorganic  
particle loading on water quality in the  
Oslofjord region**



## Preface

This project was performed by NIVA on behalf of the Norwegian Environment Agency in the period June to December 2020.

We thank Kai Sørensen and Sabine Marty (NIVA) for contributing observational data on particle size distributions (LISST) and water samples for analysis of organic and total particulate matter. We also thank Andrew King (NIVA) for help with extracting relevant Ferrybox data, and André Staalstrøm (NIVA) for contributing Figure 1. We thank Knut-Frode Dagestad (met.no) for help with developing the OpenDrift sediment module.

Bergen, 14 December 2020

*Phil Wallhead*  
(*project leader*)

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## Summary

A modelling study with associated observational work was performed to investigate the potential impacts of reduced inorganic particle loading on water quality in the Oslofjord region. An inorganic sediment dynamics module was developed and coupled to a physical-biogeochemical marine model (MARTINI800, initially developed within the NFR project MARTINI) and a Lagrangian particle-tracking software was developed and applied to complement and test assumptions of the sediment dynamics module. Water samples from a recent (2020) cruise in the Glomma estuary were analysed to determine concentrations of particulate organic, total suspended, and inorganic suspended matter. The marine model showed substantial skill in hindcasting observations from the ØKOKYST-Skagerrak program 2017-2019, as well as the 2020 observations from the Glomma estuary, although a potential limitation in simulating deep water renewal events was identified. Comparing the hindcast results with a scenario simulation, in which all riverine inorganic particle concentrations were reduced to zero, suggested that: i) total particulate concentrations in the Oslofjord would be strongly reduced in areas where they are presently high, such as the Glomma estuary; ii) this would result in significant (up to 20-30%) increases in annual mean euphotic depths in areas such as the Glomma estuary; iii) the improvement in water clarity would be partially offset by an intensification of phytoplankton blooms, due to increased light availability for phytoplankton growth, but this would not significantly affect minimum concentrations of dissolved oxygen in the bottom water. The particle-tracking analysis suggested that the non-cohesive (sandy) particle type is unlikely to have a significant impact beyond a few km of the Glomma river mouth, and that the cohesive particle type (mud/clay) is likely to dominate the broader-scale impacts. We conclude that a reduction of riverine inorganic particle loading, with a focus on fine-grained mud/clay particles, could be a worthwhile strategy to improve water quality in shallow water regions, such as the Glomma estuary, where the improvement in water clarity and substrate availability may facilitate the regrowth of benthic macroflora. Caution is required, however, regarding modelling uncertainties and the risks of exacerbating eutrophication and potential for harmful algal blooms; we would therefore recommend more focused modelling and observational work, and investigations of the potential need for concurrent reductions in riverine nutrient loading, before any implementation of large-scale measures to reduce inorganic particle loading.

# Sammendrag

Tittel: Mulige effekter av reduserte tilførsler av uorganiske partikler på vannkvaliteten i oslofjorden  
År: 2021

Forfatter(e): Phil Wallhead, Trond Kristiansen og Helene Frigstad

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En modellstudie med tilhørende datainnsamling ble utført for å undersøke mulige effekter av reduserte tilførsler av uorganiske partikler på vannkvaliteten i Oslofjordområdet. Gjennom dette prosjektet ble det utviklet en sedimentdynamikk-modul, som ble koplet til en fysisk-biogeokjemisk marin modell (MARTINI800, utviklet gjennom NFR-prosjektet MARTINI). I tillegg ble en lagrangiansk partikkelsporings software utviklet for å støtte og teste antagelsene i sedimentdynamikk-modulen. Vannprøver fra et tokt rundt elvemunningen av Glomma i 2020 ble analysert for å få mer kunnskap om konsentrasjonene av organiske, totalt suspenderte og uorganiske suspenderte partikler. Den marine modellen presterte bra når den ble testet mot historiske data (hindcast) fra ØKOKYST Skagerrak 2017-2019 og data fra Glomma i 2020, men det ble oppdaget en mulig begrensning i å simulere dypvannsfornyning. I dette prosjektet ble det utført en sammenligning mellom simuleringene for hindcast (2017-2019) og et scenario hvor alle elvetilførslene av uorganiske partikler ble satt til null, og dette viste at: i) de totale partikkelkonsentrasjonene i Oslofjorden ville blitt betydelig redusert i områder hvor de nå er høye, slik som rundt elvemunningen til Glomma; ii) dette ville gi en signifikant (opp til 20-30%) økning i den årlige gjennomsnittlige dybden av den eufotiske sonen i kystområdene rundt utløpet til Glomma; iii) forbedringen i vannkvalitet kan bli delvis forskyvet av økt intensitet i oppblomstring av planteplankton, på grunn av bedre lystilgjengelighet for vekst av planteplankton. Likevel, er det ikke ventet at økningen i biomasse av planteplankton ville ha en negativ effekt på oksygenkonsentrasjonene i bunnvannet. Analysene av partikkelsporingene tilsier at de ikke-klebrige (sandholdige) partiklene sannsynligvis ikke har en betydelig innvirkning på vannmassene mer enn et par kilometer fra utløpet av Glomma, og at de klebrige partiklene (gjørme/leire) sannsynligvis har størst innvirkning på større geografisk skala. Vi konkluderer med at en reduksjon i tilførsler av partikler fra elver, med fokus på finkornet gjørme/leire partikler, kan ha betydning for å forbedre vannkvaliteten i grunne kystområdene, slik som rundt utløpet av Glomma. I disse områdene kan en forbedring i vannklarheten og tilgjengeligheten på bunnsubstrat legge til rette for en gjenvekst av bentisk makroflora. Det er viktig å understreke at man må vise forsiktighet i forhold til usikkerheter i modellberegninger og potensialet for å forsterke skadelige algeoppblomstringer; vi vil derfor anbefale mer detaljerte studier, som inkluderer mer høy-oppløselige modeller og muligens moduler for bentisk makroflora, for man implementerer stor-skala tiltak for å redusere partikkelbelastningen.

# 1 Introduction

Among Norwegian coastal regions, the Oslofjord region has suffered some of the strongest impacts of human activities on coastal water quality, including eutrophication, invasive species, littering, and pollution driven by emissions from industry, agriculture, and wastewater treatment facilities (OSPAR, 2017). Traditionally, investigations of the causes of decreased water quality have tended to focus on the supply of dissolved inorganic nutrients (e.g. nitrate, phosphate) to coastal waters, as a driver of excessive algal production and subsequent oxygen consumption (eutrophication). However, there is an increasing awareness of the need to also consider inputs of dissolved organic matter and particulates which may alter marine production and/or the marine environment through changes in light attenuation (Frigstad et al., 2020). In particular, the outer Oslofjord region has seen dramatic long-term shallowing of the lower depth limit of kelp species (Moy et al., 2008) and it is thought that this may be partly driven by inputs of organic matter and inorganic particles from the Glomma river. As pressures from climate change and anthropogenic emissions driven by growing populations are expected to increase in the coming decades, it is important to consider a broad range of potential management interventions that may safeguard and improve water quality in the Oslofjord region (as part of the “Helhetlig tiltaksplan for en ren og rik Oslofjord med et aktivt friluftsliv”).

During 2018-2020, NIVA developed an ocean biogeochemical model for the Oslofjord and wider Skagerrak region (“MARTINI800”) as part of an NFR project (MARTINI) investigating regional water quality and potential impacts of coastal inputs. The MARTINI800 model simulates the 3D ocean physics coupled to a biogeochemical model including a complex planktonic food web and its interactions with seawater chemistry (nutrients, organic matter, oxygen, carbonate chemistry). However, within the MARTINI project this model was not developed to explicitly account for inorganic particles. The present MARTINI-extension project was therefore developed with three main objectives:

- 1) to couple the MARTINI800 model with a sediment dynamics module to account for the interactions of inorganic particles with the marine ecosystem and water quality;
- 2) to supplement existing observations relating to inorganic particles in the Oslofjord region;
- 3) to use the MARTINI model to investigate the impact of inorganic particle inputs on water quality in the Oslofjord region and potential effects of reducing these inputs.



## 2 Methods

### 2.1 Observed suspended particulate matter concentrations

There is a lack of observations on the inorganic fraction of suspended particles, as it is the total suspended matter (TSM) and particulate organic carbon (POC) that are most commonly measured in the coastal monitoring programs. Therefore, we extended the sampling for ØKOKYST and the Outer Oslofjord monitoring programs, with surface (0 m) observations of selected parameters at 7 stations in September 2020 (see Table 1). We measured POC and particulate organic nitrogen (PON), in addition to suspended tørrstoff (STS) and suspended gløderest (SGR). Note that there is a technical difference between TSM and STS measurements, due to the use of different filters, but this should be negligible for our purposes, and we will later use STS data as estimates of TSM.

STS and SGR are not routinely measured in the coastal waters but were included here to enable us to differentiate between organic and inorganic fractions of the suspended particulate matter. Suspended tørrstoff (STS) is the dry weight of all suspended particles retained on a GF/F-filter (approx.  $> 0.7 \mu\text{m}$ ). The filter is rinsed with distilled water to remove salt in the marine samples; this is a critical step that can cause bias if not done properly. The filter then is combusted ( $480 \text{ }^\circ\text{C}$ ) and the residue (suspended gløderest, SGR) is determined by weighing. The organic matter in the sample will be lost in the combustion process, hence the SGR should represent the inorganic fraction, while the organic fraction can be calculated by subtraction.

Table 1. Stations with extended sampling in September 2020.

Station name	Station code	Latitude ( $^\circ\text{N}$ )	Longitude ( $^\circ\text{E}$ )	Date (dd/mm/yyyy)
Sandesund	L0	59.2709	11.0920	07/09/2020
Glomma v/Fredrikstadbrua	L1	59.2047	10.9502	08/09/2020
Kjøkkøy	L5	59.1465	10.9617	08/09/2020
Leira	Ø1	59.1365	10.8339	08/09/2020
Ramsøy	I1	59.1094	11.0020	08/09/2020
Torbjørnskjær	VT3	59.0360	10.6652	07/09/2020
Missingene	VT65	59.1867	10.6917	08/09/2020

To estimate size distributions of the suspended particulate matter, we used Laser In Situ Scattering Transmissometry (LISST) instrument. The LISST measures the intensity of its laser beam scattered forward by the particles at 32 angles. The scattering angles are then inverted to give particle size distributions as volume and number concentrations for 32 size classes logarithmically spaced from 1.25 to  $250 \mu\text{m}$ , based on Mie theory for spherical particles.

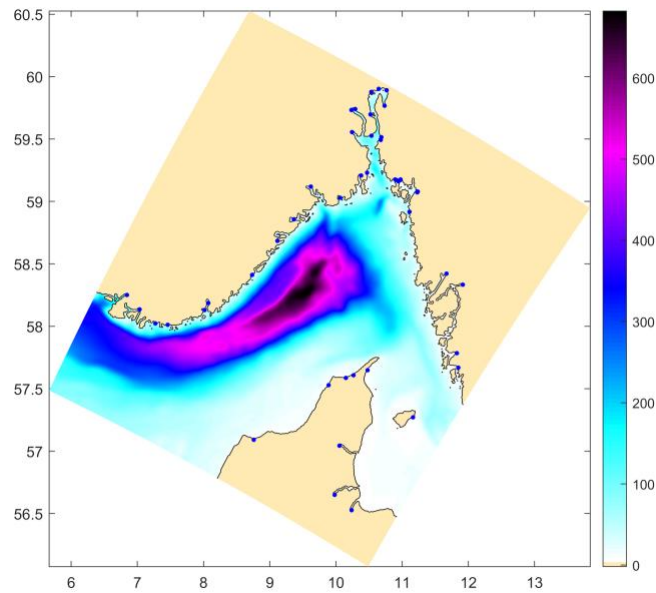
### 2.2 The MARTINI800 marine ecosystem model

Here we give a brief overview of the MARTINI800 model structure (2.2.1) followed by more detailed explanation of the aspects most relevant to inorganic particle modelling, namely the sediment dynamics module (2.2.2) and the sediment river inputs (2.2.3).

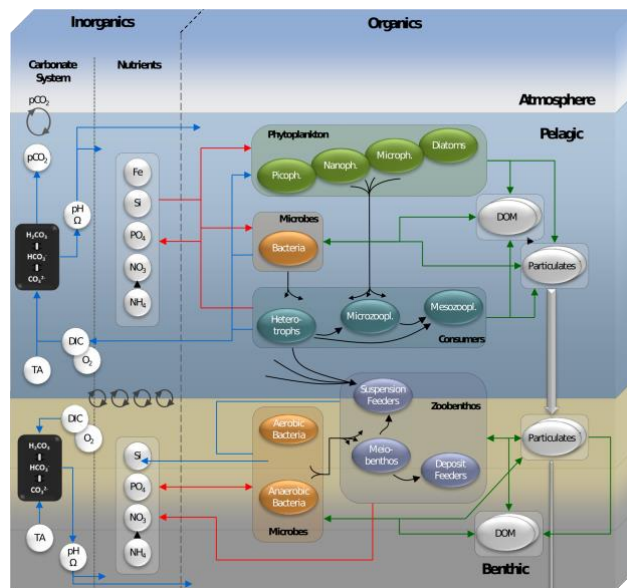
#### 2.2.1 MARTINI800 model structure

The MARTINI800 marine ecosystem model was built on a ROMS 3D physical ocean circulation model (Shchepetkin and McWilliams, 2005), configured on a grid with 800 m horizontal spatial resolution (Figure 1). The ROMS model was coupled to a biogeochemical model based on the ERSEM model

(Butenschon et al., 2016; Figure 2) that has been adapted at NIVA for Nordic planktonic ecosystems. The physical and ecosystem models were coupled using the Framework for Aquatic Biogeochemical Models (FABM; Bruggeman and Bolding, 2014). In the present project we added a sediment dynamics module based on the Community Coastal Sediment Transport Model (Warner et al., 2008) which was further developed to include flocculation/disaggregation processes using the floc model FLOCMOD (Verney et al., 2011; Sherwood et al., 2018) within the COAWST branch of the ROMS code. The model is forced by atmospheric variables derived from MEPS downscaling reanalysis (MET.no), river discharge data from NVE, boundary conditions from TOPAZ reanalysis, and river biogeochemical concentrations and temperatures derived from Vanmiljø and NIVA internal data archives.



**Figure 1.** MARTINI800 model region. Blue dots show model inputs from rivers. Longitude (deg E) is shown on the x-axis, and latitude (deg N) is shown on the y-axis. The colour scale shows the model water depth in metres.

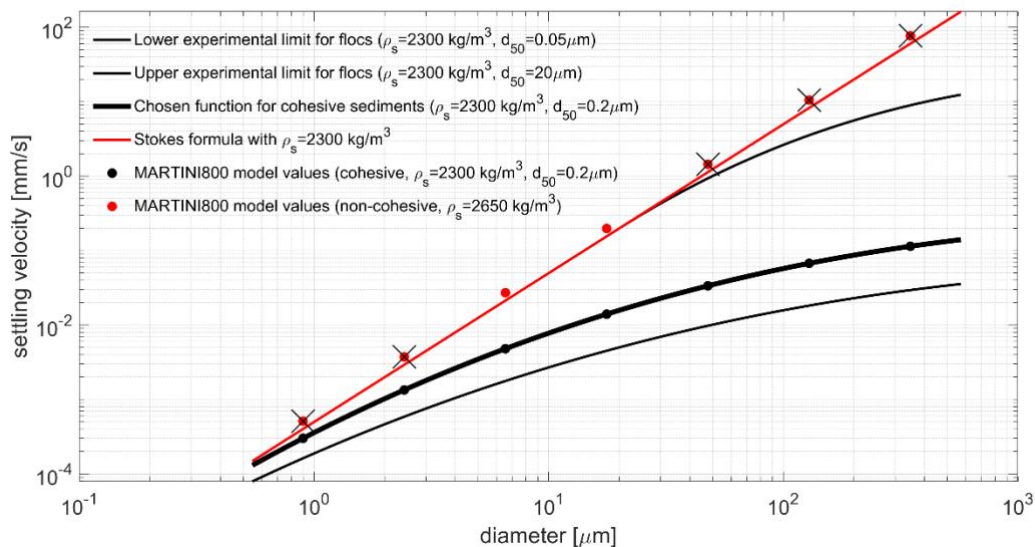


**Figure 2.** The ERSEM marine ecosystem model on which the MARTINI biogeochemical module is based (figure from Butenschon et al., 2016).

## 2.2.2 MARTINI800 inorganic sediment module

In the ROMS sediment module, particles are represented as either “cohesive” (clay, some silt grains) or “non-cohesive” (sand, some silt grains) particle types, and each of these types is resolved into a user-defined number of size classes. With the floc module activated, the cohesive particle fractions will aggregate/flocculate, transferring mass to larger size classes with larger settling velocities, and also disaggregate due to turbulent shear and collisions, transferring mass to smaller size classes with lower settling velocities (see Sherwood et al., 2018). Important input parameters include the densities and settling velocities of the floc/particle size classes, as well as the rate/efficiency parameters describing the interactions between flocs (collision/flocculation efficiency, shear fragmentation rate etc.).

After reviewing the literature, we concluded that the variable-fractal-dimension floc model of Khelifa and Hill (2006) would be the best approach to describe the densities and settling velocities of the cohesive particle classes. In this model, the fractal dimension  $F$  of the flocs varies with floc size, decreasing from  $F=3$  at the size of the primary (constituent) particles and reaching  $F=2$  at a larger floc size  $D_{fc}$  (we use the default value  $D_{fc} = 2000 \mu\text{m}$  recommended by Khelifa and Hill, 2006). This decrease makes intuitive sense, since the flocs will be more “solid” as we approach the size of the constituent primary particles, and has been experimentally verified (e.g. Vahedi and Gorczyca, 2011, Fig. 5). Consequently, the floc settling velocities tend towards those given Stokes’ formula at small sizes, but increase less rapidly than predicted by Stokes’ formula as the floc size increases (Figure 3).



**Figure 3.** Settling velocities as a function of particle/floc diameter, showing the range of values for flocs from the Khelifa and Hill (2006) function which encompass the experimental data (thin black lines), the chosen function to represent cohesive particles in the MARTINI800 model (thick black line), the corresponding predictions from applying Stokes’ formula (thin red line), and the adopted values for size classes within the MARTINI800 model for cohesive particles (black dots) and non-cohesive particles (red dots). Crosses show size classes that were excluded from the model, either because the input concentration was neglected (2 smallest sizes) or due to large settling velocity which would cause numerical instability (3 largest sizes).  $\rho_s$  is the assumed solid density of primary particles, and  $d_{50}$  is the assumed median diameter of primary particles.

As noted by Khelifa and Hill (2006), the primary particle size is a major source of uncertainty in the floc model, that can explain most of the spread in the experimental data for settling velocity vs. floc size. In reality, the primary particles are likely to have a range of different sizes, and a correction factor is available to account for this heterogeneity within the Khelifa and Hill (2006) model. In

principle, it should be possible to measure the primary particle size distribution in sea or river water samples, by applying suitable disaggregation treatments. Such data were not however available for our study region, and so we have adopted the recommended pragmatic solution of assuming a single primary particle size representing the median diameter  $d_{50}$ . Khelifa and Hill (2006) suggest a realistic range of 0.05 – 20  $\mu\text{m}$  for  $d_{50}$  and a default value of 1  $\mu\text{m}$  (Figure 3). However, our LISST data showed that a significant fraction of the particles/flocs were  $<2 \mu\text{m}$  (clay particles), suggesting that a smaller value of  $d_{50}$  would be more appropriate. We therefore chose  $d_{50}=0.2 \mu\text{m}$ , a low value but well within the range supported by experimental data. For the other parameters of the Khelifa and Hill (2006) model we used the recommended default values. These choices result in the thick black curve shown in Figure 3.

For the parameters of the flocculation process, in lieu of any observation to infer region-specific values, we have kept the default values used in the demonstration input script. In particular this includes a collision efficiency  $\alpha = 0.35$  and a shear fragmentation rate  $\beta = 0.15$ . Verney et al. (2011) derived optimal values of  $\alpha = 0.35$  and  $\beta = 0.12$  by comparing FLOCMOD predictions with field observations; however it was found that  $\beta=0.12$  led to numerical instability, so we have kept the default value of 0.15.

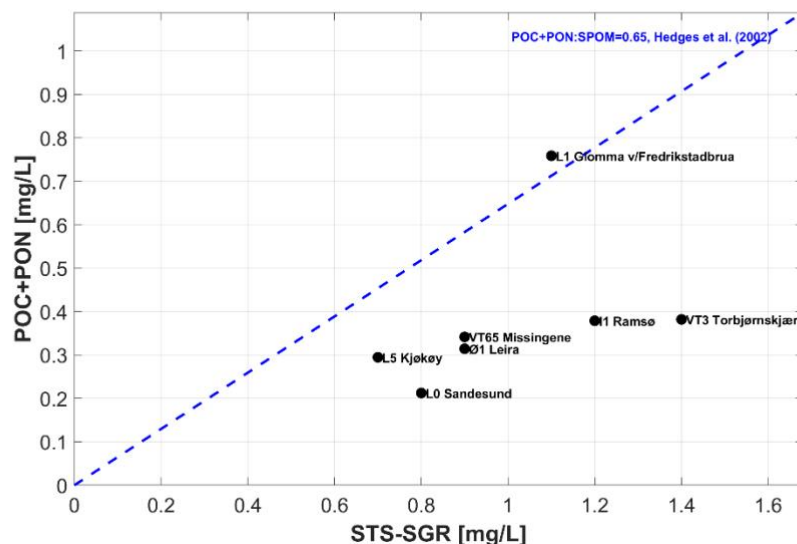
Some development of the ROMS sediment module code was necessary to implement the Khelifa and Hill (2006) model, and also to improve the stability of the numerical algorithm used to simulate the flocculation dynamics (to avoid the need for an impractically-short time step).

### 2.2.3 MARTINI800 river sediment inputs

To estimate river inputs of sedimentary particles, we first collated observational data from Vannmiljø and NIVA archives for Suspended Particulate Matter (SPM, or Suspendert tørrstoff, STS) concentrations from all rivers within the MARTINI800 domain (Figure 1, Danish river data came from the ODA database; Swedish STS data were not found, so they were filled using a linear regression model  $\text{STS} = a \times \log(\text{discharge}) + b$ , based to the available Nordic data). As with other biogeochemical variables, the observational data were kernel-smoothed over space to the sampling positions of the dominant rivers within each catchment, such that the concentrations in the model rivers (representing each catchment) largely reflected the concentrations sampled in the dominant rivers where available. The concentrations were also smoothed over time and interpolated to provide daily inputs to the marine model.

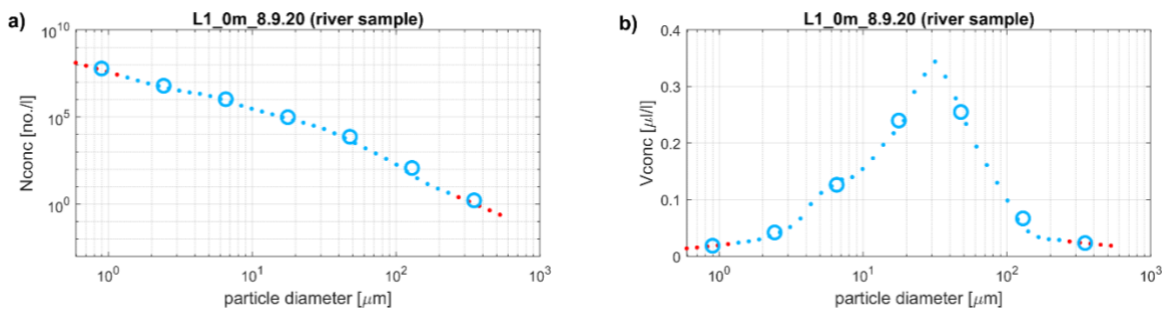
The total SPM in rivers includes contributions from some particulates that are already included as riverine inputs to the marine biogeochemical model (i.e. particulate organic carbon, nitrogen, and phosphorus (POC, PON, POP), biogenic silica (opal), and calcite). To calculate the input concentration of inorganic particles for the sediment dynamics module (excluding those input to the marine biogeochemical model) we subtracted from SPM an estimate of the total particulate organic dry mass [mg/L] based on the riverine POC+PON+POP. Here we assumed an average organic matter stoichiometry of  $\text{C}_{106}\text{H}_{177}\text{O}_{37}\text{N}_{16}\text{PS}_{0.4}$  (Middelburg, 2019, based on Hedges et al. 2002) which implies that the sum of particulate organic CNP mass is 66% of the total particulate organic dry mass. This resulted in input concentrations roughly 12% smaller than SPM. Strictly speaking, the contributions from biogenic silica and calcite should also have been subtracted (this would have resulted in input 18% smaller than SPM); however, given the large uncertainties in our estimates of riverine opal and calcite, we opted in favour of a slight overestimation by subtracting only the organic components.

The Hedges et al. stoichiometry seems to be a reliable average global estimate for marine organic matter, agreeing well with a previous estimate by Anderson (1995) (see Middelburg, 2019, and Sarmiento and Gruber, 2006 for further discussion). However, there can be local and seasonal variations around this average stoichiometry, and moreover we are applying it here to river organic matter, which may have a different average stoichiometry. We therefore sought to test this conversion factor using simultaneous measurements of POC, PON, STS, and SGR (“gløderest”) from an oceanographic cruise in September 2020 that included both river and ocean samples (supported by the Horizon 2020 project DCS4COP). In theory, if the SGR can be considered to measure the inorganic fraction of STS, then the difference (STS-SGR) (“glødetap”) should measure the total organic dry mass. Hence the measured mass ratios (POC+PON):(STS-SGR) can be compared to the ratios predicted by the Hedges et al. stoichiometry (see Figure 4). This analysis suggested that the riverine samples at L1 Glomma were consistent with the ratios predicted by the Hedges et al. stoichiometry, but the other riverine sample (L0 Sandnesund) and marine samples showed variable and generally lower mass ratios. After considering various possible measurement biases, including the potential for some inorganic matter to be lost during the heat treatment (Hedges et al., 2002), and possible interference from salt when measuring STS/SGR at low concentrations, we concluded that there was not strong enough evidence here to refute or improve upon the literature-based ratios. We therefore applied the Hedges et al. stoichiometry as described above to estimate the riverine input concentrations for the inorganic sediment module.



**Figure 4.** Cruise observations of (Particulate Organic Carbon + Particulate Organic Nitrogen) vs. Suspended Particulate Organic Matter (estimated from STS-SGR) in surface waters at the different sampled stations. Dashed lines show literature ratios (POC+PON):SPOM based on the composition of general marine particulate organic matter (blue, Hedges et al., 2002).

To fully specify the inputs to the inorganic sediment module, we need to specify not only the total concentration of riverine particles, but also their nature i.e. the distribution of mass between particle size classes, and cohesive vs. non-cohesive fractions. We estimated size fractions using LISST data from the DCS4COP cruise (September 2020) for the river station L1 Glomma (see Figure 5). The LISST instrument provided number and volume concentrations in 32 size classes with equal spacing on a log scale (small blue dots). To estimate fractions for the 7 model size classes, the LISST data were first extrapolated to add 5 classes at the lower and upper ends (by linearly extrapolating number concentration on a log-log scale and then computing volume concentrations, see small red dots). The extended LISST data were then averaged into the 7 model size bins which, by design, coincided exactly with groups of 6 consecutive LISST data bins (see large blue circles).



**Figure 5.** Particle number concentrations (a) and volume concentrations (b) in the river water sample from station L1 Glomma (near Fredrikstadbrua) during September 2020. Small blue dots show the LISST measurements, small red dots show extrapolated data, large blue circles show average concentrations within the chosen model size classes (7 sizes).

Given the volume concentration fractions in model size classes, the next step was to fractionate each size class fraction into cohesive (mud/clay/silt) vs. non-cohesive (sand/silt) subfractions. We were unable to find measurements of cohesive particle fractions at the mouth of the Glomma, or indeed any Norwegian rivers. However, the size of the sediment particles gives some information on their likely cohesiveness. According to Wolanski et al. (2013), cohesive sediments (muds or clays) have a mean particle size  $<4 \mu\text{m}$ , non-cohesive sediments (sand) have a mean size  $>64 \mu\text{m}$ , while silt has an intermediate mean particle size and is weakly cohesive. Based on this, we assumed that all model size fractions with median size  $<4 \mu\text{m}$  were 100% cohesive, and that the cohesive subfraction reduces linearly with increasing median size, such that the cohesive subfraction at  $64 \mu\text{m}$  is 50%. Next, we derived mass fractions from the volume fractions using the floc density model of Khelifa and Hill (2006) for the cohesive particle classes, and assuming a constant density of  $2650 \text{ kg/m}^3$  for the non-cohesive classes (Sherwood et al., 2018). The net result was that most of the sedimentary mass (77%) was assigned to the middle three size classes ( $4.0\text{-}10.8 \mu\text{m}$ ,  $10.8\text{-}29.0 \mu\text{m}$ ,  $29.0\text{-}78.4 \mu\text{m}$ ) for both cohesive and non-cohesive fractions (cf. Figure 5b).

The resulting mass fractions were then applied to the derived input total particle concentrations of all MARTINI model rivers to generate input concentrations for all inorganic particle classes. The smallest two size classes for non-cohesive particles were excluded from the model because their calculated river input concentrations were zero (see crosses in Figure 3). The largest three size classes for non-cohesive particles were also excluded because their high settling velocities would cause numerical instabilities in the MARTINI model (see Figure 3). These larger particles are expected to settle very close to the river mouths, such that their range of influence is likely negligible on the scale of the MARTINI model. However, this latter assumption was tested using the particle-tracking analysis (see next section).

## 2.3 Particle tracking with OpenDrift software

The dispersal and settling of particle input from river mouths are key processes in assessing the marine effects of riverine particle loading, and their representation within the ROMS-ERSEM model is subject to various uncertainties and assumptions (see section 2.2). We therefore decided to further investigate these processes and test our assumptions by applying a particle tracking software to the particle input from the Glomma river. This was done only for the non-cohesive particles, since the flocculation and disaggregation processes were problematic to represent within the particle tracking approach.

Individual particles with varying diameters, but constant densities, were released for each month of the year 2019 in a radius of 300 m around a point near to the Glomma river mouth (10.96°E, 59.17°N). To quantify drift and deposition (i.e. settling on the seafloor), we developed a sediment module and applied it to the open-source particle tracking framework OpenDrift developed by met.no (Dagestad et al. 2018, <https://opendrift.github.io/>). The combined modelling framework allowed us to simulate the horizontal drift of particles due to currents, including wind effects (Stokes drift) and vertical mixing from turbulence, and accounting for sinking and deposition. The spatial and vertical positions of individual particles were tracked at hourly timesteps using the MARTINI800 physical (ROMS) model results as forcing for advection by ocean currents.

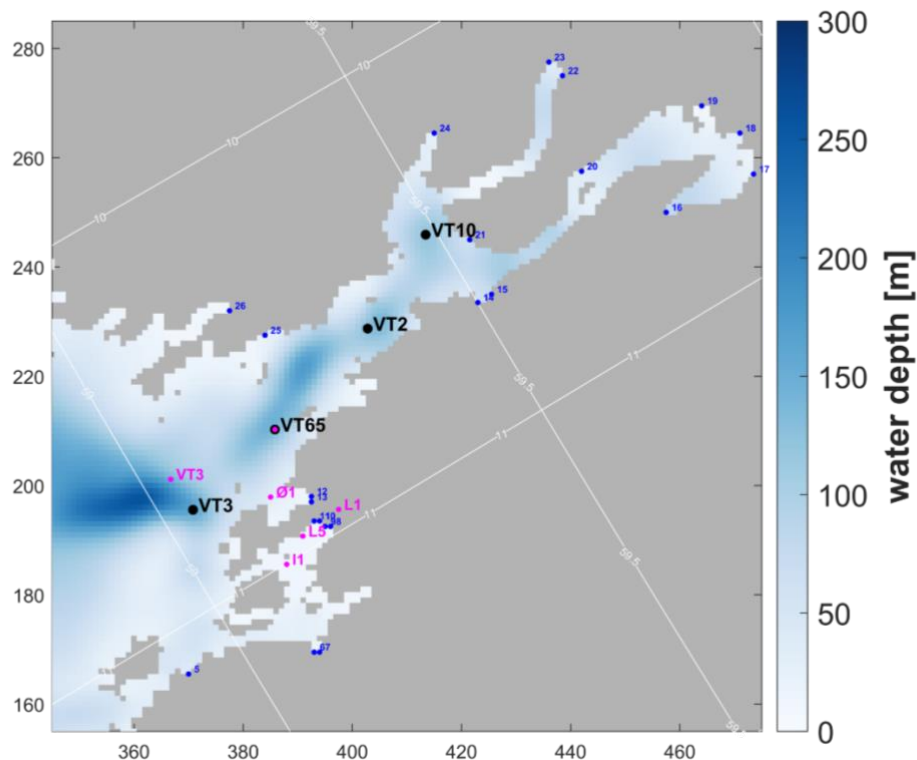
Particle sizes were assigned following a uniform distribution between the minimum and maximum size class diameters (6.5 and 348.1  $\mu\text{m}$ ) for which non-cohesive particle input was estimated to be  $>0$  when setting up the ROMS-ERSEM simulation (namely, the largest 5 size classes shown as red dots in Figure 3). Note that the mass distribution within the size range is not important here, since we later normalize our results to give probabilities of dispersion to different locations. As in the ROMS-ERSEM simulation, all non-cohesive particles had density  $2650 \text{ kg/m}^3$  and settling velocity following Stokes' law (see Figure 3). Particles were defined as settled when they reached the seafloor, but could also be resuspended if the bottom currents exceeded 0.5 m/s.

Note that the particle tracking approach was not subject to the same numerical constraints as MARTINI800, and was able to simulate the larger particles that had been excluded for numerical reasons from the ROMS-ERSEM model (see crosses on the largest 3 size classes in Figure 3). Hence we were able to test the assumption made by the MARTINI800 model that the largest 3 non-cohesive size classes could be neglected due to limited dispersal.

### 3 Results and Discussion

#### 3.1 MARTINI800 model validation

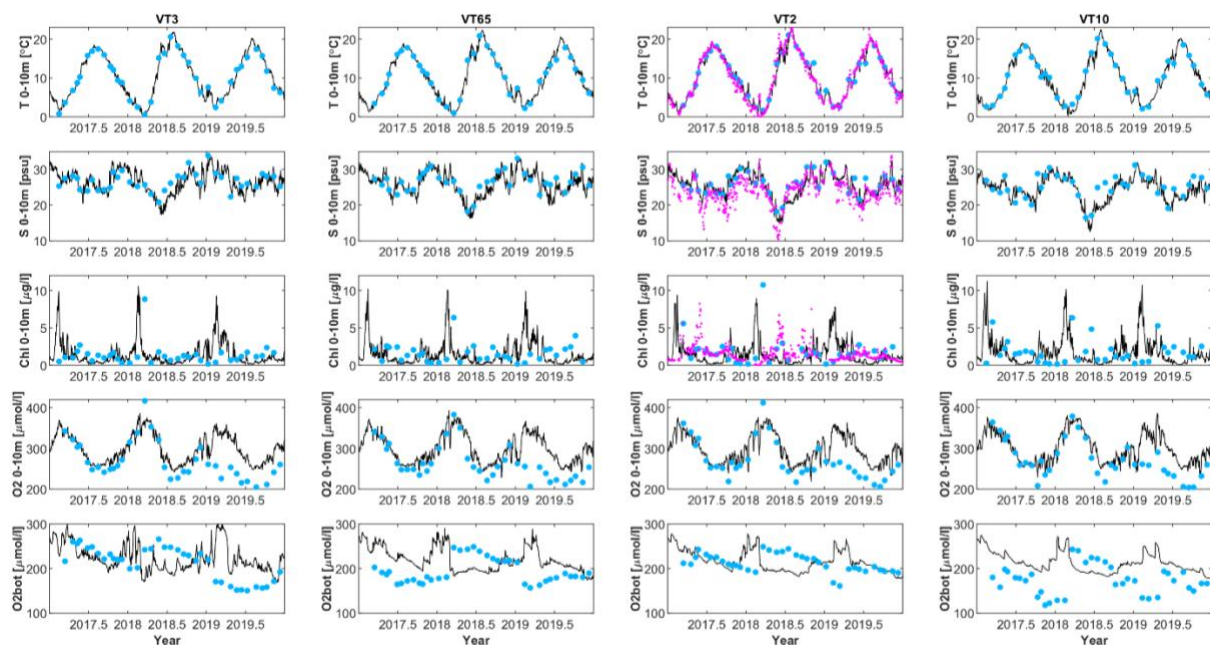
Here we attempt to validate the MARTINI800 model for the Oslofjord region, using biogeochemical time series observations at stations VT3, VT65, VT2, VT10 from the ØKOKYST-Skagerrak monitoring program 2017-2019 (see Figure 6, large black dots), supplemented with STS-SGR observations from the DCS4COP cruise during September 2020 (small magenta dots).



**Figure 6.** MARTINI800 model subdomain covering the Oslofjord region, showing the model bathymetry (background colour), the main sampling stations from the ØKOKYST-Skagerrak monitoring program 2017-2019 (large black dots), the sampling stations from the DCS4COP cruise during September 2020 (small magenta dots), and the positions of the model river outlets (small blue dots). Note that the DCS4COP sampling station L1 was a Glomma river sample (Fredrikstadbrua) and lies in the land mask of the MARTINI800 model grid, while the station named “VT3” during the DCS4COP cruise was a few km west of the station VT3 during the ØKOKYST-Skagerrak monitoring program. White lines show latitude and longitude, while the x and y axes show model grid cell indices (increments of 800 m horizontal distance).



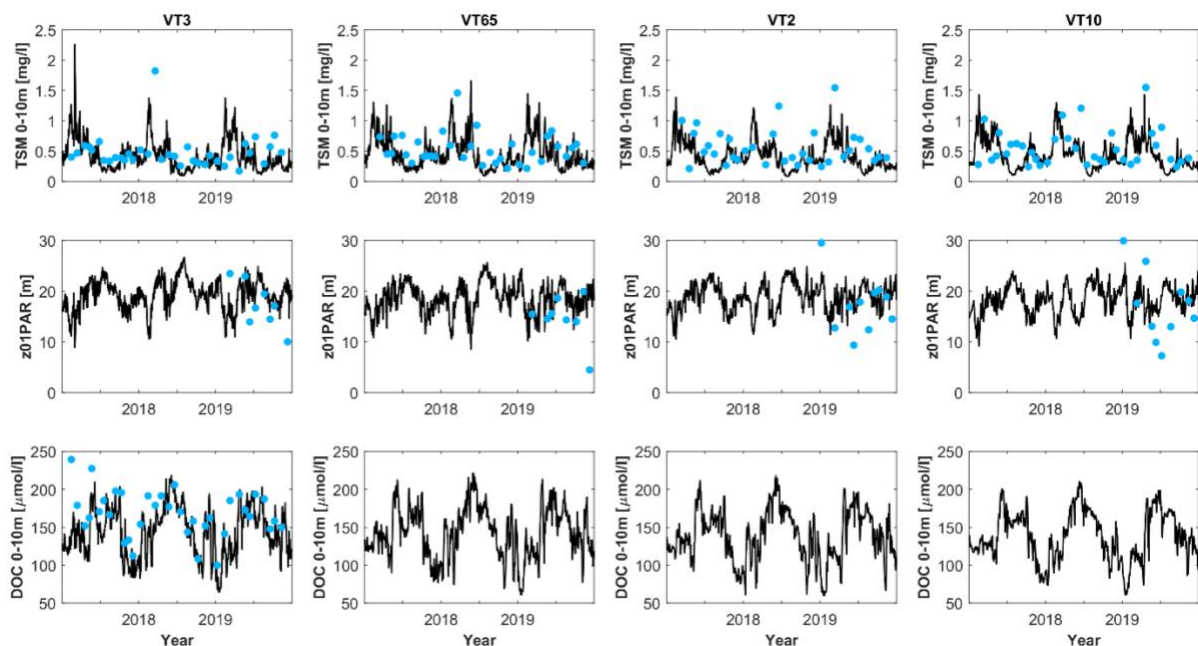
In terms of biogeochemical variability, the overall patterns in the ØKOKYST-Skagerrak observations (Figure 7, blue dots) are quite consistent with the model simulation (black lines) over the three year period 2017-2019. Here we limit comparisons to the surface (0-10m average) physical variables (temperature T and salinity S) and the biochemical variables most relevant to evaluations of water quality, namely the surface chlorophyll *a* (Chl), surface dissolved oxygen (O2) and the bottom water dissolved oxygen (O2bot, measured by the CTD probe within a few metres of the sea floor). For station VT2, Ferrybox data (see NIVA ØKOKYST-Skagerrak report, Fagerli et al., 2020) were available within a sufficiently small radius (0.5 km) that they could be used to extend the station time series data (with higher temporal resolution, see small magenta dots in Figure 7). Physical variables show very good agreement between model and observations, noting that the Ferrybox data are from 4 m depth while the bottle samples and model output are averaged over 0-10 m (this may explain the slightly lower Ferrybox salinity). The magnitude of algal blooms appears to be well simulated (see Chl in Figure 7), although the timing of the main bloom in winter/spring may be too early in the model. Dissolved oxygen levels at surface and bottom also appear to be generally well simulated, except during early 2019.



**Figure 7.** Time series validation of the MARTINI800 biogeochemical model, for surface (0-10 m average) temperature (T), salinity (S), dissolved oxygen (O2), and bottom water dissolved oxygen (O2bot). Large blue dots show bottle sample observations from the ØKOKYST-Skagerrak monitoring program. Small magenta dots show Ferrybox observations (4 m depth) within 0.5 km of the stations. Black lines show daily-average output from the MARTINI800 model at the bottle sample locations and depths. Columns show the main Outer-Ofsløfjord stations: VT3 (Torbjørnskjær, 59.0407N, 10.7608E), VT65 (Missingen, 59.1866N, 10.6916E), VT2 (Bastø, 59.3586N, 10.5905E), VT10 (Breianger vest, 59.4867N, 10.4583E).

During early 2019, observations in Outer Ofsløfjord show reduced dissolved oxygen levels both at surface and at depth, most likely due to deep water renewal events in the Inner Ofsløfjord and surrounding fjords (Fagerli et al., 2020). It appears that the model could not simulate these events, perhaps due to insufficient spatial resolution (here 800 m in the horizontal) to represent the inner fjords. These events may also explain the generally low chlorophyll *a* levels observed during 2019, suggesting a possible inhibition of the winter/spring bloom, except at VT10.

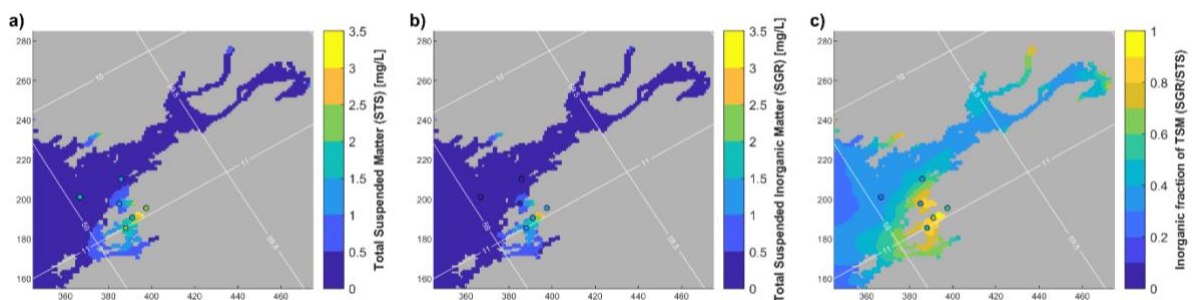
Thanks to the present project, the model now simulates Total Suspended Matter (TSM), including contributions from inorganic sediment particles and from particles (organic and inorganic) generated by the simulated marine ecosystem. The model output for surface TSM agrees well with observations from the ØKOKYST-Skagerrak program, both in terms of mean concentration and levels of temporal variability (Figure 8). We also show in Figure 8 the euphotic depths (depth of 1 % photosynthetically active radiation relative to surface) from the model and from observations made during 2019. Here the model shows good agreement with the observed annual mean euphotic depths (between 15 and 20 m for all four stations) although some of the shallow observed summertime values appear to be overestimated. This is most likely due to an underestimation of summertime chlorophyll (see Figure 7) since the variations in dissolved organic carbon (DOC) (and presumably its contribution to light attenuation) appear to be well reproduced by the model (Figure 8, bottom row).



**Figure 8.** Time series validation of the MARTINI800 biogeochemical model, for surface (0-10 m average) total suspended matter (TSM), euphotic depth (where photosynthetically active radiation is 1% of the surface value, z01PAR), and surface dissolved organic carbon (DOC). Large blue dots show bottle sample observations from the ØKOKYST-Skagerrak monitoring program. Black lines show daily-average output from the MARTINI800 model at the bottle sample locations and depths. Columns show the main Outer-Oslofjord stations: VT3 (Torbjørnskjær, 59.0407N, 10.7608E), VT65 (Missingen, 59.1866N, 10.6916E), VT2 (Bastø, 59.3586N, 10.5905E), VT10 (Breianger vest, 59.4867N, 10.4583E).

A simple correlation analysis of the model output shows that the euphotic depths at VT3, VT65, VT2, and VT10 are strongly negatively correlated with chlorophyll *a* ( $\rho = -0.7$  to  $-0.6$ ) and with TSM ( $\rho = -0.8$  to  $-0.7$ ) and only weakly correlated with DOC ( $\rho = 0$  to  $0.3$ ). Also, TSM is strongly positively correlated with chlorophyll *a* ( $\rho = 0.8$ ). This suggests that, within the model, chlorophyll *a* is the dominant contributor to light attenuation, with lesser contributions from non-algal particles and DOC, which can contribute to coloured dissolved organic matter (cDOM), at these particular stations.

Finally, we compare the model output with (STS, SGR) observations from September 2020 (Figure 9). Note that since we did not have resources to run the model through 2020, we compare here with the climatological model output for September (2017-2019). This model output (Figure 9, background colour) is generally consistent with the observations (coloured dots on same colour scale), bearing in mind that short-term variability (or ‘spikiness’) can raise the observed values significantly above the climatological monthly mean (cf. Figure 8, top row). TSM decreases rapidly from relatively high values in the Glomma estuary to low values almost everywhere else, confirming that the Glomma is the dominate source of TSM in the region (Figure 9a). The inorganic fraction, the Total Suspended Inorganic Matter (TSIM, Figure 9b), makes up the bulk of the TSM, with the fraction of TSM decreasing from high values (80-100%) in the Glomma estuary and near the Aulielva, Drammenselva, Lysakerelva and Akerselva outlets, decreasing smoothly to lower values (30-50%) in the central Outer Oslofjord (Figure 9c).



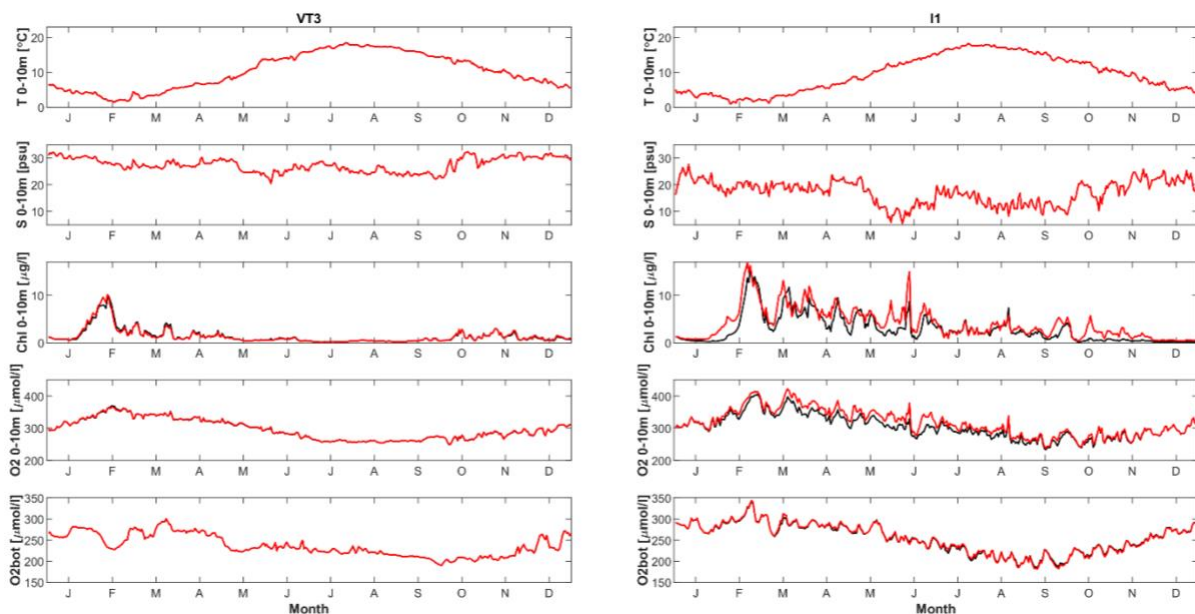
**Figure 9.** Surface concentrations of total suspended matter (TSM, a), total suspended inorganic matter (TSIM, b) and the inorganic fraction of TSM as a % (c). Background colour shows climatological output for September 2017-2019 from the MARTINI800 biogeochemical model, while coloured dots (on the same colour scale) show observed values from the DCS4COP cruise during September 2020. Observational estimates of TSM were made using suspended tørrstoff (STS, a), TSIM was estimated using suspended gløderest (SGR, b), and the inorganic fraction of TSM was estimated as  $(100 \times \text{SGR}/\text{STS})$ .

Note that, if we repeat the time series correlation analysis for model output at station I1 in the central Glomma estuary (Ramsøy, 59.1094N, 11.0020E, see Figure 6), the correlations are quite different to those at the ØKOKYST-Skagerrak stations. The euphotic depth is again best correlated with TSM ( $\rho = -0.85$ ) but here, chlorophyll *a* is poorly correlated with euphotic depth ( $\rho = -0.1$ ) and TSM ( $\rho = 0.1$ ). Instead, the TSM is highly correlated with TSIM ( $\rho = 0.94$ ), reflecting that fact that most of the TSM is from inorganic sediment particles. Euphotic depth correlates more strongly with DOC here ( $\rho = -0.4$ ), but not as strongly as it does with TSM. In summary, the model confirms the expectations that: i) Outer Oslofjord TSM concentrations are highest in the Glomma estuary, ii) most of this TSM is from inorganic particles input by the Glomma, iii) these inorganic particles have a major/dominant effect on light attenuation in the Glomma/Hvaler estuary.

### 3.2 MARTINI800 scenarios of reduced inorganic particle loading

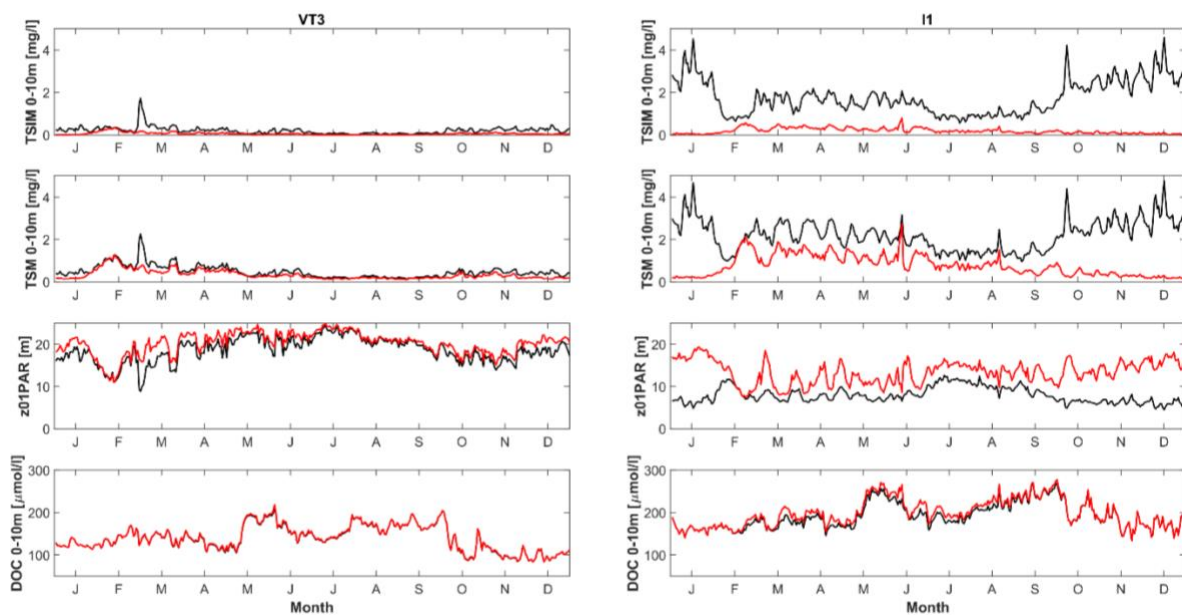
Here we use the MARTINI800 model to explore the consequences of reduced inorganic particle loading to the Outer Oslofjord region. We consider a simple scenario in which the riverine inorganic particle input is reduced to zero for the entire MARTINI800 domain. This may not be a realistic scenario, but it does allow us to place an upper limit on the potential impacts of reduced inorganic particle input. Also, our scenario run is limited to one year (2017), due to limited resources; this should be sufficient to reveal the major effects on water column biogeochemistry, but is unlikely to suffice for analysing benthic impacts due to the longer equilibration times involved.

First, we repeat the station time series analysis of section 3.1 (Figures 7,8), but now showing only model output, from both the original simulation (Figure 10, black lines) and a scenario simulation with riverine inorganic particle input reduced to zero (red lines). We show only VT3 from the ØKOKYST-Skagerrak stations, since the impacts are similar in (VT65, VT2, VT10), and also add an extra station I1 from the central Glomma estuary (Ramsøy, 59.1094N, 11.0020E, see Figure 6). Red lines overlap with black for temperature (T) and salinity (S), since the particles have no feedback on physics in this model (in reality there would be a small impact on heat absorption, but that is neglected here). At VT3, the impacts of particle loading reduction on chlorophyll *a* and dissolved oxygen are negligible. At I1 there is a significant increase in bloom intensity (15% increase in annual mean, 10% increase in 90<sup>th</sup> percentile), but smaller/negligible impacts on dissolved oxygen.



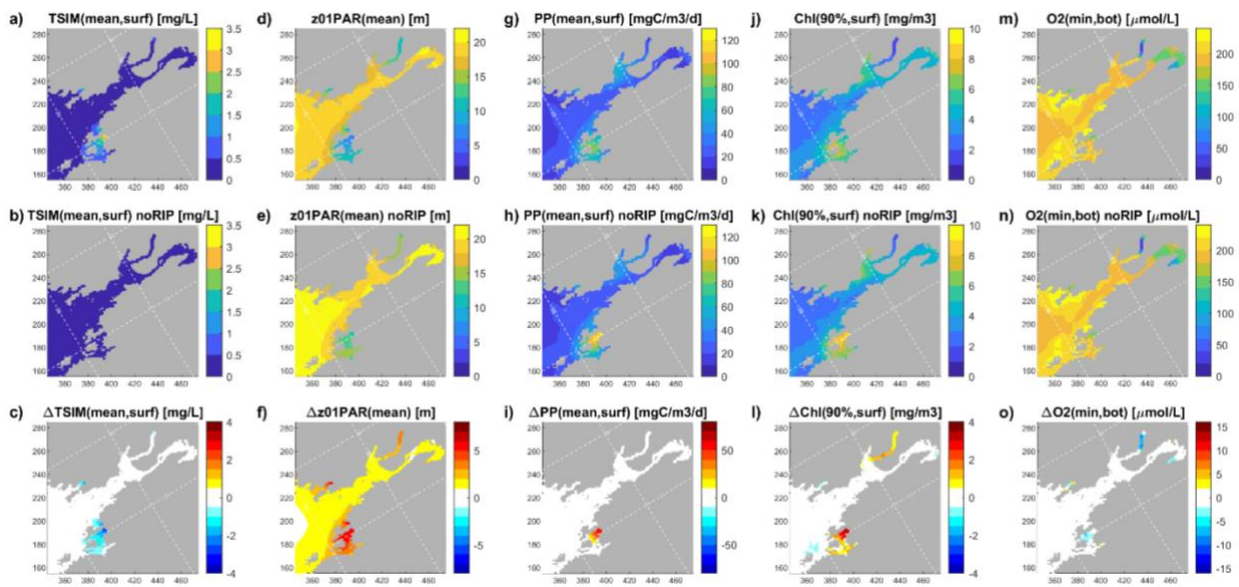
**Figure 10.** Station time series output for 2017 from the MARTINI800 biogeochemical model, for both the original hindcast simulation (black lines) and the scenario simulation with zero inorganic particle input (red lines). Different rows show surface (0-10 m average) temperature (T), salinity (S), dissolved oxygen (O2), and bottom water dissolved oxygen (O2bot). Columns show different stations: VT3 (Torbjørnskjær, 59.0407N, 10.7608E), and I1 (Ramsøy, 59.1094N, 11.0020E, in the Glomma estuary). Red and black lines overlap for temperature and salinity.

The impacts on inorganic particle concentrations (Total Suspended Inorganic Matter, TSIM) are strong at both stations (Figure 11). Note that TSIM is not reduced to zero, because some inorganic particulate matter is produced by the modelled marine planktonic ecosystem (mainly opal from diatoms and calcite from coccolithophores). At I1, the reduction in TSIM is partially offset by an increase in phytoplankton production at I1 (see chlorophyll *a* in Figure 10), but the result is still a strong reduction in Total Suspended Matter (TSM, see Figure 11). The increase in euphotic depth, or improvement in water clarity, is small/negligible at VT3, but is significant at I1, despite the increase in chlorophyll production (annual mean euphotic depth increases by 22%, from 8.6 m to 10.4 m). Note, however, that water clarity at I1 remains well short of that at VT3 (annual mean euphotic depth = 19.8 m); this is partly because the chlorophyll *a* and TSM remain higher than at VT3 (Figures 10,11) but also due to the roughly 2 times higher concentration of dissolved organic matter and associated light-absorbing fraction (cDOM), which is not significantly impacted by the reduced particle loading (Figure 11, bottom row).



**Figure 11.** Station time series output for 2017 from the MARTINI800 biogeochemical model, for both the original hindcast simulation (black lines) and the scenario simulation with zero inorganic particle input (red lines). Different rows show surface (0-10 m average) total suspended inorganic matter (TSIM), surface total suspended matter (TSM), euphotic depth (where photosynthetically active radiation is 1% of the surface value, z01PAR), and surface dissolved organic carbon (DOC). Columns show different stations: VT3 (Torbjørnskjær, 59.0407N, 10.7608E), and I1 (Ramsøy, 59.1094N, 11.0020E, in the Glomma estuary).

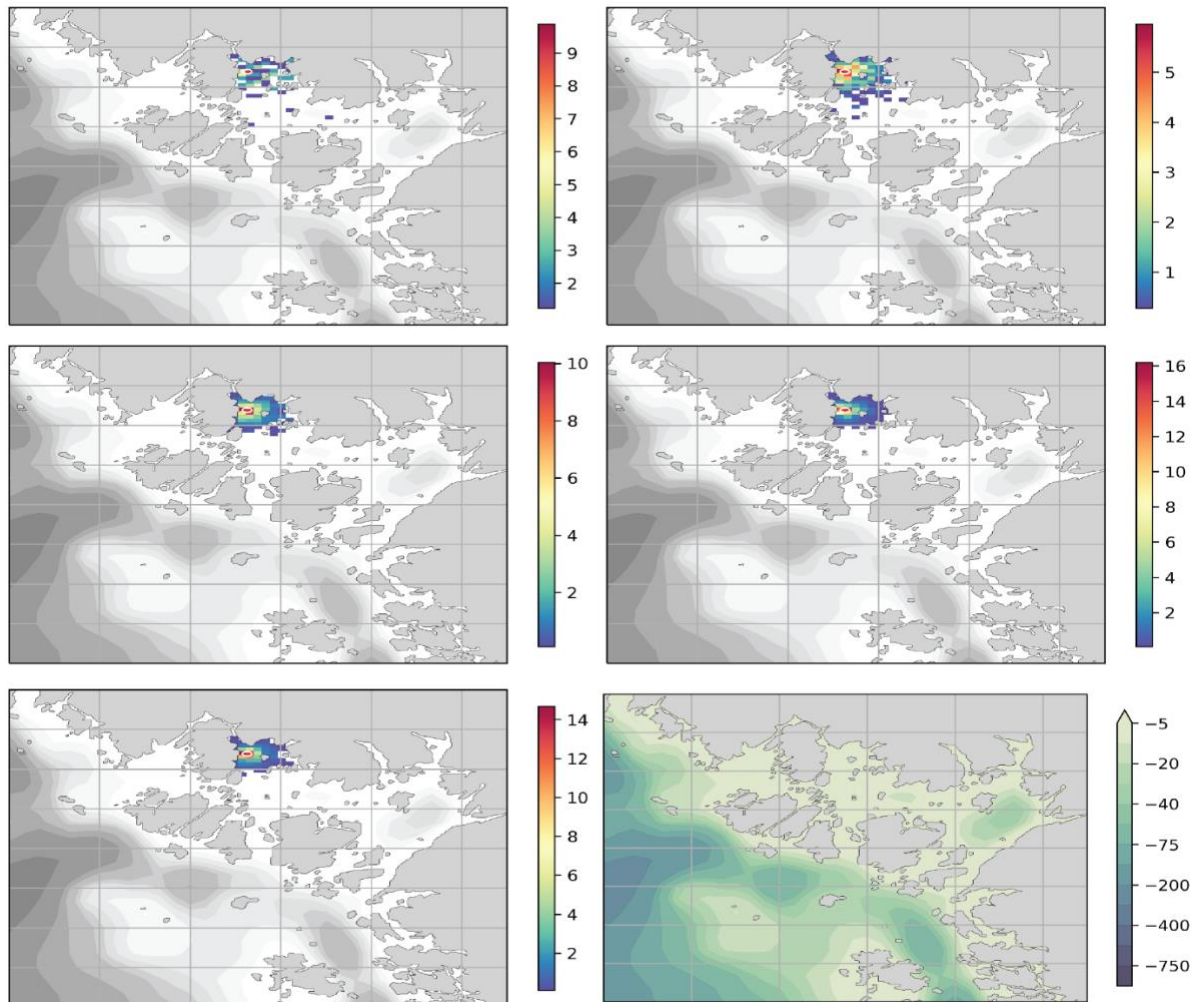
Finally, we map the potential impacts of the particle loading reduction in the Oslofjord region using different metrics of water quality (Figure 12). If riverine inorganic particle loading is eliminated, the concentration of Total Suspended Inorganic Matter is reduced, most strongly in the Glomma/Hvaler estuary (Figure 12a-c). This leads to a general increase in annual mean euphotic depth (1% PAR), of around 1-2 m increase in the central Outer Oslofjord and up to 3-6 m increase in the Glomma estuary, Tønsbergfjord, and Drammensfjord (Figure 12d-f), and a general increase in surface net primary production by phytoplankton, significant only in the Glomma estuary (Figure 12g-i, note that primary production is mainly subsurface in Drammensfjord). Also, the 90<sup>th</sup> percentile of surface chlorophyll *a* (calculated from daily averages) is significantly increased (by 2-4 mg/m<sup>3</sup>) in the Glomma estuary and in Drammensfjord (Figure 12j-l), while the annual minimum bottom dissolved oxygen concentrations in these areas are slightly reduced (by 5-10 μmol/L, or 0.1-0.2 ml/l, Figure 12m-o). Note, however, that the present biogeochemical model does not include benthic macroflora; in reality these may raise bottom oxygen concentrations by net photosynthesis in shallow water areas, such as the Glomma estuary, where improved water clarity may facilitate regrowth.



**Figure 12.** Modelled impacts of eliminating riverine inorganic particle input on Oslofjord marine biogeochemistry and water quality. Top row shows results from the original hindcast simulation for 2017 with ‘present-day’ levels of particle input. Middle row shows corresponding results for a scenario simulation for 2017 with all river inputs of inorganic particles set to zero (noRIP). Bottom row shows the differences (scenario minus hindcast). Columns from left to right show: surface Total Suspended Inorganic Matter (TSIM, annual means), euphotic depth (where photosynthetically active radiation is 1% of the surface value, z01PAR, annual means), surface net primary production by phytoplankton (PP, annual means), surface chlorophyll *a* (90<sup>th</sup> percentiles of daily values), and bottom dissolved oxygen (annual minima of daily values).

### 3.3 OpenDrift results for non-cohesive inorganic particle dispersion from Glomma

Figure 13 shows dispersal probabilities for non-cohesive (sand/silt) particles from the Glomma, estimated by particle tracking for 5 size classes, plus the regional water depth (bottom right). The larger particles sank rapidly to the bottom and had negligible chance of spreading beyond Kjøkøya at around 59.13N (Figure 13, middle and bottom rows). This supports the assumption made by the ROMS-ERSEM model that the 3 largest non-cohesive size classes have negligible impact beyond a confined region close to the Glomma river mouth. However, the results here also suggest that even the two smaller non-cohesive size classes (with slower sinking speeds) have quite limited dispersion, and are unlikely to reach as far as the central Glomma estuary (Figure 13, top row). This suggests that the non-cohesive (sand/silt) inorganic particles likely play a minor role in impacting the broader-scale water quality in the outer Oslofjord, with the major role played by the cohesive inorganic particles (mud/clay/silt). This is mainly due to: i) the shallow water depth in the Glomma/Hvaler estuary (Figure 13, bottom right), ii) the slower sinking speeds of the cohesive particles (flocs) for a given particle size (Figure 3), and iii) the predominantly cohesive nature of the smallest and slowest-sinking particles (Wolanski et al., 2013).



**Figure 13.** Dispersal probabilities (%) for non-cohesive (sand/silt) particles originating from the Glomma, estimating using a Lagrangian particle tracking approach. Different subplots show results for 5 different size fractions: upper left (0–12.1  $\mu\text{m}$ ), upper right (12.1–32.7  $\mu\text{m}$ ), middle left (32.7–88.3  $\mu\text{m}$ ), middle right (88.3–238.5  $\mu\text{m}$ ), bottom left (238.5–348.1  $\mu\text{m}$ ). Bottom right plot shows the water depth in metres.

## 4 Conclusions

Studies of potential benefits of modified inputs to marine systems need to consider potential side-effects and unintended consequences. Reduced inputs of inorganic particles from rivers may increase water clarity, and thereby encourage growth of valued macroflora such as kelp. However, the improved clarity may also improve the growth conditions for phytoplankton, potentially making some areas more susceptible to eutrophication (Cloern, 2001) and harmful algal blooms (Wang et al., 2016). In the case of the Oslofjord, simulations herein from a regional marine sediment and biogeochemical model (MARTINI800) suggested that a 100% reduction in riverine inorganic particle input would lead to a major reduction in total suspended particulate matter in areas where it is currently high, most notably the Glomma/Hvaler estuary. In the model this caused a general increase in euphotic depth (depth of 1% light level), reaching up to 6 m in the Glomma estuary, which in turn increased phytoplankton production and peak chlorophyll concentrations during algal blooms, and led to a small decrease in annual minimum bottom oxygen concentrations in the Glomma estuary and Drammensfjord. However, in shallow regions such as the Glomma estuary, increased bottom oxygen consumption due to respiration of stronger phytoplankton blooms may in reality be counterbalanced by a regrowth of oxygen-producing macroflora, which were not accounted for in the present model. We conclude that, if effective measures and technologies become available, it could be worthwhile to reduce inputs of inorganic particles from the Glomma river, since this could improve macroflora growth conditions in the shallow-water region of the Glomma estuary. Such measures should pay particular attention to the fine-grained mud/clay particles and flocs which have a greater potential to spread beyond input locations. Applications to other rivers such as the Drammen deserve more caution, however, and may only exacerbate water quality issues in absence of the potential for regrowth of benthic macroflora.

Concurrent to measures for reducing inorganic particle loadings (which would act to improve light conditions), there should be considerations of reductions in inorganic nutrient supply to the outer Oslofjord (e.g. Stalstrøm et al, 2021), which could counteract any potential negative side-effects on excessive phytoplankton growth, including the potential for harmful algal blooms. The MARTINI800 model could be used to test the combined effect of inorganic nutrient and inorganic particle reductions on the water quality and ecological effects in the Oslofjord region.

Despite various modelling uncertainties and challenges, in part detailed herein, mechanistic marine models such as MARTINI800 are achieving a level of predictive skill (we hope demonstrated herein) that suggests they can be useful to decision-makers, as part of a broader framework that acknowledges modelling uncertainty. This study has highlighted two possible priority areas for future model development to better address issues related to Oslofjord water quality: i) adequate (spatial) resolution of physical processes and fluxes associated with deep water renewal events in fjords; ii) inclusion of marine vegetation (benthic macroflora) and its feedbacks on marine biogeochemistry and water quality. Regular field observations and monitoring remain essential to provide input and test/validation data for model development, and we suggest that the needs of models should be considered in the planning of observational campaigns. For understanding impacts of particle loading, marine modelling efforts may benefit in particular from more freshwater observational data on the nature of riverine particles entering the marine environment (e.g. grain size fractions, clay vs. silt vs. sand fractions, organic matter stoichiometry), and more marine observations of spectral light penetration and absorption/backscattering coefficients (if possible, also resolved for specific seawater constituents). The dynamics of particles and dissolved organic matter in estuarine areas (flocculation, disaggregation etc.) remain obvious areas of uncertainty in terms of



developing models that are adapted/tuned for Norwegian coastal waters; this could be addressed with more size-fractionated data from e.g. LISST instruments, and more in-depth model comparisons with existing data beyond what was possible within the resources of this project.

In view of the risks of exacerbating eutrophication and increasing the potential for harmful algal blooms, any large-scale application of particle loading reduction should be preceded by further investigations involving more-focused marine models, with higher spatial resolution in target areas such as the Glomma estuary, and perhaps including modules for benthic macroflora. Nevertheless, given that the present model (MARTINI800) was not designed to with a specific focus on Outer Oslofjord or the Glomma estuary, the results of the present application are encouraging. Ongoing model development work should continue to interact with stakeholders in environmental management, to ensure that the needs of this user group remain in focus.

## 5 References

- Anderson, L.A., 1995. On the hydrogen and oxygen content of marine plankton. *Deep-Sea Res.* 42, 1675– 1680.
- Bruggeman, J. and Bolding, K., 2014. A general framework for aquatic biogeochemical models, *Environmental Modelling & Software*, <http://dx.doi.org/10.1016/j.envsoft.2014.04.002>
- Butenschön, M., Clark, J., Aldridge, J.N., Allen, J.I., Artioli, Y., Blackford, J., Bruggeman, J., Cazenave, P., Ciavatta, S., Kay, S., Lessin, G., van Leeuwen, S., van der Molen, J., de Mora, L., Polimene, L., Saille, S., Stephens, N., Torres, R., 2016. ERSEM 15.06: a generic model for marine biogeochemistry and the ecosystem dynamics of the lower trophic levels. *Geosci. Model Dev.* 9, 1293e1339. <http://dx.doi.org/10.5194/gmd-9-1293-2016>.
- Cloern, J. E., 2001. Our evolving conceptual model of the coastal eutrophication problem. *Mar. Ecol. Prog. Ser.* 210, 223-253.
- Dagestad, K.-F., Röhrs, J., Breivik, Ø., and Ådlandsvik, B.: OpenDrift v1.0: a generic framework for trajectory modelling, *Geosci. Model Dev.*, 11, 1405-1420, <https://doi.org/10.5194/gmd-11-1405-2018>, 2018.
- Fagerli, C. W., Trannum, H. C., Staalstrøm, A., Eikrem, W., Sørensen, K., Marty, S., Frigstad, H., & Gitmark, J. K., 2020. ØKOKYST – DP Skagerrak. Årsrapport 2019. Norsk institutt for vannforskning. <https://niva.brage.unit.no/niva-xmlui/handle/11250/2679486>
- Frigstad, H., Harvey, T., Deininger, A., & Poste, A., 2020. *Increased light attenuation in Norwegian coastal waters - A literature review*. <https://www.miljodirektoratet.no/globalassets/publikasjoner/m1808/m1808.pdf>
- Hedges, J. I., Baldock, J.A., Gélinas, Y., Lee, C., Peterson, M.L., Wakeham, S.G., 2002. The biochemical and elemental compositions of marine plankton: a NMR perspective. *Mar Chem* 78:47–63.
- Middelburg, J. J., 2019. *Marine Carbon Biogeochemistry*, Springer Briefs in Earth System Sciences, 1, [https://doi.org/10.1007/978-3-030-10822-9\\_1](https://doi.org/10.1007/978-3-030-10822-9_1)

Moy, F., Christie, H., Steen, H., Stalnacke, P., Aksnes, D., Aure, J., Bekkby, T., Fredriksen, S., Gitmark, J., Hackett, B., Magnusson, J., Pengerud, A., Sjtun, K., Sorensen, K., Tveiten, L., Oygarden, L., & Asen, P., 2008. *Sluttrapport fra Sukkertareprosjektet 2005-2008*.

<https://www.miljodirektoratet.no/globalassets/publikasjoner/klif2/publikasjoner/2467/ta2467.pdf>

Khelifa, A. and Hill, P. S., 2006. Models for effective density and settling velocity of flocs, *J. Hydraul. Res.*, 44, 390–401.

OSPAR. 2017. OSPAR Intermediate Assessment 2017.

Shchepetkin, A. F. and J.C. McWilliams, 2005. The Regional Ocean Modeling System (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model, *Ocean Model.* 9, 347–404.

Sherwood, C. R., Aretxabaleta, A. L., Harris, C. K., Rinehimer, J. P., Verney, R., and Ferré, B., 2018. Cohesive and mixed sediment in the Regional Ocean Modeling System (ROMS v3.6) implemented in the Coupled Ocean–Atmosphere–Wave–Sediment Transport Modeling System (COAWST r1234), *Geosci. Model Dev.*, 11, 1849–1871, <https://doi.org/10.5194/gmd-11-1849-2018>

Vahedi, A., Gorczyca, B., 2011. Application of fractal dimensions to study the structure of flocs formed in lime softening process. *Journal of Water Research* 45 (2), 545-556.

Verney, R., Lafite, R., Brun-Cottan, J. C., and Le Hir, P., 2011. Behaviour of a floc population during a tidal cycle: Laboratory experiments and numerical modeling, *Cont. Shelf Res.*, 31, S64–S83, <https://doi.org/10.1016/j.csr.2010.02.005>

Wang, B., Xin, M., Sun, X., Wei, Q., and Zhang, X., 2016. Does reduced sediment load contribute to increased outbreaks of harmful algal blooms off the Changjiang Estuary? *Acta Oceanol. Sin.* , 35(8), 16–21.

Warner, J. C., Sherwood, C. R., Signell, R. P., Harris, C. K., and Arango, H. G., 2008. Development of a three-dimensional, regional, coupled wave, current, and sediment-transport model, *Comput. Geosci.*, 34, 1284–1306.

Wolanski, E., Andutta F.P., Delhez, E., 2013. Estuarine hydrology. In: Bengtsson L, Herschy R, Fairbridge R (eds) *Encyclopedia of lakes and reservoirs*. Springer, New York.

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