REPORT SNO. 7812-2023

Using *in situ* sensor-based monitoring to study impacts of climate change on river water quality and element fluxes

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REPORT

Title	Serial number	Date
Using *in situ* sensor-based monitoring to study impacts of climate change on river water quality and element fluxes	7812-2023	November 2022
Author(s)	**Topic group**	**Distribution**
Amanda Poste, Leah Jackson-Blake, Maeve McGovern, Øyvind Kaste, James Sample, Odd Arne Skogan, Kari Austnes, Uta Brandt, Rolf Høgberget	Climate	Open
	Geographical area	**Pages**
	Norway	42 + appendices

Client(s)	Client's reference
Norwegian Environment Agency	Gunn Lise Haugestøl
Client's publication:	Printed NIVA
M-2392 | 2022	Project number 200313.4

Summary

The report contains an analysis of high-frequency sensor data from two rivers included in the Norwegian River Monitoring Programme; Storelva in southern Norway and Målselva in northern Norway. The main aim of the report is to combine in situ sensor-based monitoring data with climate, hydrology and water chemistry data to study impacts of climate change on river water quality and element fluxes. The report also highlights challenges, opportunities and the strong potential for sensor-based monitoring to yield new knowledge related to climate change impacts on river water quality.

Four keywords	Fire emneord
1. Environmental monitoring in rivers	1. Miljøovervåking i elver
2. Sensor-based monitoring	2. Sensorbasert overvåking
3. Water quality and fluxes	3. Vannkvalitet og flukser
4. Climate change	4. Klimaendring

This report is quality assured in accordance with NIVA's quality system and approved by:

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ISBN 978-82-577-7548-3
NIVA-report ISSN 1894-7948

Using *in situ* sensor-based monitoring to study climate change impacts on river water quality and element fluxes

Preface

“Integrated climate monitoring” is a new concept that has recently been included across several of the Norwegian Environment Agency's freshwater and coastal monitoring programs. The goal of this initiative is to gain more knowledge from existing monitoring about the effects of climate change on aquatic ecosystems. To support this, the Norwegian River Monitoring Programme (in Norwegian: Elveovervåkingsprogrammet) was expanded to include four stations with *in situ* sensor-based monitoring. While two of these stations were established recently, the other two stations, located in Storelva in southern Norway and Målselva in northern Norway, were established prior to being included in the monitoring programme, and have time series stretching back to 2017 and 2015, respectively, and as such, are well-suited for assessing the utility of sensor-based river monitoring approaches.

As part of the new “Integrated climate monitoring” component of the river monitoring programme, in May 2022, the Norwegian Environment Agency commissioned NIVA to prepare a report on "use of sensor data to study climate effects with high time resolution", using data from the Storelva and Målselva rivers. The data compilation and analysis included in this report was also supported in part by the Framsenter ‘Catchment to Coast’ research programme (co-led by A. Poste) and NIVA’s strategic initiative on “Global Change at high latitudes” (led by Heleen de Wit and Helene Frigstad).

Contributors to the report (and the data included in the report) include those listed as co-authors, as well as many colleagues and local field assistants that have been involved in sample collection, maintenance and calibration of sensor stations, data compilation and presentation, and discussion of results over the years the stations have been operational. Here, special thanks are due to Pernilla Carlsson, Juan Pardo, Marina Vàzquez Alonso and Zofia Rudjord. Juan Pardo and Eva Skarbøvik also provided feedback on the report text. Quality assurance of the report has been carried out by Hans Fredrik Veiteberg Braaten.

Contact persons at The Norwegian Environment Agency have been Gunn Lise Haugestøl and Pål Inge Synsfjell. Thanks to all involved for a good collaboration.

Tromsø, November 2022

Amanda Poste

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Summary

There is increasing interest in the potential for sensor-based monitoring approaches to be used for understanding climate change impacts on aquatic systems, with a focus on how water quality responds to long-term and seasonal changes in climate, hydrology and land-cover as well as to extreme climate and weather events (e.g. droughts and floods). These approaches have high potential to complement traditional long-term monitoring approaches based on e.g. monthly water sampling, which are highly valuable for assessing long-term trends and broad seasonal patterns, but do not sufficiently capture dynamic responses of water quality to changes in hydroclimatic conditions (including responses to increasingly frequent extreme climate and weather events). These new possibilities have led to the establishment of new sensor-based monitoring stations as part of national river monitoring programmes in Norway. The current report aimed to compile and analyze existing data from the two sensor stations in the Norwegian River Monitoring Programme where the longest time series are available: Storelva in southern Norway (since 2015) and Målselva in northern Norway (since mid-2017).

For both study rivers, combining *in situ* sensor data with data on hydroclimatic drivers (air temperature, precipitation, water discharge) yielded important insight into main drivers of seasonality and interannual variability in water quality. It revealed strong between-site differences, owing to the large latitudinal and climatic gradient as well as to contrasting landscape properties and catchment processes. In particular, when high-frequency sensor data for turbidity (a proxy for Suspended Particulate Matter - SPM) and Fluorescent Dissolved Organic Matter (FDOM) were combined with discharge, it was possible to gain a more nuanced understanding of how hydroclimatic conditions interact with landscape controls on the mobilization and downstream transport of SPM and DOM (as well as particle and OM-associated elements).

Exploration of concentration–discharge (CQ) relationships in sensor data from rivers can provide valuable insight into catchment processes that control runoff chemistry. Concentration vs. discharge plots showed a clear positive relationship for turbidity in Målselva in all seasons, suggesting similar processes related to sediment mobilization from the catchment throughout the year. In Storelva, the relationship was much less clear, indicating a greater variety of sediment sources as well as erosion and transport processes in this system. For FDOM in Målselva, the variation in FDOM over subsequent snow melt or storm events showed distinct hysteresis loops that provide information related to chemical sources and pathways throughout individual and repeated floods. Overall, sensor-based measurements reveal complex temporal dynamics that are obscured by traditional sampling frequencies and enable new insights into the function of watersheds and streams in response to climate forcing. These approaches therefore also provide important insight into upstream terrestrial processes (e.g. related to soil carbon accumulation and terrestrial-aquatic export), allowing for a more holistic integrated landscape scale approach to understanding climate impacts.

A key application of *in situ* sensor data is the potential to infer water chemistry with a high temporal resolution that cannot be achieved through manual sampling approaches. We assessed whether sensor data could be used as a ‘proxy’ for other water chemistry variables by testing for relationships between sensor data and lab-measured water chemistry for grab samples (typically collected monthly). In Storelva, we found that sensor-based turbidity was positively correlated with grab sample turbidity, as well as concentrations of SPM, total phosphorus (TP), particulate carbon (PartC) and nitrogen (PartN). Surprisingly, there was a weaker correlation between sensor-based turbidity and SPM in grab samples from Målselva. As expected, FDOM was positively related to dissolved organic

carbon (DOC) concentrations in lab-analyzed water samples for both rivers. While for Storelva, the relationship between DOC and FDOM was relatively consistent across seasons, in Målselva, samples collected during spring snowmelt (May/June) tended to have high DOC concentrations relative to FDOM values compared to samples collected at other times of year.

Based on linear regression, FDOM was a robust proxy for DOC concentrations in both study rivers. Meanwhile SPM was significantly positively related to sensor-measured turbidity in Storelva, although with weaker explanatory power and higher variability compared to DOC-FDOM relationships. SPM was not significantly related to turbidity in Målselva due to a strong decoupling of SPM and turbidity at higher turbidity levels. Building on the observed relationships, we compared flux estimates relying on traditional methods based on monthly grab samples to sensor-based estimates, and found sensor-based flux estimates to be more robust during periods of rapid change in river discharge and chemistry (e.g. during spring snow melt, when sensor-based DOC flux estimates were up to 30% higher in Målselva).

The current study revealed some challenges and opportunities related to the sensor-based monitoring in the Norwegian River Monitoring Programme. We therefore provide a list of recommendations related to ongoing and potential future sensor-based monitoring. Future work should focus on the following key points: (1) Increased frequency of water sample collection for lab analysis or use of automatic water samplers during the first 1-2 years of operation, (2) robust site-specific data correction approaches, e.g. for effects of temperature and turbidity on FDOM measurements, (3) regular maintenance and calibration of sensors, (4) co-location of future sensors with existing (or new) hydrologic monitoring stations, (5) exploring the potential utility of additional sensors such as nitrate or UV absorbance, and (6) explore possibilities for additional sensor stations in rivers, as well as at upstream (tributaries, lakes) and downstream coastal sites.

In conclusion, *in situ* sensor-based monitoring is emerging as a promising approach for understanding links between hydrology, climate and water quality over a range temporal scales that can capture interannual variability, seasonal patterns, water quality responses to high flow events and droughts, and even within-event dynamics. There are many challenges associated with sensor-based monitoring, including costs of sensors and associated infrastructure, including maintenance and operation, although these are typically much lower than the costs of high frequency manual sampling and laboratory analysis. There is a high potential for using sensor-based monitoring approaches to build process-understanding related to water quality responses to climate and hydrology, including seasonality and extreme climate and weather events. In particular, nesting sensor-based monitoring approaches within existing long-term monitoring programmes provides a unique opportunity to build new knowledge about hydroclimatic drivers of water chemistry in the context of documented decadal climate and water quality trends.

Sammendrag

Tittel: Using *in situ* sensor-based monitoring approaches to study climate change impacts on river water quality and element fluxes.
År: 2022
Forfatter(e): Amanda Poste, Leah Jackson-Blake, Maeve McGovern, Øyvind Kaste, James Sample, Odd Arne Skogan, Kari Austnes, Uta Brandt, Rolf Høgberget
Utgiver: Norsk institutt for vannforskning, ISBN 978-82-577-7548-3

Det er økende interesse for å ta i bruk sensorbaserte overvåkingsmetoder til å få bedre innblikk i effektene av klimaendringer på akvatiske systemer. Det gir en mulighet til å studere hvordan vannkvaliteten påvirkes av ekstreme vær- og klimahendelser (f.eks. tørke og flom), så vel som langsiktige og sesongmessige endringer i klima, hydrologi og vegetasjonsdekke. Sensorer har stort potensiale for å komplementere tradisjonelle overvåkingsmetoder basert på månedlig vannprøvetaking. Denne type tradisjonell månedlig overvåking er svært verdifull for å vurdere langsiktige trender og generelle sesongmønstre, men er mindre egnet til å dokumentere vannkjemiske responser på endringer i hydroklimatiske forhold (bl.a. stadig hyppigere forekomst av ekstreme vær- og klimahendelser). De nye mulighetene sensorer gir for å studere klimaeffekter på vann har ført til etablering av nye sensorbaserte målestasjoner innenfor den nasjonale elveovervåkingen. Denne rapporten inneholder en analyse av data fra to av sensorstasjonene innenfor det nasjonale Elveovervåkingsprogrammet som har de lengste tidsseriene; Storelva i Sør-Norge (data siden 2015) og Målselva i Nord-Norge (data siden midten av 2017).

For begge elvene ga en kombinasjon av sensorbaserte vannkvalitetsdata med hydroklimatiske parametere (lufttemperatur, nedbør, vannføring) verdifull innsikt i de viktigste driverne for variasjon i vannkvalitet mellom sesonger og år. Det avdekket også store forskjeller mellom elvene, både som følge av den store gradienten i breddegrad og klima, men også på grunn av kontraster med hensyn til landskapstyper og nedbørfeltprosesser. Kombinasjon av sensordata for turbiditet[1] og FDOM[2] med vannføring gav eksempelvis en nærmere forståelse av hvordan klimatiske og hydrologiske forhold påvirker mobilisering og transport mellom land og vann av suspenderte partikler (SPM), løst organisk materiale (DOM) og stoffer som er bundet til partikler eller organisk materiale.

Forholdet mellom sensor-målte konsentrasjoner og vannføring (CQ-forhold) kan gi viktig informasjon om nedbørfeltprosesser som styrer avrenning av kjemiske forbindelser fra land til vann. Det var en tydelig positiv sammenheng mellom sensor-målt turbiditet og vannføring i Målselva, noe som indikerer at prosessene som styrer mobilisering og transport av SPM er forholdsvis like året rundt. I Storelva var sammenhengene mindre klare, og det indikerer en større variasjon i kilder av sediment samt erosjon og transport av sedimenter i dette vassdraget. I Målselva viste plott av sensor-målt FDOM og vannføring et tydelig hysteresis-mønster[3] som indikerer at kildene til- og utlekkingen av organisk materiale varierer i løpet av en flom og ved gjentatte flommer innenfor et begrenset tidsrom. Dette avdekker en kompleks tidsmessig dynamikk som ikke vil vises ved tradisjonelle prøvetakingsfrekvenser, og som gir ny innsikt i hvordan nedbørfelter responderer på ulike former for

[1] «Proxy» (substitutt) for suspenderte partikler – SPM
[2] Fluorescent Dissolved Organic Matter. «Proxy» (substitutt) for løst organisk materiale – DOM
[3] Her: Syklisk, ikke-lineær sammenheng mellom FDOM og vannføring på økende og minkende flom

klimapåvirkninger. Dette gir også viktig innsikt inntil terrestriske prosesser (for eksempel, relater til akkumulering av jordkarbon og land-vann karboneksport), som kan bidra til en mer helhetlig integrert tilnærming for å forstå klimaeffekter på landskapskala.

Et viktig bruksområde for *in situ* sensordata er muligheten til å dokumentere vannkjemiske forhold med en mye høyere tidsoppløsning enn det som kan oppnås ved manuelle prøvetakingsmetoder. Vi undersøkte om sensordata kunne brukes som en "proxy" for andre vannkjemivariabler ved å teste for sammenhenger mellom sensordata og laboratoriemålt vannkjemi basert på månedlige stikkprøver. For Storelva fant vi at sensorbasert turbiditet var positivt korrelert med manuelle målinger av turbiditet, SPM, totalt fosfor (TP), samt partikulært karbon (PartC) og nitrogen (PartN). Overraskende nok var det en svakere sammenheng mellom sensorbasert turbiditet og målt SPM i Målselva. Som forventet var FDOM positivt korrelert med målte konsentrasjoner av organisk karbon (DOC og TOC) i begge elvene. Mens Storelva hadde et relativt konsistent forhold mellom DOC og FDOM på tvers av ulike årstider, hadde Målselva en tendens til høyere DOC/FDOM-forhold under snøsmeltingsperioden (mai/juni) sammenlignet med andre tider av året.

Basert på lineær regresjon var FDOM en robust «proxy» for DOC-konsentrasjoner i begge elvene. Sensormålt turbiditet viste en signifikant positiv sammenheng med SPM i Storelva, men med svakere forklaringsgrad og større variabilitet enn tilfellet var med DOC-FDOM. SPM var ikke signifikant relatert til turbiditet i Målselva på grunn av store avvik mellom SPM og turbiditet ved høyere turbiditetsnivåer. Basert på disse sammenhengene beregnet vi sensorbaserte estimater av DOC- og SPM-flukser (transport) i elvene som i sin tur ble sammenlignet med estimater som var basert på tradisjonell månedlig prøvetaking og lab-analyser. Resultatene viste at de sensorbaserte fluksestimatene var mer robuste i perioder med raske endringer i vannføring og stoffkonsentrasjoner. F.eks. i forbindelse med snøsmelting da den sensor-baserte DOC-fluksen i Målselva var opptil 30% høyere enn fluksen som var basert på tradisjonell månedlig prøvetaking.

Det gjennomførte arbeidet avdekket noen utfordringer samt flere muligheter knyttet til sensorbasert overvåking innenfor Elveovervåkingsprogrammet. Rapporten inneholder en liste med anbefalinger knyttet til pågående og potensiell fremtidig sensorbasert overvåking. Disse er: (1) Økt frekvens i vannprøvetaking eller buk av automatiske vannprøvetakere i løpet av de første 1-2 årene med drift på nye sensorstasjoner, (2) robuste og stedsspesifikke prosedyrer for datakorreksjon, f.eks. med hensyn til effekter av temperatur og turbiditet på FDOM-målinger, (3) regelmessig vedlikehold og kalibrering av sensorer, (4) samlokalisering av fremtidige sensorer med eksisterende (eller nye) hydrologiske overvåkingsstasjoner (5) utforske muligheter og nytte av å inkludere nye typer av sensorer som f.eks. nitrat- eller UV-absorbans, og (6) etablere sensorstasjoner i flere elver, eventuelt sideelver/innsjøer, samt i nedstrøms kystlokaliteter.

Vår konklusjon er at *in situ* sensorbasert overvåking framstår som en lovende tilnærming for å forstå sammenhenger mellom hydrologi, klima og vannkvalitet på ulike tidsskalaer som kan fange opp variasjon mellom år, sesongmessige mønstre og dynamiske endringer i vannkvalitet i forbindelse med flom- og tørkehendelser. Selv om det kan være mange utfordringer knyttet til sensorbasert overvåking, inkludert kostnader til sensorer, infrastruktur, drift og vedlikehold, vil det likevel være rimeligere enn å gjennomføre høyintensiv manuell prøvetaking med tilhørende laboratorieanalyser. Det er et stort potensial for å bruke sensorbaserte overvåkingsmetoder for å øke prosessforståelsen knyttet til vannkvalitetsresponser på klima og hydrologi, inkludert sesongvariasjoner og ekstreme vær- og klimahendelser. Spesielt vil sensorbasert overvåking innenfor de eksisterende, langsiktige overvåkingsprogrammene gi en unik mulighet til å etablere ny kunnskap om hydroklimatiske drivere for klima- og vannkvalitetstrender som er observert i løpet av de seneste tiårene.

1 Introduction

1.1 Detecting climate change impacts through long-term environmental monitoring: Challenges and opportunities

Climate change is already exerting measurable impacts around the world, including Norway. These impacts include changes in temperature, precipitation and runoff; vegetation changes; and increased frequency of extreme climate and weather events, including floods and droughts (IPCC 2021). Long-term changes in land-cover and climate, as well as shorter term events can strongly impact river discharge and water quality, driving changes in the flux of particulate and dissolved material (including nutrients, organic matter, inorganic particles and contaminants) from land to streams, lakes, rivers, and eventually the sea (Gibson et al. 2022). These decadal and event-scale changes in water quality and riverine fluxes are also expected to result in a broad range of implications for impacted freshwater and coastal ecosystems and the services they provide (Poste et al. 2021, Irrgang et al. 2022).

Despite the importance of understanding climate change impacts on water quality, strong variability in water chemistry over seasonal, event-scale or even hourly time scales complicates our ability to reliably detect climate change impacts on river water quality and riverine fluxes. Many long-term river monitoring programmes rely on manual monthly sampling. This also applies to the Norwegian River Monitoring Programme, although since 2017 sensor-based monitoring has been included in the programme for two rivers (Storelva and Målselva). As monthly manual sampling time series become longer, they provide important insight into long-term and broad-scale patterns and trends in river water chemistry (Kaste et al. 2022). However, because monthly sampling frequency has a bias towards capturing water quality during low flow periods (Skarbøvik et al. 2012) it is difficult to detect climate-driven changes in water quality, such as altered timing and magnitude of snowmelt floods, or increased frequency of floods, droughts and other extreme climate and weather events.

In particular, in northern river catchments, floods may often account for a large fraction of the total annual discharge, playing a key role in the mobilization and transport of particulate and dissolved material from land to freshwater and downstream coastal ecosystems (Ahmed et al. 2020, Holmes et al. 2012, Poste et al. 2021). For example, for a range of Arctic rivers, spring snowmelt (also known as 'freshet') has been shown to deliver up to 50% of total annual fluxes of dissolved organic carbon (DOC) and mercury (Hg) during a matter of weeks (Holmes et al. 2012, Finlay et al. 2006, Zolkos et al. 2020). Since floods only last a matter of weeks, or even days, it is challenging, yet critical, to document the impacts of these high flow events on river water quality, and their contribution to total annual fluxes of terrestrial material from land to sea on a detailed level (Poste et al. 2021).

Despite these challenges, pairing of traditional field-based monitoring approaches with new technologies such as *in situ* sensor-based monitoring, autonomous sampling, and remote sensing offer a promising way forward for detection of long-term and seasonal changes, as well as effects of extreme climate and weather events (including along the river-coast continuum). *In situ* sensors are capable of measuring a growing number of water quality parameters in the natural environment (e.g. temperature, conductivity, pH, turbidity, fluorescent dissolved organic matter (FDOM; the portion of coloured DOM that fluoresces) and UV-VIS absorption (absorption in the UV-visible light range), chlorophyll fluorescence, dissolved gases (e.g. O_2 and CO_2), and nutrients (e.g. nitrate)). Hence, sensors are increasingly used in research related to links between climate drivers and water quality, including in streams, lakes, rivers and coastal waters (O'Grady et al. 2021).

In rivers, sensor-based approaches are providing important new insight into climate and hydrologic drivers of water quality, including understanding mobilization and transport of particles and organic matter during high flow events and the role of season as well as prior high flow events or drought in shaping the impact of these events on water quality (e.g. Pellerin et al. 2012, Burns et al. 2019). Sensor-based approaches can also be a cost-effective alternative to traditional grab sampling for monitoring of river water quality where high frequency measurements are needed to meet monitoring and/or research needs. Furthermore, by pairing traditional water chemistry analysis of manual samples with *in situ* sensor data, several studies have developed empirical relationships between sensor data and measured concentrations. For example, sensor measurements of conductivity, turbidity and FDOM have been paired with discrete water samples of suspended particulate matter (SPM), DOC, nitrate (NO_3) and particulate nutrients and carbon (e.g. Snyder et al. 2018, Burns et al. 2019, Kärämi et al. 2020), which can then be used to infer water chemistry and riverine fluxes (by pairing with discharge data) with high temporal frequency.

1.2 Background and objectives for the current study

For the program period 2021-2025 the Norwegian Environment Agency (Miljødirektoratet) has introduced a new concept called "integrated climate monitoring" across several national monitoring programs, including the Norwegian River Monitoring Program. The goal of this initiative is to gain more knowledge from existing monitoring about the effects of climate change on aquatic ecosystems, including increased coordination across national freshwater and coastal monitoring programs. As part of this effort, in 2021 the Norwegian River Monitoring Programme was expanded to include four stations with *in situ* sensor-based monitoring. While two of these stations were established recently, the other two stations, located in Storelva in southern Norway and Målselva in northern Norway, were established prior to being included in the monitoring programme, and have time series stretching back to 2017 and 2015, respectively. As such, they are well-suited for assessing the utility of sensor-based river monitoring approaches.

As part of the "integrated climate monitoring" component of the Norwegian River Monitoring Programme, the Norwegian Environment Agency has commissioned NIVA to prepare a report on "use of sensor data to study climate effects with high time resolution", using data from the Storelva and Målselva rivers.

The objectives of the work are to:

- Test whether sensor data can serve as a proxy for other water quality parameters (e.g. of DOC, SPM, nutrients and ions)
- Combine sensor data with water flow to estimate fluxes (e.g. of DOC and SPM) with high time resolution
- Compare estimated fluxes between sensor-based and 'traditional' methods on different timescales
- Use sensor data to assess how seasonality and specific climate events impact water quality
- Provide an overview of opportunities and challenges associated with sensor-based monitoring of water quality

2 Methods

2.1 General approach

While this report includes a discussion about the broader possibilities and challenges related to the use of *in situ* sensor-based monitoring approaches in river systems, at the core of this report is an analysis of available sensor data in combination with climate, hydrology and water chemistry data for two rivers included in the Norwegian River Monitoring programme; Storelva and Målselva.

In our analysis, we focus on the period 2017–2021, and take two main approaches:

1. Firstly, we focus on evaluating the links between air temperature, precipitation and runoff and sensor-based water quality measurements. In particular, we assess how water quality variables respond to seasonal patterns and between-year variation in climate and hydrology, as well as shorter-term climate events, including floods and droughts.
2. Secondly, where possible, we develop empirical relationships between sensor data and water chemistry data from monthly grab samples. These relationships are then used to infer riverine fluxes (e.g. of elements and/or particulate matter) with high temporal resolution, e.g. connected to individual flooding events. We also compare sensor-based flux estimates with 'traditional' flux estimates based on monthly sampling, giving important insight into the added value of complementing traditional field-sampling based monitoring with sensor-based approaches.

2.2 NIVA's river monitoring sensor stations

Four stations with in-situ sensor-based monitoring are currently included in the Norwegian River Monitoring Programme: Storelva, Målselva, Vorma and Leira.

The sensor stations in Storelva and Målselva have been operated by NIVA since 2015 and 2017, respectively, while the stations in Vorma and Leira (both in the Glomma watercourse) have been in operation since autumn 2021. In addition to these stations, there are also two new sensor stations that have been established in connection with the Norwegian Reference River Monitoring Programme (Gudbrandsdalslågen and Sjoa; also in the Glomma watercourse).

For this report we have focused on the stations with the longest time series: Storelva in southern Norway and Målselva in northern Norway (see **Figure 1** and for a map and **Table 1** for additional details about the two study rivers).

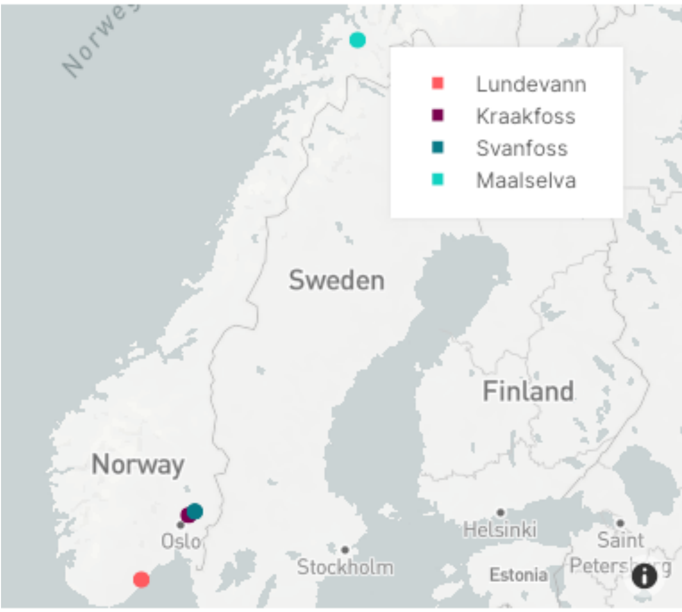

Figure 1. Map showing locations of NIVA's *in situ* sensor-based river monitoring stations included in the Norwegian River Monitoring Programme. Note that station names (aside from Målselva) used in this map are the names of the NVE stations where sensor sites are located (Lundevann in Storelva, Kråkfoss in Leira, and Svanfoss in Vorma).

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

		Storelva	**Målselva**
Catchment area	km²	407	5586
Latitude	ºN	58.7	9.0
Longitude	ºE	69.1	18.6
Max altitude	m.a.s.l. *	506	1714
Mean altitude	m.a.s.l.	204	688
Mean runoff (1961-1990)	L/s/km²	24.0	28.6
Land cover			
Uplands, non-forested	%	0.0	58.4
Glaciers	%	0.0	0.5
Forest	%	83.5	26.3
Wetlands/peat	%	4.5	4.3
Lakes	%	9.0	5.7
Agricultural land	%	1.8	0.6
Urban	%	0.1	0.1
Non-classified	%	1.1	4.1

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

In Storelva and Målselva, the sensor stations are in the same locations where manual samples are collected monthly for the Norwegian River Monitoring Programme (Kaste et al. 2022). In Storelva, water from the river is pumped a few meters to an instrument container with flow cells equipped with sensors that continuously measure water temperature, pH, conductivity, turbidity and fluorescent dissolved organic matter (FDOM). In Målselva, sensors for the same parameters are mounted in a rig that is immersed in the river water. To ensure high quality continuous data, the stations are visited at regular intervals for service and maintenance. Data from both stations are recorded on an hourly basis, transferred to NIVA's server and are openly available at the following link: Elveovervåking (niva.no).

Additional technical details related to the stations are available in **Appendix A**, while an example of how the data are presented in NIVA's openly available online portal is included in **Appendix B**.

For the sensors deployed at these stations, an overview of typical environmental applications, expected relationships with water chemistry, and links between sensor values and ecologically relevant processes is provided in **Table 2**.

Table 2. Overview of sensor-derived variables measured in the two study rivers and their typical applications and ecological relevance.

Sensors	Main applications and ecological relevance
Water temperature	Provides insight into long-term trends and seasonality in temperature, as well as temperature responses to e.g. flow regulation (in regulated watercourses) and extreme climate and weather events (e.g. heat waves and droughts). Since many aquatic organisms, including fish, are sensitive to temperature (e.g. narrow thermal tolerance ranges or high sensitivity during specific life stages), high frequency temperature data provide useful insight into climate change risks related to both long- and short-term temperature increases.
Conductivity	A measure of water's ability to transmit an electrical current and correlated with the concentration of ions in water. Can provide insight into seasonal and event-scale changes in water sources and flow pathways (e.g. groundwater contribution during periods of low flow, ion elution from seasonal snowpack and surface soils during early spring snowmelt, dilution of ion concentrations during high flow during late snowmelt and rainfall-driven floods).
pH	A measure of concentration of H^+ ions in water. While surface waters naturally exhibit between-system differences and seasonal (and shorter-term) variability in pH values, acidification due to long-range transported air pollution has led to reduced pH in many north temperate freshwater systems, with a range of consequences for aquatic biodiversity, including populations of salmonids and bivalves. Despite reductions in acid precipitation, altered catchment soil chemistry means that many systems have yet to fully recover, and even rivers and catchments that are limed to increase and stabilize pH can experience episodic decreases in pH in response to climate events, which can pose a threat to aquatic organisms and ecosystem health.
Turbidity	A measure of the degree of scattering of light in the water, and closely related to suspended particulate matter (SPM) concentrations and water clarity. Sensor-based turbidity is often used to infer concentrations and fluxes (when paired with discharge) of SPM as well as particle-associated nutrients (especially phosphorus), carbon and contaminants. Pairing high frequency turbidity data with discharge can also provide insight into sources and mobilization of particulate matter in monitored catchments. High turbidity in rivers can also indicate low light availability in rivers, as well as downstream lakes and coastal waters, with potential for reduced aquatic primary production due to light limitation of photosynthesis.
FDOM	Related to the amount of fluorescent dissolved organic matter (the fraction of DOM that fluoresces). Typically used as a proxy for dissolved organic carbon (DOC) concentrations, with the potential to be used to infer concentrations and fluxes (when paired with discharge) of DOC as well as organic matter-associated nutrients and metals (including Hg) and other contaminants. Also gives insight into optical properties of river water, since DOM can contribute substantially to light attenuation in fresh and coastal surface waters and may, alongside turbidity, lead to light limitation of aquatic primary production. Similarly to turbidity, pairing high-frequency FDOM data with discharge provides important insight into sources and mobilization of DOM in monitored catchments, and how DOM dynamics change seasonally and in response to high flow events (or series of high flow events).

2.3 Sources of data

2.3.1 Climate and hydrology data

Temperature and precipitation data (from 2017–2021) were retrieved using NVE's Gridded Time Series (GTS) API (accessed on 30.09.22) and averaged over the catchment area upstream of the sensor stations. Catchment boundaries used for extraction of climate data were derived, using the sensor station coordinates, from the Norwegian Water Resources and Energy Directorate (NVE)'s NEVINA system (https://nevina.nve.no/; accessed on 30.09.22).

River discharge data were obtained from NVE's real-time stations at Lundevann (station ID 18.4.0.), which is located close to the sensor station in Storelva, and Målselvfossen (station ID 196.35.0), located 15 km upstream of the sensor station in Målselva (source: https://sildre.nve.no/). For Målselva, river discharge at the sensor station (catchment area = 5586 km^2) was estimated by area-scaling the measured discharge at the upstream Målselvfossen station (catchment area = 3039 km^2). This is an approximation, as only around half the discharge expected at the sensor site is captured by the NVE gauging station. The ungauged catchment area includes the large Altevatnet reservoir which is regulated and is likely to show a broader and flatter increase in flow after rainfall or snowmelt than the Målselvfossen catchment.

2.3.2 *In situ* sensor data

Available *in situ* sensor-based river monitoring data from 2017–2021 were compiled for both study rivers. The sensor-based monitoring stations in the rivers provide hourly temperature, pH, conductivity, turbidity, and FDOM measurements (see section 2.2 and Appendix A for additional details regarding sensor-based monitoring in these rivers).

Post-processing of the sensor data to check for and remove erroneous and suspect data is necessary before further interpretation and analysis of sensor data and involved the following steps:

1) Prior to analyses we excluded erroneous data and clear outliers, based on observed drifts, step changes, and/or abrupt low or high values that were not related to observed changes in river discharge.

2) Temperature is known to impact sensor-based FDOM measurements through quenching, leading to lower FDOM values at higher temperatures (Ryder et al. 2012). As such, FDOM data are often temperature-corrected in order to account for variable quenching linked to seasonal and even diurnal temperature changes. Temperature correction of the FDOM data at Storelva was done in accordance with Ryder et al. (2012), using an intercept of 100 and adjusting the slope to optimize the correlation between temperature-corrected FDOM and dissolved organic carbon (DOC) concentration. Temperature correction did not improve the correlation between FDOM and DOC at Målselva, and so was not carried out. Although turbidity is also known to interfere with accurate measurement of FDOM (Saraceno et al. 2017), turbidity corrections were not applied at the study sites, since this would require additional sampling and analysis of filtered and unfiltered water samples in order to establish a site-specific correction factor.

Main changes to the raw data from Målselva resulting from quality assurance procedures included the removal of 728 values, most related to low pH in addition to all FDOM values in 2021. For Storelva, 12 010 values were removed, mostly due to inconsistencies in pH and turbidity, as well as conductivity values that were far below what would be expected for true values (<2 mS/m). FDOM data from mid-

2020 to end of 2021 in Målselva was excluded from the current report, due to step-changes in sensor values that require further investigation and correction.

2.3.3 Water quality data from manual sampling

As previously mentioned, the two study rivers are monitored on a monthly basis as part of the Norwegian River Monitoring Programme. This monitoring involves manual water sampling and detailed chemical analysis of a broad range of water quality variables, including pH, conductivity, turbidity; SPM; total nitrogen and phosphorus (Tot-N, Tot-P); inorganic nutrients (nitrate (NO_3), ammonium (NH_4), phosphate (PO_4), silicate (SiO_2)); particulate phosphorus and nitrogen (Part-P, Part-N); total, dissolved and particulate organic carbon (TOC, DOC, POC); dissolved organic matter absorption spectra (cDOM); as well as several metals, including mercury (Hg).

Data included in the current study, alongside detailed methodology for field sampling and chemical analyses, are described in the annual reports from the Norwegian River Monitoring Programme (Kaste et al. 2022, and previous reports).

2.4 Data analysis

Relationships between *in situ* sensor data and climate and hydrology, as well as discrete grab samples and were investigated using spearman rank correlations with p-values adjusted for multiple comparisons using the Bonferroni correction. The significance level was set at $p < 0.01$. For variables measured in both the lab and by the sensor (pH, turbidity, conductivity) we used linear regression to compare the two measurement methods. We further used linear regression for building empirical relationships between conceptually linked variables (DOC vs. FDOM, SPM vs turbidity). These linear regressions were then used to calculate daily concentrations for DOC and SPM from the sensor-based measurements of FDOM and turbidity, respectively. In Målselva, we grouped the data according to whether they corresponded to the spring freshet or not (assumed to be May and June) and carried out two separate regressions for these periods. When exploring concentration-discharge (CQ) relationships (Section 3.2), we grouped the data by season. Given their differences in latitude, we used 3 seasons in Målselva (May and June: spring, July and August: summer, otherwise winter), and 4 in Storelva (March, April and May: spring, June, July and August: summer, September, October and November: autumn, December, January and February: winter).

To estimate daily fluxes of DOC and SPM (Section 3.4), we multiplied daily concentrations estimated using regressions between sensor and grab data by daily discharge. These sensor-based flux estimates were compared to estimations calculated using linear interpolation based on monthly discrete grab samples, as well as linear interpolation using higher resolution grab sampling during spring freshet at Målselva. Sensor-based and discrete grab sample based estimations of daily fluxes were then summed to monthly and annual fluxes, and also compared to annual fluxes calculated using the OSPAR method, a discharge-based ratio-estimation method typically used by the river monitoring program. This method follows the recommendations in the RID Principles (OSPAR Agreement 2014:04; § 6.13 b), can handle irregular sampling frequency and includes flood samples in the annual load calculations (www.ospar.org; Skarbøvik et al. 2017).

3 Results and discussion

3.1 Climate, hydrology and sensor-derived water quality

The two rivers included in the current analysis differ strongly in their climate, hydrology and sensor-derived water quality (**Figure 2**, **Figure 3**). In particular, the latitudinal difference between the sites (**Table 1**) creates differences in seasonality, with much stronger seasonal patterns in temperature, precipitation, river discharge and water quality (including conductivity, turbidity and FDOM) observed in the subarctic Målselva river compared to the boreal Storelva system in southern Norway. Previous studies in these systems have also reported between-river differences in water chemistry and its seasonality (Schultze et al. 2022). In Storelva (which drains a heavily forested catchment), DOC concentrations are typically 4-fold higher than those observed in Målselva (where unforested mountainous regions cover a substantial portion of the catchment). Total N and P as well as inorganic N concentrations are also higher in Storelva than in Målselva, while PO_4 concentrations are approximately 5-fold higher in Målselva than in Storelva due to higher sediment loads (Schultze et al. 2022, Kaste et al. 2022)

In Storelva (**Figure 2**), broad-scale seasonality is observed in air and water temperature, while river discharge is characterized by rapid responses to precipitation events with a relatively quick return to baseline flow after flood peaks. The largest flood events typically occur during late autumn, although high flow events occur during all seasons in this river, including during winter, with strong between-year variation. Storelva has been heavily affected by acidification from long-range transported air pollution, and since the 1990s the river has been limed, with a target pH value of 6.4 year-round to protect salmon, sea trout and the freshwater pearl mussel. Continuous monitoring of pH in this river reveals periodic drops in pH, particularly during flooding events late in the year, providing insight into both the efficacy of liming as well as the frequency and duration of low pH events. Conductivity values tend to peak during longer periods of low flow (with highest values observed during summer 2020) but also respond to high flow events throughout the year. In Storelva, there is high variability in turbidity year-round, with peaks in turbidity occurring in all seasons, although these peaks are not always well-aligned with periods of high flow. Meanwhile, FDOM values in Storelva tend to be highest in autumn and early winter, with lowest values during periods of low flow during summer. A post-summer increase in FDOM in response to increased water flow is observed for several of the years for which sensor data are available, although later in autumn there is a tendency toward dilution of the FDOM signal during floods, suggesting that earlier flooding may have already ‘flushed out’ the easily mobilizable fraction of the soil DOM pool (more about this in Section 3.2).

In Målselva, high latitude paired with the presence of high-altitude mountainous regions in the catchment leads to low temperatures and a hydrograph that is dominated by snowmelt during May and June (**Figure 3**). A substantial fraction of the precipitation that falls between October and April ends up accumulated in the snowpack, although climate change is driving a shift toward increased frequency of autumn and winter rainfall events in this region (Vormoor et al. 2016). In contrast with Storelva, where the hydrograph is not dominated by large snowmelt peaks, sensor-based water quality in Målselva data exhibits clear seasonality, with peaks in FDOM and turbidity during spring (associated with snow melt) and late autumn (associated with rainfall-driven high flow events), and reduced conductivity (and to a lesser extent pH) during periods of high flow. The high degree of variability in discharge and sensor values during the spring snowmelt period (May/June) reflects the multi-phase snowmelt (with multiple flow peaks) that is typical in this river, where the large elevation range leads to variable snowmelt timing across the catchment.

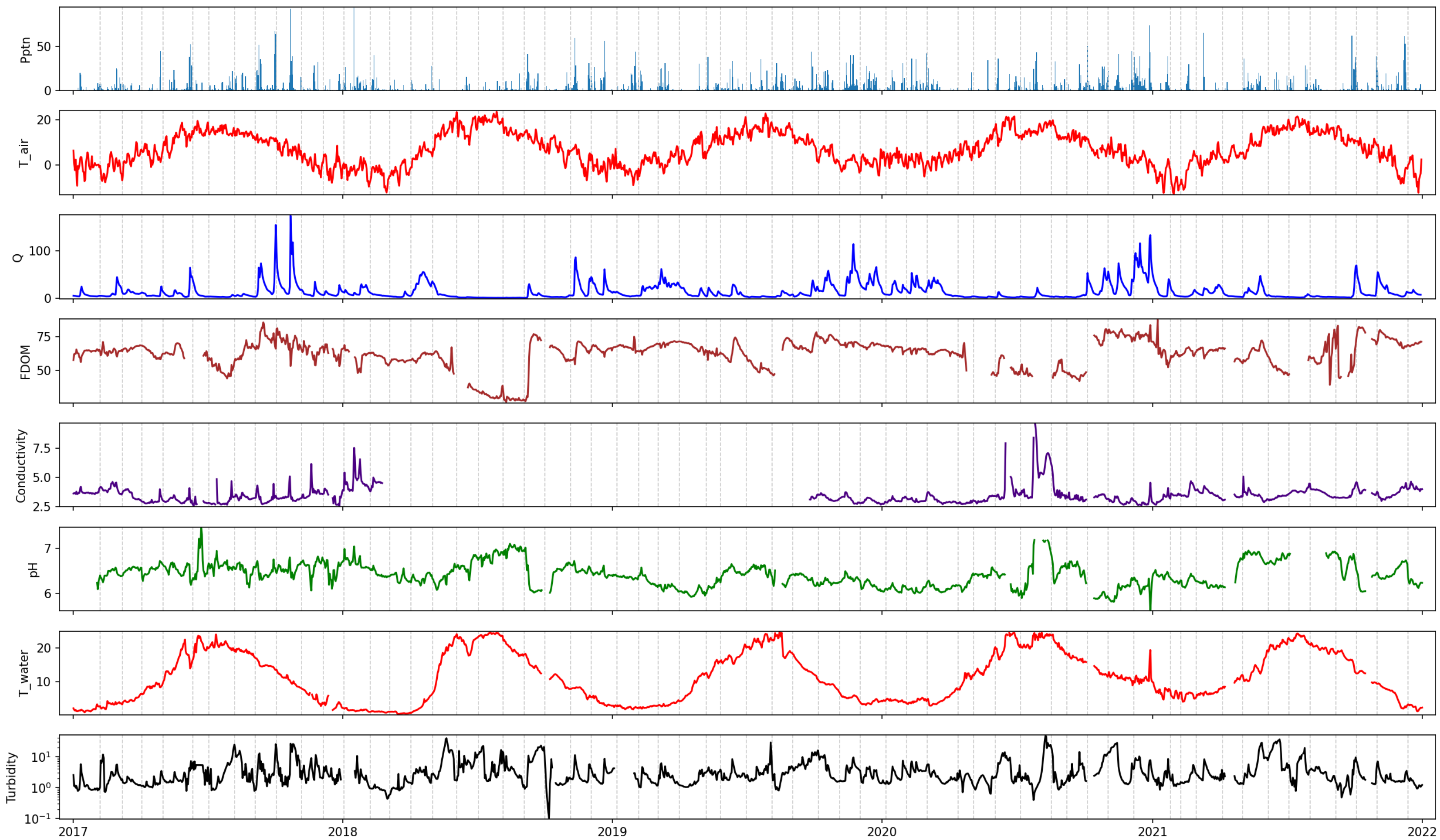

Figure 2. Time series for weather variables (Pptn: precipitation, T_air: air temperature), discharge (Q) and *in situ* sensor observations for Storelva (T_water is water temperature). Vertical lines show grab sampling dates.

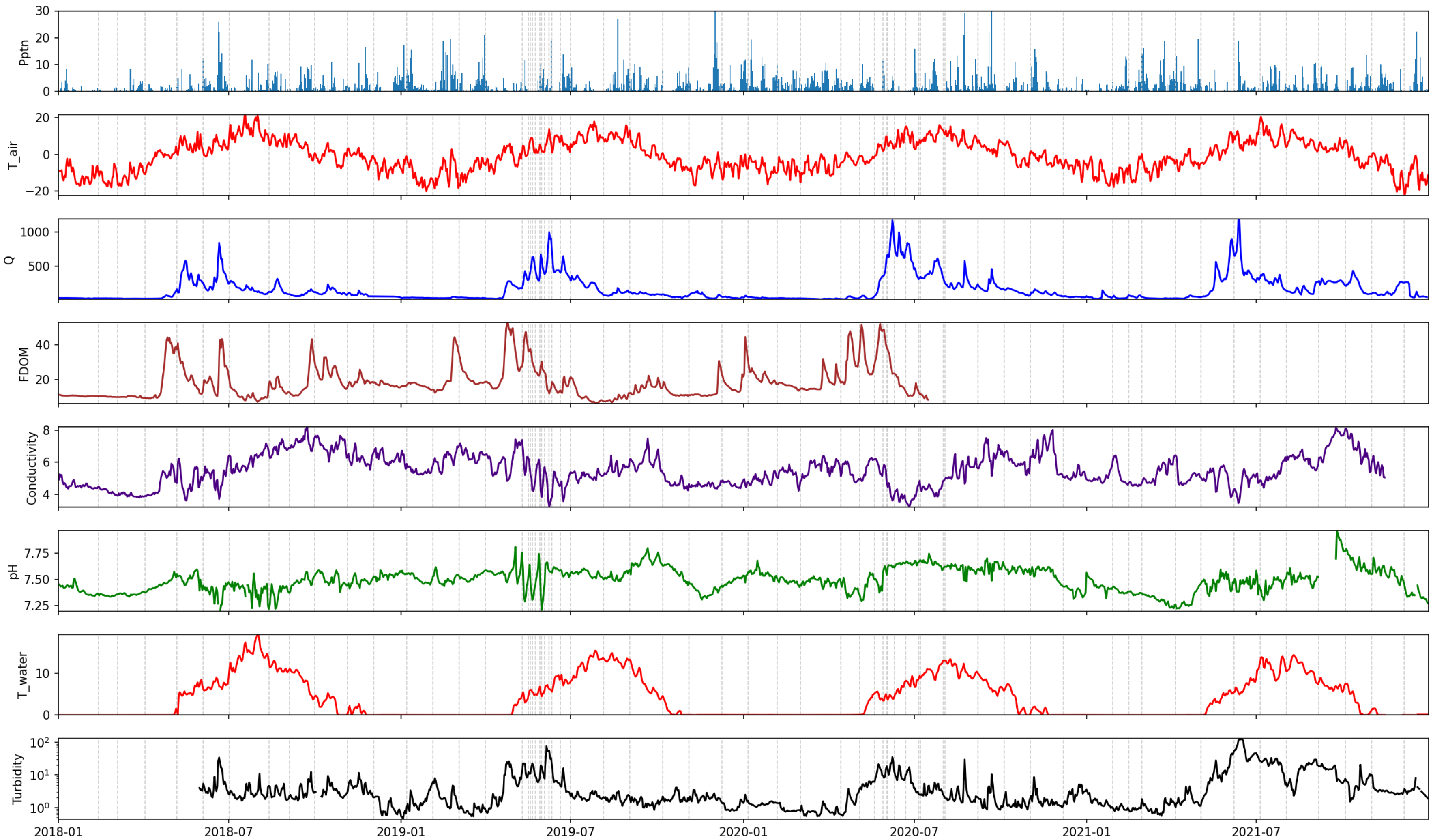

Figure 3. Time series for weather variables (Pptn: precipitation, T_air: air temperature), discharge (Q) and *in situ* sensor observations for Målselva (T_water is water temperature). Vertical lines show grab sampling dates, including extra high frequency sampling during spring 2019 and 2020.

This high degree of variability in water quality during the spring snowmelt period is also consistent with previous studies where higher frequency water sampling during May and June has revealed high variability in discharge and water chemistry (with data from 2019 (see **Figure 4**) and 2020 (Poste et al. 2021)). The sensor data also reveal how strong between-year variability in seasonal patterns impact river water quality. For example, we observed differences in water quality variability between years with stable cold winter conditions *vs.* years with significant winter thaw events (e.g. early 2018 *vs.* 2020) as well as years with and without substantial late summer/autumn rainfall events (e.g. 2018 vs. 2019). Sensor-based water quality measurements also varied strongly between year for springtime, in relation to differences in timing, size and number of flow peaks during spring snowmelt (e.g. earlier freshet with a shorter duration in 2019 than in 2020)..

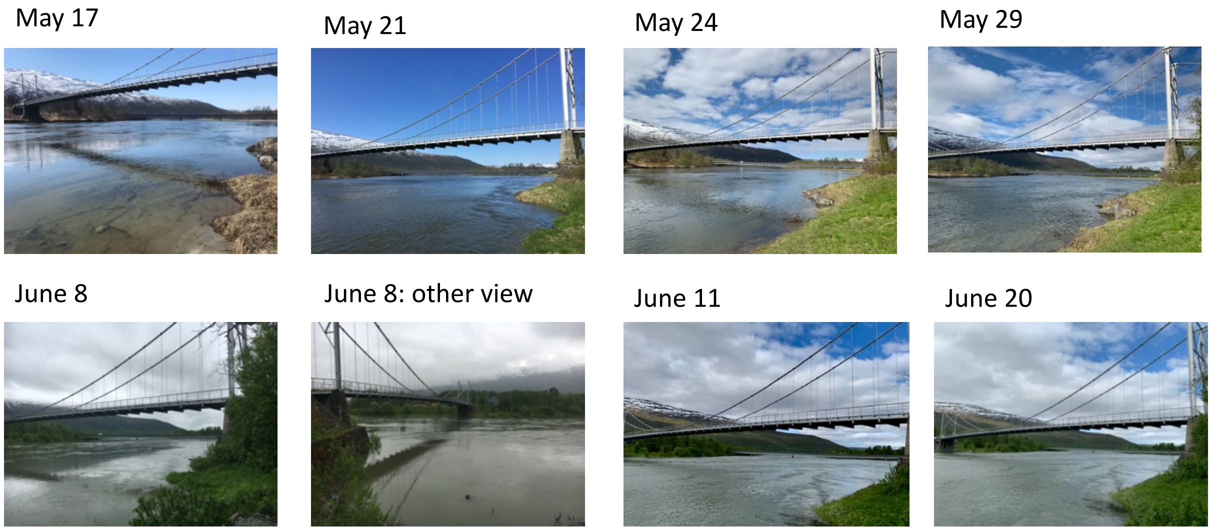

Figure 4. Photos from near the Målselva sensor station during spring snowmelt in 2019 highlighting visible changes and between-date variability in water level and turbidity over the course of the snowmelt period. Photos taken by M. McGovern, P. Carlsson and O. Christensen.

For both study rivers, combining *in situ* sensor data with data on hydroclimatic drivers in the study catchments yields insights into the main drivers of seasonality and interannual variability in sensor-derived water quality (**Figure 2, Figure 3, Figure 5**). In particular, sensor data highlighted the role of high flow events in mobilization and downstream transport of organic matter (elevated FDOM during periods of high flow, particularly during the early phases of high flow events, see Section 3.2) and SPM (elevated turbidity during high flow). Meanwhile, high conductivity during periods of low flow and reduced conductivity during snow melt events (**Figure 2, Figure 3**) likely reflects the importance of solute-rich groundwater inputs in controlling fluxes of major ions during low flow periods in late summer and early autumn, and the role of high flow in diluting riverine major ion concentrations, especially during spring snow melt. These observations are also closely aligned with observations from other sensor-based monitoring studies in northern rivers, which have observed similar positive relationships between discharge and FDOM (especially during spring snowmelt, e.g. Pellerin et al. 2012) and turbidity (e.g. Kämäri et al. 2018), and negative relationships between discharge and conductivity (e.g. Koenig et al. 2017).

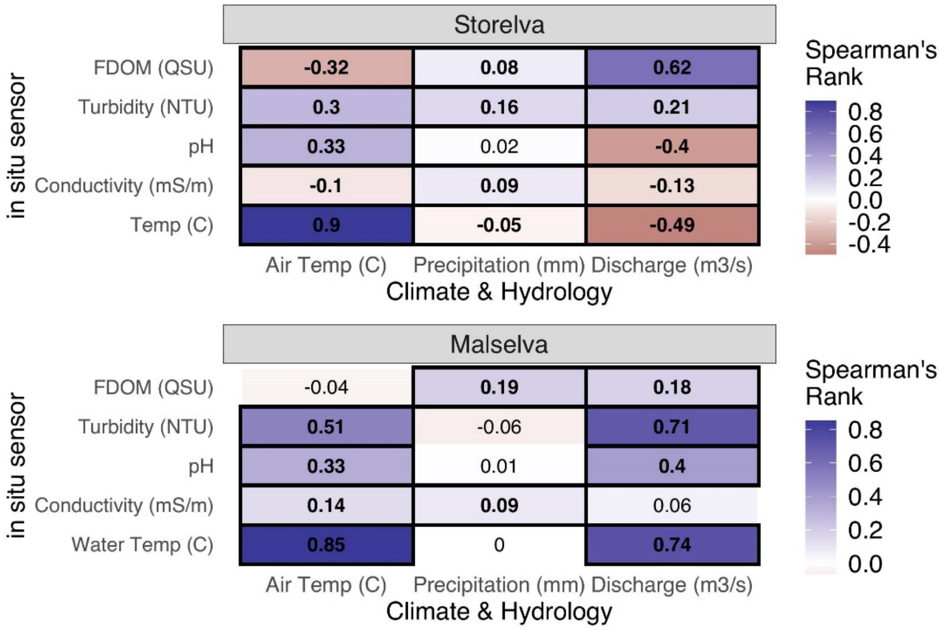

Figure 5. Spearman Rank correlations between in-situ sensor measurements, air temperature, precipitation and discharge based on all available years of data for Storelva (top) and Målselva (bottom). Bold outline shows where $p < 0.01$.

3.2 Linking seasonal and event-scale drivers to sensor-derived water quality

By measuring water quality at high frequency, sensors enable observations of catchments and streams at time scales which are compatible with their fundamental hydrological, elemental and biological drivers. This in turn allows sensor data to be used to better understand these drivers, a crucial first step in predicting future change.

A fundamental tool for using sensor data to better understand the catchment processes that control runoff chemistry is the exploration of concentration–discharge (CQ) relationships (e.g. Koenig et al. 2017). River chemistry tends to change in response to increased flow events in two main ways: (1) if the chemical variable has a constant *point source* (e.g. phosphorus in sewage treatment work outflows), then as the river discharge increases, concentration tends to decrease due to dilution; or (2) if the chemical variable is only transported to the river during rainfall events (e.g. DOC or nitrate stored in soil water), i.e. it has a *diffuse source*, then as river discharge increases, concentration increases. In many systems, a combination of dilution and mobilisation are seen during high flow events, according to the relative importance of point versus diffuse sources. CQ relationships therefore provide a powerful means of inferring nutrient, sediment and carbon sources to rivers (Koenig et al. 2017, Rode et al. 2016). Although it is beyond the scope of this report to carry out a detailed analysis of the CQ relationships at Målselva and Storelva, some examples are explored below to illustrate the benefits of sensor data.

For turbidity, in Målselva there is a clear positive relationship with discharge (Spearman's R=0.65, p<0.001), although there is much scatter (**Figure 6**). Although both discharge and turbidity are highest in spring, the gradient of the CQ line (in log-log space) is similar between seasons, suggesting similar mobilisation processes operating throughout the year in response to rainfall-runoff events. The turbidity CQ relationship in Storelva is positive but much weaker than in Målselva (Spearman's R=0.21, p<0.001) and less uniform, suggesting a greater variety of sediment sources and mobilization processes, where turbidity responds differently to flow events throughout the year.

For FDOM, in Målselva we see a general increase with increasing discharge (Spearman's R=0.22, p<0.001), although there is great variability in the gradient of the CQ relationship between seasons, flow events, and even within a single event (particularly during the spring snow melt period; discussed below). As with turbidity, in Storelva the FDOM shows a more variable response to discharge than in Målselva. The relationship is generally positive (Spearman's R=0.57, p<0.001), but in **Figure 2** and **Figure 6** we can see high flow events also causing dilution (e.g. the large autumn loop in **Figure 6**). In both cases, a more detailed examination of the variability in the CQ relationships across seasons and events can be used to infer how sources and processing of FDOM vary through time and space (although beyond the scope of this report).

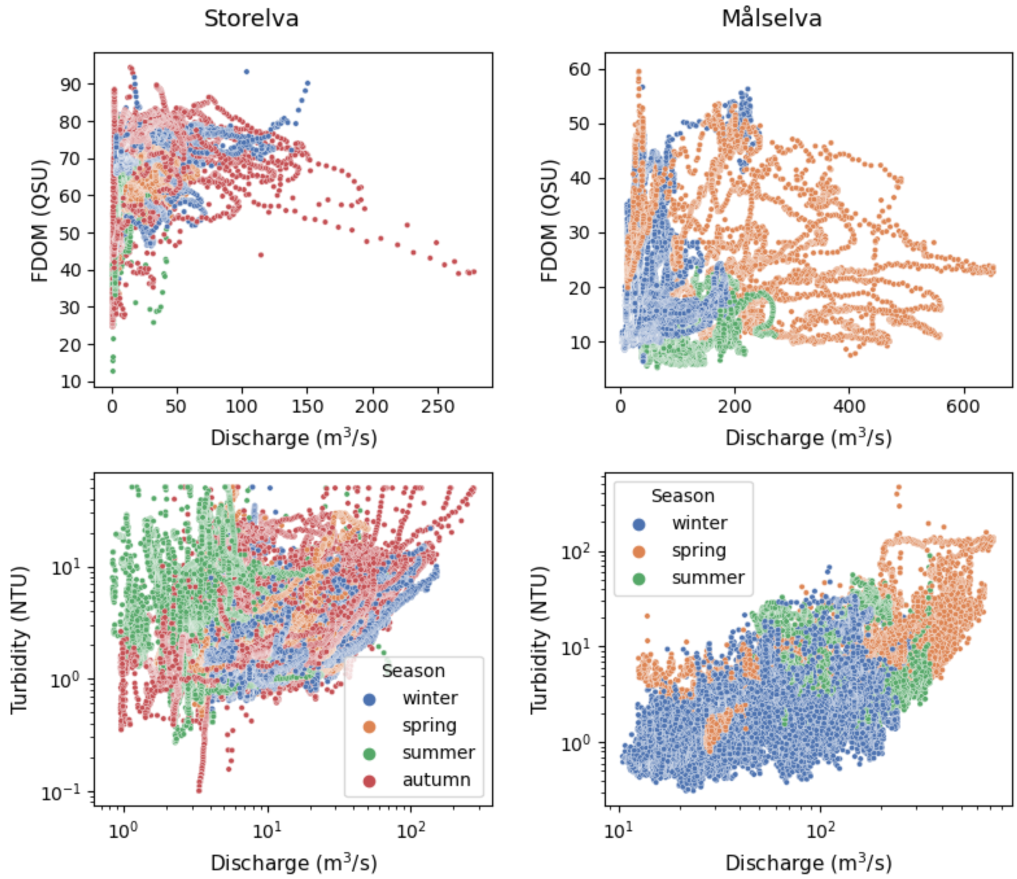

Figure 6. Concentration versus discharge plots for hourly FDOM and turbidity in Storelva (left) and Målselva (right), including all available data from all years. Points are coloured based on season.

These CQ plots can be challenging to interpret without visualizing events individually. We have therefore selected an example event from each river system for further exploration (**Figure 7**). For Storelva, we selected a flow peak in early autumn 2018 at the end of a dry period (**Figure 7**, left panel). River flow increased dramatically over a 1-2 day period. The high-frequency sensor data allows us to see that turbidity increased *before* the discharge increased, indicating rapid flushing of an in-channel or near-channel sediment source. Turbidity levels were then sustained at high levels even as discharge declined, implying continued sediment inputs from more distant sources and a ready supply of sediment. Meanwhile FDOM increased much more slowly, lagging behind the increase in discharge, suggesting that FDOM is derived from more distant sources than turbidity. Once again, FDOM levels remained high despite decreasing discharge late in the event, potentially because hydrological connectivity between soils and the watercourse was still high.

For Målselva, we selected the spring snowmelt period in 2019, when six distinct snowmelt periods led to six discharge peaks (**Figure 7**, right panel). Each of these was accompanied by an increase in turbidity, where the height of the turbidity peak was roughly proportional to the height of the discharge peak. This indicates a ready supply of sediment across all flow events. Meanwhile, the FDOM peak was highest during the first snowmelt event and declined progressively thereafter, despite the flow peaks following the opposite pattern and increasing over time. FDOM even showed dilution by the 5th event, i.e. the flow peak was accompanied by a decline in concentrations rather than an increase. This general decline in CQ slope with successive flow events could be caused by (1) source-exhaustion, whereby the store of soil water FDOM becomes depleted during successive events, and/or (2) variable sources of FDOM during different events, with more C-rich soils providing the main inputs during earlier thaw events (e.g. in more lowland areas), whilst inputs from C-poor soils begin to dominate later in the snowmelt season, as the thaw progressively moves to higher elevations in the catchment. A combination of both explanations is likely, and certainly the dilution seen during the 5th event is an indication of source-exhaustion. By the 6th flow event the QC relationship is positive again, potentially reflecting the fact that soil porewater DOC concentrations tend to increase throughout the growing season.

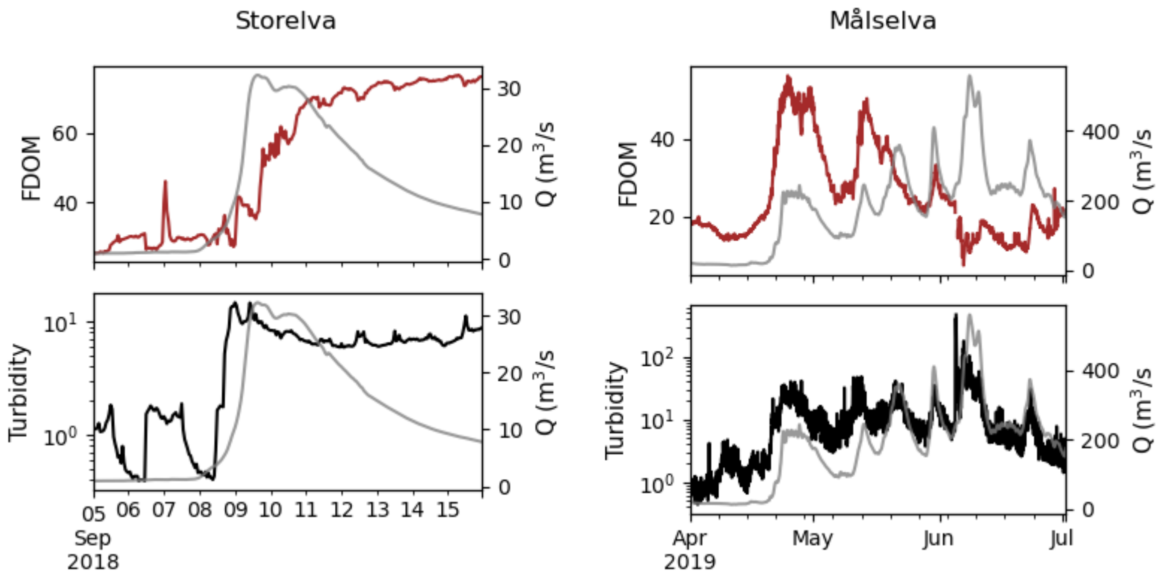

Figure 7. Sensor-based FDOM (red lines) and turbidity (black lines) alongside river discharge (grey lines) for selected high flow periods in Storelva (left; heavy rainfall period during autumn 2018) and Målselva (right; 2019 spring snowmelt period with multiple snowmelt peaks).

For FDOM in Målselva, the variation over subsequent snowmelt events can also be analysed by looking at so-called *hysteresis* loops. In general, CQ relationship over single flow events tends to have a cyclical form (hysteresis), and the shape of the hysteresis loop provides extra valuable information on chemical sources and pathways (e.g. Evans and Davies, 1998). In Målselva, we see a clear pattern of declining CQ slope over the progressive high flow events during the 2019 snowmelt period (**Figure 8**).

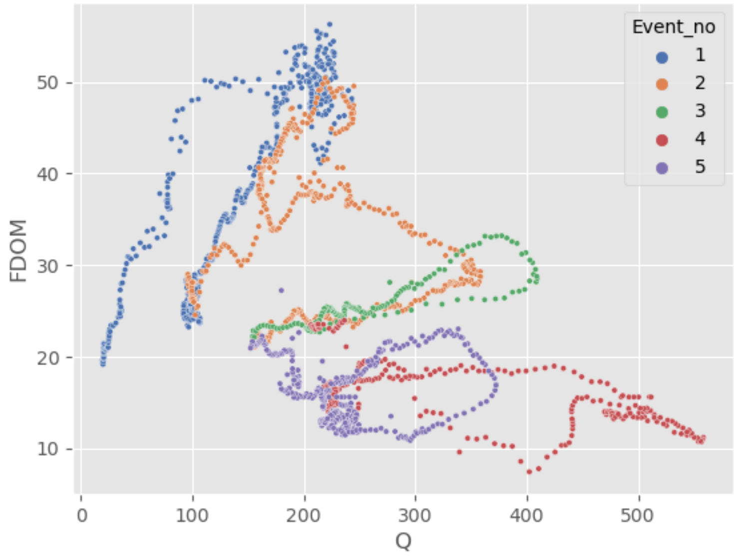

Figure 8. FDOM vs. discharge (Q) plot for the first five sequential high flow events during spring 2019 in Målselva (see **Figure 7**). Note the distinct hysteresis loops and the decrease in the slope of the FDOM-Q relationship over the first four events, until event 5 (in July), by which time soil water DOC is starting to increase due to increased terrestrial productivity.

Here, we have explored several ways in which sensors can provide insights into internal, traditionally hard-to-observe, catchment processes. Other relevant examples would be measuring episodic low pH events, which would be missed by low-frequency sampling and yet can be toxic to juvenile fish (Kroglund et al. 2008). Overall, sensor-based measurements reveal complex temporal dynamics that are obscured by traditional sampling frequencies, thereby enabling new insights into the inner-workings of watersheds and streams. This improved understanding allows for more robust management decisions to safeguard water quality (e.g. implementing appropriate nutrient or sediment reduction measures, which target the right source areas and/or transport pathways). The process knowledge gained through higher-frequency monitoring also provides crucial system understanding which allows us to build better (qualitative or process-based) models of the system, which in turn is required to predict future changes in water quality under future climate and land use change.

3.3 Using *in situ* sensor data as a proxy for water chemistry

A key application of *in situ* sensor data is the potential to use sensor measurements to infer water chemistry with a high temporal resolution that cannot be achieved through manual sampling approaches, or even with automatic sampler systems. However, the ability to estimate river water chemistry from sensor data depends on whether it is possible to establish robust predictive relationships between sensor data and measured water chemistry in manually collected samples.

We tested for relationships between sensor data and data from grab samples for two sets of variables:

1) ***'matching variables':*** including relationships between sensor-based pH, conductivity and turbidity measurements and values from laboratory analysis of manual samples (**Figure 9**);

2) ***'proxies':*** including relationships between sensor-based water quality data and other water chemistry variables, such as concentrations of dissolved, total and particulate organic carbon and nutrients, as well as selected major ions (**Figure 10**, **Figure 11**).

In addition to an exploratory correlation analysis across all measured sensor and water chemistry variables, we focused on testing for relationships that have been well-documented elsewhere in the literature (e.g. between FDOM and DOC/TOC, and between SPM and turbidity).

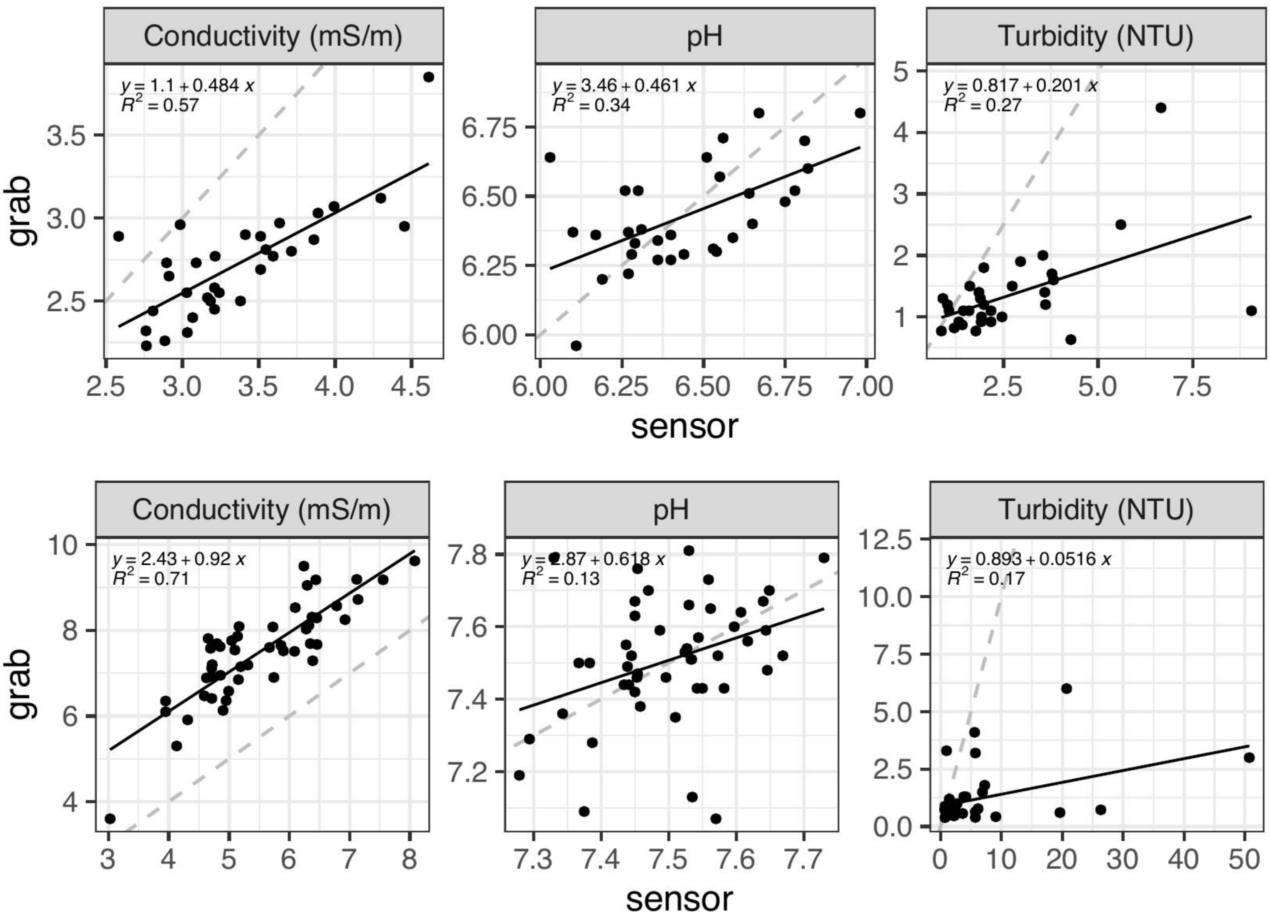

Figure 9. Relationships between in situ sensor measurements and discrete grab samples for *matching variables* for Storelva (top) and Målselva (bottom). The gray dashed line denotes a 1:1 relationship.

For 'matching variables', we generally found good agreement between *in situ* sensor-based and laboratory measurements of conductivity, with weaker relationships between sensor and lab-based values for pH (especially in Målselva) and turbidity (at both sites) (**Figure 9**). For pH, the lack of agreement is partially attributable to the stable pH in Målselva (typically remaining close to pH=7.5), since it is easier to obtain a strong relationship between manual and sensor-based measurements at sites that exhibit higher variability in relevant water chemistry variables (e.g. due to seasonal changes in water chemistry and/or strong responses to flooding/drought events). Regular maintenance and calibration of sensors is also particularly important for pH (which tends to experience more pronounced drift over time that e.g. conductivity sensors), which is particularly challenging in the high latitude Målselva system, where heavy snow and ice cover can often limit access to the sensor station during more than half of the year. Furthermore, pH is likely to be more sensitive to wait times between sample collection and analysis than conductivity, including during transport to the lab and storage while waiting for analysis, however this is likely to be a consistent bias related to sampling shipping and storage routines. For turbidity, the lack of agreement is not surprising, as various studies have shown that different turbidity measurement devices often disagree by a factor of two to five, depending on the nature of the sediment, and generally show curvilinear relationships that diverge more as turbidity increases (e.g. Lewis et al. 2007). Comparing turbidity across (field- or lab-based) sensors is therefore highly challenging, and it is more meaningful to focus on relationships with SPM, which tend to be much more consistent regardless of turbidity measurement device (Rymszewicz et al. 2017).

When exploring whether sensor data could be used as a 'proxy' for other water chemistry variables, we found that there were several water chemistry variables that were significantly correlated with sensor data. Although temperature was correlated with many water chemistry variables for both rivers, this is likely primarily a reflection of co-occurring seasonal changes in temperature and water chemistry, rather than a direct impact of temperature on water chemistry. Sensor-based conductivity was positively related to Ca^{2+} in both rivers and with pH in Målselva, while in Storelva, sensor-based pH and Ca^{2+} were positively correlated.

Sensor-based turbidity was positively correlated with SPM, PartC, PartN, and TP in Storelva, while in Målselva turbidity was positively correlated with pH and negatively correlated with NO_3 (at a 1% significance level). The turbidity-SPM correlation in Målselva was significant at a 5% significance level, but not at 1% (contrary to our expectations) (**Figure 10**, **Figure 11**). The lack of strong correlation between turbidity and SPM in Målselva is likely a reflection of high variability in the SPM/turbidity relationship, particularly at high turbidity values. This variability can in part reflect strong seasonal and event-scale changes in particulate matter properties (e.g. particle size, geochemical composition) due to shifts in sources and mobilization of particulate matter from different parts of this large and heterogeneous catchment with lowlands, forests and unvegetated mountainous regions that differ strongly in their geology and soil properties. It may also be in part due to local-scale turbulence and sediment accumulation in the pipe where sensors are directly deployed in the river, in contrast to the water intake system used in Storelva (technical details for sensor infrastructure in Appendix A). Air bubbles may also contribute to sensor-based turbidity measurements in Målselva, either due to turbulence in the sensor pipe, or potentially the large Målselvfossen waterfall ~15 km upstream.

FDOM was positively related to several (often non-overlapping) variables in the two rivers, including DOC, TOC and SiO_2 (in both rivers); PO_4 (in Storelva), and TN and TP (in Målselva). FDOM was negatively related to pH in Storelva (**Figure 10**, **Figure 11**). As expected, organic C concentrations and FDOM were correlated, while other relationships observed may reflect co-occurring seasonality across a broad range of variables within the sites (e.g. with high OC and nutrient loads often co-occurring during periods of high flow).

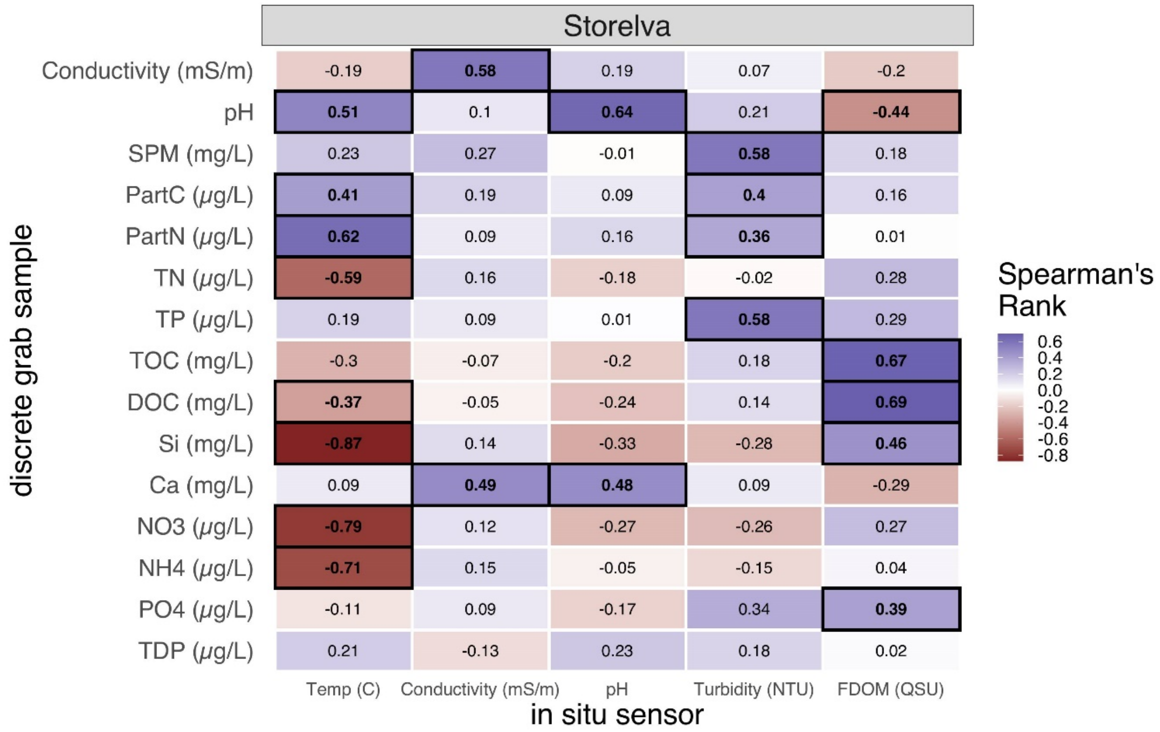

Figure 10. Spearman Rank correlations between sensor and grab samples for water chemistry variables based on all available years of data for Storelva (n=58 paired sensor and manual water samples). Bold outline shows where $p < 0.01$.

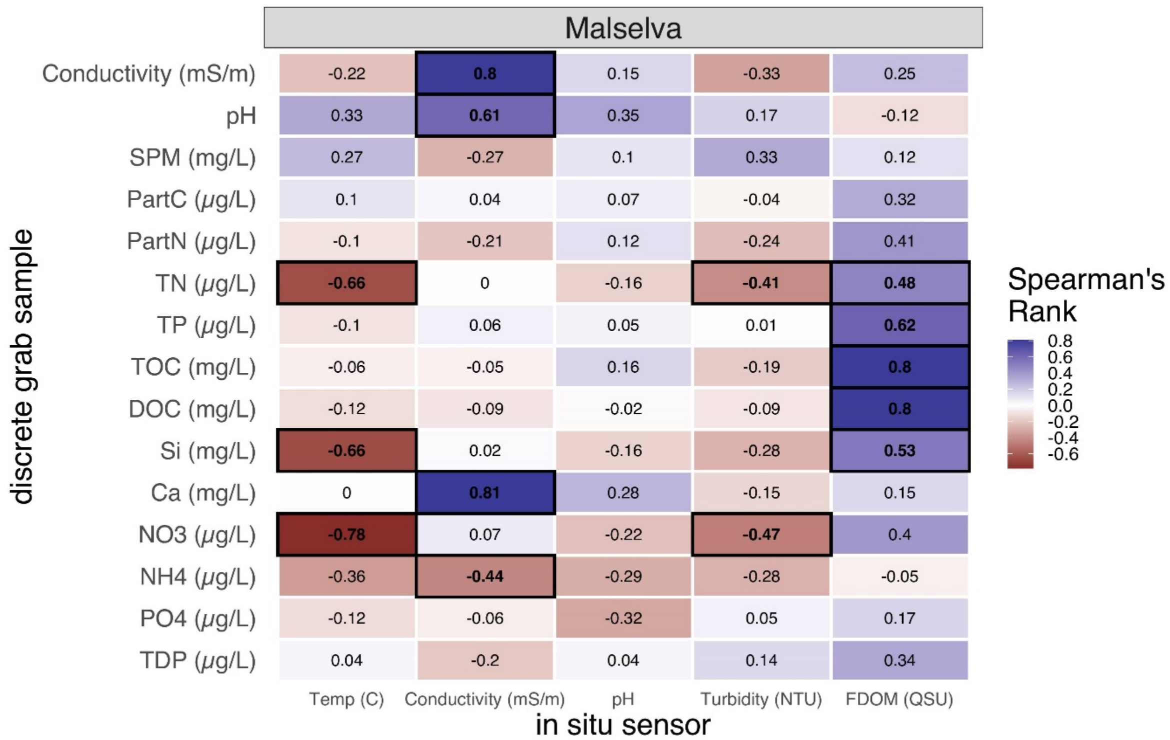

Figure 11. Spearman Rank correlations between sensor and grab samples for water chemistry variables based on all available years of data for Målselva (n = 50 paired sensor and manual water samples). Bold outline shows where $p < 0.01$.

While these results point to the potential for sensor-based monitoring to yield insight into a broad range of water chemistry variables, a high degree of variability in the relationships (likely including variability related to seasonal changes in the direction and strength of these relationships) paired with a lack of clear mechanistic explanations for some of the observed relationships suggests that weaker correlations without plausible causal relationships should be treated with caution. Further work would also include an assessment of seasonal differences in relationships between sensor data and measured water chemistry, both to improve our ability to use sensor data to infer river water chemistry, as well as to gain insight into between-season differences in drivers of water chemistry in these rivers.

Given the expected relationships between sensor-based turbidity and SPM concentrations and FDOM values and DOC concentrations, and the significant correlations observed between these variables (with the exception of turbidity in Målselv), we tested for linear relationships between sensor data and measured water chemistry for these variable pairs (**Figure 12**). The aim was to develop empirical relationships that would allow sensor data to be used as a proxy for SPM concentrations (turbidity) and DOC concentrations (FDOM).

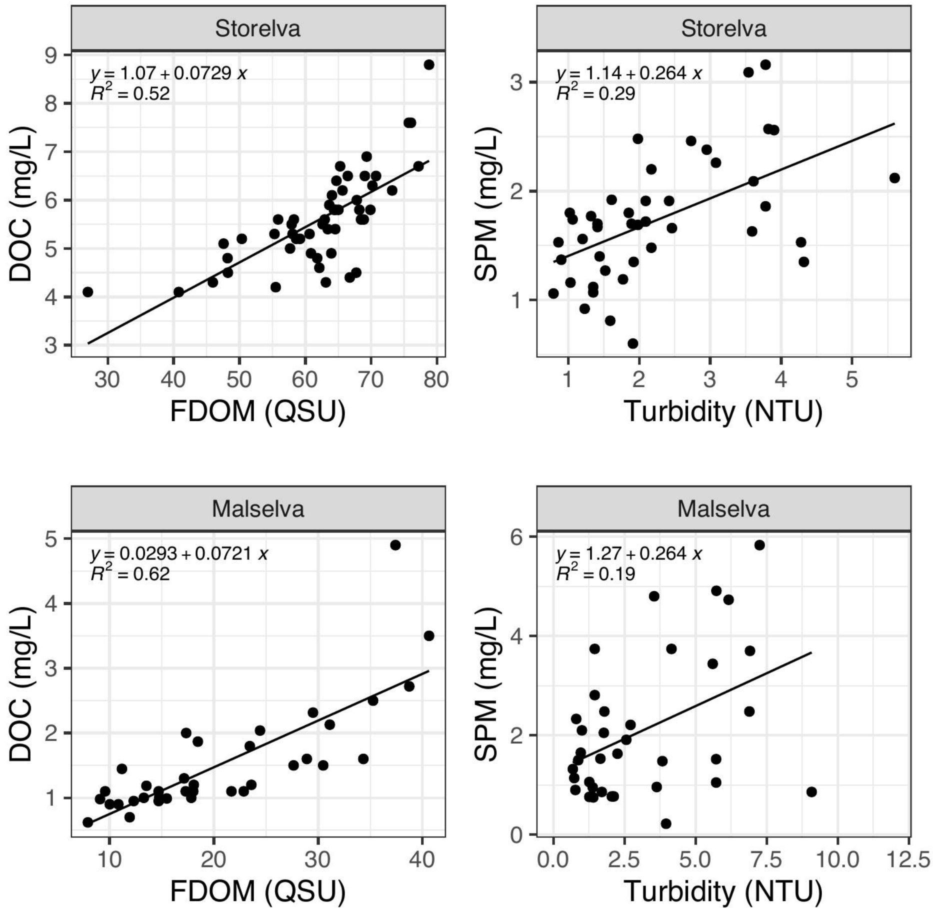

Figure 12. Relationships between *in situ* sensor-based measurements and discrete grab samples for DOC vs. FDOM and SPM vs. turbidity in Storelva (top left and right, respectively), and Målselva (bottom left and right, respectively). Regressions include all available paired data. Results of linear regression are shown in the figures. All regressions were significant ($p < 0.001$) except for SPM vs. turbidity relationship in Målselva ($p = 0.42$).

While for Storelva, the relationship between DOC and FDOM was relatively consistent across seasons, in Målselva, samples collected during spring snowmelt (May and June) tended to have high DOC concentrations for a given FDOM value compared to samples collected during other times of the year (**Figure 13**). This may in part reflect seasonal changes in DOM absorption properties in high latitude rivers, with fresher (and less humic) DOM transported from the litter layer and surface soils during early snowmelt, where frozen soils restrict flow pathways to the snow-soil interface, with an increase in humic-rich soil-derived OM during high flow events later in the season (Kaiser et al. 2017). However, it should also be noted that FDOM signals can be attenuated by particulate matter, with underestimation of FDOM where particle loads are high (Downing et al. 2012; Saraceno et al. 2017). This suggests that elevated turbidity in Målselva during spring snowmelt peaks could lead to underestimation of DOC based on FDOM. This highlights the need for more detailed follow-up work to generate site-specific turbidity-based correction factors for this site (e.g. as described in Saraceno et al. 2017). Based on Downing et al. (2012), a turbidity of 50 FNU could result in a 10% attenuation of FDOM, while turbidity between 100–250 FNU could result in 20–40% attenuation. Given the strong apparent seasonality in the DOC-FDOM relationship in Målselva, we also carried out independent linear regressions for samples collected during freshet (May/June, including higher frequency samples collected in 2019) and those collected during the remainder of the year and found a much steeper regression slope during freshet (**Figure 13**).

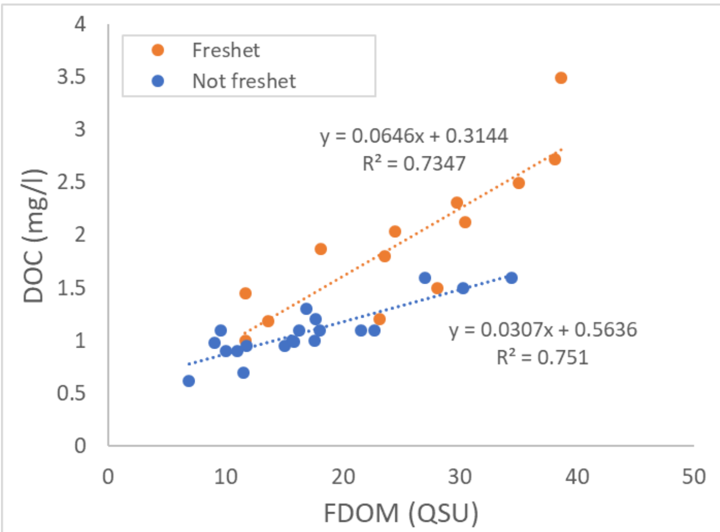

Figure 13. Contrasting relationships between DOC and FDOM in Målselva for the snowmelt period (defined as May and June) and non-snowmelt periods (remainder of year).

3.4 Comparing flux estimates based on *in situ* sensor data with those derived from grab sampling

To assess potential differences between flux estimates relying on traditional monthly sampling and sensor-based estimates, we generated time series of daily fluxes of DOC and SPM for both rivers. The turbidity-SPM regression in Målselva was not significant (Section 3.3), so sensor-based SPM fluxes for Målselva should be treated as indicative only, highlighting both the potential for sensor-based fluxes to provide more detailed flux estimates, and yet also the vulnerability of sensor-based estimates to the strength of the underlying regressions.

Daily fluxes were calculated by multiplying daily mean discharge by an estimate of daily mean concentration. Daily mean concentration was calculated using two methods (see section 2.4 for additional details regarding these approaches), with two variants on method 2 at Målselva:

1) **Sensor-based: Using linear regressions between grab samples and in situ sensor measurements**, as presented in section 3.3 (FDOM for DOC and turbidity for SPM). If reliable regressions can be obtained, then this method has the power to produce the most accurate flux estimates by capturing variability in concentrations at high temporal resolution. However, this method is only as good as the underlying regressions.

2a) **Interpolation-based: Interpolation of monthly grab sample concentrations**. This is the simplest approach, which is commonly applied. To produce accurate flux estimates, this approach requires that the sampling strategy captures major flow events. As this is generally not the case with uniform (e.g. monthly) regular sampling, we would generally expect this kind of flux estimation method to *underestimate fluxes when positive QC relationships are present, and overestimate fluxes when negative QC relationships are present.*

2b) **Interpolation-based (extra samples): Interpolation of grab samples including higher sampling frequency during spring snowmelt in Målselva**. At Målselva, targeted higher-frequency sampling campaigns were carried out in 2019 (for DOC and SPM) and 2020 (only SPM data available). This additional sampling is not typical for routine monitoring, and so was included as a separate flux estimate to method 2a and should result in more robust flux estimates than method 2a.

In addition, annual fluxes were calculated using the OSPAR method (see Section 2.4 for details). Note that CQ relationships can also be used to calculate fluxes from relatively low-frequency grab sampling data, provided there are strong linear CQ relationships in the data, but here we chose to focus on the most widespread simple method used (linear interpolation), as well as the method used in OSPAR reporting of annual fluxes.

3.4.1 Storelva

Estimated daily concentrations and fluxes of DOC and SPM for Storelva are shown in **Figure 14** and **Figure 15**, respectively. For DOC, whilst the interpolation-based estimate of daily DOC concentration is coarse, it follows similar patterns to the FDOM-derived estimate, resulting in similar daily flux estimates between methods. For SPM, the interpolation-based concentration misses most of the peaks, although these tend to occur when discharge is low, meaning that the daily flux estimates are similar, though generally a little lower using the interpolation method.

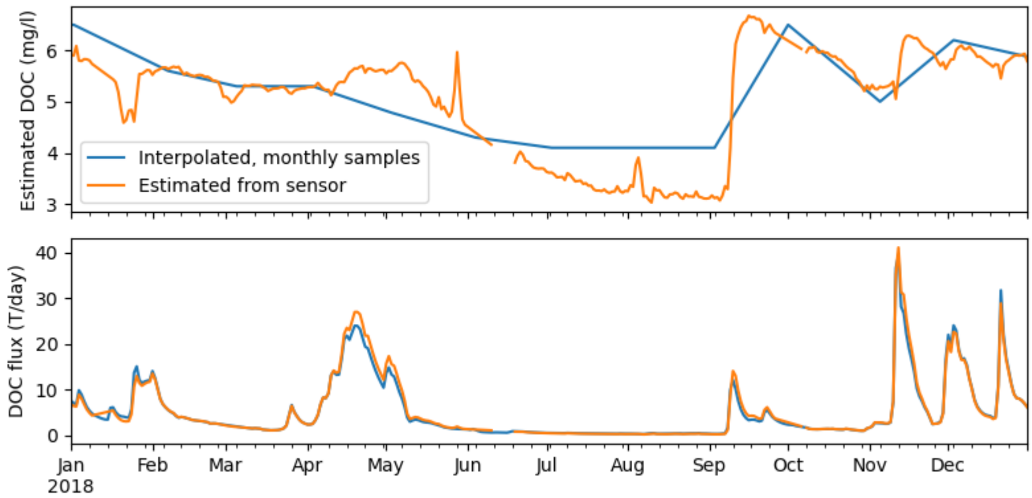

Figure 14. Estimated daily DOC concentrations (top) and fluxes (bottom) in Storelva for an example year (2018).

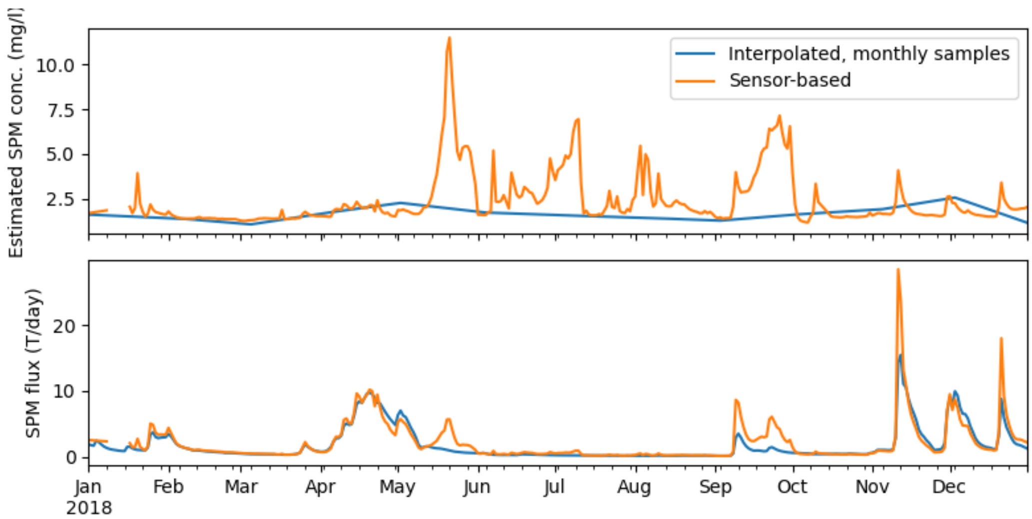

Figure 15. Estimated daily SPM concentrations (top) and fluxes (bottom) in Storelva for an example year (2018).

Comparing monthly (**Figure 16**) and annual (

Figure 17, **Table 3**) fluxes in Storelva over all years we see a similar story, with relatively small (<20%) and inconsistent differences between DOC fluxes derived between the two methods, depending on when the grab sample happened to be taken. The difference between SPM flux estimates was larger between methods (**Figure 16**), and very much dependent on errors introduced by the coarse linear interpolation of the grab samples. These errors sometimes lead to interpolation-based fluxes underestimating compared to the sensor-based fluxes (e.g. by 26% in 2019), and other times overestimating (e.g. by 23% in 2021). Annual DOC and SPM fluxes calculated using the OSPAR method were somewhat larger in 2017 (especially for SPM), but otherwise similar (

Figure 17).

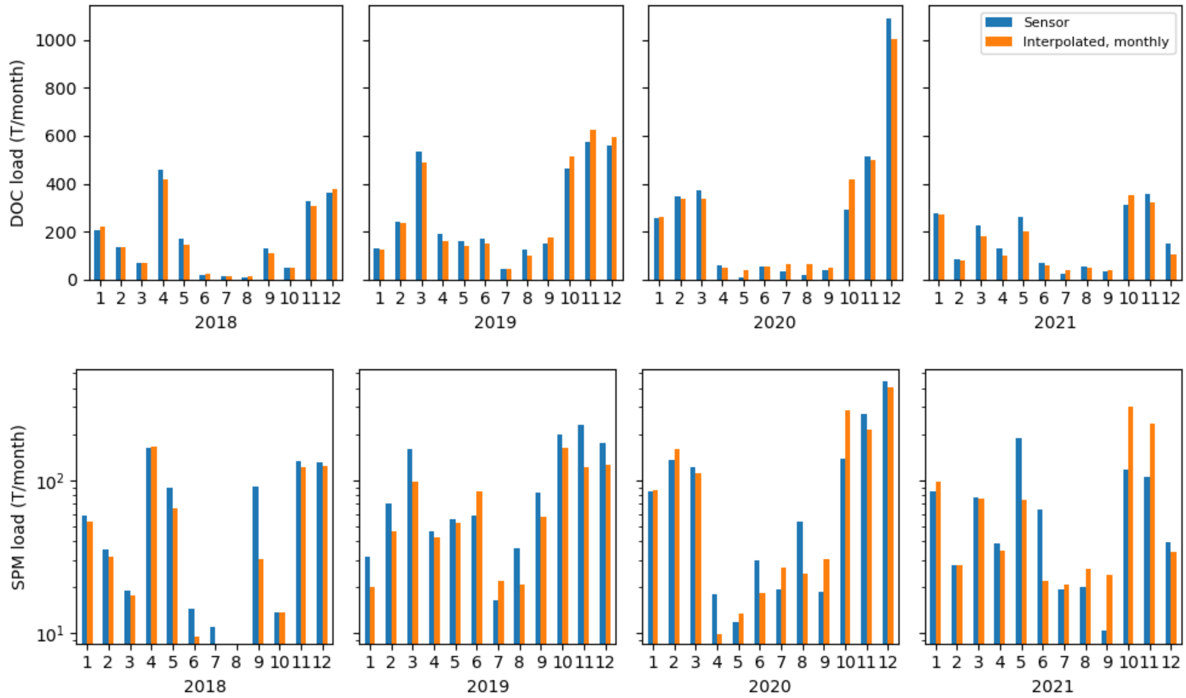

Figure 16. Monthly fluxes of DOC and SPM (tonnes/month) in Storelva, derived using the two methods.

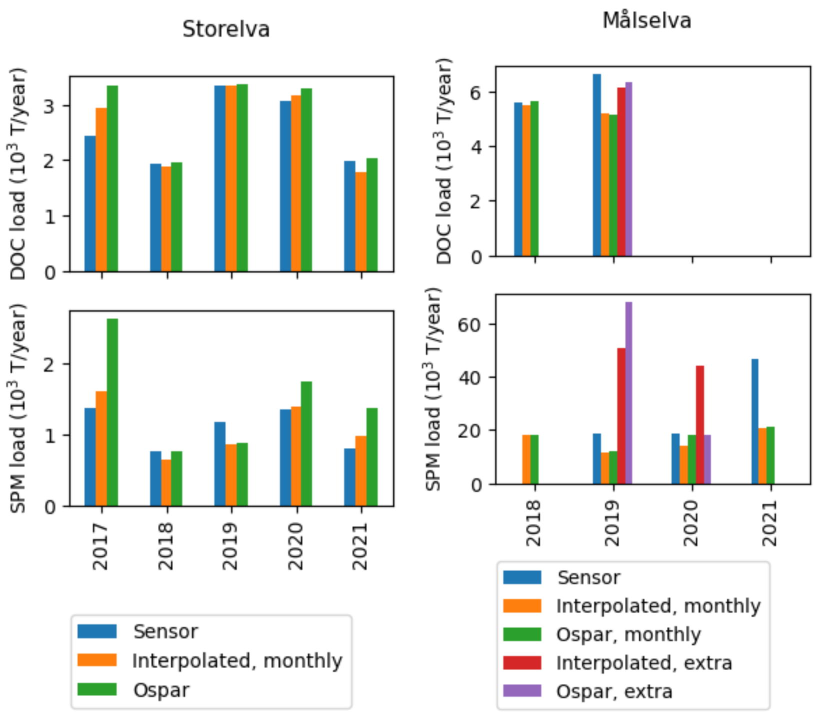

Figure 17. Estimated annual fluxes of DOC and SPM in Storelva (left) and Målselva (right)

Table 3. Annual flux estimates (10^3 tonnes) of DOC and SPM in Storelva and Målselva, and in Målselva split into freshet (May and June) versus non-freshet periods. Annual fluxes are highlighted in grey.

Var	Method	Period	Storelva					Målselva			
			2017	2018	2019	2020	2021	2018	2019	2020	2021
DOC	Sensor	Freshet						3.10	4.07	4.21	
		Not freshet						2.50	2.55		
		Annual	2.44	1.94	3.34	3.08	1.97	5.60	6.63		
	Interpolation (monthly)	Freshet						2.87	2.85		
		Not freshet						2.64	2.35		
		Annual	2.93	1.88	3.35	3.17	1.79	5.51	5.21		
	Interpolation (extra)	Freshet							3.80		
		Not freshet							2.35		
		Annual							6.15		
	Ospar (monthly)	Annual	3.35	1.95	3.37	3.31	2.03	5.63	5.17		
	Ospar (extra)	Annual							6.33		
SPM	Sensor	Freshet							13.5	11.2	30.7
		Not freshet							5.16	7.44	16.0
		Annual	1.36	0.77	1.16	1.34	0.79		18.6	18.7	46.7
	Interpolation (monthly)	Freshet						13.9	6.97	4.98	13.1
		Not freshet						4.37	4.60	9.18	7.59
		Annual	1.61	0.64	0.86	1.38	0.97	18.3	11.6	14.2	20.7
	Interpolation (extra)	Freshet							46.3	35.8	
		Not freshet							4.60	8.33	
		Annual							50.9	44.1	
	Ospar (monthly)	Annual	2.62	0.75	0.87	1.75	1.36		67.9	18.0	
	Ospar (extra)	Annual						18.0	11.9	18.0	21.0

Overall, for Storelva, the sensor-based flux estimates are likely to be slightly more robust than the interpolation-based estimates, due to the infrequent manual sampling not capturing variability in concentrations. However, Storelva generally shows relatively low variability in FDOM-derived concentration over time and the turbidity variation, although more than the FDOM, is also not great. This may be because of the presence of a large lake (Vegår) upstream of the monitoring point, which buffers the hydrological and chemical variability in the river. It therefore means that the sensor data provides only small improvements on the flux estimates derived using traditional sampling.

3.4.2 Målselva

Estimated daily concentrations and fluxes of DOC and SPM for Målselva for an example period (spring snowmelt 2019) are shown in **Figure 18** and **Figure 19**, respectively. For both variables, the sensor-based estimate captures all the flow events. Estimates based on linear interpolation were reasonable when grab sampling frequency was high, but at regular monthly sampling intervals almost all of the high flow events were missed. In 2018 by contrast (data not shown), the monthly sampling happened to capture a high DOC concentration in May, leading to an overestimation of daily fluxes throughout April-June.

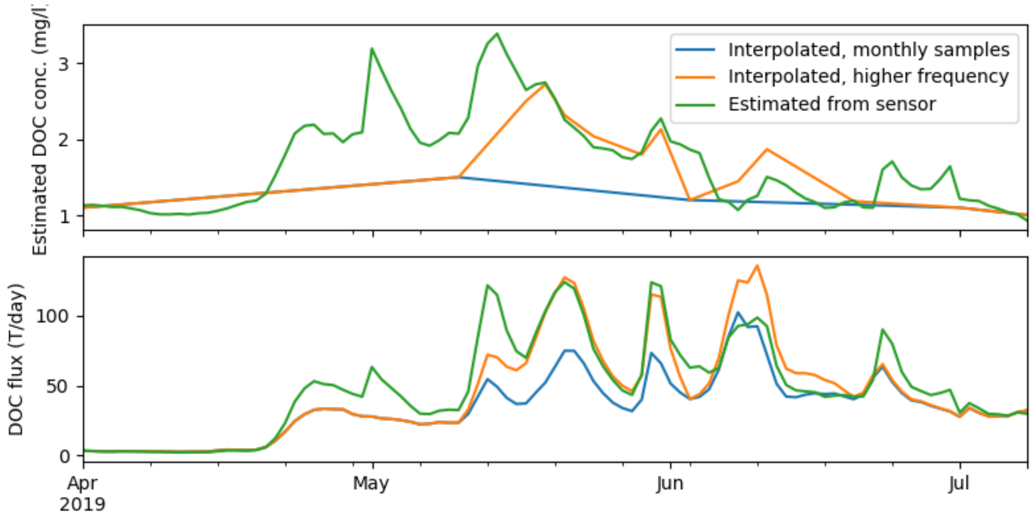

Figure 18. Estimated daily DOC concentrations (top) and fluxes (bottom) in Målselva during spring snowmelt 2019.

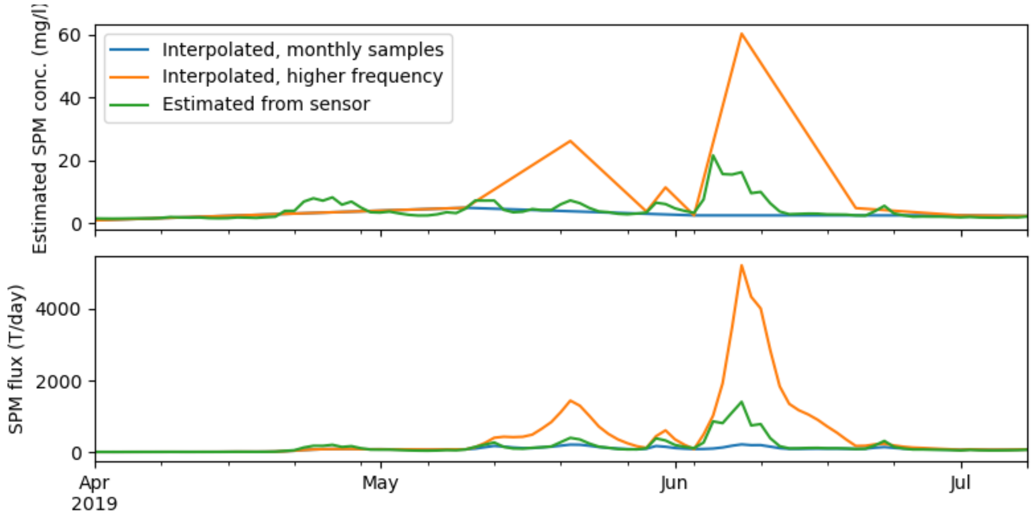

Figure 19. Estimated daily SPM concentrations (top) and fluxes (bottom) in Målselva during spring snowmelt 2019.

Monthly DOC flux estimates are shown in **Figure 20**, where we see that sensor-based estimates, and estimates based on using extra higher-frequency grab samples, provide the highest values during the snowmelt season (aside from during May 2018, as mentioned above). Outside this snowmelt period, water chemistry and discharge are less variable, and so the two methods provide more comparable estimates. Monthly SPM flux estimates (**Figure 20**) in general follow the same pattern: sensor-derived flux estimates are higher, as are estimates using the higher frequency grab samples. The main difference to DOC is that this pattern is sometimes seen outside the snowmelt season, notably throughout much of 2021. The observed between-year differences in the monthly distribution of estimated fluxes also reflect how differences in seasonal patterns (e.g. timing and size of spring snowmelt, or prevalence of summer/autumn rainfall events and mid-winter thaw events) can impact fluxes, giving important insight into how future climate change-driven shifts in seasonal events could impact both total fluxes and timing of DOC and SPM fluxes to the coastal environment.

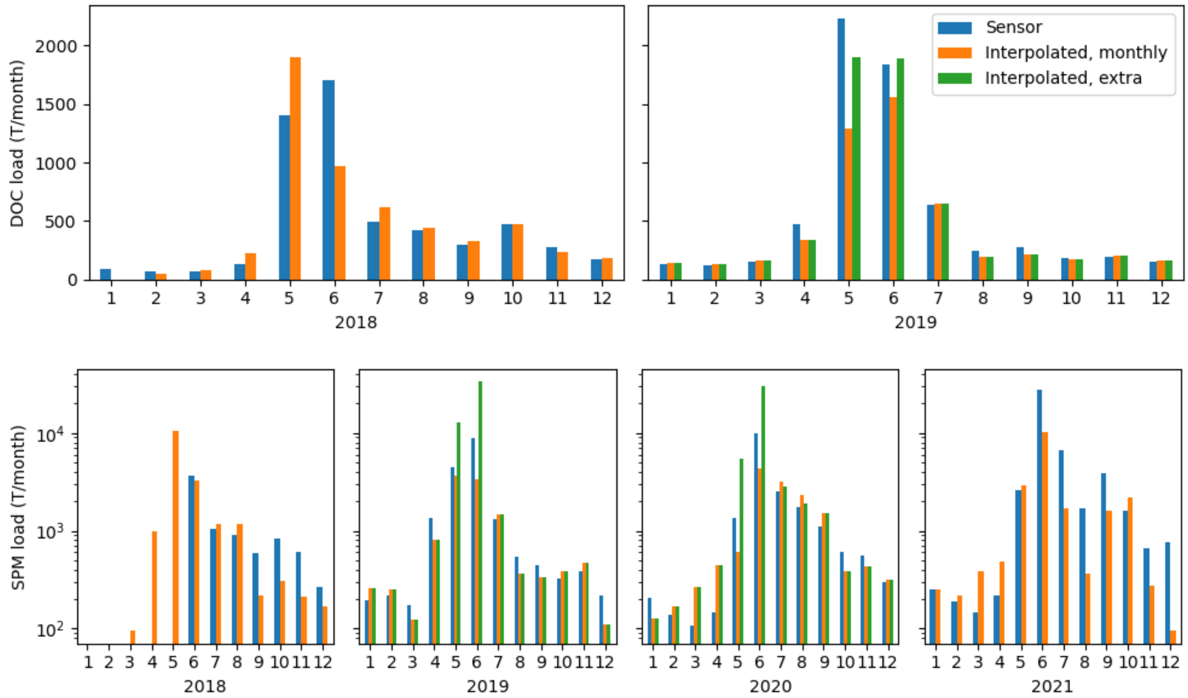

Figure 20. Monthly fluxes of DOC and SPM (tonnes/month) in Målselva, derived using the three methods. N.B. turbidity was only measured from mid-2018.

The linear interpolation-based annual DOC flux was 20% lower than the sensor-based flux in 2019 but only 1% lower in 2018 (**Table 3**). However, differences in freshet flux estimates between methods were more substantial (7% in 2018, 30% in 2019), as freshet fluxes made up around 60% of the total annual DOC flux (**Table 3**). These errors are substantial, and of potential significance given the importance of DOC fluxes on marine ecosystems (e.g. for the spring phytoplankton bloom).

3.4.3 Sensors as a tool for estimating fluxes

Overall, sensors captured changes in concentration during high flow events, which were often either missed by routine monthly sampling, leading to underestimate of fluxes compared to sensor-based methods, or else captured, leading to over-estimation. Overall, sensor-derived fluxes appeared to be more robust compared to interpolation-based methods using monthly samples. This was particularly the case for Målselva during the spring snow melt season. However, a stratified sampling approach, whereby manual sampling occurs more frequently during high flow events, resulted in similar flux estimates in Målselva to sensor-based estimates, and is likely a more robust method for estimating SPM flux wherever the relationship between turbidity and SPM is weak (Section 3.3). More generally, the value of high-frequency sensor data for providing accurate flux estimates depends on: (1) the nature of the CQ relationship (e.g. in systems where there is a strong increase in concentration with discharge, it becomes particularly important to capture concentrations during high flow events, when fluxes are highest), and (2) what timescales discharge and concentration vary over relative to the grab sampling frequency. For example, in flashy systems where high flow events typically only last a day or two, monthly or even weekly sampling will not capture changing concentration over these events, and sensors become crucial. This was the case in Målselva during spring freshet and is often the case when studying sediment transport in smaller catchments. Meanwhile, in slow-responding systems (e.g. where flow is buffered by a large groundwater input or the presence of a large lake upstream), then both discharge and concentration may vary more slowly, meaning variability is reasonably well-captured by routine monitoring programmes. This was largely the case in Storelva.

4 Lessons, suggestions and future perspectives

4.1 Lessons from the current study

There is increasing interest in the potential for sensor-based monitoring approaches to be used for understanding climate change impacts on aquatic systems, with a focus on how water quality responds to long-term and seasonal changes in climate, hydrology and land-cover as well as to extreme climate and weather events (e.g. droughts and floods). These new possibilities have led to the establishment of new sensor-based monitoring stations as part of national river monitoring programmes in Norway. The current report aimed to compile and analyze existing data from the two sensor stations in the Norwegian River Monitoring Programme where the longest time series are available (Storelva and Målselva; both operated by NIVA prior to inclusion in the monitoring programme).

By combining *in situ* sensor-based water quality measurements with data on climate and hydrology (river discharge), we observed strong between-site differences (including a higher degree of seasonality in the snowmelt-dominated subarctic Målselva system), broad-scale seasonal patterns in water quality and response to high flow events, as well as a high degree of interannual variability. In particular, when high frequency sensor data for turbidity (as a proxy for SPM) and FDOM (as a proxy for DOC) were combined with discharge (e.g. in C-Q plots) it was possible to gain a more nuanced understanding of how hydroclimatic conditions interact with landscape controls on mobilization and downstream transport of SPM and DOM (as well as particle and OM-associated elements). Furthermore, our preliminary analysis of water quality dynamics over successive high flow events during spring freshet highlights the potential for sensor data to provide insight into potential source-depletion and/or distant vs. proximal sources of both SPM and DOM. This could in turn be combined with higher resolution catchment-scale data on for example snow cover and melt events in order to explore changing contributions from parts of the catchment that differ in their vegetation cover, soil properties as well as geology.

Based on linear regression, FDOM was a robust proxy for DOC concentrations in both study rivers. Meanwhile turbidity was positively related to SPM in both rivers, although with weaker explanatory power and higher variability in Målselva. Here we also observed seasonal differences in the DOC-FDOM relationship, with higher-than-expected DOC concentrations during the snowmelt period. Building on these relationships, we compared sensor-inferred flux estimates (over event, monthly and annual time scales) for SPM and DOC with estimates derived from traditional linear interpolation. Results showed the value of sensor-derived flux estimates was particularly high during periods of high flow variability in concentrations and discharge, which are typically not captured by traditional sampling. This can lead to over-estimation of fluxes, but typically under-estimation is more common, and can be substantial (e.g. traditional flux estimates underestimated the Målselva spring freshet DOC flux by up to 30%).

4.2 Challenges and suggestions for future opportunities

The current study also revealed some challenges and opportunities related to ongoing and potential future sensor-based monitoring in the Norwegian River Monitoring Programme (and other relevant monitoring programmes). In particular, we highlight the following challenges and future opportunities:

1) *Increased frequency of water sample collection for lab analysis during the first 1-2 years of operation*. In order to use sensor data to infer water chemistry (and fluxes), there is a critical need for sufficient match-up data to develop robust site-specific relationships between water

chemistry and sensor data, ideally with high enough seasonal coverage to assess whether there is a need for seasonally-resolved relationships in order to accurately infer water chemistry and fluxes from sensor data. Increased sampling frequency could be achieved through a combination of manual sampling and potential deployment of an automatic water sampling system. Automatic sampling would be particularly relevant during snowmelt and other periods of high flow where capturing dynamic water chemistry across a series of flow peaks could improve our ability to estimate concentrations and fluxes during periods of high flow. Such sampling efforts could also target additional variables of interest where we expect potential relationships with sensor data (e.g. Hg is likely to be closely related to FDOM, given its tight coupling to organic matter transport and cycling in the aquatic environment).

2) *Robust site-specific data correction approaches.* Alongside higher frequency manual (and potentially automatic) sampling to improve sensor vs. grab sample relationships, additional samples should be collected in order to develop site-specific correction factors for e.g. attenuation of FDOM by turbidity (e.g. as described in Saraceno et al. 2017).

3) *Regular maintenance and calibration of sensors.* Regular maintenance and calibration of sensors, both in the field and through factory calibration, are important for avoiding drift in sensor measurements and limiting challenges related to sediment accumulation or biofilm growth on sensors. However, it should be noted that conditions in northern rivers can be demanding, with opportunities for maintenance sometimes limited by long periods of ice cover and high flow, and sometimes requiring creative solutions. Alongside regular maintenance, robust quality assurance routines for incoming data are also an important tool for ensuring that the data being collected are robust and to be able to respond quickly to technical problems at the stations.

4) *Where possible, continue to co-locate sensors with existing hydrologic monitoring stations.* There is a strong potential to couple sensor-based water quality monitoring infrastructure to NVE's broad-scale network of hydrologic monitoring stations (as is the case for three of the four sensor stations included in the Norwegian River Monitoring Programme). The co-location of hydrologic and water quality monitoring stations has the potential to provide a unique distributed platform for studying impacts of climate change on water quality and riverine fluxes. For sites where it is not possible to co-locate sensor stations with discharge monitoring stations, efforts should be made to ensure availability of robust flow data, through monitoring and/or modelling approaches.

5) *Test the potential utility of additional sensors.* There are many sensors available on the market that may be relevant for the Norwegian River Monitoring Programme (and other relevant programmes), which could be deployed over a shorter test-period to evaluate the utility of the sensor. For example, given the strong focus on land-ocean nutrient fluxes in the Norwegian River Monitoring Programme, a test deployment of a nitrate sensor (Burns et al. 2019) could take advantage of extensive existing data from long-term monitoring, and could provide relevant insight into availability and transport of nitrate and the implications for downstream ecosystems (including freshwater and coastal primary producers). Meanwhile, a UV-VIS sensor (Zhu et al. 2021) could provide information on absorption properties of riverine DOM. While FDOM is mainly a proxy for DOM quantity, the absorbance spectrum gives information on both DOM quantity and quality, and as such can provide insight into the bioavailability of riverine DOM for uptake into freshwater and coastal microbial food webs.

6) *Consider additional sensor stations in rivers, as well as at upstream (tributaries, lakes) and downstream coastal sites*. By increasing the number of sensor-based monitoring stations to capture broader ranges in latitude, climate, hydrology and catchment land-use could provide unique opportunities to understand common drivers and contrasting dynamics across a diversity of systems. Furthermore, by considering pairing sensor stations in rivers with sensor-based monitoring of a common set of variables both upstream and downstream will provide important insight into how climate change impacts can cascade across ecosystem boundaries and how upstream processes can shape downstream freshwater and coastal ecosystem structure and function (e.g. in response to a flood or a drought).

4.3 Conclusion and future perspectives

The results of the current study highlight both opportunities and challenges related to sensor-based monitoring in northern river systems. Sensor data provided a unique opportunity to study water quality responses to seasonal and event-scale variability, as well as interannual differences in hydroclimatic conditions. In particular, sensor data provided insight into: 1) between-season differences in stability/variability of water chemistry (by capturing a broader range of hydrologic conditions than typically captured through monthly sampling); 2) differences in the responses of sensor-derived water quality to high flow conditions, between sensor variables, between rivers, and between seasons; 3) nuanced insight into concentration dynamics *within* high flow events as well as across subsequent high flow events. Improving our understanding of these processes is crucial for improved management of sensitive downstream freshwater and coastal ecosystems, as well to predicting how freshwaters will change in the future.

Climate change is leading to long-term changes in the amount and seasonal distribution of runoff in northern catchments, including changes in the magnitude and timing of spring snowmelt and increased frequency of extreme climate and weather events, such as droughts or floods. In particular, high flow events (including during spring snowmelt) can contribute substantially to total annual element fluxes. However, despite the importance of these events for understanding mobilization, transport and potential downstream ecological effects of catchment-derived particulate and dissolved material, it is highly challenging to capture these high flow events based on routine (e.g. monthly) monitoring. In the marine environment, a shift toward earlier spring snowmelt could lead to increased overlap between the coastal spring phytoplankton bloom and the delivery of freshwater and light-attenuating particles and dissolved organic matter to the coastal environment, which could lead to light limitation of photosynthesis during a key time-period for production that is critical in supporting coastal food webs (Frigstad et al. 2020).

To meet these challenges, *in situ* sensor-based monitoring is emerging as a promising approach for understanding links between hydrology, climate and water quality over a range temporal scales that can capture interannual variability, seasonal patterns, water quality responses to high flow events and droughts, and even within-event dynamics. An increasing number of commercially available sensors is also creating new opportunities for understanding in-stream dynamics of a broad range of water chemistry variables (O'Grady et al. 2021), and for pairing with discharge to infer riverine fluxes (e.g. of organic C, nutrients, SPM) with high temporal resolution. As outlined in Section 4.2, there are many challenges associated with sensor-based monitoring, including related to developing robust site-specific relationships and correction factors for linking sensor data to in-stream water chemistry, however most of these challenges can be overcome. Costs of sensors and associated infrastructure as well as costs associated with maintenance and operation can also be high, although are typically much lower than the costs of high frequency manual sampling and laboratory analysis. In summary, there is a high potential for using sensor-based monitoring approaches to build process-understanding related to water quality responses to climate and hydrology, including seasonality and extreme climate and weather events. In particular, nesting sensor-based monitoring approaches within existing long-term monitoring programmes provides a unique opportunity to build new knowledge about hydroclimatic drivers of water chemistry in the context of documented decadal climate and water quality trends.

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Appendix A. Technical details for sensor stations

Storelva sensor station:

This station has been operational since 2015. At this station, water is pumped from the river to a small utility shed where sensor-based measurements are made as water passes through the system.

Figure A1. Photo from the Storelva sensor station showing the utility shed where the sensors are located.

Loggers and sensors:

Logger:	Campbell CR1000X datalogger since June 2022, INTAB PC-logger before June 2022
Sensors:	
- Temperature	Amagruss EC-SSS-PT 100 termoelement
- Conductivity	Polymetron 9125 conductivity transmitter
- pH	Polymetron 9135 pH transmitter
- Turbidity	HF MicroTOL
- CDOM	TriOS microFlu-CDOM

Målselva sensor station:

This station has been operational since 2017. At this station, sensors are deployed directly in the river through a pipe. The pipe is anchored in place through burial in the riverbed along the river bank, while the far end of the pipe is exposed to the freely flowing river. There are large openings at the far end of the pipe where the sensors sit, allowing free passage of water and avoiding clogging while also providing protection for the sensors.

Figure A2. Photos from the Målselva sensor station showing the location of the sensor (near the old E6 bridge at Moen), location of the pipe through which sensors are deployed and the logger box.

Loggers and sensors:

Logger:	Campbell CR6 datalogger
Sensors:	
- Temperature	Sea-bird SBE 38 Digital Oceanographic Thermometer
- Conductivity	Ponsel C4E Conductivity sensor
- pH	Ponsel PHEHT: pH, redox, temperature sensor
- Turbidity	AML Tu Xchange turbidity sensor
- CDOM	TriOS microFlu-CDOM

Appendix B. Open data for sensor stations

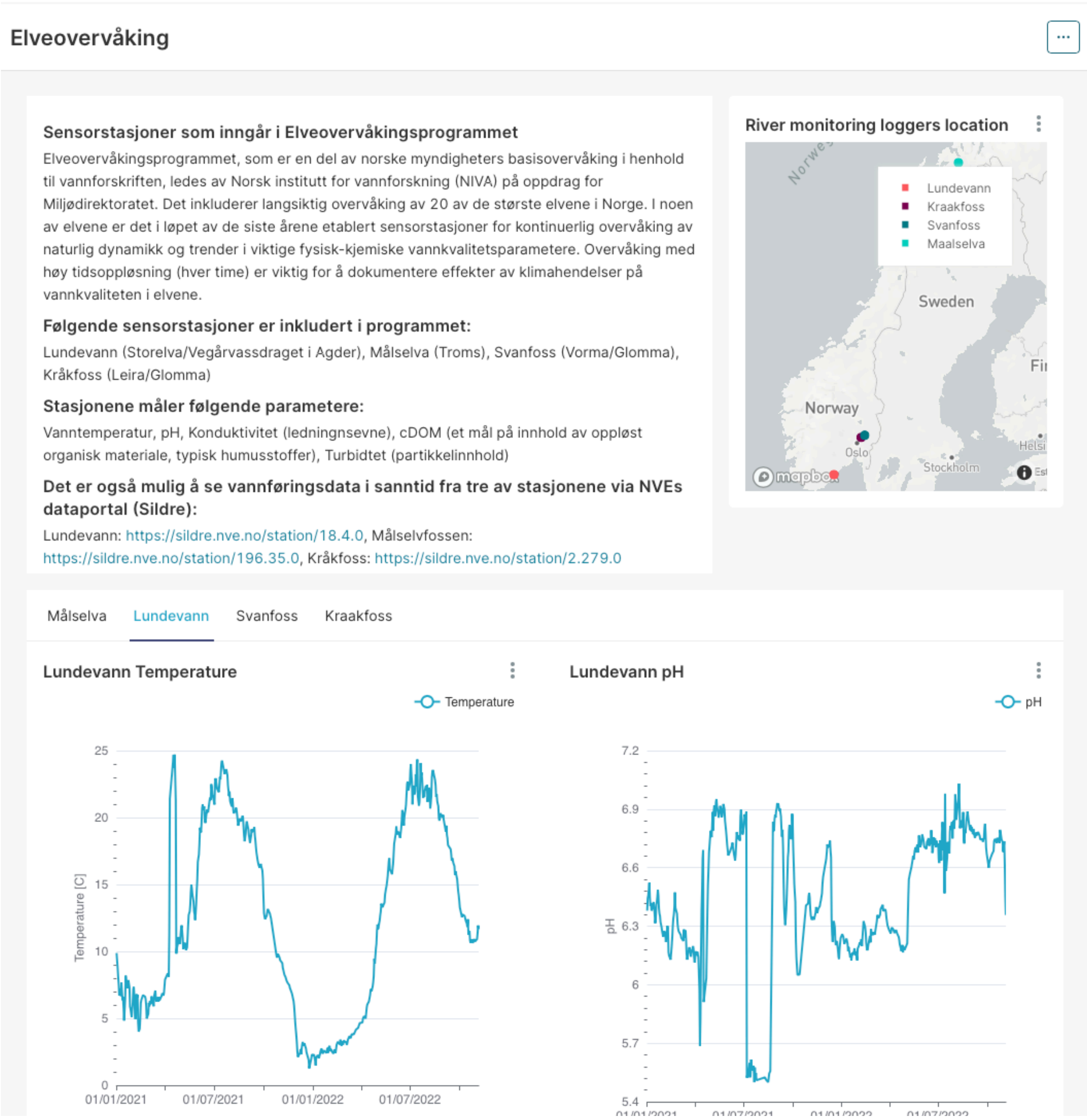

Figure B1. Data from all four sensor stations included in the Norwegian River Monitoring Programme are recorded on an hourly basis, transferred to NIVA's server and are openly available at the following link: [Elveovervåking (niva.no)](). Above is a screen-capture for the Storelva station (located at Lundevann), providing an example of how these data are presented in NIVA's openly available online portal.

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