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The impact of the spring 2020 snowmelt floods on physicochemical conditions in three Norwegian river-fjord-coastal systems

Photo: Amanda Poste, NIVA

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REPORT

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Summary

Due to very high snow accumulation in the winter of 2019/2020, the Norwegian Water Resources and Energy Directorate (NVE) in late May 2020 issued flood forecasts predicting extremely high flood risk for parts of northern Norway and high flood risk for rivers in south-eastern Norway with mountainous catchments. To capture impacts of these potentially extreme snowmelt floods on water chemistry in rivers and coastal waters, extra sampling campaigns were carried out in three selected river-fjord systems: Glomma river-Ytre Oslofjord-Skagerrak in southern Norway, and the Målselv river-Målselvfjord-Straumsfjorden and Tana river-Tanafjord systems in northern Norway. The overarching goal was to study the impact of the 2020 spring freshet (i.e. snowmelt flood) on river water chemistry, land-ocean fluxes, and physicochemical conditions in coastal waters. In this report we describe between-site differences and seasonal patterns in river and coastal water chemistry based on existing data from national river (2016–2020) and coastal (2017–2020) monitoring in the three study regions, and then use these to provide context for the data from the spring 2020-sampling campaign, with a focus on suspended particulate matter (SPM), dissolved organic carbon (DOC), and nutrients. This report also highlights the complexity of identifying climate change impacts along the terrestrial-freshwater-marine continuum and the need for tighter cross-disciplinary and cross-ecosystem integration between monitoring programmes.

Four keywords	Fire emneord
1. Spring freshet	1. Vårflom
2. Rivers	2. Elver
3. Coastal waters	3. Kystvann
4. Water quality	4. Vannkvalitet

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The impact of the spring 2020 snowmelt floods on physicochemical conditions in three Norwegian river-fjord-coastal systems

Preface

In late May 2020 the Norwegian Water Resources and Energy Directorate (NVE) issued flood forecasts predicting extremely high flood risk for parts of northern Norway and high flood risk for rivers in south-eastern Norway with mountainous catchments. In order to capture the impacts of these potentially extreme snowmelt floods on water chemistry in Norwegian rivers and coastal waters, NIVA approached the Norwegian Environment Agency (Miljødirektoratet) who agreed to support extra riverine and coastal sampling campaigns in three selected river-fjord systems that are all included in ongoing, long-term monitoring programmes. The sites included the Glomma river-Ytre Oslofjord-Skagerrak system in southern Norway, and the Målselv river-Målselvfjord-Straumsfjorden and Tana river-Tanafjord systems in northern Norway.

The proposal from NIVA for extra funding to carry out the sampling campaign was sent to Miljødirektoratet on May 29th 2020 and received a positive response on June 2nd 2020. The contact persons at Miljødirektoratet were Gunn Lise Haugestøl, Preben Danielsen, Karen Fjøsne, and Pål Inge Synsfjell. In addition to this extra funding, the current study was supported by ongoing monitoring activities within the national river and coastal monitoring programmes (Elveovervåkingsprogrammet and ØKOKYST; supported by Miljødirektoratet), and the Outer Oslofjord monitoring programme (supported by Fagrådet for Ytre Oslofjord). Finally, this project was also supported by NIVA's strategic initiative on "Global change at high latitudes" (NoLa; led by Heleen de Wit and Andrew King). We thank Miljødirektoratet, Fagrådet for Ytre Oslofjord, and NIVA for their support.

The work presented in this report was carried out as a joint effort by NIVA and Akvaplan-niva. Most chemical analyses were carried out at NIVA's lab in Oslo, with some parameters analysed at the Akvaplan-niva lab in Trømsø. Several colleagues and local field assistants have been involved in the sampling campaign, sample preparation and analysis. In particular, we would like to thank Liv Bente Skancke for help with planning and administration; Pernilla Carlsson, Oskar Christensen, Martin Dahl Torp and Espen Lund for help with field work and sample processing; Erwin Kers, Elena Martinez and Emelie Skogsberg for help with lab analyses; and James Sample for help with flux calculations.

Tromsø, September 2021

Amanda Poste

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Summary

Due to high snow accumulation during the winter of 2019/2020, the Norwegian Water Resources and Energy Directorate (NVE) issued flood forecasts in late May 2020 predicting extremely high flood risk for parts of northern Norway and high flood risk for rivers in south-eastern Norway with mountainous catchments. In order to capture the impacts of these potentially extreme snowmelt floods on water chemistry in rivers and coastal waters, extra sampling campaigns were carried out from late-May to mid-July in three selected river-fjord systems that are all included in ongoing, long-term monitoring programmes: Glomma river-Ytre Oslofjord-Skagerrak in southern Norway, and Målselv river-Målselvfjord-Straumsfjorden and Tana river-Tanafjord in northern Norway. The overarching goal was to study the impact of the 2020 spring snowmelt floods (also known as 'spring freshet') on river water chemistry, land-ocean fluxes, and physicochemical conditions in coastal waters.

Despite the projections for large snow melt floods in 2020, the peak discharge values observed during spring freshet for our three study rivers all fell below 10-year flood levels. Although we were not able to capture an extreme climate event in the current study, we have generated new data, new experience with assessing multidimensional (temporal and spatial, e.g. lateral transport from land to coast and coastal hydrography) datasets and gained valuable insight into the role of spring freshet in shaping river water chemistry, land-ocean fluxes, and coastal physical and chemical conditions. The results of the current study highlight the importance of spring freshet in delivering freshwater and terrestrial material from land to sea, where high springtime concentrations of several chemical constituents converge with very high discharge, resulting in large fluxes over a period of days to weeks. This is particularly true for the two northern study systems where spring freshet often delivers well over half of the total annual inputs of freshwater, dissolved organic carbon (DOC), suspended particulate matter (SPM), total nitrogen (tot-N) and total phosphorus (tot-P) to the coastal environment. This study highlights the high variability of river water chemistry during the spring freshet period. DOC and nutrient concentrations were often highest during early freshet and declined during peak and late freshet, due to dilution effects.

Inputs from land had a demonstrable impact on coastal physical and chemical conditions, with low surface water salinities, increased stratification, and elevated SPM, silicate (SiO_2), nitrate + nitrite (NO_3 + NO_2), DOC and $SUVA_{254}$[1] at coastal monitoring stations during spring freshet. Taken together, these changes in stratification, light availability and nutrient and DOC concentrations are likely to have a broad range of impacts on coastal ecosystem structure and function. However, the degree to which river inputs had an impact on these coastal stations, which are quite far from the river outlets, depended on fjord morphometry and the degree of exchange with offshore marine waters. The inclusion of inner fjord sites highlighted the much stronger impact of riverine inputs in inner fjords and closer to river outlets, suggesting that the current coastal monitoring programme Ecosystem Monitoring in Coastal Waters (ØKOKYST); might benefit from including stations along a river to fjord transect at selected sites focusing on land-ocean interactions, such as for example the Målselv river-Målselvfjord-Straumsfjorden integrated climate monitoring study region.

The high degree of variability in discharge, river water chemistry, and marine physicochemical conditions suggest that current monthly riverine and coastal monitoring regimes may not adequately capture spring freshet dynamics. For rivers, this can lead to large uncertainties in estimates of annual fluxes of nutrients, DOC and contaminants. In the coastal environment, this can hinder our ability to

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[1] specific UV absorption at 254 nm; used as an indicator for terrestrial dissolved organic matter

understand how spring freshet intersects with other seasonal processes, such as the spring phytoplankton bloom and/or periods of nutrient limitation. Climate change is also likely to impact spring freshet timing, magnitude and progression, with uncertain impacts on river water quality and downstream coastal ecosystems. Long-term changes in timing and fluxes of freshwater and terrestrial material from land to coastal ecosystems may also impact the role of coastal and shelf systems in the global C-cycle, through effects on the balance between coastal primary production and respiration, C-burial in coastal sediments, and ocean acidification.

Given the close links between climate change impacts on land, freshwater and marine environments, there is an increasing need to take interdisciplinary cross-ecosystem approaches to studying the potential effects of global change, including extreme events, on northern ecosystems. Extreme events are by their very nature difficult to predict and ad-hoc adaptation of existing monitoring to capture extreme events is challenging, since these programs are designed for observations of long-term rather than episodic change, and are not designed to pair data across ecosystem (terrestrial, freshwater, coastal, marine) boundaries.

We recommend pairing of traditional field-based monitoring approaches with new technologies such as *in* situ sensor-based monitoring, autonomous sampling and remote sensing as a promising way forward for adaptive monitoring of long-term and seasonal change and effects of extreme climate events along the terrestrial-freshwater-marine continuum.

Sammendrag

Tittel:	Effekter av snøsmeltingsflommer våren 2020 på fysisk-kjemiske forhold i tre norske elv-fjord-kyst systemer
År:	2021
Forfatter(e):	Amanda Poste, Øyvind Kaste, Helene Frigstad, Heleen de Wit, Therese Harvey, Louise Valestrand, Anne Deininger, Tina Bryntesen, Lisa-Marie Delpech, Guttorm Christensen
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På grunn av ekstraordinært store snømengder i fjellet vinteren 2019/2020 varslet Norges vassdrags- og energidirektorat (NVE) i mai 2020 om stor sannsynlighet for ekstrem vårflom, spesielt for elver i Nord-Norge og elver i Sør-Norge med en stor andel høyfjell i nedbørfeltene. For å dokumentere effekter av de varslete flommene på vannkjemi i elver og kystvann, ble det fra slutten av mai til midten av juli 2020 gjennomført ekstra prøvetakingskampanjer i tre utvalgte elv-fjord systemer som er knyttet til nasjonale overvåkingsprogrammer: Glomma-Ytre Oslofjord-Skagerrak i Sør-Norge og Målselv-Målselvfjord-Straumsfjorden, samt Tana-Tanafjord i Nord-Norge. Hovedmålet med arbeidet var å studere effekten av snøsmeltingsflommene på vannkjemi i elvene, stofftransport fra land til hav og fysisk-kjemiske forhold i kystvannet.

Snøsmeltingsflommene viste seg i etterkant å bli mindre dramatiske enn varslet, og flomtoppene i de tre elvene endte opp under nivået for en 10-års flom. Selv om vi ikke var i stand til å fange en ekstrem værhendelse i løpet av prøvetakingskampanjen, har vi likevel generert nye data og fått verdifull innsikt i hvordan flommene påvirket vannkjemien i elvene, stofftransport fra land til hav og fysisk-kjemiske forhold i kystvannet. Resultatene fra undersøkelsen fremhever viktigheten av vårflommene i forhold til ferskvannspåvirkning av fjordene og i forhold til å transportere terrestrisk materiale ut i kystvannet. Høye stoffkonsentrasjoner i kombinasjon med stor vannføring førte til svært høy transport av partikler, organisk stoff og næringssalter ut i kystvannet i den perioden flommene varte. Dette gjaldt særlig i de to nordligste elv-fjord systemene, der vårflommene bidro med godt over halvparten av de årlige tilførslene av ferskvann, løst organisk karbon (DOC), suspenderte partikler (SPM), totalt nitrogen (tot-N) og totalt fosfor (tot-P) til kystvannet. Undersøkelsen dokumenterte også at det var stor variasjon i elvenes vannkjemi i de ulike fasene av vårflommen. Konsentrasjonene av DOC og næringssalter var ofte høyest i den tidlige fasen av flommen, for deretter å avta under selve flomtoppen og i tiden etter på grunn av fortynningseffekter.

Tilførslene fra land hadde også en tydelig innvirkning på fysiske og kjemiske forhold i kystvannet. Det ble målt redusert salinitet, økt vertikal lagdeling i vannsøylen, samt forhøyet SPM, silikat, nitrat+nitritt og SUVA_{254}[2] på kyststasjonene i forbindelse med vårflommen i elvene. Samlet sett vil disse endringene i stratifisering/lagdeling, lystilgjengelighet samt konsentrasjoner av DOC og næringssalter sannsynligvis ha et bredt spekter av påvirkninger på kystøkosystemenes struktur og funksjon. Effekten av elvetilførslene på ØKOKYST-stasjonene som lå lengst fra elveutløpene var avhengig av fjordenes morfometri (terskler m.v.) og graden av utveksling med havvann utenfra. Våre utvalgte stasjoner lenger inn i fjordene viste en mye sterkere påvirkning fra elvene. Det illustrerer at dagens ØKOKYST-program bare i begrenset grad er i stand til å dokumentere effekter av tilførsler fra land, og at programmet i et klima-overvåkingsperspektiv ville profitere på å også inkludere stasjoner lenger inn i fjordene, som vist her for Målselv-Målselvfjord-Straumsfjorden.

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[2] Spesifikk UV absorbans ved 254 nm; ofte brukt som indikator for terrestrisk organisk materiale

Den store og raske variasjonen i vannføring, elvenes vannkjemi og fysisk/kjemiske forhold i kystvannet viser at prøvetakingsfrekvensen i dagens overvåkingsprogrammer ikke er tilstrekkelig til å fange opp effektene av flom. For elvene fører dette til store usikkerheter i estimatene for årlig transport av næringssalter, organisk karbon og miljøgifter. I kystområdene fører det til manglende grunnlag for å forstå hvordan vårflommen i elvene spiller inn i forhold til andre sesongbetingete hendelser som våroppblomstring av planteplankton og næringsstoffbegrensning utover i vekstsesongen. Klimaendringene vil sannsynligvis også påvirke tidspunkt, størrelse og forløp av vårflommen, noe som i neste omgang vil kunne ha konsekvenser for vannkvalitet i elvene og i kystvannet. Langsiktige endringer i tidspunkt for- og mengde av tilført ferskvann og terrestrisk materiale fra land kan også påvirke kystøkosystemenes rolle i den globale karbonsyklusen gjennom endringer i balansen mellom primærproduksjon og respirasjon i kystvannet, sedimentasjon/lagring av karbon i sedimentet og forsuring av havet.

Gitt de nære koblingene mellom klimaendringer og effekter på land, ferskvann og marint miljø er det nå et økende behov for interdisiplinære tilnærminger på tvers av økosystemer når man skal studere effekter av klimaendringer, inkludert ekstreme værhendelser, på nordlige økosystemer. Ekstreme værhendelser er vanskelige å forutse, og de fanges sjelden opp av tradisjonelle miljøovervåkings-programmer som hovedsakelig er designet for å observere langsiktige endringer. I tillegg er overvåkingsprogrammene vanligvis avgrenset til gitte økosystemtyper (terrestrisk, ferskvann, kyst, hav) og mindre tilpasset til å studere påvirkninger og responser på tvers av de ulike systemene.

Vi anbefaler å supplere de tradisjonelle overvåkingsmetodene med nye teknologiske løsninger i form av sensorbasert overvåking i elv og sjø, automatisk/fjernstyrt prøvetaking og fjernmålingsteknikker. Dette kan gi nye og utvidete muligheter for å kunne dokumentere effekter av både langsiktige klimaendringer, sesongmessige forskyvninger og ekstreme værhendelser på tvers av terrestriske-, ferskvanns- og marine økosystemer.

1 Introduction

1.1 Spring freshet as a key driver of river water chemistry and land-ocean fluxes

In northern river catchments, spring snowmelt (also known as '*spring freshet*') can often account for half of the total annual discharge, playing a key role in the mobilization and transport of suspended particulate matter (SPM), nutrients, organic matter and contaminants from land to freshwater and downstream coastal ecosystems (Ahmed et al., 2020, Holmes et al. 2012). The spring freshet period is also often characterized by distinct river water chemistry, with concentrations of dissolved organic carbon (DOC), SPM, nutrients, and contaminants (including mercury; Hg) that are generally higher than at other times of year (Braaten et al. 2020, Skarbøvik et al. 2012).

Taken together, high discharge paired with elevated concentrations can lead to very high fluxes of DOC, nutrients, SPM and Hg during a very short time period. For example, for a range of Arctic rivers, spring freshet has been shown to deliver up to 50% of total annual fluxes of dissolved organic carbon and Hg during a matter of weeks (Holmes et al. 2012, Finlay et al. 2006, Zolkos et al. 2020). Since the spring freshet often lasts only a few weeks (with the discharge peak, or peaks, lasting only a few days), it is challenging, yet critical, to document the impacts of spring freshet on river water quality, or the contribution of freshet to total annual fluxes of terrestrial material from land to sea on a detailed level based on regular monitoring (e.g. monthly sampling in the Norwegian River Monitoring Programme).

Furthermore, river water chemistry is often very different during the early phases of a high flow event (e.g. higher DOC and Hg concentrations) compared to after the flood peak has passed, when dilution of DOC and nutrients is often seen. This suggests that to accurately capture the dynamics and progression of riverine transport of dissolved and particulate matter throughout spring freshet, samples should ideally be taken before, during and after each of the main flood peaks during the snowmelt progression.

1.2 Potential impacts of spring freshet on affected coastal systems

Intense 'pulses' of inputs from land to sea during freshet can be expected to have strong impacts on physical, chemical and biological conditions in impacted coastal waters. These effects can include shifts in salinity, temperature and stratification; reduced light availability due to increased light attenuation by terrestrial particles and dissolved organic matter (DOM); increased sedimentation rates; changes in nutrient and DOC availability; and changes in the contamination of coastal waters and food webs. Taken together, these changes can have important implications for coastal water quality (Frigstad et al. 2020b, Deininger et al. 2020, McGovern et al. 2020a, Schultze et al. *submitted*); productivity (Opdahl et al. 2019); benthic and pelagic community structure and function (Frigstad et al. 2018, McGovern et al. 2020b); and contamination of coastal waters, sediments and food webs (summarized by McGovern et al. 2019).

Furthermore, the high river discharge associated with spring freshet can create extensive buoyant river plumes, leading to strongly stratified coastal waters, retaining freshwater and terrestrial material in the surface water layer where they can be transported much farther offshore than during periods of lower flow (Frigstad et al. 2020a). This suggests that the spatial extent of riverine impact on coastal ecosystems is likely to be particularly high during the productive spring/summer period.

While the spring phytoplankton bloom in mid-high latitude Norwegian coastal systems typically occurs between February/March to April (Wassmann et al. 1991), preceding spring freshet (Frigstad et al. 2020a), the timing and duration of both spring freshet and the spring phytoplankton bloom may change due to climate change, due to changes in e.g. precipitation, snow-melt, water column stratification and light availability. This highlights the need to understand how the timing of spring freshet aligns with other key seasonal processes in the marine environment, such as the spring phytoplankton bloom or the onset of summer stratification and/or nutrient-limited conditions in surface waters.

Also related to spring freshet and river discharge, there has been a long-term reduction in water clarity in Norwegian coastal waters over the last decades, termed “coastal darkening” (Aksnes et al. 2009, see also references summarized in a recent literature review on increased light attenuation in Norwegian coastal waters; Frigstad et al. 2020b) which has been connected to reduced salinity in the Norwegian Coastal Current and linked to an increase in the riverine discharge and transport of organic material from Norwegian rivers (Braaten et al. 2020). This increase in riverine run-off has been attributed to effects of climate change, in addition to other human impacts, and is expected to increase in the future (Larsen et al. 2011; de Wit et al. 2016). Potential biological effects of coastal darkening that have been suggested include a delay in the onset of the spring bloom (Opdahl et al. 2019), increases in jellyfish blooms (Aksnes et al. 2009), and a decrease in the maximum depth for growth of macroalgae in Skagerrak (Frigstad et al. 2018, Fagerli et al. 2020). However there remains a need for process-based studies on the drivers and impacts of coastal darkening, linking riverine and coastal data across the salinity gradient for Norwegian systems.

1.3 Background and objectives for the current study

Based on projections pointing to the potential for extreme snowmelt floods during spring 2020 for several Norwegian rivers, NIVA approached the Norwegian Environment Agency, who agreed to support a study designed to capture the impacts of extreme snowmelt floods on water chemistry in Norwegian rivers and coastal waters. This additional funding supported riverine and coastal sampling campaigns in three selected river-fjord systems that are all included in ongoing, long-term monitoring programmes. The sites included the Målselv-Målselvfjord-Straumsfjorden and Tana river-Tanafjord systems in northern Norway, and the Glomma river-Ytre Oslofjord-Skagerrak system in southern Norway.

Our overarching goal was to study the impact of the 2020 spring freshet on river water chemistry, land-ocean fluxes, and physicochemical conditions in coastal waters. To achieve this, we took an integrated approach by combining riverine and coastal monitoring data (from the national river monitoring programme [Elveovervåkingsprogrammet] and the national coastal monitoring programme [ØKOKYST]) together with data from extra sampling during the spring 2020 freshet period (defined here as from late May to early July 2020). This extra sampling was designed to provide increased sampling frequency, sampling transects linking river and coastal monitoring stations, and data for selected variables that are not regularly monitored across the freshwater-marine continuum.

In this report we describe between-site differences and seasonal patterns in river and coastal water chemistry based on existing data from river (2016–2020) and coastal (2017–2020) monitoring in the three study regions, and then combine these with the extra 2020-sampling campaign data to evaluate the role of riverine inputs as a source of SPM, DOC and nutrients to coastal waters during spring in comparison with other seasons. Based on the 2020 spring freshet sampling campaigns, we characterize variability of water chemistry during freshet (e.g. changes between early to peak to late freshet) and provide data on how select water chemistry variables change along gradients from river outlet to outer fjord. We discuss the findings in the context of integrated climate monitoring along the aquatic continuum (from catchment to coast) as well as expected climate change.

2 Methods

2.1 Study sites

The field study included dedicated sampling during spring freshet for three rivers and their adjacent coastal waters, including the following sites (**Table 1**, **Figure 1,** ***also see Appendix***):

1) Glomma river, outer Oslofjord, Skagerrak (southern Norway)
2) Målselv river, Målselvfjord, Straumsfjorden (northern Norway)
3) Tana river, inner Tanafjord, outer Tanafjord (northern Norway)

The three study rivers are monitored on a monthly basis (16 times a year for Glomma) as a part of the Norwegian river monitoring programme (Elveovervåkingsprogrammet), while sampling stations in Skagerrak (VT3 + VT65), Straumsfjorden (VR54) and outer Tanafjord (VR24) are part of the national coastal monitoring programme (ØKOKYST). Straumsfjorden is also included in the Ocean Acidification programme. Additional stations in the Glomma river estuary (see section 2.2) are monitored as part of a regional monitoring program (Overvåking av Ytre Oslofjord; supported by Fagrådet for Ytre Oslofjord). Although Målselvfjord and inner Tanafjord are not part of existing monitoring programmes, the sampling stations in these fjords provide an important link between observations in the rivers and at the coastal monitoring stations (**Figure 1**). For the Målselv river, the nearest coastal monitoring station is at Straumsfjorden (VR54), 31 km from the river outlet. Meanwhile for the Tana river, coastal monitoring (at VR24) takes place in outer Tanafjord, 29 km from the river outlet. For Målselvfjord, NIVA also has detailed physical, chemical and ecological data available from the past 5 years through several research projects focusing on land-ocean interactions (e.g. Frigstad et al. 2020a, McGovern et al. 2020b, Schultze et al. *submitted*).

The selection of sites where long-term monitoring data are available provides important context for our additional freshet sampling. In addition, the Glomma river catchment/outer Oslofjord/Skagerrak has been identified by the Norwegian Environment Agency as a study region for 'Integrated Climate Monitoring', with a goal of integrating and linking climate data to field and sensor-based data across multiple freshwater and marine monitoring programmes in order to provide much-needed insight into impacts of climate change along the entire terrestrial-freshwater-marine gradient (i.e. the continuum from catchment to streams, lakes, rivers and the coast).

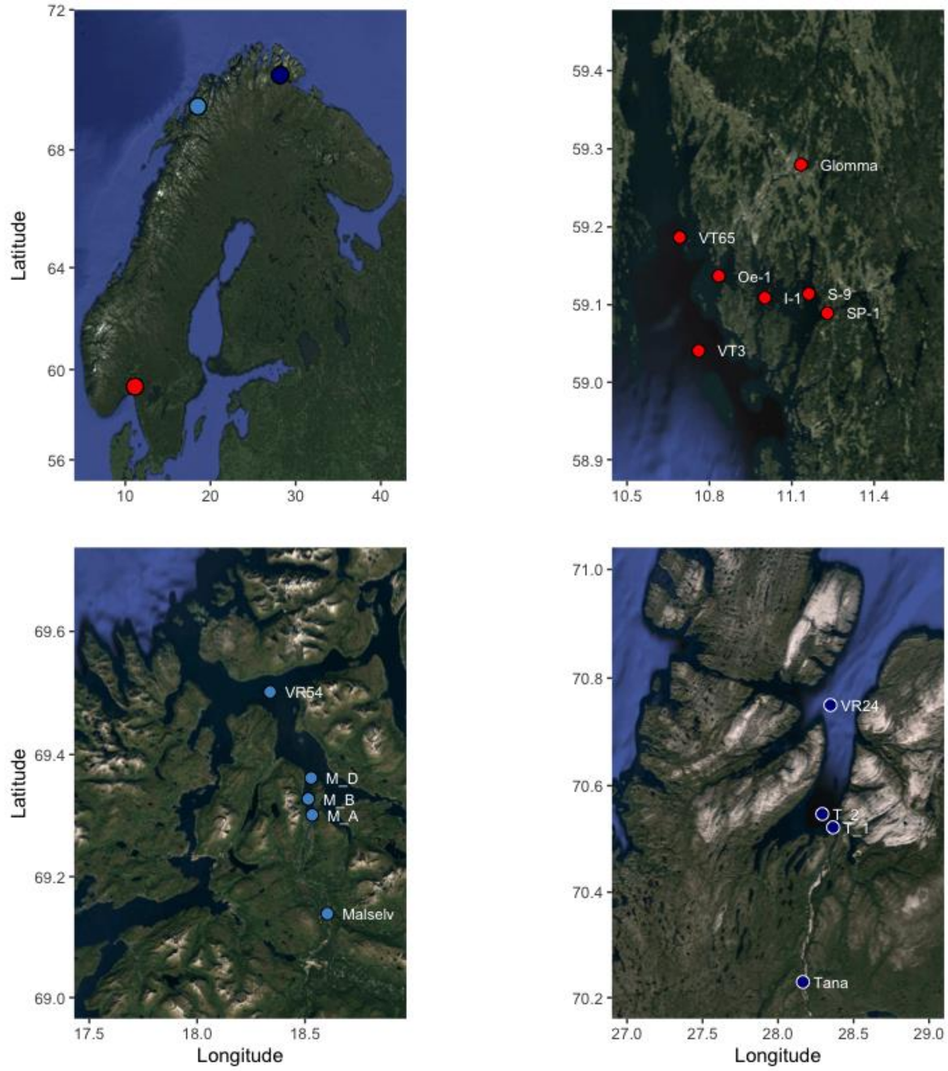

Figure 1. Maps showing the location of the study sites. Top left: map of Scandinavia with the study regions indicated; top right: study stations in the Glomma river-Outer Oslofjord-Skagerrak system; bottom left: study stations in the Målselv river-Målselvfjord-Straumsfjorden system; bottom right: study stations in the Tana river-Tanafjord system (source for background maps: Google Maps).

Table 1. Catchment characteristics of study rivers. Data from https://nevina.nve.no/.

		Glomma	Målselv	Tana
Catchment area	km^2	41771	5586	15219
Max altitude	*m.a.s.l.	2463	1714	1064
Mean altitude	m.a.s.l.	734	688	340
Mean runoff (1961-1990)	L/s/km^2	16.8	28.6	11.7
Land cover				
Uplands, non-forested	%	25.2	58.4	18.8
Glaciers	%	0.7	0.5	0.0
Forest	%	50.4	26.3	52.9
Wetlands/peat	%	7.2	4.3	12.3
Lakes	%	4.9	5.7	4.8
Agricultural land	%	6.3	0.6	0.3
Urban	%	0.5	0.1	0.1
Non-classified	%	4.9	4.1	11.0

*m.a.s.l. = meters above sea level

2.2 Extra samples collected during spring 2020

Overviews of stations, sampling dates and parameters analysed during the sampling campaign can be found in the Appendix (**Appendix table A1-3**). River water samples from the Glomma, Målselv and Tana rivers were collected from the stations that are included in Elveovervåkingsprogrammet (Braaten et al. 2020), where all stations are sampled on a monthly basis, except in the Glomma river where samples are collected more frequently (3 times per month) in May and June. In the current study, two additional sampling rounds were carried out in the Glomma and Tana rivers (targeting early and late freshet, with an extended set of parameters) while 5 extra rounds were carried out in the Målselv river (**Appendix table A1**). For marine coastal waters impacted by the Glomma river and estuary, additional parameters were included in the June and July field cruises for 6 monitoring stations included in the ØKOKYST Skagerrak programme (Fagerli et al. 2020) and the Outer Oslofjord monitoring programme (Engesmo et al. 2020) (**Appendix table A3, Figure 1**).

Three stations in the inner Målselvfjord were sampled two times in June (**Appendix table A2, Figure 1**). The stations are not part of any national monitoring programme, but have been sampled semi-regularly by NIVA (2-6 times a year since 2016, capturing all seasons). Further out in the fjord system additional parameters were sampled in June (two cruises) for VR54 Straumsfjorden (**Appendix table A3**), which is included in both the ØKOKYST Delprogram Norskehavet Nord (I) (Velvin et al. 2020) and the Ocean Acidification monitoring programme (Jones et al. 2020).

Two stations in inner Tanafjord were sampled in June (**Appendix table A2, Figure 1**). These are new stations with no previous data available, and were added in order to provide a gradient including the river, the strongly river-influenced inner fjord and the coastal monitoring station (VR24 Tanafjord), located in the outermost part of the fjord. Two cruises were carried out at the VR24 Tanafjord station during the relevant time period (**Appendix table A3**) which is included in the ØKOKYST Delprogram Barentshavet monitoring programme (Mannvik et al. 2020).

Station coordinates are presented in **Appendix B**.

2.3 Water quality sampling and analyses

2.3.1 River stations

Sampling methodology and analyses of standard chemical parameters are described in the annual reports from the Norwegian River Monitoring Programme (Braaten et al. 2020). Extra parameters analyzed in connection with the VårFlom project (see methods in chapter 2.4) included:

- total and inorganic suspended particulate matter (SPM, SPM_{inorg})
- total and methyl mercury (Tot-Hg, MeHg)
- optical characterization of chromophoric dissolved organic matter (cDOM) based on absorption spectra (cDOM absorption)

Analytical methods for these “extra parameters” are described in chapter 2.4

2.3.2 Inner fjord stations

The inner stations in Målselvfjord and Tanafjord are not part of any national monitoring programme, but sampling methods and general chemical analyses **(Appendix table A2)** were following the same protocols as in ØKOKYST (e.g., Fagerli et al. 2020). Extra parameters analyzed in connection with the

VårFlom project were the same as for the river stations. In addition, extra samples were taken during regular cruises on stations in the outer Oslofjord programme (Engesmo et al. 2020).

2.3.3 Outer fjord stations

Sampling methodology and analyses of standard chemical parameters are described in the annual reports from the ØKOKYST programmes (Mannvik et al. 2020; Velvin et al. 2020; Fagerli et al. 2020) and the Ocean Acidification Monitoring Programme (Jones et al. 2020). Extra parameters analyzed in connection with the VårFlom project included DOC and cDOM absorption at VT3 and VR54 (**Appendix table A3**).

2.4 Analytical methods for "extra parameters"

2.4.1 Total and inorganic suspended particulate matter (SPM, SPM_{inorg})

For additional river and inner fjord samples from the two northern systems, suspended particulate matter (SPM) was collected on a Whatman GF/F glass-fibre filter (nominal pore size of 0.7 µm), and stored frozen until further processing. SPM concentrations were determined gravimetrically after drying filters at 104 °C for ~1 h (or until weight had stabilized). The inorganic fraction of the SPM (SPM_{inorg}) was determined based on loss-on-ignition by combusting the dried and weighed SPM filters at 450 °C for 1 h, allowing them to cool in a desiccator and then re-weighing (Strickland and Parsons 1972, Doerffer 2002).

2.4.2 TotHg, MeHg and DOC

Hg analysis for river and inner fjord water was carried out at NIVA. Tot-Hg was determined based on USEPA method 1631 (also see Braaten et al. 2020), while MeHg was determined as described in Braaten et al. (2014). Meanwhile, DOC concentrations for outer fjord stations were determined as described in Fagerli et al. (2020).

2.4.3 cDOM absorption

In order to gain insight into sources, molecular structure and absorption properties of dissolved organic matter (DOM), we measured cDOM absorption spectra for the extra river, inner fjord and outer fjord samples (excluding VR24). Briefly, sample water was filtered through 0.2 µm polycarbonate filters and stored cold at 4 ℃ and dark in 100 mL amber glass bottles until analysis. Absorption spectra were measured on a Cary 3000 UV-Vis dual-beam spectrophotometer from Agilent Technologies by measuring absorbance between 190-900 nm at 1 nm intervals using a quartz cuvette with a 10 cm pathlength (with the exception of one sample from Tana river (20.06.2020), where a 1 cm pathlength was used, due to insufficient sample volume). The samples were blank corrected directly in the spectrophotometer by setting a baseline with Milli Q water in both beams, and by directly measuring each sample against the baseline. Data were processed and analyzed in R using the using a Gaussian decomposition model approach described in Massicotte & Markager (2016) and the R-package ˈcdomˈ.

Relevant wavelengths and metrics known to be indicators for DOC concentrations or DOM molecular structure were extracted as described in Helms et al. (2008). In the current report we focus on the specific UV absorption at 254 nm ($SUVA_{254}$; calculated by dividing the absorbance at 254 nm (cm^{-1}) by DOC concentration). $SUVA_{254}$ is widely used as an indicator for terrestrial and highly coloured sources of DOM, with high $SUVA_{254}$ values linked to DOM with high molecular weight and high aromatic content (Weishaar et al. 2003, Hansen et al. 2016).

2.5 Hydrologic data

River discharge data for the Glomma, Målselv and Tana rivers were retrieved from the stations 2.605 Solbergfoss, 196.35 Målselvfossen, and 234.18 Polmak, respectively. All stations are operated by the Norwegian Water Resources and Energy Directorate (NVE), with data available both on hourly and daily basis. It should be noted that the 2020 data shown in this report are real-time measurements, which have not yet been quality assured by NVE's standard protocols (correction for river ice, etc.).

3 Results and discussion

3.1 Seasonality in riverine discharge, water chemistry and fluxes (2016–2020)

3.1.1 River discharge

In all three rivers, the highest annual discharge was associated with spring snowmelt floods, with peak discharge typically occurring between late May and mid-June (**Figure 2**). In the Glomma river, the snowmelt flood tends to be distributed over a longer time period due to the larger elevation differences in this large "mountain to fjord" catchment. The lower parts of this catchment are also characterized by unstable winters with occasional flood events, leading to very high discharge during other times of the year (e.g. during autumn 2020). In the Målselv river, there are often multiple discharge peaks between late May and late June, reflecting differences in timing of snowmelt between the lower elevations and the more mountainous areas in this catchment. In the Tana river, spring freshet typically includes a more pronounced single peak in late May or early June, but in some years snowmelt is distributed across multiple smaller peaks.

The highest discharge in 2020 occurred on June 10th in the Glomma river, and on June 8th in the Målselv and Tana rivers (**Figure 2**). Despite the projections for large snow melt floods in spring 2020, the peak discharge values observed during spring freshet for our three study rivers all fell below 10-year flood levels (source: NVE). In the Tana river, the maximum flow during spring freshet (2345 m^3/s) fell between the 5 and 10-year flood levels, while in the Målselv river, maximum flow (637 m^3/s) fell between an average spring flood and a 5-year flood. In the Glomma river, the study river with the largest catchment and highest annual discharge, the maximum flow during spring freshet was 1846 m^3/s, similar to values for an average spring flood.

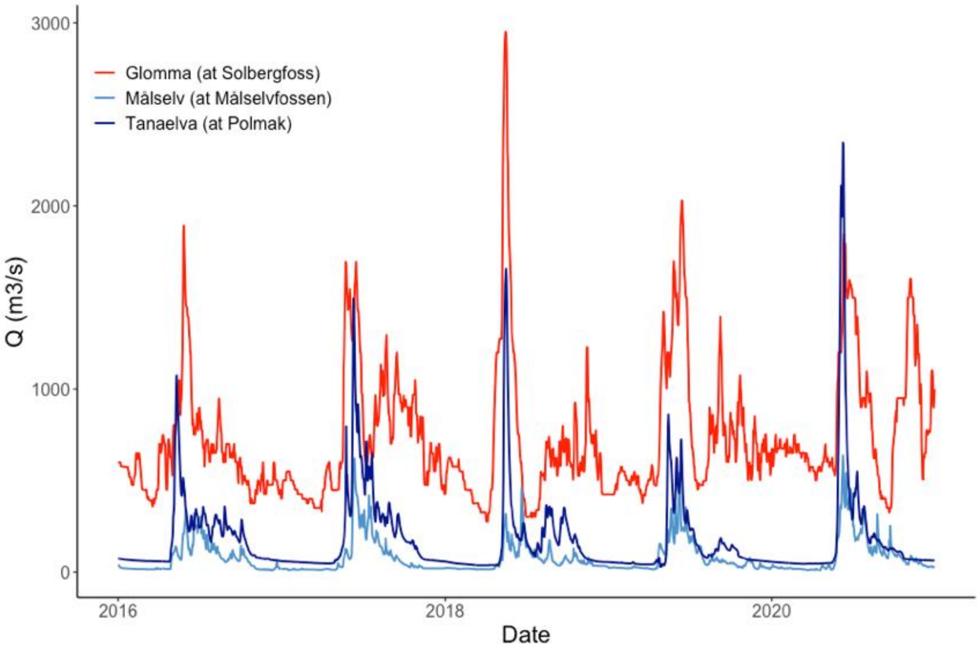

Figure 2. Daily discharge from 2016-2020 at NVE stations 2.605 Solbergfoss (Glomma watercourse), 196.35 Målselvfossen (Målselv watercourse), and 234.18 Polmak (Tana watercourse). Data for 2020 are not yet quality controlled by NVE's standard routines.

3.1.2 Between-river differences and seasonal patterns

Between-river differences and seasonality in water chemistry are discussed in detail for these rivers in Braaten et al. (2020). Briefly, all three study systems exhibited a high degree of seasonality in river water chemistry, especially for the northern rivers. For all three rivers, water chemistry during the spring freshet period is indeed distinct from chemistry in other seasons with most of the measured variables experiencing concentration peaks during the spring freshet period between May–July (**Figure 3**). For example, in the Målselv river, SPM concentrations during freshet are often an order of magnitude higher than those observed during the rest of the year, while TOC, DOC, tot-P and PO_4 concentrations are typically 3- to 4-fold higher than at other times of the year. Elevated TOC and DOC concentrations associated with spring freshet are also observed in the Tana and Glomma rivers, however, these more carbon-rich catchments also support higher C concentrations during other seasons (**Figure 3**). A notable exception to this pattern is observed for NO_3 + NO_2, where concentrations are typically highest during winter when the demand for inorganic nitrogen by terrestrial vegetation is low.

Despite seasonal variability, there were some consistent between-river differences in water chemistry that can be linked to their catchment characteristics (cf. **Table 1**). SiO_2 and TOC concentrations were highest and SPM concentrations were lowest in the Tana river, which drains a Si- and C-rich catchment that is relatively ‘flat’ (low slope). In contrast, the Målselv river catchment drains a relatively carbon-poor mountainous landscape, where higher slopes and lack of vegetation lead to lower TOC but also higher SPM concentrations. The particularly high SPM peaks in the Målselv river during floods likely arise from riverbank erosion in the lower meandering parts of river. The Glomma river has elevated tot-N concentrations relative to the other two rivers, likely reflecting large areas with intensive agriculture, higher atmospheric N deposition, and higher population density in this catchment (Bækken et al. 2008). Clay-rich soils in the lower parts of the catchment also contribute to elevated SPM loads in the Glomma river during floods.

Daily fluxes of SPM, TOC, SiO_2, tot-P and tot-N were estimated for the three study rivers as described in Braaten et al. (2020) (**Figure 4**). Based on estimated fluxes, especially in the north, the spring freshet is the dominant driver for land-ocean fluxes. For example, in 2020, estimated fluxes in the Tana river from mid-May to end of June accounted for 83, 68, 40, 73, and 56 % of the annual load of SPM, TOC, SiO_2, tot-P and tot-N, respectively, whereas in the Målselv river estimated fluxes during this time period accounted for 81, 59, 46, 82, and 52 % of annual loads for the same variables.

In the Glomma river, element fluxes are more evenly distributed over the year with substantial transport also during winter. This is likely due to a combination of the longer snowmelt period and occasional winter flood events in this catchment (see section 3.1.1), the dampening effect of large lake reservoirs in the catchment(e.g. lakes Mjøsa and Øyern), and the higher degree of human impact on this catchment compared to the two northern study rivers.

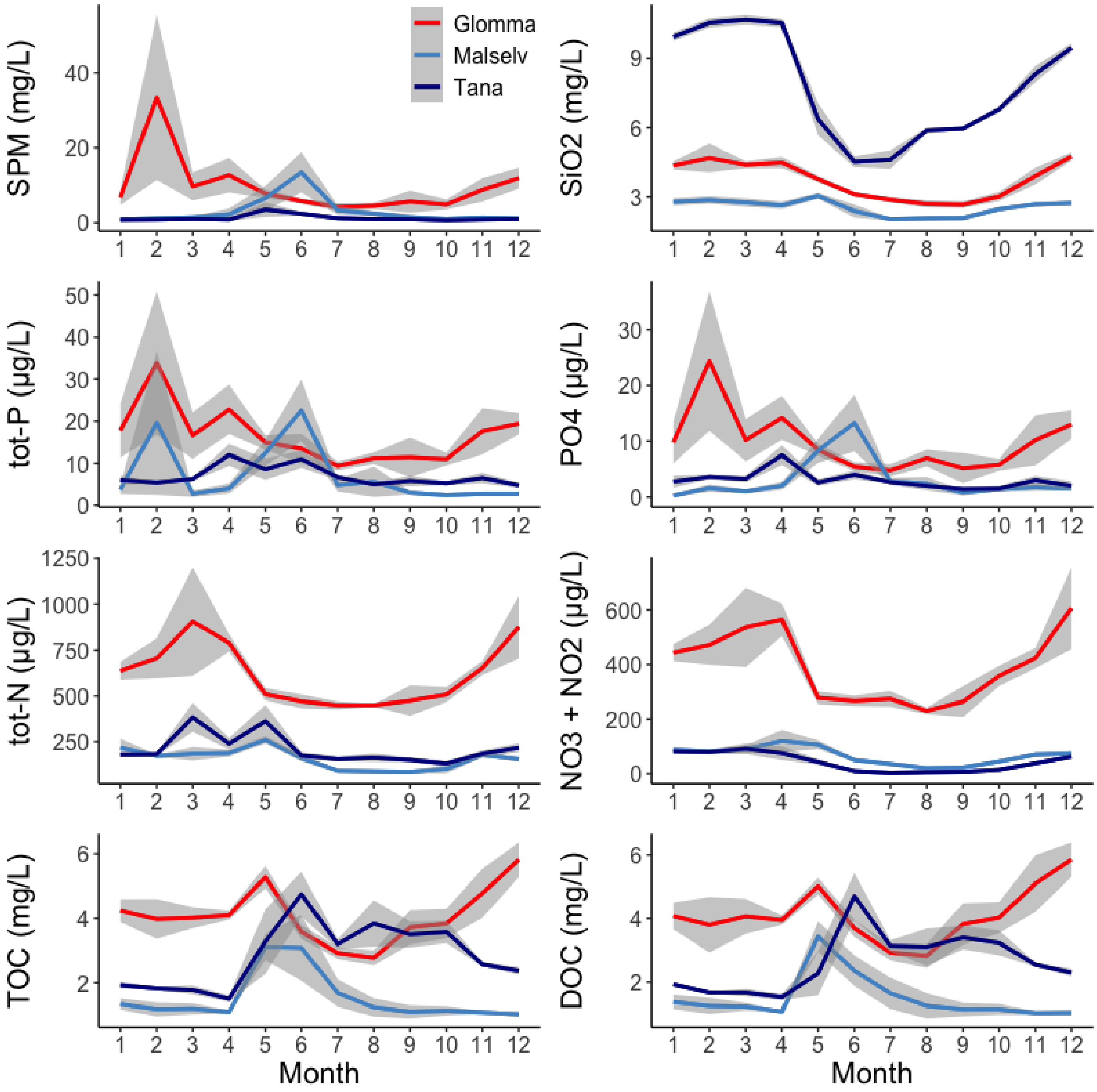

Figure 3. Mean monthly concentrations of SPM, total and dissolved nutrients, TOC and DOC in the three study rivers based on data from 2016-2020. Source: Elveovervåkingsprogrammet. Colours represent study river, line plots connect mean monthly values from 2016-2020, while the shaded area represents the standard deviation for this same time period.

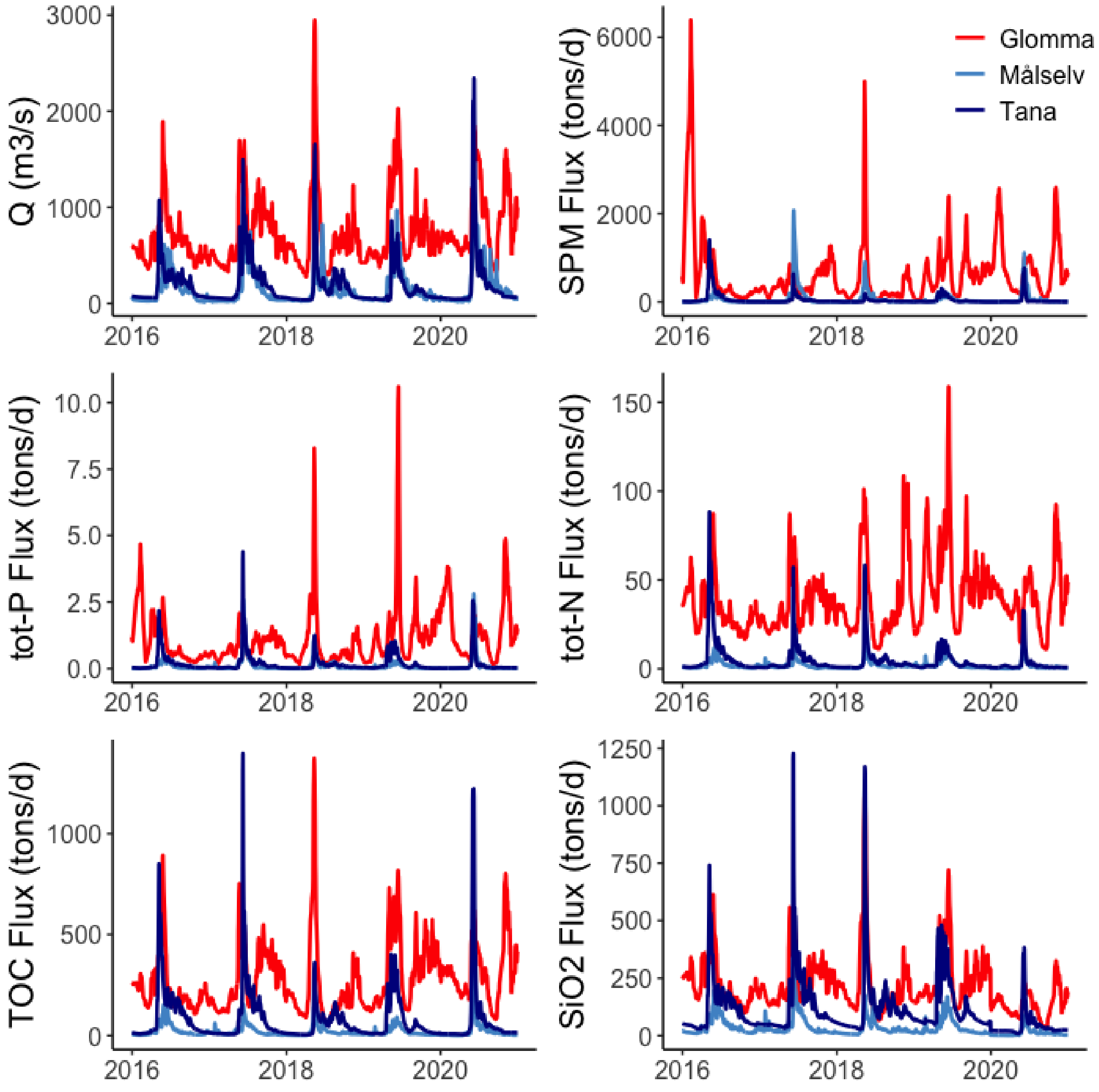

Figure 4. River discharge and fluxes of suspended particulate matter (SPM), total phosphorus (tot-P), total nitrogen (tot-N), total organic carbon (TOC), and silicate (SiO_2) in the Glomma, Målselv and Tana rivers for 2016-2020. Note that the discharge estimates for the Målselv river are scaled based on measured discharge at Målselvfossen (NVE station 196.35). Sources: NVE, Elveovervåkingsprogrammet.

3.2 Seasonality in physical and chemical conditions in coastal waters (2017–2020)

3.2.1 Physical conditions: Between-site differences and seasonal patterns

Based on data from the ØKOKYST monitoring programme (2017-2020), we characterized the main between-site differences in the three coastal study sites.

The Torbjørnskjær station in Oslofjord (VT3) has a different physical regime than the two northern coastal study sites (**Figure 5**). Here, the upper water column (down to around 30 m) is mostly stratified year-round, due to high freshwater influence from large rivers draining into the Skagerrak region as well as influence from advected waters from the southern North Sea and the Baltic Sea (see also Frigstad et al. 2020). The minimum salinity in the 2017-2020 period was observed during late summer, not during spring freshet, when salinity was as low as 14 psu in surface waters in August 2020, however in most years the lowest salinities tended to be observed between April and June. Summer temperatures are generally higher (surface water temperatures > 20 °C in 2018) and high salinities (34-35 psu) are found below approximately 50 m year-round.

The physical conditions at the Straumsfjorden station (VR54; **Figure 6**) are similar to Tanafjord (**Figure 7**), with freshwater influence observed during spring and summer months in the surface layer (< 5 m), although with lower salinities in the surface layer (minimum value of 4 psu observed in June 2020). The surface freshwater lens was more persistent than at the Tanafjord station most years, especially in 2020 where low salinity surface water was observed until October. Aside from these summer periods of surface salinity stratification, the station is mostly marine and well mixed, with mixing extending to the bottom (150 m) during late summer/fall.

The Tanafjord station (VR24) is the most marine station of the three coastal regions, with relatively high salinities (34-35 psu) year-round (**Figure 7**). Influence of freshwater in the surface layer (< 5 m) was observed during summer (June-August), with minimum salinity of ~27 psu in July 2020. This surface freshwater lens typically lasted 1-3 months, and below this layer the station was well mixed year-round, with mixing extending down to >100 m during late summer/early autumn.

The lower salinity and more persistent freshwater layer in Straumsfjorden compared to Tanafjord likely reflects differences in the morphometry of these coastal systems, where Straumsfjorden is located in a narrower fjord system that limits exchange with the open marine environment, the coastal monitoring station in outer Tanafjord is more exposed, leading to a higher degree of mixing and exchange with offshore marine waters. Meanwhile, differences in the duration of freshwater influence likely reflect the longer snowmelt season for the mountainous landscape in the Målselv river catchment and Straumsfjorden region compared to in the Tana river catchment.

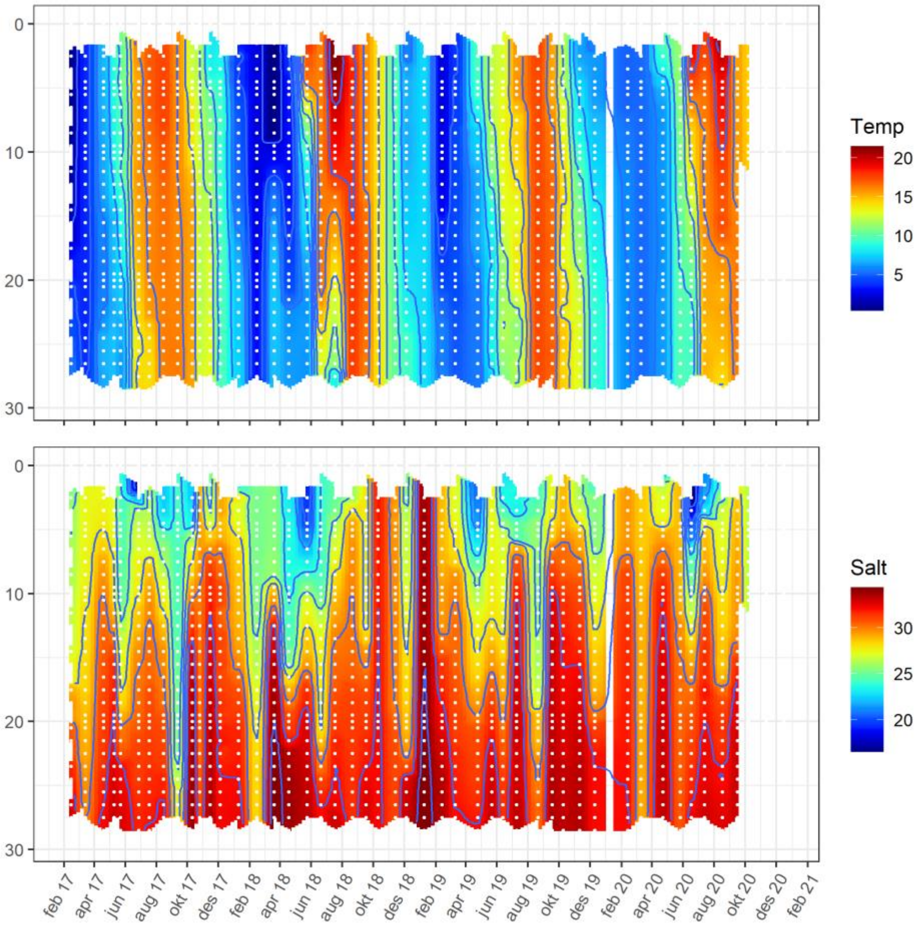

Figure 5. Temperature (upper) and salinity (lower) in the upper water column (0-30m) at the Torbjørnskjær (VT3) station. Dots show measured values, and interpolated values in colors.

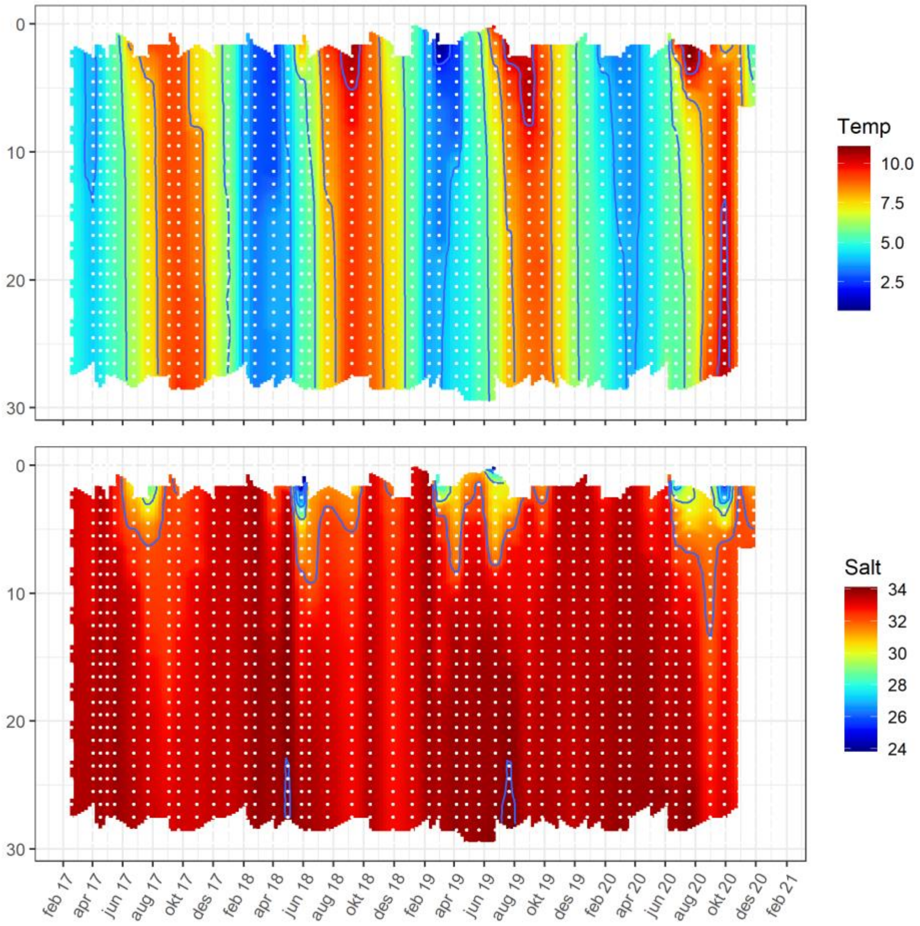

Figure 6. Temperature (upper) and salinity (lower) in the upper water column (0-30m) at the Straumsfjorden (VR54) station. Dots show measured values, and interpolated values in colors.

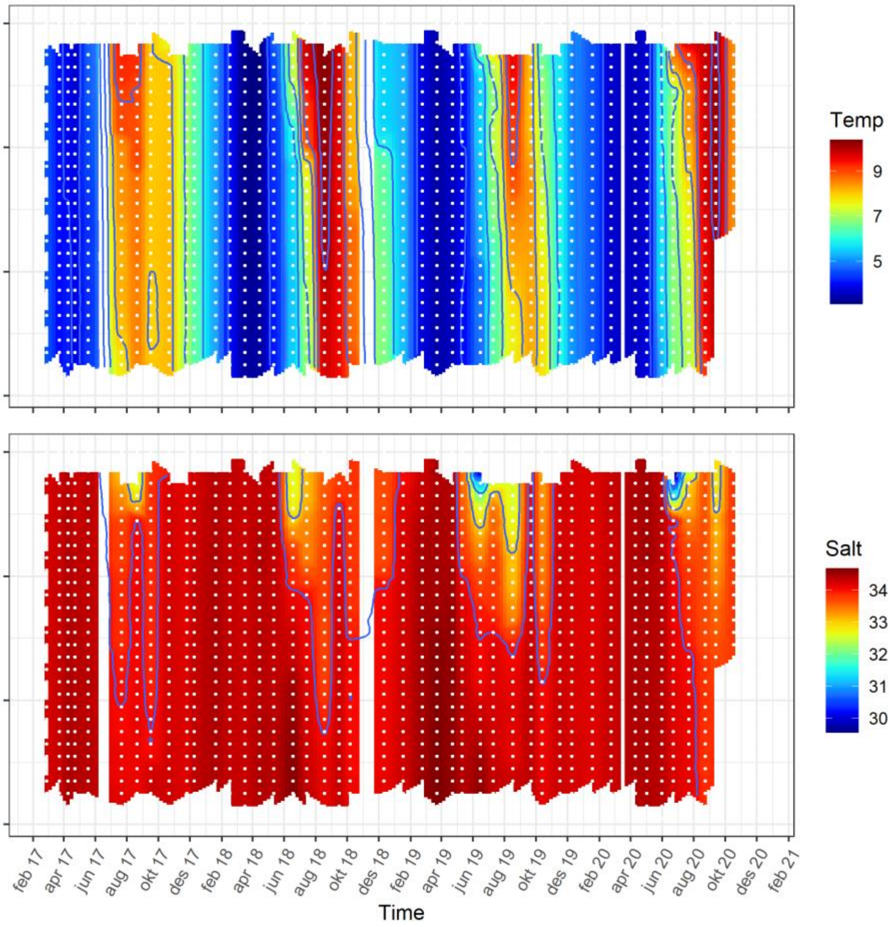

Figure 7. Temperature (upper) and salinity (lower) in the upper water column (0-30m) at the Tanafjord (VR24) station. Dots show measured values, and interpolated values in colors.

3.2.2 Water chemistry: Between-site differences and seasonality

At the Torbjørnskjær station (Oslofjord) surface water NO_3 + NO_2 and PO_4 concentrations were depleted from early spring to late autumn in most years, due to the stronger stratification in the upper water column (**Figure 8**). DOC concentrations were high (> 2 mg/L) in the lower salinity water for large periods of the year, with high DOC concentrations corresponding to minimum salinity values in the surface waters in June 2020. A strong phytoplankton bloom (reaching chlorophyll *a* (Chla) values of 10 µg/l) was detected in March 2018, following a period of high NO_3 concentrations in the water column, likely caused by mixing with deeper nutrient-rich waters.

At the Straumsfjorden station, the drawdown of nutrients (NO_3 + NO_2 and PO_4) was less uniform in the upper water column, indicating stratification due to salinity during parts of the spring/summer period (**Figure 9**). The highest Chla values were observed in July 2019 (5 µg/l), which may have been fueled in part by riverine nutrient inputs during spring (as indicated by low salinity and high NO_3).

At the Tanafjord station nutrients (NO_3 + NO_2 and PO_4) were depleted from approximately May until late fall each year in the whole upper water column (0-30 m), indicating no stratification or only weak stratification during this period (**Figure 10**). Nutrients were generally replenished by mixing with deeper water masses during late fall/winter. Spring phytoplankton blooms were detected in May–July in 2017, 2019 and 2020, with the highest Chla values (6 µg/l) observed at 30 m during July 2019. This sub-surface bloom was concurrent with low salinity and high TSM (1 mg/l) in the surface water layer (0-5 m).

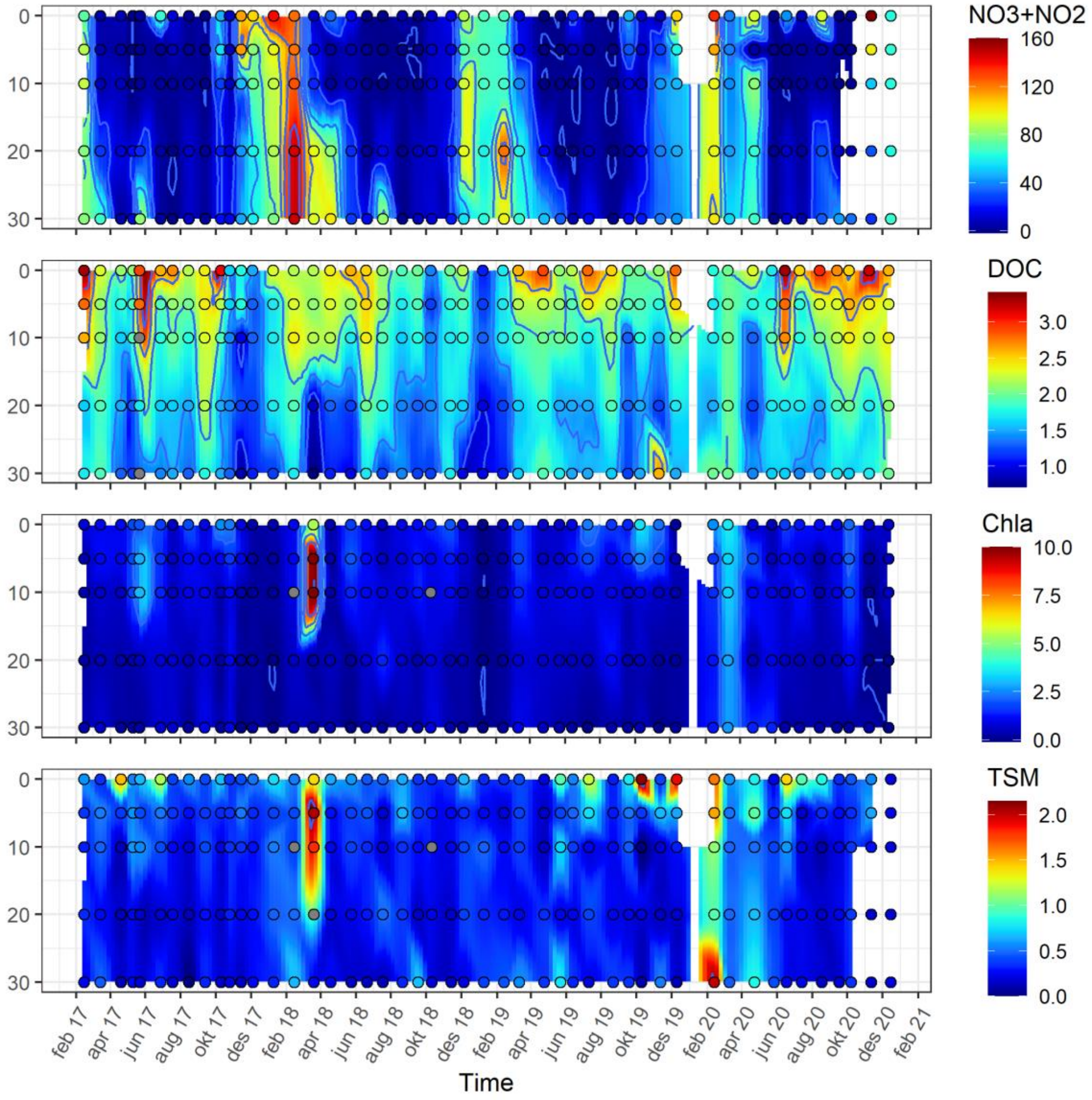

Figure 8. Concentrations of NO_3+NO_2, DOC, Chla and TSM in the upper water column (0-30m) at the Torbjørnskjær (VT3) station. Dots show measured values, and interpolated values in colors.

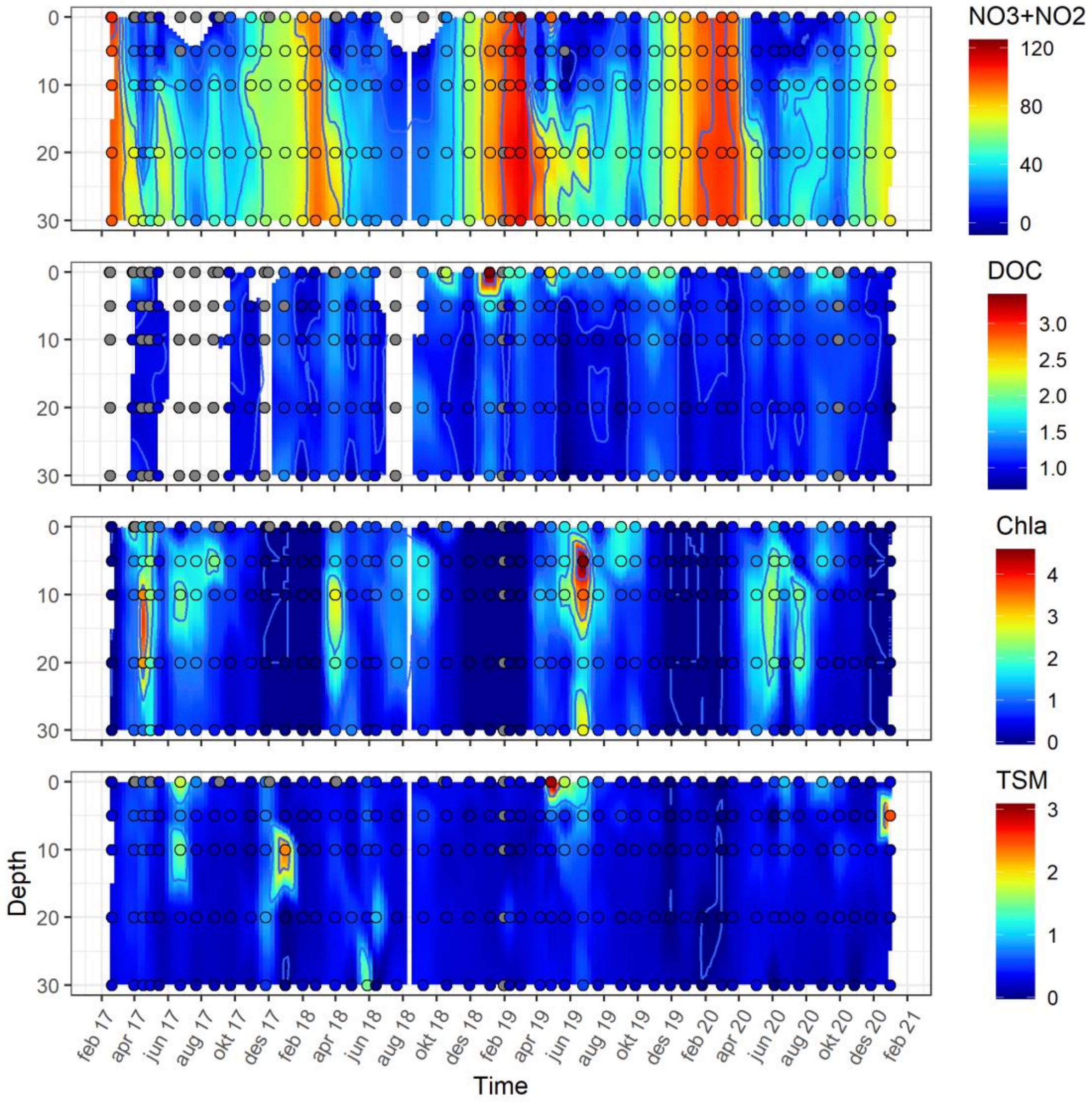

Figure 9. Concentrations of NO_3+NO_2, DOC, Chla and TSM in the upper water column (0-30m) at the Straumsfjorden (VR54) station. Dots show measured values, and interpolated values in colors.

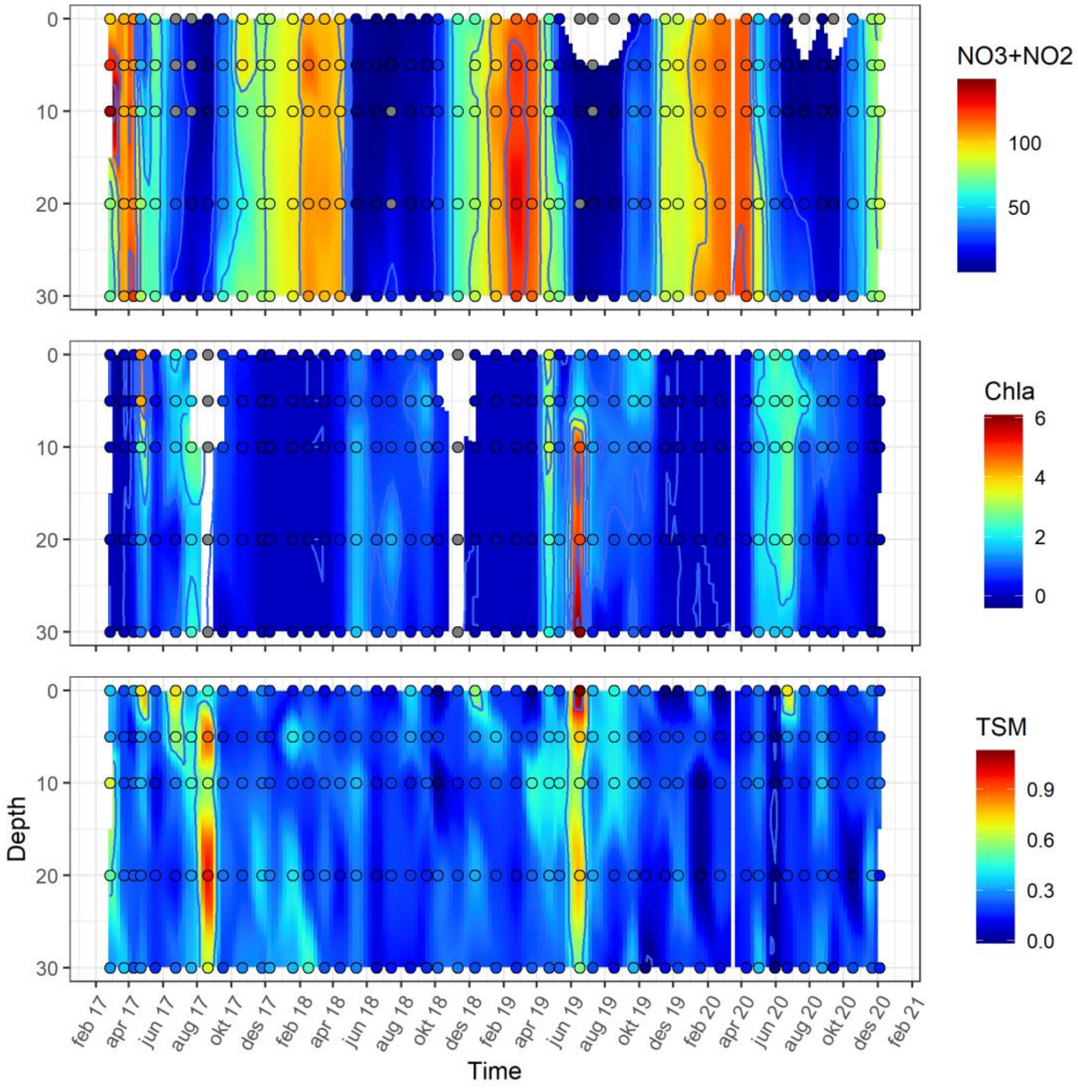

Figure 10. Concentrations of NO_3+NO_2, Chla and TSM in the upper water column (0-30m) at the Tanafjord (VR24) station. Dots show measured values, and interpolated values in colors.

3.2.3 Coastal physical and chemical conditions: Summary

In general, the two northern coastal systems (Straumsfjorden and Tanafjord) are characterized by marine water masses (high salinities) year-round, with stronger freshwater influence in the surface layer (0-5 m) during periods of high riverine inflow during the spring snowmelt period in May–July. Most years, the Straumsfjorden system has lower salinities and more prolonged periods of freshwater influence than Tanafjord. For both northern systems, this freshwater influence creates a shallow freshwater lens, which are characterized by high NO_3 + NO_2, SiO_2 (not shown), DOC and TSM concentrations. Nutrient concentrations in the surface layer are often low due to depletion linked to biological activity before this period. However, the riverine inflow of nutrients appears to stimulate blooms (elevated Chla concentrations), which the monthly sampling may not fully be able to capture, since biological uptake and remineralization can be rapid.

In contrast, the southern coastal system (Torbjørnskjær/Oslofjord) is more permanently influenced by freshwater and the upper water column is stratified for large periods of the year. DOC concentrations are higher year-round than in the northern coastal systems with peak DOC concentrations in the surface waters corresponding to minimum salinities during peak freshwater discharge in June in the Glomma and eastern Norwegian rivers.

3.3 Impacts of spring freshet along the freshwater-marine continuum

3.3.1 Spring freshet as a source of DOC and nutrients to the coastal environment

As described in section 3.1, the northern study rivers experience larger seasonal changes in river water chemistry, including substantial differences in concentrations of nutrients, organic C, suspended particles and Hg between spring and the rest of the year. Differences between water chemistry during spring freshet and in other seasons were less pronounced for the southern study system (Glomma). The combination of these elevated concentrations with the substantial contribution of spring freshet to total annual discharge in the northern rivers means that spring freshet plays a more pronounced role in delivering freshwater and terrestrial material to coastal systems in northern Norway than more southerly systems (**Figure 4**), where the terrestrial and Baltic Sea inflow are more evenly distributed throughout the year.

The impact of riverine inputs on water quality in coastal waters also depends on the water quality in the affected marine waters. For example, when nutrient and DOC concentrations in the marine environment are low, inputs from rivers could act as an important source of inorganic nutrients and organic matter for coastal phytoplankton and bacteria. By combining existing monitoring data (2017–2020) on concentrations of DOC and dissolved inorganic nutrients for the three study rivers with data from the coastal monitoring stations (at two depth intervals: 0–15m and >15m), we were able to evaluate differences in concentrations between rivers, coastal surface waters, and coastal deep waters; both for the spring period and for the rest of the year (**Figure 11**).

We found that in the Glomma river-outer Oslofjord system, the river seemed to be a source of DOC, SiO_2 and NO_3 + NO_2 throughout the year, with elevated DOC concentrations in surface waters, likely reflecting the large pool of terrestrial DOC present in the stratified surface waters of the Oslofjord/Skagerrak system. During spring freshet both Målselv and Tana rivers were sources of DOC to the marine environment, however, in other seasons, only the DOC-rich Tana river had higher concentrations than are typically found in northern Norwegian coastal waters (often <1 mg/L; Schultze et al. *submitted*, Frigstad et al. 2020). Like Glomma, both of the northern rivers were also sources of SiO_2 to the marine environment in all seasons. These inputs of SiO_2 are likely to be particularly important for diatoms, which have high SiO_2 requirements, and have a high ecological significance, playing a key role in C-export and burial and having the ability to outcompete other groups of (sometimes harmful) phytoplankton.

Meanwhile inorganic N and P concentrations were typically lower than or similar to concentrations in coastal waters. However, in the Målselv river, spring NO_3 + NO_2 concentrations were elevated relative to fjord surface waters. The low springtime NO_3 concentrations observed in coastal surface waters relative to deeper waters (and river waters) is a result of nutrient drawdown during the spring phytoplankton bloom, combined with increasing stratification of the water column. Seasonal changes typically result in strong nutrient limitation of phytoplankton primary production in the coastal environment. As such, during this post-bloom nutrient-limited period, inputs of terrestrial nutrients are likely to act as a key source of new nutrients to support primary production in the coastal environment. This contrast between low springtime coastal NO_3 concentrations and elevated riverine concentrations was particularly apparent for Glomma and Målselv (**Figure 11**) highlighting the potential for spring freshet to play a role in supporting post-spring bloom primary production in river-influenced coastal waters.

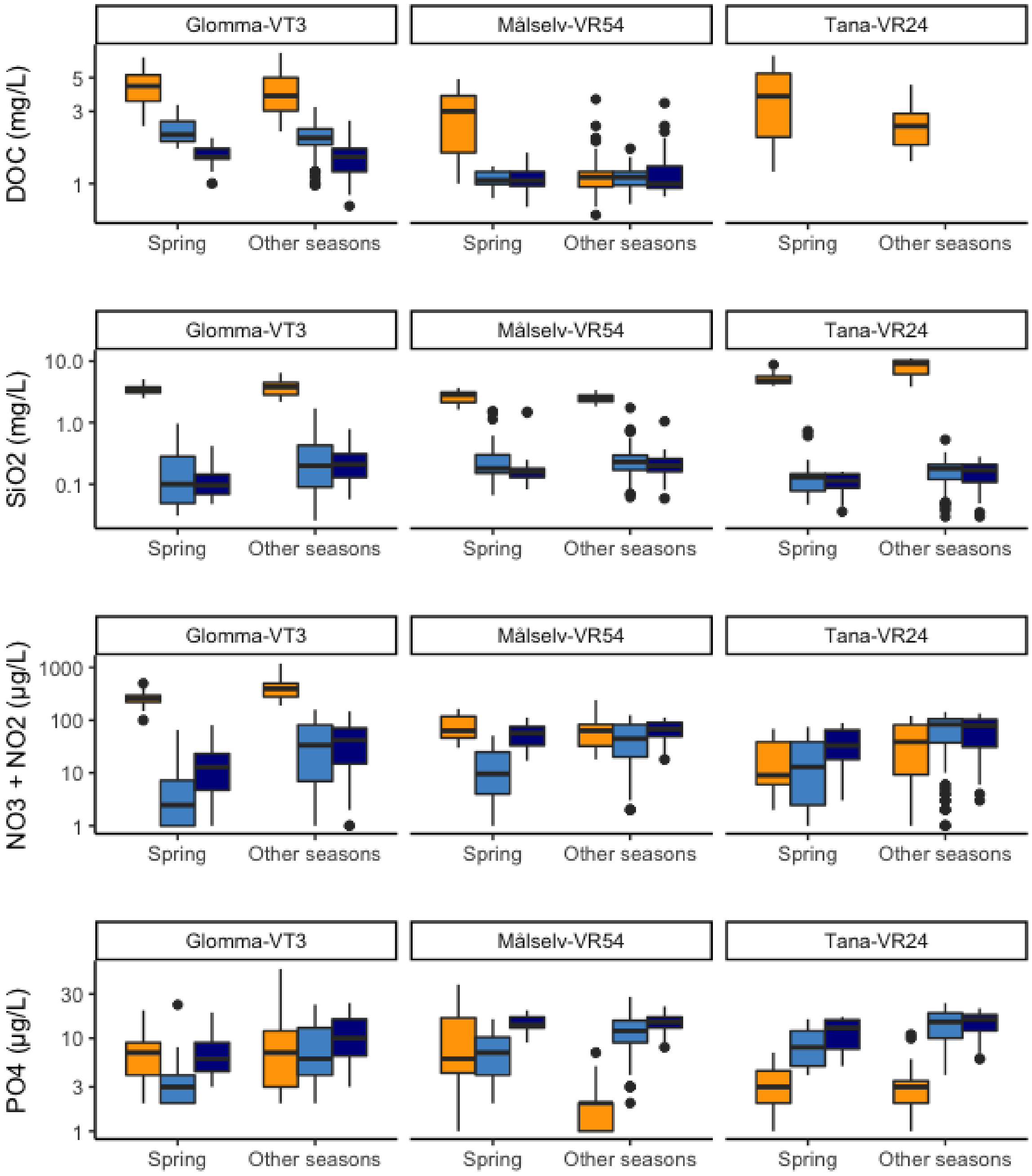

Figure 11. Boxplots of concentration data for dissolved inorganic nutrients and DOC along freshwater to marine gradients for all study systems, contrasting spring (Apr–Jun) and other seasons. Data are from 2017-2020 for paired river and coastal monitoring stations for all three system systems (source: Elveovervåkingsprogrammet, ØKOKYST). Boxplots show the median, first and third quartiles, range of the data and outliers, while colours indicate the water mass sampled, with rivers shown in orange, coastal surface waters (0-15 m; shown in light blue), and coastal deep waters (>15 m; shown in dark blue).

3.3.2 River water chemistry during the 2020 spring freshet

Based on our samples during the 2020 spring freshet, we observed elevated riverine concentrations for several of the measured water chemistry variables relative to observations from other seasons. The observed concentrations were also often elevated compared to typical springtime (Apr–Jun) concentrations (**Figure 12**, **Table 2**). Based on the 2020 data, for both the Målselv and Tana rivers, we observed elevated concentrations of SPM, TOC, DOC, $NO_3 + NO_2$, PO_4 and Hg (both TotHg and MeHg) relative to the rest of the year, but also relative to the long-term mean values for springtime. In contrast, in the Glomma river the spring freshet samples were characterized by concentrations of organic C, nutrients, and SPM that were often similar to, or lower than, the mean annual and mean springtime values (**Figure 12**). The elevated concentrations in the Tana and Målselv rivers relative to previous springtime data may reflect that our higher frequency sampling was able to capture 'peak concentration' periods during freshet, but also likely reflects the fact that mean springtime values were based on data from April–June, where data from April (and sometimes May) do not reflect freshet conditions. In the Glomma river, the lower concentrations observed during the spring 2020 freshet relative to mean springtime and annual concentrations could reflect dilution in this large and more human-impacted river system, where catchment inputs of nutrients, SPM and TOC may be more closely associated with agricultural or other anthropogenic inputs rather than snowmelt processes.

In addition to highlighting differences in water chemistry between spring freshet and the rest of the year (**Figure 12**, **Table 2**), the higher frequency sampling carried out in the current study also provided insight into how SPM, TOC/DOC, nutrient and Hg concentrations vary within the spring freshet period. Here, we expected the highest concentrations during the early phase of the event, as 'fresh' pools of terrestrial particles and dissolved constituents are mobilized and transported downstream, and expected decreasing concentrations when discharge peaks and declines, due to dilution effects. For all three study sites, we observed higher TOC and TotHg concentrations during early freshet than during late freshet, although concentrations in the northern rivers were still higher during late freshet than are typical for the rest of the year

Spring freshet is often characterized by several discharge peaks, varying in magnitude, each of which can drive short-term responses in water chemistry. This is apparent in our spring 2020 data, where additional sampling allowed us to capture a range of hydrologic conditions, including early, peak and late freshet

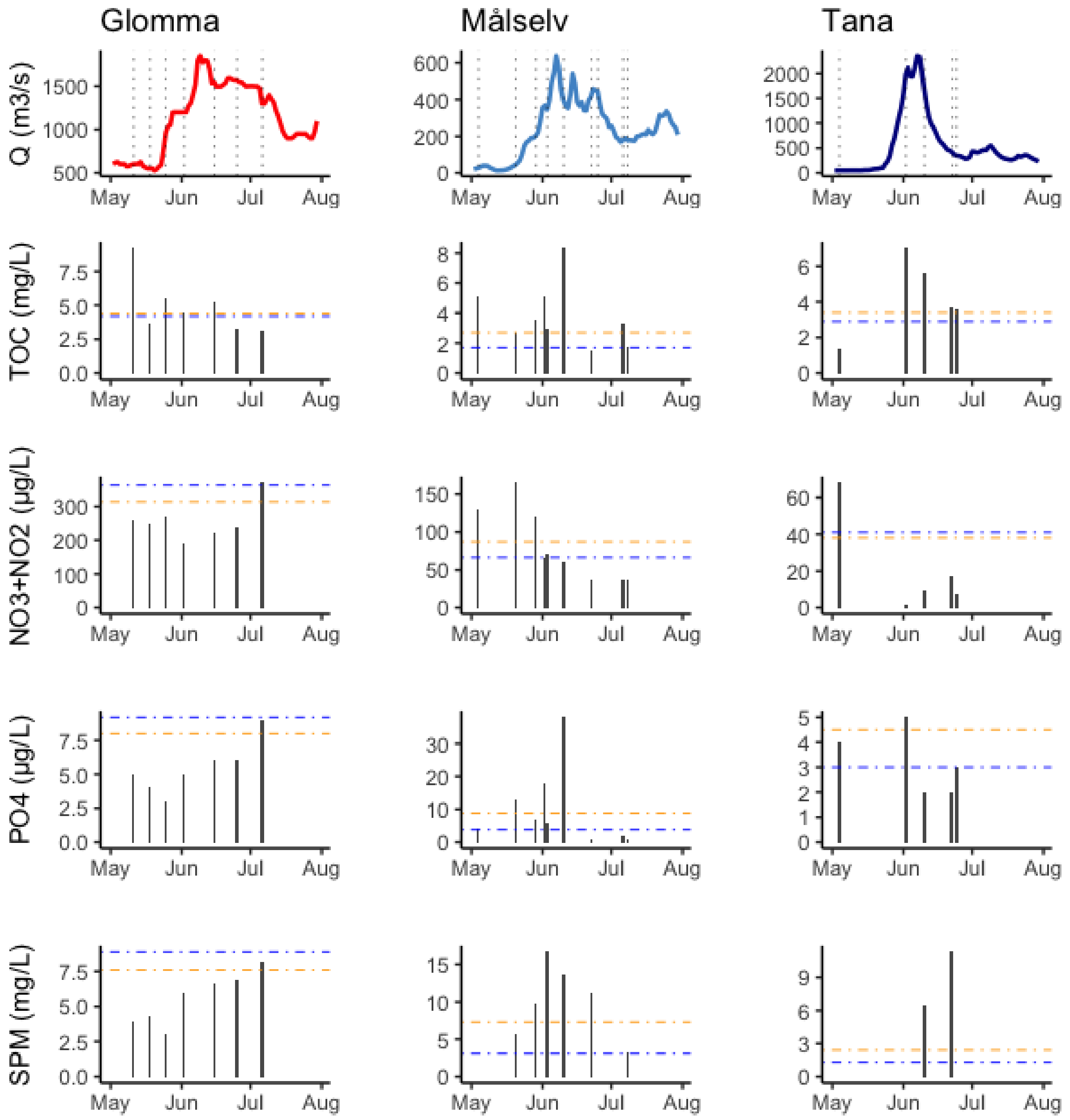

Figure 12. Panel showing: daily discharge (Q) and sampling dates (shown as dotted vertical lines in the hydrology plots); and concentrations of TOC, SPM, NO_3 + NO_2 and PO_4 (shown as black vertical bars in the water chemistry plots) for the three study rivers during spring freshet 2020 (May–Jul). Mean annual and mean springtime concentrations for these rivers/variables are displayed in each plot as blue (mean annual) and orange (mean springtime) dotted lines (based on 2016-2020 data from Elveovervåkingsprogrammet). Note that y-axis scales differ and that hydrologic data for 2020 are not yet quality controlled by NVE.

Table 2. Comparison of river water chemistry between the 2020 spring freshet, and mean annual and mean springtime (Apr–Jun) data (based on 2016–2020 data from Elveovervåkingsprogrammet) for select variables not included in **Figure 12**.

	Glomma			Målselv			Tana		
Variable	Freshet 2020	Spring mean	Annual mean	Freshet 2020	Spring mean	Annual mean	Freshet 2020	Spring mean	Annual mean
DOC (mg/L)	4.8	4.3	4.2	3.1	2.4	1.6	4.8	3.1	2.9
SiO_2 (mg/L)	3.20	3.59	3.66	2.34	2.70	2.55	4.17	6.74	7.69
TotHg* (ng/L)	0.9	-	1.8	1.2	-	0.5	2.0	-	1.2
MeHg* (ng/L)	0.03	-	-	<0.02–0.04	all <0.02	all <0.02	0.05	-	-
$SUVA_{254}$ (L/mg-C/m)	7.7	4.2	4.0	6.6	4.3	3.3	6.8	4.1 ± 0.3	3.7 ± 0.3
SPM (mg/L)	5.6	7.6	8.9	10.1	7.3	3.1	8.9	2.4	1.3
SPM_{inorg} (mg/L)	-	-	-	8.9	-	-	6.3	-	-

*Note: Detection limits for TotHg using previous methods often gave results that were below detection. However, data from 2019 use the same method as the current study, and were used to calculate spring/annual means. MeHg is not monitored in these rivers, however, unpublished data are available from other seasons for Målselv, and were used to calculate spring/annual means (Poste *unpublished data*).

3.3.3 Impacts of the 2020 spring freshet on coastal waters

The degree to which riverine inputs impact coastal waters depends strongly on the riverine-marine fluxes and differences in water chemistry between riverine and marine waters (see section 3.2.1), but also depends on the hydrodynamic conditions in the receiving coastal waters (e.g. stratification, water currents and exchange with the open-marine system). As such, the strongest coastal impacts of riverine inputs should occur where land-ocean fluxes are high and where exchange with the open ocean is low, thus increasing the residence time (and potential impact) of freshwater and terrestrial material in the coastal system (e.g. in a narrow fjord with a shallow sill, where there is limited tidal influence). Biological uptake of terrestrial and marine-derived material will also impact observed concentrations of e.g. DOC, nutrients and Hg.

In order to determine the spatial extent and degree of impact of the 2020 spring freshet on adjacent coastal waters, we paired sampling at river and coastal monitoring stations with sampling at extra inner fjord stations in Målselvfjord and Tanafjord (not part of ongoing monitoring programmes; (**Figure 14**, **Figure 15**). These additional sampling sites provided valuable 'spring freshet snapshots', linking water quality observations in the river with observations from the coastal monitoring sites which are far from the river outlets. In southern Norway, we collected additional samples for 6 coastal monitoring stations (**Figure 13**) for a mid-June 'spring freshet snapshot' for outer Oslofjord and Skagerrak, providing insight into the spatial distribution and extent of riverine influence in this coastal region. Extra samples for analysis of select relevant variables (including DOC, cDOM, SPM, TotHg, MeHg) were collected for several of these study sites, where they were not already being collected as part of ongoing monitoring programmes.

The figures below present water quality data for three transects:

- stations along a semi-transect from the Glomma river and river estuary to Torbjørnskjær (VT3) sampled between 15-18.06.2020 (**Figure 13**)
- a transect from the Målselv river to Straumsfjorden (VR54) sampled on 04.06.2020 and 22.06.2020 (**Figure 14**)
- a transect from Tana river to outer Tanafjord (VR24) sampled on 22.06.2020 (**Figure 15**). Note that the river and inner fjord sites were also sampled on 10.06.2020 but are not shown in the figures.

These ‘snapshots’ reveal an extensive freshwater footprint in the coastal environment during spring freshet for all three of the study regions, with reduced surface water salinities and distinct water chemistry. Substantial freshet-associated fluxes of freshwater and terrestrial material resulted in reduced surface water salinity and increased stratification (as also observed in section 3.2), reduced Secchi depth, as well as increased SPM, DOC, and Hg concentrations in marine surface waters. The strongest impacts on salinity, light availability and water chemistry were observed for inner fjord and nearshore stations, although these effects were still apparent (although dampened) at the outermost monitoring stations in the top 10 m. For the Målselv river-Straumsfjorden transect, the river plume extended well-beyond Målselvfjord, leading to surface water salinities <1.5 psu throughout Målselvfjord on both sampling dates. At Straumsfjorden surface water salinity was 32.4 psu during the early freshet campaign and only 4.5 psu for the late freshet campaign.

In particular, spring freshet was a source of DOC to the coastal environment, with higher DOC concentrations observed in surface waters compared to deep marine waters, and a strong negative relationship between salinity and DOC observed for the Glomma, Målselv and Tana river transect data (r^2_{adj} values of 0.88, 0.71, and 0.64 respectively; all $P<0.05$). For the Målselv river, where we carried out two ‘snapshot’ campaigns during both early and late freshet, the higher concentrations of riverine DOC during early freshet than during late freshet are also reflected in the surface water concentrations along the entire transect (**Figure 14**).

While spring freshet acts as an important source of DOC to the coastal environment for all three study systems, the substantial DOC fluxes from land to sea also had a strong impact on dissolved organic matter (DOM) composition and quality in the coastal environment. Based on cDOM absorption properties (which provide insight into the origin, molecular weight and chemical composition of DOM), DOM in the rivers and throughout the coastal surface waters appeared to be primarily of terrestrial origin, highly coloured and with high molecular weight. Mean $SUVA_{254}$ values during our spring freshet ‘snapshot campaigns’ were 6.6–7.7 L/mg-C/m in rivers; 6.4–6.6 in fjord surface waters, and 2.7–3.0 in deep marine waters. While in the current report we focus on $SUVA_{254}$ as a particularly relevant absorption metric that is positively correlated with highly coloured and high molecular weight DOM of terrestrial origin (Weishaar et al. 2003), our observations of strong contribution of terrestrial DOM to the coastal DOM pool are also supported by other metrics that were calculated but are not presented here (e.g. spectral slopes, slope ratios). These additional metrics also suggested a strong contrast between the DOM composition in surface and deep marine waters, with higher molecular weight terrestrial DOM dominating in surface waters, and lower molecular weight DOM likely derived from marine phytoplankton dominating in deeper marine waters (T. Harvey, *unpublished data*).

Dissolved organic material (DOM) can act as a source of energy for bacteria, although terrestrial DOM is often assumed to be less bioavailable to bacteria than DOM derived from aquatic phytoplankton (Blanchet et al. 2017). However, several recent studies have highlighted that during spring freshet, riverine DOM is often more bioavailable than at other times of the year (Kaiser et al. 2017). This is linked to a higher contribution of DOM from the organic-rich snow-soil interface during snowmelt, including DOM derived from leaf litter and vegetation from the previous growing season (Kaiser et al. 2017).

High concentrations of highly-coloured terrestrial DOM in freshet-impacted coastal waters can also be expected to have important implications for coastal light availability, with high cDOM loads leading to a higher light attenuation, reducing the light available for phytosynthesis by phytoplankton and benthic algae (Frigstad et al. 2020b). Freshet-associated increases in SPM linked with an increase in turbidity will have a similar and potentially synergistic negative effect on the light attenuation, in addition to driving increased sedimentation rates with potential consequences for benthic communities (McGovern et al. 2020b). Recent observations of increasing light attenuation in Norwegian coastal waters have led to increased concern and research interest related to potential impacts on coastal ecosystems (as summarized by Frigstad et al. 2020b). However, there remains a need for understanding the drivers, trends, spatiotemporal extent, and effects of these changes. Given the potential for spring freshet to reduce coastal light availability over broad spatial scales, and/or to provide nutrients and DOC for nutrient-limited microbial communities, there is a need to determine the degree to which the spring freshet and the spring phytoplankton bloom are coupled (or uncoupled) in time, and how this could shift due to climate change. This topic could be further explored within the context of “integrated climate monitoring” in the national monitoring programs (ØKOKYST, Elveovervåkningsprogrammet and Ocean acidification programme).

Mercury (Hg), is a contaminant of concern for both coastal food webs and fisheries. In both its inorganic and methylated (MeHg) forms, Hg is closely associated with organic carbon in the environment, with mobilization, transport and fate of Hg closely linked to C-cycling. Since Hg is not included in the coastal monitoring programme, and only TotHg (but not MeHg) is included in the river monitoring programme, the current study provided an opportunity to characterize the role of spring freshet as a source of TotHg and MeHg to the coastal environment. Analysis of a subset of samples from the two northern transects revealed TotHg concentrations in rivers and inner fjord surface water that were 8-fold higher than in deep (20 m) marine waters for Målselv river-Målselvfjord, and were 16-fold higher than in deep marine waters for Tana river-Tanafjord (Målselv: river: 1.2 ± 0.03, surface fjord: 1.2 ± 0.2, deep fjord: 0.15 ± 0.02; Tana: river: 2.0 ± 0.7, surface fjord 2.2 ± 1.0, deep fjord: 0.13). For MeHg, there were no strong differences in concentration between the river and fjord waters, likely reflecting low riverine concentrations paired with *in situ* MeHg production in the coastal environment.

For NO_3 + NO_2, we observed similar patterns to those observed for Hg, with elevated concentrations in rivers and coastal surface waters, suggesting that during spring freshet, these study rivers are likely substantial sources of nitrogen to the coastal system. However, unlike DOC, where concentrations were elevated at all surface water stations along the three study transects, surface water NO_3 concentrations were low for several of the stations in our southern ‘spring freshet snapshot’ and for the outermost station in our late freshet Målselv river-Straumsfjorden (VR54) transect (**Figure 14**). These low concentrations likely reflect drawdown of NO_3 by phytoplankton and/or bacteria, once again highlighting the potential role of spring freshet in supporting primary and bacterial production in the coastal environment. This also highlights the value of supplementing the ØKOKYST monitoring programme with inner fjord stations to capture key processes (e.g. nutrient and DOC uptake, sedimentation, bloom timing) occurring in between rivers and nearby coastal monitoring stations, which can often be quite far away from the river outlets.

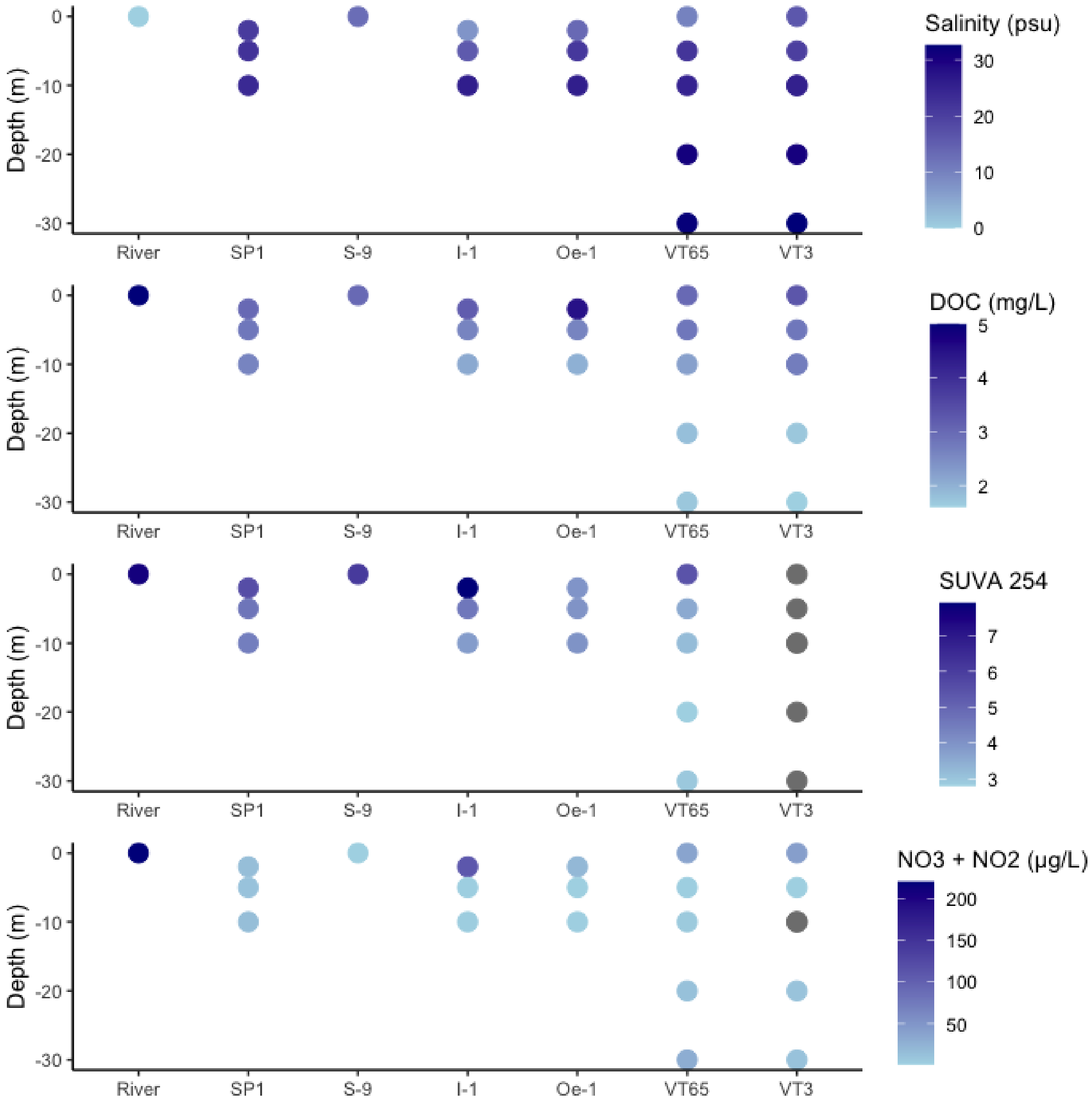

Figure 13. Selected water quality parameters along a freshwater to marine semi-transect for sites included in the freshet sampling campaign in Glomma river-Oslofjord-Skagerrak (June 16-18th 2020). Stations include the Glomma river, stations in Glomma river estuary (SP1, S-9, I-1, Oe-1; outer Oslofjord monitoring programme) and coastal stations (VT65, VT3; ØKOKYST) (cf. map in **Figure 1**). Grey points indicate that data were not collected.

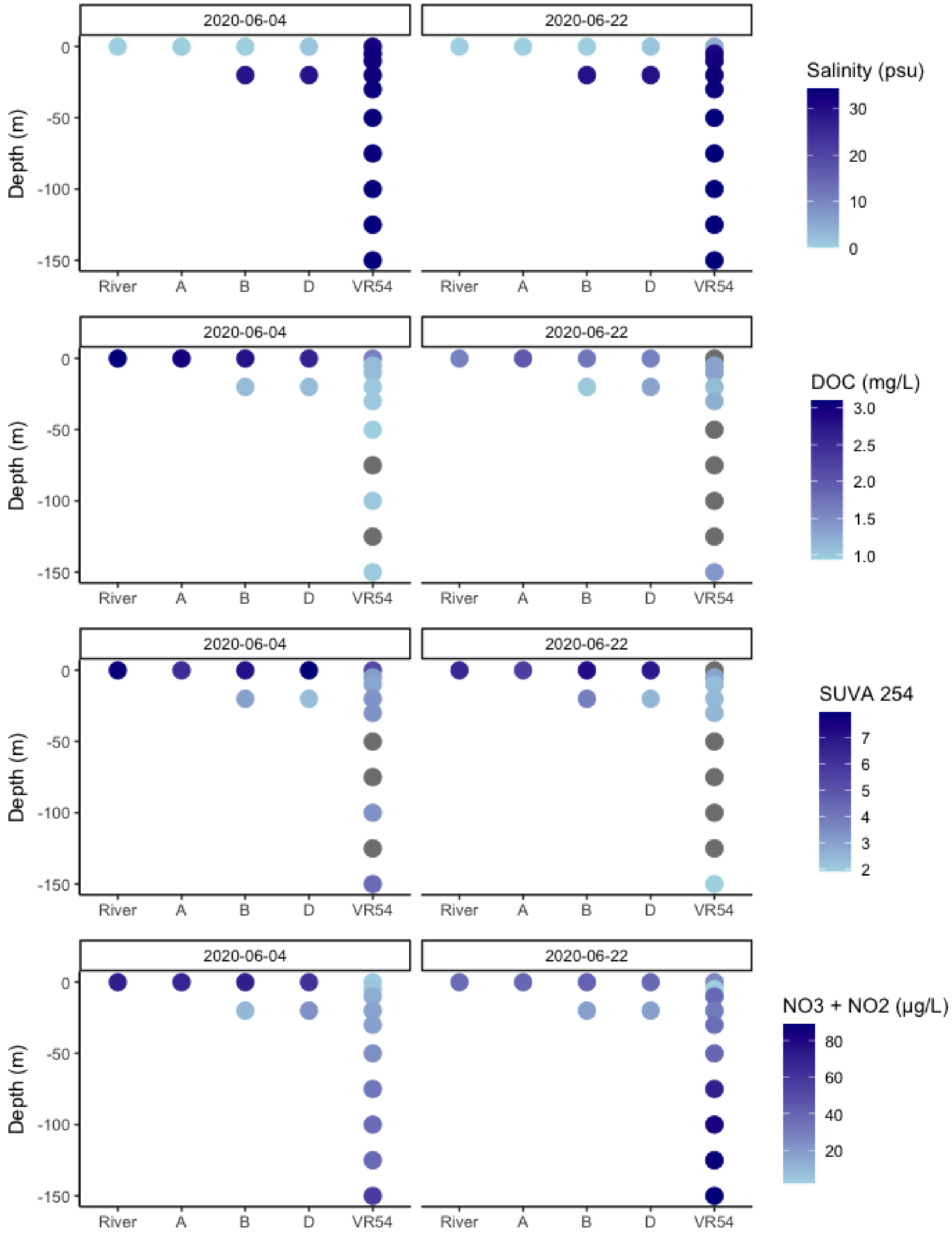

Figure 14. Selected water quality parameters along a freshwater to marine transect for early and late freshet sampling campaigns in Målselv river-Målselvfjord-Straumsfjorden (June 4th and 22nd, 2020). Stations are arranged from river toward outer fjord along the x-axis, and include the Målselv river, inner fjord stations in Målselvfjord (A, B, D) and the Straumsfjorden ØKOKYST monitoring station (VR54) (cf. map in **Figure 1**). Grey points indicate that data were not collected.

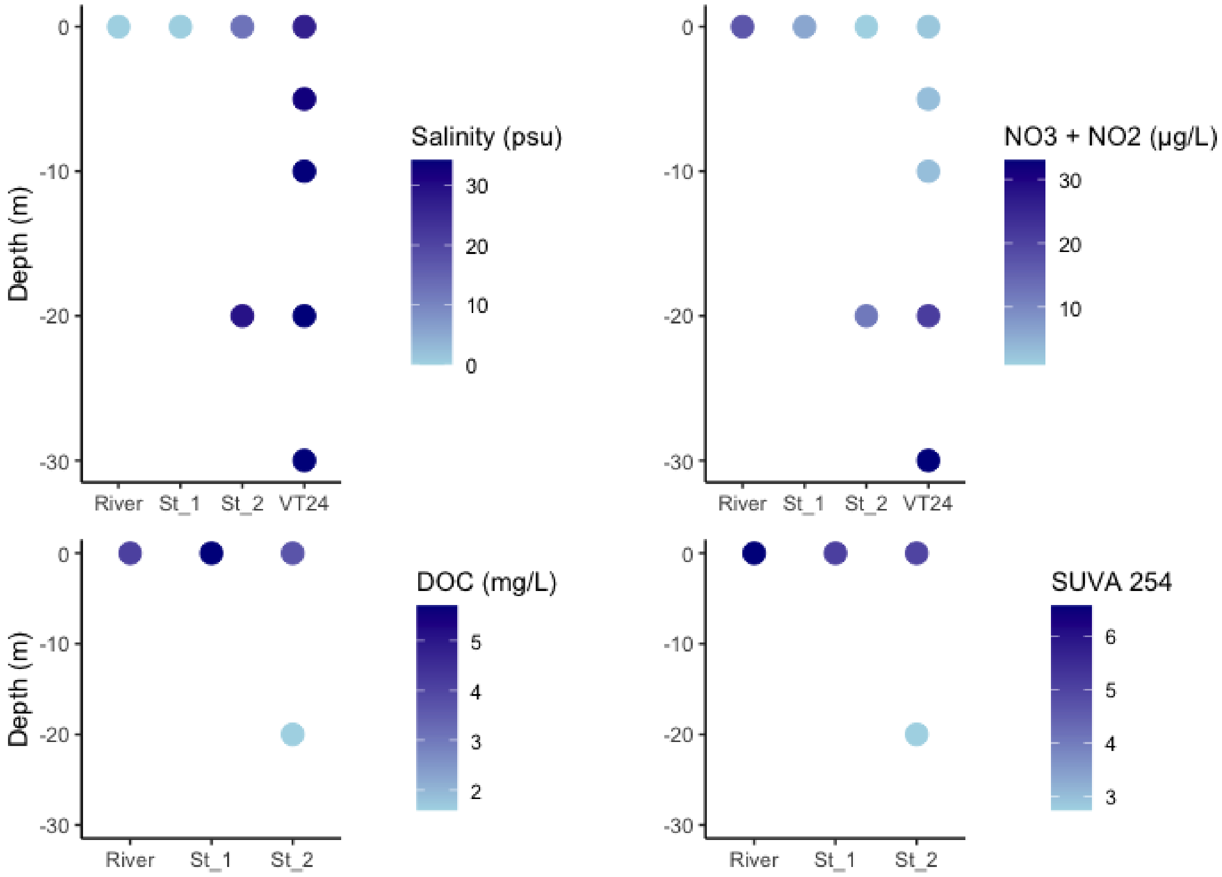

Figure 15. Select water quality parameters along a freshwater to marine transect for a freshet sampling campaign in Tana river-Tanafjord (June 22nd, 2020). Stations are arranged from river toward outer fjord along the x-axis, and include the Tana river, stations in inner Tanafjord (St_1, St_2) and the Tanafjord ØKOKYST monitoring station (VR24) (cf. map in **Figure 1**). Note that samples for analysis of DOC and cDOM absorption spectra were not collected for VR24.

4 Conclusions

The current study was initiated due to projections for extreme snowmelt floods in several Norwegian river catchments, with the goal of capturing the impacts of an extreme event on river water quality, land-ocean fluxes and physical and chemical conditions in the downstream coastal environment. However, in the end, the peak discharge during spring freshet was above average flood levels[3] but below 10-year flood levels for all three study systems, implying that we did not capture an extreme climate event. Although we did not capture extreme snowmelt floods, by combining existing monitoring data (providing year-round data for several years) with data from our additional sampling campaigns in spring 2020 (providing increased sampling frequency and spatial resolution), this study has provided valuable new data and insight into the role of spring freshet in shaping river water chemistry, land-ocean fluxes, and coastal physical and chemical conditions.

The results of the current study highlight the importance of spring freshet in delivering freshwater and terrestrial material from land to sea, where high springtime concentrations of several chemical constituents converge with very high discharge, resulting in large fluxes over a period of days to weeks. This is particularly true for the two northern study systems where spring freshet often delivers well over half (and up to three quarters) of the total annual inputs of freshwater, DOC, SPM, TN and TP to the coastal environment. Our study also highlights the high variability of river water chemistry during the spring freshet period, with DOC and nutrient concentrations often highest during early freshet and declining during peak and late freshet, due to dilution effects.

Inputs from land also had a demonstrable impact on coastal physical and chemical conditions, with low surface water salinities, increased stratification, and elevated SPM, SiO_2, $NO_3 + NO_2$, DOC and $SUVA_{254}$ (as an indicator of terrestrial DOM) at coastal monitoring stations during spring freshet. Taken together these changes in stratification, light availability and nutrient and DOC concentrations (and bioavailability) are likely to have a broad range of impacts on coastal ecosystem structure and function. However, the degree to which river inputs had an impact on these coastal stations, which are quite far from the river outlets, depended on fjord morphometry and the degree of exchange with offshore marine waters. The inclusion of inner fjord sites highlighted the much stronger impact of riverine inputs in inner fjords and closer to river outlets, suggesting that the current ØKOKYST programme would benefit from including stations along a river to fjord transect in selected sites focusing on land-ocean interactions, such as for example the Målselv river-Målselvfjord-Straumsfjorden integrated climate monitoring study region.

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[3] An average flood (normal flood) is defined by NVE as the mean of the highest discharge measured each year over a long period of time (e.g., 30 years or more).

5 Next steps and future perspectives

The high degree of variability in discharge, river water chemistry, and marine environmental variables (water column structure, water chemistry, phytoplankton bloom timing) suggest that current monthly riverine and coastal monitoring regimes do not adequately capture spring freshet dynamics. For rivers, this can lead to large uncertainties when estimating fluxes during the spring freshet period (and thereby for the year). In the coastal environment, this can complicate our ability to understand how spring freshet intersects with other short-term seasonal processes, such as the spring phytoplankton bloom and/or periods of nutrient limitation. Additionally, long-term processes such as climate change will also impact spring freshet timing, magnitude and progression (e.g. number of peaks, duration), with uncertain impacts on river water quality and downstream coastal ecosystems.

One of the most dramatic hydrologic changes taking place in many Norwegian catchments due to climate change is a shift toward increased high flow events in autumn and winter. Like spring freshet, high flow events at other times of the year will mobilize and transport terrestrial material downstream, leading to changes in freshwater and coastal water quality. Changes in the timing and magnitude of land-ocean fluxes of freshwater and terrestrial particles, organic matter, nutrients and contaminants can be expected to have a broad range of impacts on coastal ecosystems and the services they provide, such as pelagic and benthic primary production, spring bloom dynamics, carbon cycling and burial, biodiversity and food web structure, and accumulation of pollutants in coastal organisms (e.g. Frigstad et al. 2020a,b, McGovern et al. 2020a,b, Delpech et al. 2021).

Our study points to a need for an increased effort to capture these events and their impacts in current and future environmental monitoring programmes. Extreme events are by their very nature difficult to predict, as was demonstrated here when the actual flow events were more moderate than expected based on the NVE predictions. Furthermore, we experienced that ad hoc adaptation of existing monitoring to capture extreme events is challenging, since these programs are designed for observations of long-term rather than episodic change, and are not designed to pair data across ecosystem (terrestrial, freshwater, coastal, marine) boundaries.

Given the close links between climate change impacts on land, freshwater and marine coastal environments, there is an increasing need to take interdisciplinary cross-ecosystem approaches to studying the potential effects of global change on northern ecosystems. In the current study, impacts of high flow events on riverine and coastal water quality were captured through increased sampling frequency and increased monitoring effort in nearshore coastal areas. In the future, pairing these kinds of traditional field-based monitoring approaches with new technologies such as *in situ* sensor-based monitoring, autonomous sampling and remote sensing can offer a promising way forward for adaptive monitoring of long-term and seasonal change as well as effects of extreme climate events, providing information of higher temporal and spatial resolution than current monitoring programs. This combination of field-based and sensor-based monitoring in rivers (e.g. as is ongoing in the Målselv river) and the coastal zone (e.g. the autonomous sensor measurements included in the ØKOKYST FerryBox programme) will generate valuable new information for studies on the impacts of spring freshet and high flow events on river chemistry, land-ocean fluxes and coastal physicochemical conditions.

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Appendix A.

Table A1. Spring 2020 sample overview, rivers. Includes regular monitoring samples and extra spring freshet samples (see ‘Sampling’ column).

Station name	Date	Sampling	General chemistry*	SPM SPM(inorg)	Tot-Hg	MeHg	cDOM absorption
GLOMMA RIVER							
Glomma ved Sarpsfoss	02/06/2020	Regular	x		x		x
Glomma ved Sarpsfoss	18/06/2020	Extra	x	x	x	x	x
Glomma ved Sarpsfoss	15/06/2020	Regular	x				
Glomma ved Sarpsfoss	24/06/2020	Extra		x	x	x	x
Glomma ved Sarpsfoss	25/06/2020	Regular	x				
Glomma ved Sarpsfoss	08/07/2020	Regular	x	x	x		x
MÅLSELV RIVER							
Målselva v/gml E6-brua	20/05/2020	Extra	x	x			x
Målselva v/gml E6-brua	29/05/2020	Extra	x	x	x	x	x
Målselva v/gml E6-brua	02/06/2020	Regular	x		x		x
Målselva v/gml E6-brua	03/06/2020	Extra	x	x	x	x	x
Målselva v/gml E6-brua	10/06/2020	Extra	x	x	x	x	x
Målselva v/gml E6-brua	22/06/2020	Extra	x	x	x	x	x
Målselva v/gml E6-brua	06/07/2020	Regular	x	x	x		x
TANA RIVER							
Tanaelva	02/06/2020	Regular	x		x		x
Tanaelva	10/06/2020	Extra	x	x	x	x	x
Tanaelva	22/06/2020	Extra	x	x	x	x	x
Tanaelva	06/07/2020	Lost					

* Includes parameters analysed in Elveovervåkingsprogrammet (pH, KOND, SPM, TOC, PO_4-P, TOTP, NO_3-N, NH_4-N, TOTN, SiO_2, Ca, DOC, POC, PartN, PartP)

Table A2. Spring 2020 sample overview, inner fjords. These are ‘extra’ freshet samples, providing a gradient between river and coastal monitoring sites.

Station	Depth	Date 1	Date 2	CTD	Chem*	Chl a	Salinity	Turbidity	SPM SPM(inorg)	TotHg	MeHg	cDOM absorption
MÅLSELVFJORD												
Målselv A	0	04/06/2020	22/06/2020	x	x	x	x	x	x	x	x	x
Målselv B	0, 20	04/06/2020	22/06/2020	x	x	x	x	x	x			x
Målselv D	0, 20	04/06/2020	22/06/2020	x	x	x	x	x	x	x (20)	x (20)	x
TANAFJORD												
Tanafjord St 1	0	10/06/2020	22/06/2020	x	x	x	x	x	x	x	x	x
Tanafjord St 2	0, 20	10/06/2020**	22/06/2020	x	x	x	x	x	x	x	x	x

* **Chemistry**: DOC, NH_4-N, NO_3+NO_2-N, PO_4-P, SiO_2, TOTN_F, TOTP/F, TOTP_P

** Water sample only collected from 0 m on this date due to bad weather.

Table A3. Sample overview, outer fjords, including stations monitored through ØKOKYST (VT3, VT65, VR54, VR24) as well as the outer Oslofjord monitoring programme (S9, Ø1, I1, SP1).

Station	Name	Depth	Date 1	Date 2	Date 3	Chem*	CTD	DOC**	cDOM absorption**
OSLOFJORD /SKAGERRAK									
VT3	Torbjørnskjær	0, 5, 10, 20, 30	17/06/2020	13/07/2020		x	x	x	x
VT65	Missingen	0, 5, 10, 20, 30	16/06/2020	13/07/2020		x	x	x	x
S9	Haslau	0	16/06/2020			x	x	x	x
Ø1	Leira	2, 5, 10	16/06/2020			x	x	x	x
I1	Ramsø	2, 5, 10	16/06/2020	14/07/2020		x	x	x	x
SP1	Sponvika	2, 5, 10	16/06/2020	14/07/2020		x	x	x	x
STRAUMSFJORDEN									
VR54	Straumsfjorden	0, 5, 10, 20, 30, 50, 100, 150	04/06/2020	22/06/2020	19/07/2020	x	x	x	x
TANAFJORD									
VR24	Tanafjord	0, 5, 10, 20, 30	31/05/2020	22/06/2020	22/07/2020	x	x		

***Chemistry**: tot-P, PO_4-P, tot-N, NO_3+NO_2, NH_4-N, silicate, TSM (not for Ø1, I1, SP1), Chla, secchi depth.

**Additional DOC and cDOM absorption samples only collected for sampling dates in June.

Appendix B.

Table B1. Overview of coordinates for stations included in the current study (see Tables A1–A3 for further details).

Station	Latitude	Longitude
RIVERS		
Glomma river	59.28	11.13
Målselv river	69.14	18.60
Tana river	70.23	28.16
INNER FJORD		
Målselv A	69.30	18.53
Målselv B	69.33	18.52
Målselv D	69.36	18.53
Tanafjord St 1	70.52	28.36
Tanafjord St 2	70.55	28.29
COASTAL MONITORING		
VT3 (Torbjørnskjær)	59.04	10.76
VT65 (Missingen)	59.19	10.69
S9 (Haslau)	59.11	11.16
Ø1 (Leira)	59.14	10.83
I1 (Ramsø)	59.11	11.00
SP1 (Sponvika)	59.09	11.23
VR54 (Straumsfjorden)	69.50	18.34
VR24 (Tanafjord)	70.75	28.35

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