Norwegian University of Life Sciences
Faculty of Environmental Sciences and
Natural Resource Management

Philosophiae Doctor (PhD)
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Impact of climate and agricultural management on hydrology and water quality. A headwater catchment scale approach

Effekt av klima og jordbruk på hydrologi og vannkvalitet. En studie av små jordbruksdominerte nedbørfelt

Hannah Tabea Wenng

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PhD Supervisors

Professor Tore Krogstad
Faculty of Environmental Sciences and Natural Resource Management
Norwegian University of Life Sciences
P.O. Box 5003
NO-1432 Ås, Norway

Dr. Marianne Bechmann
Division of Environment and Natural Resources
Soil and Land Use
Norwegian Institute of Bioeconomy Research
P.O. Box 115
NO-1431 Ås, Norway

Dr. Eva Skarbøvik
Division of Environment and Natural Resources
Hydrology and Water Environment
Norwegian Institute of Bioeconomy Research
P.O. Box 115
NO-1431 Ås, Norway

Assistant Professor Hannu Marttila
Department Water Resources and Environmental Engineering
University of Oulu
P.O. Box 4300
FI-90014 University of Oulu, Finland

PhD evaluation committee

Dr. Per-Erik Mellander
Teagasc
Johnstown Castle Environmental Research Centre
IE-Wexford. Y35 Y52, Ireland

Dr. Maria Lucia Kämäri
Finnish Environment Institute (SYKE)
Latokartanonkaari 11,
FI-00790 Helsinki, Finland

Coordinator of the committee

Professor Gunnhild Riise
Faculty of Environmental Science and Natural Resource Management
Norwegian University of Life Science
P.O. Box 5003
NO-1432 Ås, Norway

Für Hanna und Hans

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The first time when I thought to become a researcher, I was seven or eight years old. I wanted to study marine biology, get hired on a ship and study whales and the ocean. The next time when I wanted to become a researcher, I was around 20, I wanted to study ice, snow, and glaciers in the Alps, unfortunately I am a bad skier. And now? I do research in hydrology and water quality of surface water, at least the element water is a constant in my life. From time to time during my PhD I thought, I want to become an activist. A PhD is maybe not a drawback becoming an activist, but a logical step towards the right direction, when I think about all these inspiring people such as Jane Goodall, Vandana Shiva and Niko Paech who delivered material to read and listen to in my free time. On the journey towards a PhD, many people accompanied me, and I want to say thank you:

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Ås, 20th of August 2021

Hannah Wenng

SUMMARY

Eutrophication and degradation of water quality are global problems and affect many freshwater and coastal systems. Agricultural areas are major contributors of nutrients and soil particles in streams and lakes. The objectives of this study were to discuss the impacts on water quality and quantity of expected land use changes due to a transition to bioeconomy (the green shift) in Norwegian agricultural catchments; to detect trends in climate and hydrology; and to describe and understand catchment processes related to runoff, soil and nutrient losses.

The study has been carried out in seven Norwegian small headwater catchments and has included analyses of long-term data series (26 years) as well as collection of new data, in particular high-frequency sensor data on turbidity and water samples for a stable water isotope (^{18}O, ^{2}H) analysis. Moreover, data from a network of Nordic catchments (69 sites in total) have been included in the study. Analysis for the thesis was done using latest statistical and time series analytical methods.

Pressures on deterioration of water quality related to bioeconomy activities have been discussed based on data from 69 Nordic catchments. A green shift in Nordic agriculture might imply more intensive land use or clearing of new land. Our study showed that agricultural sites show the highest concentration and fluxes of total nitrogen and phosphorus compared to forestry-impacted and natural catchments. In addition, pressures from climate change (droughts and heavy rainfalls) and their combined effects can pose severe threats to water quality in Nordic regions.

The analysis for seven Norwegian catchments revealed changes in meteorological inputs and hydrological responses. The annual mean temperature increased significantly during 26 years of observations in six of the seven studied catchments. This increase in temperature affected evaporation, the hydrological regime, the snow water equivalent, nutrient concentration, and the length of the growing season.

In four of seven catchments the snow water equivalent decreased significantly during winter, and only one catchment showed an increase. The change in the snow regime affects the hydrology of the snow-dominated catchments (main runoff events due to snowmelt periods). Hydrological patterns varied between the seven catchments depending on whether they were located at the coast (rain-dominant) or inland (snow-dominant).

In the rain-dominated catchments precipitation and discharge showed a strong coherence. Snow-dominated catchments showed a weaker coherence, because precipitation as snow is not immediately available for discharge. Snow precipitation does not translate to

discharge until snowmelt occurs. Extreme conditions, as in 2010 (relative low average temperature) and 2018 (drought), seemed to decrease the coherence between runoff and variables such as precipitation, snow water equivalent, and soil water storage capacity in four of the catchments. Climatic and hydrological long-term changes could be best detected at the seasonal scale. Studied variables such as discharge, turbidity, field operations, crop factor, connectivity index, soil water storage capacity, and snow water equivalent showed a strong seasonality.

In our study we also considered factors which impact the concentrations and losses of nutrients and sediments. We found that a prolonged growing season coincided with a decrease in nitrogen concentrations in cereal dominated catchments. However, this change in growing season length did not affect the farmers' sowing time, nor did they harvest earlier, assumedly because soil moisture is in this case the determining factor for soil workability.

Nutrient and sediment losses were closely linked to hydrological processes in study catchments. Results from the multivariate regression of two monitored catchments showed that discharge is one of the main drivers for sediment and particulate phosphorus concentration (explained 50% of the variation in turbidity). For nitrogen, an increase in discharge gave a dilution effect.

High frequency turbidity sensor data revealed that the concentration-discharge patterns of runoff events were characterised by turbidity peaks before discharge peaks. This indicates a rapid mobilisation of suspended sediments and particulate phosphorus. Channel bed dynamics, including stream bank erosion and remobilisation of in-stream particles contribute to these patterns. A high-water discharge in a first storm event in general reduced the sediment transport in the following event, suggesting depletion of available in-stream/near-stream material. Detecting responses of agricultural management were challenging using sensor-data.

In general, detecting responses of agricultural land management on stream water quality and quantity at catchment scale proved to be challenging due to spatial variations in field management, topography, soil, hydrology, and vegetation. Therefore, it is important to continue monitoring programs, especially where long-term datasets exist. Responses of climate, hydrology and land management on water quality were different from catchment to catchment, which is why it is important to apply land management and mitigation measures adapted and tailored to the local conditions.

SAMMENDRAG

Eutrofiering og forringet vannkvalitet er globale problemer som påvirker mange ferskvanns- og kystsystemer. Jordbruk er en av de sektorene som bidrar mest med næringsstoffer og jordpartikler i bekker, elver og innsjøer. Hensikten med denne studien har vært å diskutere effekter på vannkvalitet og hydrologi som følge av en overgang til bioøkonomi (det grønne skiftet); å oppdage trender innen klima og hydrologi; og å beskrive og forstå nedbørfelt-prosesser knyttet til avrenning, tap av jord og næringsstoffer.

Studien har blitt utført i syv norske nedbørfelt og inkluderte analyser av lange dataserier (26 år) samt innsamling av nye data, spesielt høyfrekvente sensordata av turbiditet, og vannprøver for en stabil vannisotopanalyse (^{18}O, ^{2}H). Videre er data fra et nettverk av nordiske nedbørfelt (totalt 69 felt) inkludert i studien. Dataene ble analysert med forskjellige statistiske metoder: Mann-Kendall trendanalyse, lineær blandet modell, multivariat regresjon og en såkalt wavelet coherence analyse.

Utfordringer for vannkvalitet knyttet til innføring av bioøkonomi har blitt diskutert basert på data fra 69 nordiske nedbørfelt. Et grønt skifte kan innebære mer intensiv arealbruk eller rydding av nytt land for oppdyrking. Dataene viser at jordbruksbekker allerede i dag har de høyeste konsentrasjoner og tilførsler av totalnitrogen og fosfor sammenlignet med bekker i skogbruksområder og naturlige nedbørfelt. I tillegg kommer klimaendringer (tørke og store nedbørsmengder), og den kombinerte effekten kan være en alvorlig trussel mot vannkvaliteten.

Den årlige gjennomsnittstemperaturen økte betydelig i løpet av 26 års observasjoner i alle de syv undersøkte nedbørfeltene, bortsett fra ett. Denne temperaturøkningen påvirket fordampning, det hydrologiske regimet, snøvannets ekvivalent, næringsstoffkonsentrasjon og lengden på vekstsesongen.

I fire av sju nedbørfelt ble snøvanns-ekvivalenten betydelig redusert om vinteren, og bare ett nedbørfelt hadde en økning. Denne endringen i snøregimet påvirker hydrologien i snø-dominerte nedbørfelt, dvs. der avrenningsmønster er sterkt preget av snøsmelting. Hydrologiske mønstre varierte mellom de syv nedbørfeltene, avhengig av om det var regn- eller snø-dominert, noe som igjen hang sammen med geografisk plassering (innland eller kyst).

I regn-dominerte nedbørfelt var det en tydelig sammenheng mellom nedbør og avrenning. Snø-dominerte nedbørfeltfelt viste ikke en sterk sammenheng, fordi nedbør som snø først gir økt avrenning under snøsmelting. Ekstremår som i 2010 (relativ lav gjennomsnittstemperatur) og 2018 (tørke) så ut til å redusere sammenhengen mellom avrenning og variabler som nedbør, snøvanns-ekvivalent og lagringskapasitet i jord i fire av

nedbørfeltene. Klimatiske og hydrologiske langsiktige endringer kan best oppdages på sesongskalaen. Studerte variabler som avrenning, turbiditet, dyrkingspraksis, avlingsfaktor, konnektivitet, lagringskapasitet for jordvann og snøvannekvivalenter hadde en sterk sesongavhengighet.

En forlenget vekstsesong samvarierte med reduserte nitrogenkonsentrasjoner i korndominerte nedbørfelt. En endring i vekstsesongens lengde påvirket ikke bøndenes såtid eller høstetid, antagelig fordi jordfuktighet i dette tilfellet er den avgjørende faktoren for når jorda er laglig for bearbeiding.

Næringsstoff- og sedimenttap er nært knyttet til hydrologi. Resultatene fra den multivariate regresjonen viste at avrenningen er en av hovedårsakene for sediment- og partikkelbundet fosforkonsentrasjon (forklarte 50% av variasjonen i turbiditet). For nitrogen ga en økning i avrenning en fortynningseffekt.

Turbiditet-sensordata viste at turbiditet kulminerer før avrenningen. Dette indikerer en rask mobilisering av suspenderte sedimenter og partikkelbundet fosfor. Dynamikken i bekkene, som erosjon og remobilisering av partikler, samt størrelsen av tidligere avrenningsepisoder spilte også en viktig rolle for transport av sediment.

Det er utfordrende å finne sammenhenger mellom jordbruksaktivitet og vannkvalitet og hydrologi i nedbørfelt på grunn av romlige variasjoner i topografi, jord, hydrologi, driftspraksis og vegetasjon. Derfor er det viktig å fortsette med overvåkningsprogrammer, spesielt der det finnes lange dataserier. Responsene på vannkvalitet av klima, hydrologi og jordbruk var forskjellige fra nedbørfelt til nedbørfelt, og derfor er det viktig at arealforvaltning og tiltak er tilpasset lokale forhold.

LIST OF PAPERS

Paper I

Marttila H, Lepistö A, Tolvanen A, Bechmann M, Kyllmar K, Juutinen A, Wenng H, Skarbøvik E, Futter M, Kortelainen P, Rankinen K, Hellsten S, Kløve B, Kronvang B, Kaste Ø, Lyche Solheim A, Bhattacharjee J, Rakovic J, de Wit H (2020) Potential impacts of a future Nordic bioeconomy on surface water quality. Ambio 49 (11), 1722–1735.
Doi: 10.1007/s13280-020-01355-3

Paper II

De Wit H, Lepistö A, Marttila H, Wenng H, Bechmann M, Blicher-Mathiesen G, Eklöf K, Futter M, Kortelainen P, Kronvang B, Kyllmar K, Rakovic J (2020) Land-use dominates climate controls on nitrogen and phosphorus export from managed and natural Nordic headwater catchments. Hydrological Processes 34 (25), 4831-4850.
Doi: 10.1002/hyp.13939

Paper III

Wenng H, Bechmann M, Krogstad T, Skarbøvik E (2020) Climate effects on land management and stream nitrogen concentration in small agricultural catchments in Norway. Ambio 49 (11), 1747-1758.
Doi: 10.1007/s13280-020-01359-z

Paper IV

Wenng H, Barneveld R, Bechmann M, Marttila H, Krogstad T, Skarbøvik E (2021) Sediment transport dynamics in small agricultural catchments in a cold climate: A case study from Norway. Agriculture, Ecosystems and Environment 317.
Doi: 10.1016/j.agee.2021.107484

Paper V

Wenng H, Croghan D, Bechmann M, Marttila H (2021): Hydrology under change? Long-term and seasonal changes in small agricultural catchment in Norway [*under revision*]

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SYNOPSIS

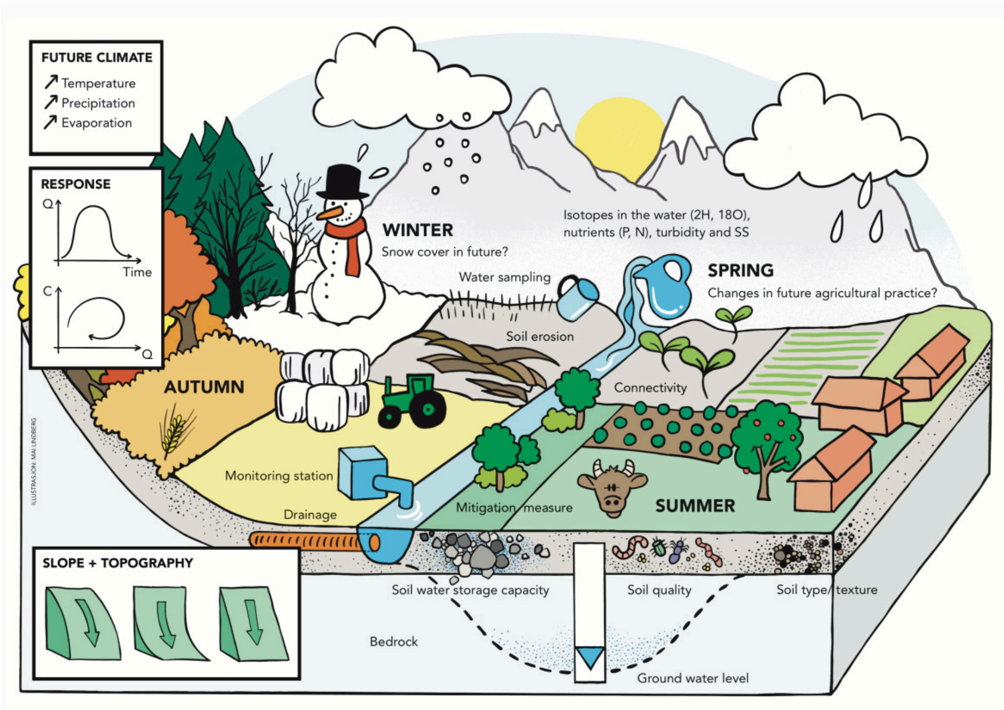

Figure 1: Catchment scale processes and their drivers during different seasons

1. INTRODUCTION

Eutrophication and bad ecological status is a global problem affecting many fresh and coastal water systems (Withers et al., 2014).

Norway and other Nordic countries are rich in fresh water of good water quality. Open water like lakes and rivers are important for the Nordic societies because they provide important ecosystem services, like drinking water. However, good water quality cannot be taken for granted. Eutrophication and degradation of water quality is also a problem for Norwegian freshwater sources (Bechmann and Stålnacke, 2019; Ulén et al., 2007).

One of the main sources of nutrients and sediment inputs worldwide is the agricultural production system. This is also the case in the Nordic countries. Although only 3% of the total area of Norway is cultivated for agricultural production, the agricultural sector still is a major contributor of phosphorus and nitrogen found in streams and lakes (Ulén et al., 2007). Therefore, the European Water Framework Directive (WFD) (EU, 2000) and other international agreements aim to avoid high nutrient loads by controlling the impact that agriculture and other land use has on water bodies. Additionally, the goal of achieving good water quality and good ecological status of water bodies is impacted by climate change and a possible change in agricultural production due to a shift towards bio-based production (known as the green shift) (Skarbøvik et al., 2020b).

Bioeconomy in Norway

The shift towards a bioeconomy is seen as a potential solution for more sustainable resource use that satisfies the increasing demand for energy and food (Hansen and Bjørkhaug, 2017; Nordic Council of Ministers, 2017; Sheppard et al., 2011). The Norwegian economy is based on fossil fuel due to a successful exploitation of North-Sea oil. A green shift is needed in Norway, which would include building an economy based on renewable resources and decoupled from environmental degradation (Hansen and Bjørkhaug, 2017). This would include land use changes for the Nordic countries, including intensification of forestry (Eyvindson et al., 2018) and crop production (Jordan et al., 2007). Studies from other countries show that such a green shift impacts the agriculture by extracting more biomass and therefore altering water quality (Jordan et al., 2007; Rosegrant et al., 2013; Welch et al., 2010). Agricultural intensification could lead to the need for higher nutrient input, intensified soil management, such as more winter cereals with more autumn tillage, and loss of nutrients (Jordan et al., 2007; Trnka et al., 2011).

The field of bioeconomy is still a young research field and the effects and consequences on water quality for the Nordic countries are rarely assessed and poorly understood (Bugge et al., 2016; Skarbøvik et al., 2020b). The green shift is not necessarily sustainable on its own terms, if our "green" actions are not sustainable (Bugge et al., 2016; Ponte, 2009). There is a need to critically evaluate the sustainability of the bioeconomy and its associated land use changes, and to discuss the effects of an increasing biomass extraction and intensified agriculture on water quality in Nordic catchments.

Climate Change in Norway

The Intergovernmental Panel on Climate Change (IPCC) has developed different Representative Concentration Pathways (RCP) for climate change research. If the RCP 4.5 (intermediate emissions/medium stabilisation scenario) is assumed for Norway, the annual median temperature is expected to rise by approximately 2.7 °C (calculated for the period 1971–2000 to 2071–2100), with the greatest change in Northern Norway (Hanssen-Bauer et al., 2015). The temperature will rise in all seasons, with the largest increase projected for the winter season.

At the same time, climate change challenges the agricultural production with altered precipitation patterns (Hanssen-Bauer et al., 2015). The RCP 4.5 scenario projects an increase of the annual median precipitation of 8% (projected for the period 1971-2000-2071-2100). The biggest relative changes of median seasonal precipitation for Norway are projected for spring and summer (12% increase) and for autumn (7% increase) (Hanssen-Bauer et al., 2015). The change in median annual discharge is projected to be relatively small with an increase of 3% (RCP 4.5, 1971-2000-2071-2100), whereas seasonal changes are bigger due to changes in precipitation and temperature (Donnelly et al., 2017; Hanssen-Bauer et al., 2015). Water discharge will increase in all seasons, except of the summer season. For summer, discharge is projected to decrease by about 23%. The biggest increase in discharge is projected for the winter months with 26%, due to more precipitation as rain compared to snow (Hanssen-Bauer et al., 2015). Changes in precipitation patterns occurring in spring and autumn are especially important for agricultural activities because it affects the workability of the soil. A too high soil moisture content impacts soil strength and trafficability (Kolberg et al., 2019).

It is projected that the number of days with heavy rainfall will increase in Norway (Hanssen-Bauer et al., 2015). Heavy rainfalls and storm events can accelerate leaching of nutrients and soil particle loss by activating different sources and pathways (Mellander et al., 2018; Sherriff et al., 2016; Stutter et al., 2008). Earlier studies, like Wilson et al., (2010), showed a tendency for more severe summer droughts for the period 1945-2005, which can lead to an accumulation of nutrients due to an increased mineralization (Børgesen and Olesen, 2011; He et al., 2018; Patil et al., 2010).

With changes in temperature and precipitation patterns, the seasonal hydrological regime and snow related processes will change (Laudon et al., 2013; Meriö et al., 2019), because the number of days with snow cover will decrease. The presence of snow is, above all, the characteristic that distinguishes the Nordic countries from countries further south (Laudon et al., 2013; Tetzlaff et al., 2015). Snow influences the runoff pathways and affects the hydrological regime of the catchment. Snow cover and freezing-thawing cycles can also affect nutrient related processes (Ala-aho et al., 2021; Liu et al., 2019). Precipitation as snow is usually not immediately active as runoff, only when temperature rises again, and then snowmelt contributes to runoff in spring (it can also happen during winter time) (Hanssen-Bauer et al., 2015; Meriö et al., 2019). Frozen soil is another aspect in cold climate hydrology, where separating water fluxes between subsurface and surface can restrict infiltration of water during snowmelt and rain periods (Ala-aho et al., 2021). In the future, hydrological processes in winter will be more dynamic due to changes in land-stream connectivity and they will transform the traditional runoff patterns into a more unpredictable runoff distribution (Tattari et al., 2017).

Moreover, the RCP 4.5 scenario projects an extension of the thermal growing season in Norway by one to two months as a result of temperature increase (calculated for the period from 1971-2000 to 2071-2100) (Hanssen-Bauer et al., 2015). Jeong et al. (2011) already showed an increase of the vegetative growing season (phenology) for the temperate zone in the Northern Hemisphere for the period 1982-2008. This is one of the reasons the Nordic countries are considered potential "winners" of climate change; due to a prolonged growing season the agricultural production could increase (Wiréhn, 2018). Consequently, this may imply earlier timing of agricultural management in spring (e.g. seedbed preparation, sowing), the introduction of new crop varieties adapted to a longer growing season, and higher yields (He et al., 2018; Wiréhn, 2018).

However, it is still unknown if a prolonged thermal growing season has or will have an impact on water quality. A prolonged growing season might reduce for example nitrogen leaching due to a better utilisation of nutrient and a longer period of a vegetation cover

(Øygarden et al., 2014; Wiréhn, 2018). Nevertheless, it is not known how agricultural management may adapt to climate change, including the potential for increased nitrogen application due to expectations of higher yields. Furthermore, it is uncertain how soil mineral nitrogen will change due to higher temperatures (He et al., 2018; Mellander et al., 2018). In a simulated Canadian study, He et al. (2018) found that soil mineral nitrogen was significantly affected by temperature and that increased temperature enhanced nitrogen mineralization.

In agricultural catchments nutrient and sediment losses are highly linked to hydrological patterns, showing a strong seasonality in cold climates (Figure 1) (Casson et al., 2019; Liu et al., 2019). Changes in the seasonal hydrological patterns will also affect the seasonal patterns of nutrient and sediment losses, and control and mitigation measures functioning (Liu et al., 2019; Tattari et al., 2017).

Catchment scale studies

Going from field scale to catchment scale and linking what is happening in the catchment to the responses in the outlet is a great challenge in a holistic system-based framework (Haygarth et al., 2012). The difference to field scale or experimental plots is that catchment studies cannot easily be repeated.

Nevertheless, the examination of nutrient and discharge processes is important for small catchments (< 10 km^2), because small headwater streams are more sensitive to suspended sediments and nutrients from local sources. Headwater catchments can give detailed insight into nutrient and discharge processes by taking into account multiple factors and pathways (Figure 1) (Brendel et al., 2019; Lefrançois et al., 2007). Furthermore, headwater catchments are a key influence on the chemistry of larger river systems and mitigation measures are most effective at that scale (Bol et al., 2018).

However, characteristics such as land use, topography, and seasonal precipitation patterns (e.g., dry summer, wet autumn) create challenging conditions for mitigating erosion and nutrient loss processes. Spatial heterogeneity and temporal variability are other challenges when it comes to knowing, describing and understanding the non-point nutrient and sediment sources at catchment scale (Figure 1) (Haygarth et al., 2012). More information is also needed from different locations, as each catchment is unique in its complexity, land-use pressures, catchment size and predominant processes (Buck et al., 2004; Haygarth et al., 2012; McMillan, 2019). Collecting observations of mostly time series data is a common strategy, when it comes to research at catchment scale (Haygarth et al., 2012).

Long-term monitoring is a well-known tool in the field of catchments studies and hydrology (Tetzlaff et al., 2017). Long-term data on water quality and quantity at catchment scale allow us to see trends and to study the effects of environmental (e.g. climate change) and land use changes (green shift) (Tetzlaff et al., 2017). These datasets enable a retro-perspective view on these topics. There is also a need for long-term monitoring data on agricultural activities to evaluate the long-term impacts of crop production and land management (Reynolds et al., 2014). Long-term monitoring data is therefore the basis of many studies worldwide (Bechmann et al., 2014; Halliday et al., 2012; Kyllmar et al., 2014; Stets et al., 2015; Tetzlaff et al., 2017).

Long-term monitoring often has its limitation in the low sample frequency of weekly to monthly grab sampling or composite sampling. Continuous sampling on a volume proportional basis gives an estimate of average concentration during a sampling period with both high and low flows (Deelstra et al., 2013). The disadvantage of these methods is, however, that short-term events with high concentrations can be missed and lead to inaccurate estimates of maximum and average concentrations (Skarbøvik and Roseth, 2015; Stutter et al., 2017). Furthermore, the high temporal variability of nutrients and suspended sediment concentration and fluxes might not be covered by these methods (Halliday et al., 2012; Skarbøvik et al., 2012). Sensor techniques can give continuous concentrations and therefore provide detailed insight into transport dynamics and the highly variable concentration patterns of particles in streams (Skarbøvik and Roseth, 2015). More frequent data collection may reduce errors in load calculations, as it can capture concentrations during all peak events (Skarbøvik et al., 2012; Valkama and Ruth, 2017). Many different studies have shown the benefits of applying high-frequency data as a source for understanding processes and for estimating nutrients and suspended sediments (Bieroza et al., 2018; Kämäri et al., 2020; Mellander et al., 2015; Sherriff et al., 2016).

Nutrient and soil particle loss is highly linked to hydrological processes. This makes it important to know and understand the hydrological regime of a catchment. Here, newer analysis methods like wavelet coherence analysis (Torrence and Compo, 1998) can be applied to analyse the relationship between climate and hydrological variables and their change over time (Carey et al., 2013). The wavelet analysis helps identify the scale and timing of temporal patterns in time series as well as periods of coherence of two variables' time series (Carey et al., 2013).

Stable water isotope data can also be useful to describe and understand the hydrological regime. Isotopes have been used already since the 1960s, initially aimed at hydrograph separation (Klaus and McDonnell, 2013). Tracers in the form of isotopes are useful tools to analyse hydrological functions and can give insight into hydrological processes and mechanisms at catchment scale (Klaus and McDonnell, 2013; Tetzlaff et al., 2015). Here, Oxygen-18 (^{18}O) and Deuterium (^{2}H) can help to understand the spatial and temporal variability of dominant flow paths and to detect changes or influences of land use on hydrology (Klaus and McDonnell, 2013; Tetzlaff et al., 2015).

Research objectives

Evaluating the effects and consequences of climate change and the bioeconomy on hydrology and water quality in agricultural catchments is essential. It is important to understand the processes within the catchments linked to pathways of water and nutrients. Especially challenging is knowing, describing and understanding the non-point nutrient and sediment sources, and dynamics at catchment scale because of its spatial heterogeneity and temporal variability (Figure 1) (Haygarth et al., 2012). Nevertheless, small headwater catchments provide a holistic framework to study land use and climate effects on hydrology and nutrient loss, because nutrient retention in small streams is less important than in larger river systems (Bol et al., 2018; Brendel et al., 2019; Weigelhofer et al., 2018). Additionally, soil characteristics, crop type and cycle and the seasonal shifts of agricultural management (field operations) must be taken into account when dealing with soil and nutrient loss from agricultural catchments (Figure 1) (Bechmann et al., 2014; Bieroza and Heathwaite, 2015; Øygarden, 2000). It is important to study the impact of land use and climate to get an idea of the effects of future land use and climate on hydrology and water quality. Identifying and conceptualising drivers and processes linked to nutrient and sediment transport in small catchments in cold climates is needed. This requires an improved understanding of how the special agronomic, biogeochemical, and hydrological characteristics of cold climates and the interactions of these characteristics influence nutrient losses.

An improved understanding of changes in hydrology, nutrient input and runoff processes at catchment scale in cold climates is of high interest for both land managers and researchers. Land managers and researchers need this knowledge to develop and apply land use strategies for sustainable land management and mitigation measures to minimise the nutrient and soil particle fluxes into water bodies.

The main objective of the study was therefore to analyse data at headwater catchment scale to evaluate and discuss the impact of climate and agricultural management on hydrology and water quality. The study was divided into five sub-objectives:

1. To explore the question of water quality in the context of a potential future bioeconomy in the Nordic region (Fennoscandia), including assessing the current state of knowledge and identifying knowledge gaps pertaining to the suitability of existing monitoring and modelling tools for Nordic region (**Paper I,** opinion paper)
2. To determine the temporal and spatial trends of phosphorus and nitrogen concentrations and fluxes for different land use, climate, and runoff categories in the Nordic countries (Denmark, Finland, Sweden, Norway) (**Paper II**)
3. To explore the effect of climate on agricultural management and nitrogen loss for small agricultural catchments in Norway (**Paper III**)
4. To describe and explain the sediment dynamics of two small agricultural catchments in Norway (**Paper IV**)
5. To identify and describe the hydrological regime and changes for small agricultural catchments in Norway (**Paper V)**

2. MATERIAL and METHODS

2.1 Study areas

Papers II to V were based on monitoring data collected from catchments in Norway and other Nordic countries.

In Paper II, we conducted a Nordic study in which data records on water chemistry, discharge and climate were compiled for 69 small catchments located in Denmark (n=12), Finland (n=18), Norway (n=17) and Sweden (n=22) (Figure 2, map A). Different climate conditions and land uses were represented. All catchments were included in national monitoring programs and were implemented to study long-term effects of air quality, land use and management on water quality.

In Paper III and Paper V (Figure 2, map B), we analysed data for seven small agricultural catchments in Norway. These catchments were in the Norwegian Agricultural Monitoring Programme (JOVA), which has been maintained by the Norwegian Institute of Bioeconomy Research since 1992. We chose these catchments because they give the longest continuous time series on hydrology and land use. The widespread network made it possible to represent different Norwegian climate zones, hydrological regimes, soils, topography, and therefore also different agricultural production systems (Table 1). Monitoring stations were located at the outlet of each catchments, and all catchments were tile drained. The catchments represented the main agricultural use of the specific region: extensive grass production in the north and in the mountains (Naurstad and Volbu); intensive dairy production in western Norway (Time); a mix of dairy and cereal production in southern central Norway (Kolstad); cereal production in the south-eastern part of the country (Skuterud and Mørdre); and vegetable and cereal production in southern Norway (Vasshaglona) (Table 1).

In Paper IV, we used the catchments Mørdre and Skuterud (Figure 2, map C) as case studies for the collection of high-resolution turbidity data.

Skuterud also served as a case study for a stable water isotope analysis which was not published in an article but is part of the results presented here.

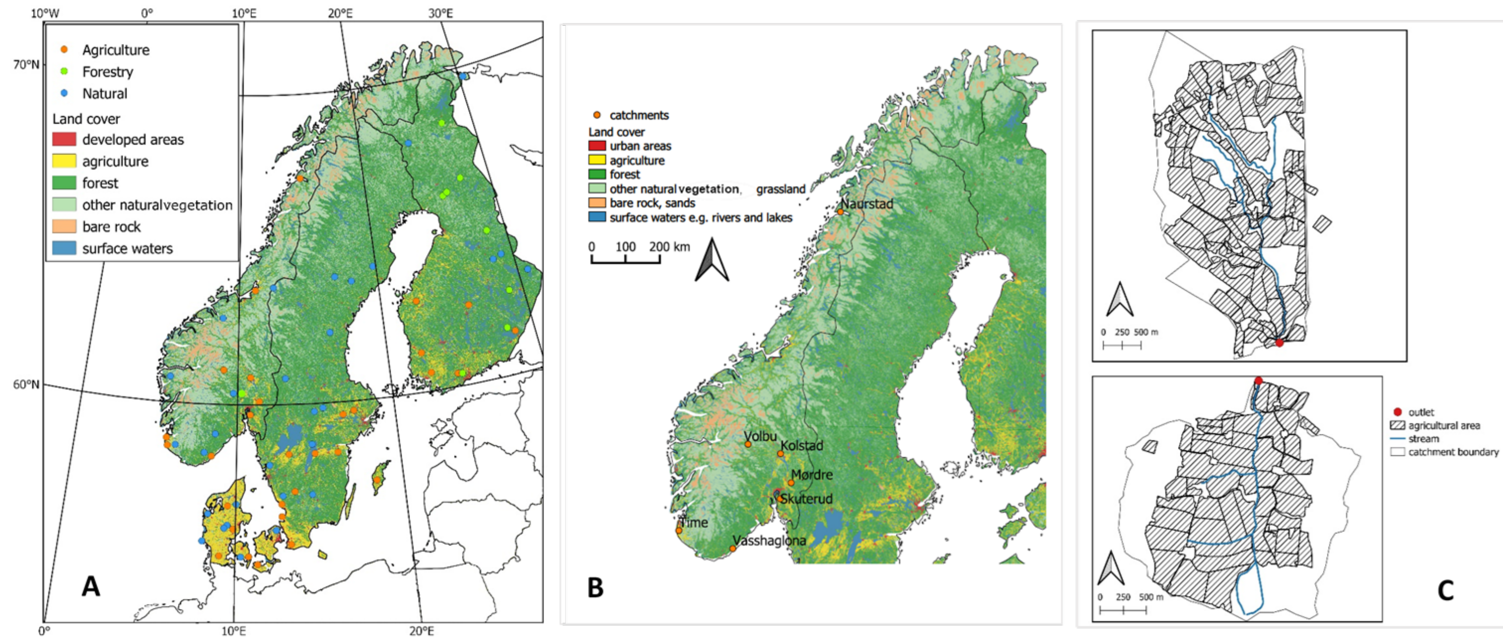

Figure 2: Location of the different catchments studied in this work. Map A: Paper II; map B: Papers III and V; map C: Paper IV.

Table 1: Catchment and climate characteristics. Monitoring period 1990's* to 2020

Catchment	Total area (ha)	Agricultural land use (%)	Main crops	Soil texture	Elevation (m.a.s.l.)	Monitoring period mean annual temperature (°C)	Monitoring period mean annual precipitation (mm)	Monitoring period mean annual Q (mm)	Start of the monitoring*
Kolstad	68	68	Cereals	Loam, loamy sand	200-318	4.4	704	371	1991
Mørdre	680	65	Cereals	Silt, silty clay, loam	130-230	5.2	724	313	1992
Naurstad	146	42	Grass	Peat soil	4-91	5.5	1264	1083	1994
Skuterud	450	62	Cereals	Silty clay, loam, silty loam	91-146	6.2	767	568	1994
Time	97	88	Grass	Loamy sand, organic	35-100	8.4	1322	804	1996
Vasshaglona	87	48	Vegetables, potatoes, cereals	Sand, loam	5-40	8.4	1497	1095	1998
Volbu	166	43	Grass	Silty sand, silty loam	440-863	3.3	644	294	1994

Table 2: Overview of datasets and methods applied in the different papers

	No. of Catchments and country	Type of data	Monitoring period	Methods used for statistical analysis.
Paper II	69 Denmark, Finland, Norway, Sweden	Long-term monitoring data	2000-2018	Mann-Kendall trend test, Partial least square regression, Linear regression
Paper III	7 Norway	Long-term monitoring data	1990's-2017	Mann-Kendall trend test, Linear mixed model, Pearson correlation
Paper IV	2 Norway	High resolution data; short-term grab sampling data, short- term monitoring data, Model-based soil data	2015-2016 2018-2019	Hysteresis index, Spearman correlation, Multivariate regression
Paper V	7 Norway	Long-term monitoring data, model-based soil, and snow data	1990's-2020 2019	Mann-Kendall trend test, Wavelet coherence analysis

2.2 Monitoring data

Long-term monitoring programme

Besides the monitoring of water quality and quantity, the JOVA monitoring program also includes information on agricultural management. Data from this programme was used in Papers II to V, either in a long-term or short-term perspective and for all or some catchments (Table 2). Water level and discharge were measured continuously at catchment outlets, using a pressure transducer combined with a Campbell data logger and a v-notch dam to convert it to discharge (flow). The data logger controlled the rate of automatic water-sampling and these sub-samples were combined as composite samples on a volume proportional (flow-weighted) basis and collected biweekly (Deelstra et al., 2013).

Annual and monthly flow-weighted concentrations were calculated by summarising daily loss over the course of a month or a year and dividing by total runoff during the corresponding period. Daily loss was calculated as daily runoff multiplied by chemical compounds concentrations in the corresponding fortnightly water sample. Precipitation and air temperature were recorded at hourly intervals at a local weather station located in or close to the catchment.

In Paper II, the Norwegian monitoring data was expanded with long-term monitoring data on water chemistry, discharge and climate from Denmark, Sweden, and Finland. Here, we used data from 69 catchments for the period 2000-2018, representing three different land types: forestry (n=30), agriculture (n=30) and natural (unmanaged, n=9). All catchments were included in national monitoring programmes. Details on the monitoring programmes are described in Paper II.

In Paper III, daily average air temperature was used to calculate the thermal growing season. The start of the thermal growing season was defined as the day on which the daily average temperature had remained higher than 5 °C for seven days. Similarly, the end was defined as the day when the daily average temperature had been lower than 5 °C for seven days (Carter, 1998; Hanssen-Bauer et al., 2015).

In Paper V, we used hydrological and climate data to calculate different indices. The daily discharge data was used to calculate flow indices such as baseflow index, high flows, and low flows using the River Analysis Package (RAP, version 3.0.8; Marsh et al., 2003). We also calculated normalized water runoff seasonality by dividing the total seasonal runoff (Qs) with total annual runoff (Qa). This gives an idea how much the different seasons contribute to the total annual runoff.

Since the 1990's, information about farm management has been collected on a yearly basis for each individual field in the JOVA programme. Farmers have provided information about crop type, sowing and harvesting dates, type and date of field operations (e.g. ploughing, sowing, harrowing), yield, amount of applied fertiliser (mineral and manure), type and number of animals, and amount and date of applied pesticides (Bechmann, 2014). In Paper III, information on fertiliser input, nitrogen balance (applied nitrogen in fertiliser and manure, minus nitrogen removed by yield), and sowing and harvesting dates were used to detect changes in the timing of field operations.

In Paper IV, we used fertiliser application and data and timing of field operations to calculate a so-called crop factor. This factor described the status of the field in terms of field operations and vegetation development. A value of 1 represents no vegetation combined with autumn tillage, while a value of 0.01 represents fully developed crop vegetation in the fields (Barneveld et al., 2019).

Seasons used in our studies were defined as winter: December–February; spring: March–May; summer: June–August; and autumn: September–November.

Figure 3: Impressions of field and laboratory work. A: filter papers with sediments after filtering the water samples, B: preparation of the phosphorus analysis, C: high-resolution turbidity sensor, D: ISCO portable sampler, E: rain gauge with tennis table ball to prevent evaporation, needed for isotope sampling, F: data logger of the turbidity sensor powered by a car battery; G: on the way to clean the turbidity sensor in Mørdre.

High-resolution turbidity data

For Paper IV, we collected high-resolution turbidity data for the catchments Mørdre and Skuterud (Table 2). Two multiparameter sensors MPS-D8 (SEBA Hydrometrie) were installed in the outlets of the catchments (Figure 3 C). Turbidity was measured every 15 minutes with an upper detection limit of 3210 Nephelometric Turbidity Units (NTUs). For Skuterud, there were two observation periods: first comprising the years 2015 and 2016, resulting from an earlier field campaign, and the second from mid-August 2018 until the end of 2019. In Mørdre, we measured turbidity from mid-August until the end of 2019. For the monitoring period 2018-2019, the sensors were equipped with a heat wire (Skuterud) and a heat lamp (Mørdre) to prevent the water from freezing and thereby ensuring winter operation. In order to maintain the sensors, we cleaned them every second week to prevent them from severe clogging (Figure 3 G). The sensors were powered using car batteries that had to be changed every second or fourth month, depending on the air temperature.

The high-frequency turbidity data were aggregated from 15-minute values to hourly values to correspond to hourly water discharge values which were used in Paper IV. The high-frequency data on turbidity were used to conduct a concentration (turbidity) discharge (c-q) hysteresis analysis (Lawler et al., 2006; Williams, 1989) for Paper IV. Before calculating the hysteresis index, the high-frequency data were checked for outliers and possible measurement errors. All turbidity values above the sensor detection limit (3210 NTU) were deleted, since we assumed that when these high values occurred in more than one time step in a row, the sensor was most probably clogged by particles or organic matter. A total of 142 runoff events were identified for Skuterud and 95 events for Mørdre. The hysteresis index was calculated as described in Lawler et al. (2006). The hysteresis index classified the events in terms of magnitude, timing of runoff and sediment peak (which comes first). Further, the hysteresis index made the runoff events comparable to each other.

Stream water grab samples

From mid-August 2018 until the end of 2019, water samples were automatically taken during runoff events by an ISCO portable sampler (Teledyne) (Figure 3 D). These water samples were used to construct calibration curves between turbidity and suspended sediments, and between turbidity and particulate phosphorus in Paper IV. We usually set up the sampler before the beginning of a rain or snow melting period. The ISCO took 24 water samples (500 ml) at hourly intervals for each event. We analysed these water samples for total phosphorus concentration, suspended sediment concentration, electrical conductivity, and turbidity in the laboratory (Figure 3, A, B).

Total phosphorus concentration was determined by oxidative digestion with potassium peroxydisulfate, which is a colorimetric method (Norwegian Standard ISO 11905-1:1997). The colorised samples were analysed by a spectrophotometer.

We analysed suspended sediment concentration by filtrating the samples using a glass fibre filter with a pore size of 1.2 µm (Whatman GF-C). We weighted the filters before filtration as well as after filtration after one hour of drying at 105 °C. Although this method is standard, it slightly underestimates the suspended sediments concentrations, because clay particles are < 2 µm and some of the fine particles will pass through the filter pores until they clog. This has to be kept in mind when analysing the resulted sediment concentrations

Turbidity measured in NTU was analysed using the turbidimeter model 2100AN from Hach. Nine events with 221 single water samples were sampled and analysed for Skuterud, while seven events with 195 single water samples were sampled and analysed for Mørdre.

Stable water isotopes

From the end of 2018 until the end of 2019, we took water grab samples for stable isotope water analysis in Skuterud. The samples were taken at different locations along the stream. Further, we installed a rain gauge to collect rainwater (Figure 3 E) and a simple piezometer to collect soil water in 1 to 1.5m depth. Water samples were also taken during three runoff events in May, August, and October. These water samples were the basis of the two-component hydrograph separation. The stream, precipitation and soil water samples were sent for analysis to the isotope laboratory of the University of Oulu, Finland. Here, they were analysed for the stable isotopes concentration of Oxygen-18 (^{18}O) and Deuterium (^{2}H). Water isotopes are expressed in standard notation as parts per mille (‰) relative to a standard (V-standard Mean Ocean Water) as $\delta^{18}O$ and $\delta^{2}H$ (Tetzlaff et al., 2015). A total of 173 water samples were collected and analysed.

2.3 Data analysis and statistics

The data analyses were based on different statistical methods, which are described in detail in the individual papers. Statistical analyses were performed in R (version 3.5.0, 3.5.2 and 4.0). A 95 % confidence interval and 5 % significance level were set throughout the statistical analyses. A 10% level was set as tendency.

In Papers II, III, and V, we applied a Mann-Kendall trend test to check the data for long-term and seasonal trends. The Mann-Kendall trend test is a rank-based, non parametric test and can account for the non-normality of hydrological data (Yue et al., 2002). The trend analysis was run in R (version 3.5.0 and 3.5.2), using the R package "*TTAinterfaceTrendAnalysis*" (Devreker and Lefebvre, 2020). We used the Theil-Sen estimator to estimate the slope of the changes in the hydrological and climate data (Sen, 1968; Theil, 1950). It determines for each sample point the median of the slope of the crossing lines (median between ranks). The Theil-Sen estimator can be applied when the data contains outliers or when data is missing. It is a robust non-parametric estimate of the slope. (Bouza-Deaño et al., 2008).

Linear regression, Pearson and Spearman correlation were applied in Papers II, III and IV. In Paper III, we applied a linear mixed model. The linear mixed model provided a technique for analysing the water quality data on the basis of non-probabilistic sampling (Giri and Qiu, 2016; Lessels and Bishop, 2013). The model was not used as a prediction tool, but to help explaining processes.

In Paper II, a Partial Least Squares regression (PLS) was conducted. This type of analysis is useful when a large set of explanatory variables is given, and variables are collinear. The goal is to extract the important information and to display patterns of similarity among the observations (Abdi, 2007).

In Paper IV, an analysis of variance (Kruskal-Wallis) and post-hoc test (Wilcoxon-Mann-Whitney) were conducted to compare the characteristics of the two catchments Skuterud and Mørdre and to determine seasonal differences in runoff. Further, multivariate regressions were compiled.

In Paper V, we used wavelet coherences to identify correlations between the flow time series and predictor variables. The wavelet analysis was done in R version 4.0 with the package "*biwavelet*". This method was applied to identify trends and periods and to explore the coupling between discharge and the different climate variables such as precipitation, temperature, evapotranspiration, snow water equivalent and soil water storage capacity. The analysis is described in detail in the methods section of Paper V.

3. MAIN RESULTS and DISCUSSION

3.1 Bioeconomy and agriculture

The European bioeconomy strategy states that more wood and crop-based biomass is needed to initiate a shift from a fossil fuel based economy to an economy based on renewable resources (European Commission, 2011). Pressures related to the green shift consist primarily of more intensive land use to increase the biomass production (Paper I). What does that imply for the agricultural areas in the Nordic countries? It implies production intensification on arable land with fertile soil and favourable climate regions (Stehfest et al., 2010) (Paper I). Further, a green shift might lead to clearing of new land for agricultural production (Stehfest et al., 2010) and utilisation of peatlands in form of a paludiculture (wet agriculture) could also be a possibility in future. These changes add new and more pressures on watercourses and potentially increase pollutant loading. Intensification, high use of fertiliser and cultivating new land might increase the leaching. In Paper II, we found that the agricultural sites showed already the highest levels of nutrient loads, followed by forestry and natural sites.

Another challenge for water is soil erosion and particulate phosphorus, especially in soils with high proportion of clay soils (Sandström et al., 2020). For farmers in areas with coarser soils, nitrogen loss can be a severe problem. These existing challenges are impacted by climate change due to e.g. droughts or increasing numbers of heavy rainfalls. Therefore, we state in Paper I that the effect of climate on nutrient and sediment runoff is a confounding factor for the assessment of mitigation measures on water quality and hydrology. Thus, there is a need for a process-based understanding of catchment-scale processes.

Climate change may be linked to an increase of the future agricultural production (Olesen et al., 2007). However, climate change has negative effects (e.g. droughts) (Wiréhn, 2018). The Nordic regions are currently undergoing major changes due to global warming. The regions are becoming warmer and wetter. Especially winters are getting warmer and wetter. Spring and autumn are getting wetter (Øygarden et al., 2014), including increased frequency of heavy rains and drought periods (water scarcity) (Mellander et al., 2018; Tsegaw et al., 2019). Changes like more frequent heavy rain events affect phosphorus, soil particles, and nitrogen lability and therefore mobilisation and transport processes. Climate change in combination with changes in land use (e.g. increased use of fertiliser) will impact the hydrology and the water quality (Rosegrant et al., 2013). As explained in Paper I, the effects of agriculture on water quality are still not well understood and there is a need for a holistic approach. Long-term monitoring programmes can be used to sustain and develop new modelling and monitoring tools, and to combine different methods and expert knowledge to sustain good water quality and to develop tailored management plans.

3.2 The hydrological trends and the link to nutrient and sediment loss

Results from the trend analyses of seven Norwegian catchments showed that hydrological trends were not easily detectable compared to trends in temperature (Papers III, V) (see section 3.3). The Mann-Kendall trend analysis conducted for precipitation in Paper V resulted in only one significant trend. Volbu showed a significant increase in annual precipitation (sen-slope 0.02).

Discharge showed more changes. A significant increase in annual mean discharge could be detected for four of seven catchments (Kolstad, Skuterud, Vasshaglona and Volbu) with sen-slopes between 0.01-0.002. The increase in the annual discharge could mainly be explained by an increase in either autumn and/or winter discharge. The seasonality of the discharge showed that summer contributed the least (9 % to 16 %) to the total annual discharge in all catchments. In the rain-dominated catchments like Naurstad, Skuterud, Time, and Vasshaglona, autumn (~30 %) and winter (30 % to 40 %) mainly contributed to the annual runoff (Papers IV, V). In snow-dominated catchments, such as Kolstad, Mørdre and Volbu, winter was an inactive hydrological season and spring contributed with 40 to 50 % to the yearly runoff due to snowmelt episodes (Paper V).

A seasonal pattern was also identified when doing a hydrograph separation based on stable water isotope data in Skuterud (Figure 4). The runoff in spring (25.05.2019) was dominated by event water (precipitation), while baseflow only played a minor role. In autumn (15.10.2019), event water also played a dominant role, but here the baseflow contributed more to the total runoff. In summer (17.8.2019), we saw a shift from event water to pre-event water. New precipitation water pushed out the old water stored in the soil, which contributed to the runoff, whereas the new water was stored in the soil.

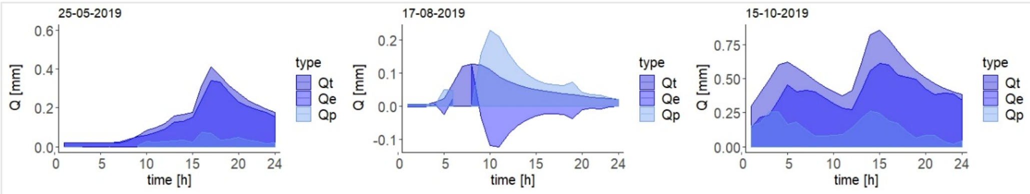

Figure 4: Hydrograph separation for three different runoff events in spring, summer, and autumn for the catchment Skuterud. Qp: pre-event water (baseflow); Qe: event water (precipitation) and Qt: runoff at time t. This figure is not shown in any of the papers.

Variables such as soil water storage capacity, hysteresis index and the connectivity index, also showed a seasonality (Paper IV). Soil water storage capacity was high in summer, when the soil was dry and could store water, but low in winter and spring, when the soil was saturated. The hysteresis index was highest in autumn and the connectivity index was highest in spring due to bare soil and ongoing field operations (e.g. ploughing). It was lowest in summer when the vegetation was fully developed. We also found seasonal patterns for turbidity and consequently for suspended sediments (Paper IV). Spring, autumn, and winter were important seasons for turbidity. In spring and autumn, this was due to high field activities, such as ploughing, in combination with rainfall (Figure 9). High turbidity during winter was due to non-permanent snow cover and rain.

Hydrology and nutrient and sediment concentration and fluxes are closely linked to each other (Casson et al., 2019; Sherriff et al., 2016). Nevertheless, in Paper II it was difficult to explain changes in concentration and fluxes of nitrogen and phosphorus with trends in hydrology. In Paper IV, we showed that discharge and turbidity were significantly positively correlated, and discharge explained more than 50 % of the variation in turbidity (Table 3). We found a connection between total nitrogen concentration and discharge (Paper III). Here, the relationship was negative, which accounts for a dilution effect. We also observed that rain intensity impacted the average runoff event turbidity values (Paper IV) (Table 3). This is important to see in the context of increasing heavy rain events in the future (Hanssen-Bauer et al., 2015; Mellander et al., 2018).

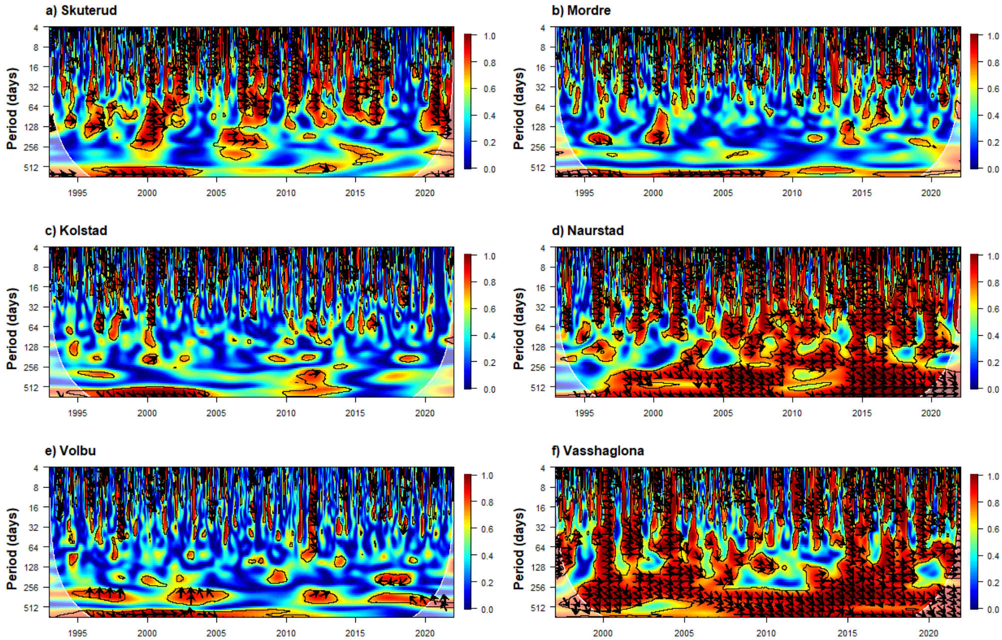

Figure 5: Wavelet coherence between discharge and precipitation for a 24-26 year period (x-axis). Periodicity of the coherence pattern is shown on the y-axis Colours indicate the strength of the relationship with red (1) to blue (0). Areas within black lines indicating 95 % significance level. A detailed description of how to read and interpret these figures is given in Paper V.

To improve the understating of hydrological processes, new techniques and a combination of different methods are needed. In Paper V, we combined a Mann-Kendall trend with a wavelet coherence analysis. Figure 5 shows the coherence over time between discharge and precipitation, which is also presented in Paper V. We can clearly see a difference between the snow and rain dominated catchments such as Naurstad, Vasshaglona and to some extend Skuterud. These catchments showed a strong coherency (red colour, Figure 5). Whereas the snow-impacted catchments showed a weak coherency (blue colour) such as Kolstad, Volbu and to some degree Mørdre. Kolstad and Volbu for example, the most inland sites, showed a small coherence during spring (0.37, 0.32) and winter (0.29, 0.23) compared to other catchments (Paper V). A detailed table with all coherences can be found in Paper V. The appearance of snowfall in the spring and winter months in inland areas led to a decoupling of discharge and precipitation. Snowfall is not immediately available for runoff generation and is first active when temperature increases. The difference between snow and rain impacted catchment can also be seen in the coherence between runoff and snow water equivalent (Paper V).

Further, we found that discharge is strongly connected to soil water storage capacity (Papers IV, V). The water storage capacity of the soil showed a significant negative correlation with mean event discharge and explained 57 to 65 % of the variability in mean event discharge. The wavelet coherence analysis in Paper V also showed this strong connection. The relation between soil water storage capacity and discharge was negative, meaning small storage capacity resulted in high discharge. Further work with wavelets could contribute to an improved understanding of changes in hydrology and in the coherence between hydrological and climate variables over time.

3.3 Temperature and the link to nutrient loss and agricultural management

The trend analysis in Papers III and V showed that the annual mean temperature increased significantly from 1990's until 2020. In Paper V, six of seven catchments showed a significant increase in annual mean temperature (sen-slope 0.05 to 0.1), except Vasshaglona. Vasshaglona, which is the most southern located catchment, has a milder climate compared to the other catchments (Table 1) and changes are projected to be smaller there (+2.2 °C increase from the current annual median air temperature) than in other Norwegian regions, like Finnmark (+4.5 °C) (Hanssen-Bauer et al., 2015). The lack of significant trends in Vasshaglona might be because changes in temperature are not detectable. The seasonal analysis in Paper V showed that air temperature increased in all seasons, with the largest increase during spring (sen-slope 0.05-0.14) and winter. Compared to all other catchment, the mountainous catchment Volbu showed the highest increase in temperature.

Although the air temperature increased for almost all catchments, the coherence between discharge and air temperature was weak as exhibited in the wavelet analysis in Paper V. The missing link between temperature and discharge in the seven Norwegian catchments may be explained by the opposite effect of temperature. Temperature affected evapotranspiration, snowfall to rain transition, and snowmelt (Blöschl et al., 2019), which affected runoff indirectly and differently. Further, other factors like land use, soil type, topography, and precipitation patterns might have had a stronger effect on runoff.

The increased temperature affected the thermal growing seasons, as shown in Paper III. The length of the growing season increased significantly in four of seven catchments, mainly due to temperature changes in spring and autumn. Warmer spring temperatures accelerates the phenological development of plants (Jeong et al., 2011; Menzel et al., 2006) and a change in thermal growing season may affect the actual agricultural growing season and management (Børgesen and Olesen, 2011; He et al., 2018; Ruosteenoja et al., 2011). The extension of the growing season is seen as one potential positive effect of climate change for food production. A shift to crop varieties better adapted to a longer growing season and a shift in sowing dates earlier in the year with simultaneous increased CO_2 concentration and precipitation could result in an increase of yield (He et al., 2018; Seehusen et al., 2015). However, even when temperature increases and the growing season gets longer, light availability will put a constraint on a positive effect, since light determines plant development and growth in northern countries (Olesen and Bindi, 2002).

Another positive effect linked to a prolonged growing season is that a longer growing season can reduce the risk of nutrient leaching due to a better utilisation of nutrients and a longer period of vegetation cover (Øygarden et al., 2014; Wiréhn, 2018). In Paper III, we found that a prolonged growing season corresponded to a reduction in nitrogen concentrations. This effect could only be seen for the catchments, where cereal production dominated, whereas in the grassland-dominated catchments such effect was not found. The difference in response might be due to differences in precipitation, fertiliser input, soil type, and permanent vegetation cover.

Considering the annual mean temperature and summer temperature, we found that these temperatures were positively related to total nitrogen and phosphorus levels found in the stream (Paper II). The linear regression showed that in forestry and natural catchments, nitrogen and phosphorus concentration and summer temperature were significantly correlated, but this relationship was not found in agricultural sites (Paper II, III). This suggested that management practice, crop type and soil type/texture acted as stronger controls on nutrient cycling than temperature (Bechmann et al., 2008).

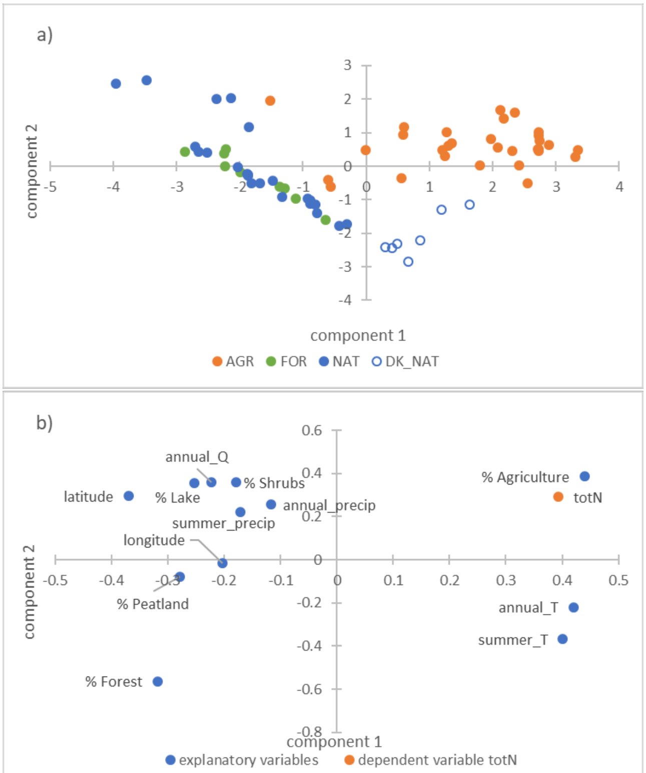

Figure: 6: a) Scoring of each single observation (catchments) for the two first components; b) Loading for the explanatory variables and the dependent variable of total nitrogen (totN).

3.4 Land use and management linked to nutrient loss

In Paper II, we found that the highest concentration and fluxes of total nitrogen and phosphorus appeared in agricultural catchments, followed by forestry and natural catchments (Figure 7). The Partial Least Square Regression showed that the nutrient concentration and fluxes are positively related to percent agricultural land in the catchments (Figure 6b, Figure 7). Independent of the countries the catchments grouped together according to their category agriculture, forestry and natural (Figure 6a, Paper II). Only the Danish natural sites showed a different pattern, which indicated the difference in natural reference conditions by the countries (Skarbøvik et al., 2020a).

The high nutrient availability in agricultural catchments is primarily driven by long-term surpluses of nitrogen and phosphorus. Whereas natural catchments gain most of their nutrients via atmospheric deposition (Vuorenmaa et al., 2017). The nutrient runoff from catchments under forest management (harvesting, drainage, fertilisation, soil tillage) can be related to application for input and to mobilisation of soil nutrient resources (Tattari et al., 2017).

The Mann-Kendall trend analysis did not result in very strong patterns, considering changes in nutrients and sediment concentration and fluxes (Papers II, III). The regional trend analysis showed a significant decrease in nitrogen concentration and fluxes across the agricultural (-15 µg total N l^{-1} year $^{-1}$) and natural sites (-0.4 µg NO_3-N l^{-1} $year^{-1}$), but individual catchments showed a few long-term trends in concentration and fluxes (Paper II). For Norway, no significant trend in nitrogen concentration could be found (Paper III). The overall decrease in nitrogen for the period 2000-2018 (Paper II) are in line with the decreasing trend in nitrogen balances for the period 2000-2016. This decline was lowest for Norway (only 3%) (Eurostat, 2020). The nitrogen balance is an indicator of how much nitrogen is available in the soils for leaching (Valkama et al., 2013). When the nitrogen balance is positive, there is a risk of more nitrogen being leached (Cherry et al., 2008; Valkama et al., 2013). The linear mixed model showed that nitrogen balance played a significant role for the total nitrogen concentration found in streams (Paper III), meaning higher nitrogen balance led to higher nitrogen concentrations. However, this relation was only found for catchments having cereal production as the main land use.

Considering phosphorus, forestry impacted catchments had a significant decrease in total phosphorus (-0.1 µg total P l^{-1} $year^{-1}$) since 2000 and agricultural sites showed a small increase in total phosphorus fluxes (+0.4 kg P km^{-2} $year^{-1}$). The newest report on the Norwegian monitoring data from agricultural catchments found that three catchments showed a significant increase and two showed a tendency to increase total phosphorus flux (Bechmann et al., 2021). Reasons for an increase in total phosphorus fluxes may differ from catchment to catchment. The increase can be linked to autumn ploughing (Paper IV), increase in discharge (Paper V) or erosion processes (Paper IV) (Bechmann et al., 2021; Bechmann and Bøe, 2021).

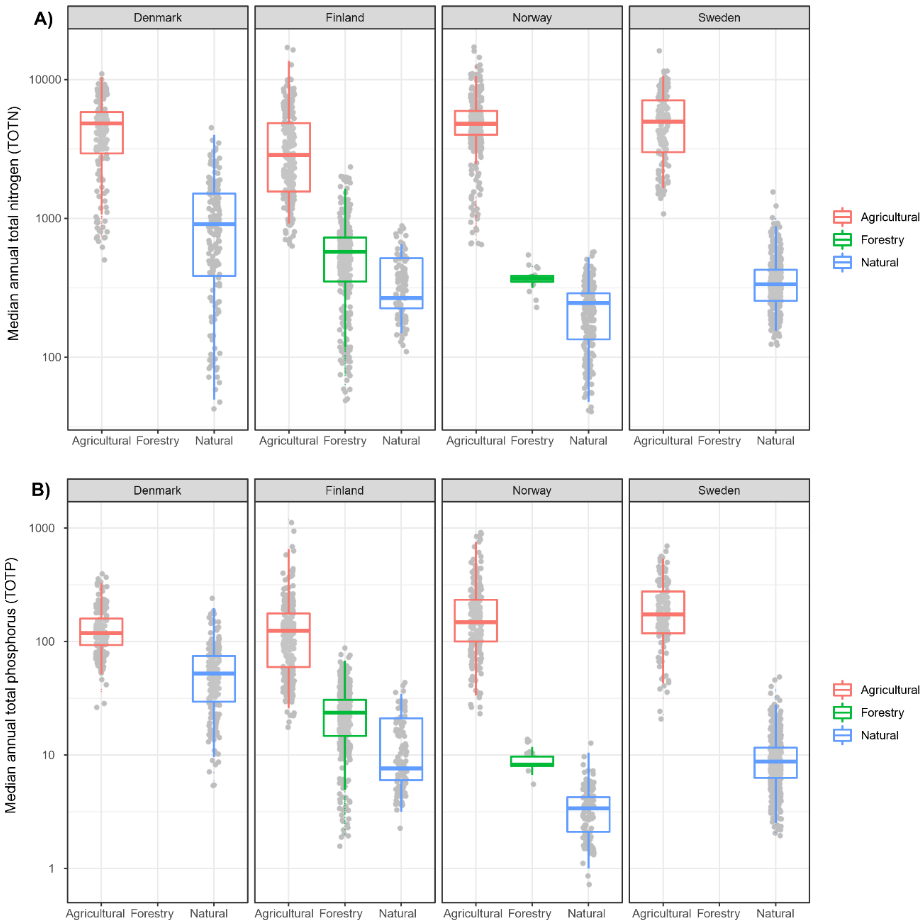

Figure 7: Concentration ranges for the grouped sites for median total Nitrogen and phosphorus, calculated for annual averages for three different land use types during 2000-2018.

We also considered whether the change in temperature, especially in spring and autumn, impacted the land management, in this case the sowing and harvesting dates. Therefore, long-term changes for sowing and harvesting dates of the cereal dominated catchments (Kolstad, Mørdre, Skuterud) were analysed. No significant changes over time could be found. We correlated the start of the growing season and the day when 50 % of the area was sown (Figure 8). Only Skuterud showed a significant correlation (R^2 0.63). However, we found that when at least one farmer had started to sow, there were significant correlations in Mørdre (R^2 0.42) and Skuterud (R^2 0.62) (Paper III). A prolonged growing season will not always lead to earlier sowing, because other factors like soil moisture also play a role. Soil moisture is one of the most limiting factor of early plant development in Norway, due to its impact on soil strength, trafficability and aeration (Kolberg et al., 2019; Riley, 2016).

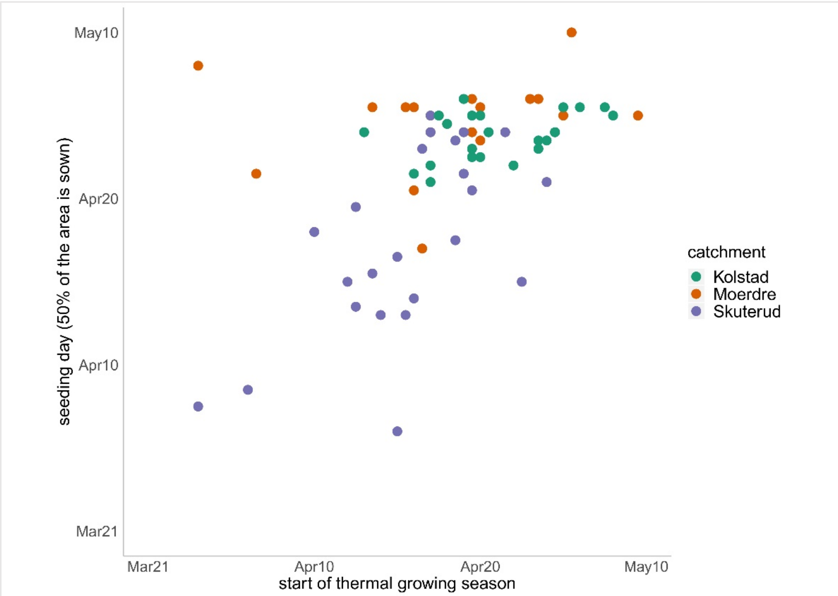

Figure 8: Pearson correlation between the first day of sowing of spring cereals and the start of the thermal growing season. R^2 for Skuterud 0.63.

3.5 Sediment transport dynamics

Improved understanding of the dynamics of sediment transport during single events may help to fit mitigation measures in time and space. The focus in Paper IV was on turbidity and suspended sediments and the basis of the analysis was high resolution turbidity data. The results of the linear regression between turbidity and total phosphorus and suspended sediments showed that turbidity is a good proxy for concentrations of phosphorus and sediments in the studied catchments (Skuterud and Mørdre). This is consistent with previous observations, including Norwegian, Swedish and Finnish agricultural catchments (Kämäri et al., 2020; Sandström et al., 2020; Skarbøvik and Roseth, 2015; Villa et al., 2019). Phosphorus is mainly soil particle bound (Walling et al., 1997) and is especially positively correlated with small particles such as clay, which have a larger relative surface area (Ballantine et al., 2009; Kleinman et al., 2011; Sandström et al., 2020). Both Skuterud and Mørdre have a high clay and silt content.

The concentration-discharge runoff patterns of the events were dominated by a clockwise hysteresis (positive hysteresis index) in all seasons in both catchments, meaning turbidity in general peaked before the discharge peak (Figure 9). The clockwise hysteresis pattern indicated a fast transport of suspended sediments and particulate phosphorus which is typical for small-scale catchments (Heidel, 1956). In this context, it is important to mention that soil texture is an important factor when it comes to hydrology and nutrient and sediment loss. Depending on the soil texture the response will be different (Sandström et al., 2020). Catchments dominated by clay soils, such as Skuterud and Mørdre, are characterised by a preferential flow through macropores and tile drains and by overland flow (which also includes runoff through manholes) (Bieroza et al., 2019; Ulén et al., 2018). On average, Mørdre had higher turbidity values during the runoff events, which can be explained by steeper channel slopes and hilly topography. Moreover, channel bed dynamics, stream bank erosion, and remobilisation of particles also play an important role for sediment loss.

Previous runoff events determine the soil moisture content and the availability of particles from both surrounding fields and channel which can be eroded and transported. In our study, it turned out that high ratios (pre-event runoff peak > event peak) were linked to rather small turbidity values at the event peak. This indicates that large pre-events flushed most of the easily available stored particles, and that less sediments were available in following events. Small ratio (pre-event runoff peak < event peak) was linked to high turbidity values.

Table 3: Significant correlations (in bolt) between event parameters mean and maximum discharge (Qmean, Qmax [m^3s^{-1}], mean turbidity ($TURB_{mean}$ [NTU]), rain intensity [mm hr-1], soil water storage capacity [mm], crop factor [-] and connectivity index [-].

	Skuterud			Mørdre		
	Q_{mean}	$TURB_{mean}$	HI	Q_{mean}	$TURB_{mean}$	HI
Q_{mean}		**0.66**	**0.54**		**0.53**	0.21
Q_{max}		**0.81**	**0.64**		**0.69**	**0.33**
Rain intensity	**0.28**	**0.4**	0.14	**0.26**	**0.63**	0.21
Water storage capacity	**-0.71**	**-0.44**	**-0.25**	**-0.7**	-0.18	0.13
Crop factor	0.11	-0.03	**0.33**	**-0.24**	-0.06	**0.28**
Connectivity index	**0.2**	0.001	**0.4**	-0.28	-0.1	**0.28**

The hysteresis index was mainly determined by maximum event discharge, crop factor and connectivity index (Table 3). A high crop factor (combined field operation and crop cover) lead to a larger hysteresis index, hence little vegetation cover combined with soil tillage resulted in a higher hysteresis index. Both the vegetation and the agricultural management (tillage, no tillage etc.) have an impact on water runoff and particle loss. A well-developed vegetation cover affects the runoff through interception, better infiltration, and soil protection (Blankenberg and Skarbøvik, 2020; Stutter et al., 2019), whereas soil cultivation can lead to loose material available for erosion (Bechmann and Bøe, 2021; Ulén et al., 2007).

A high index of connectivity (high likelihood that water and particles are transported to the stream) also corresponded to a high hysteresis index (Table 3). However, we found that the connectivity index only had a limited explanatory power for the mean event discharge (2 to 11 %) and turbidity (1 %, Table 4 in Paper IV). The difficulties in linking the index of connectivity to discharge and turbidity could be due to catchment size. The catchments we worked with are small (< 700 ha) and distances from field to stream are relatively short compared to distances in larger catchments, which may explain why the distance from field to stream was of less importance.

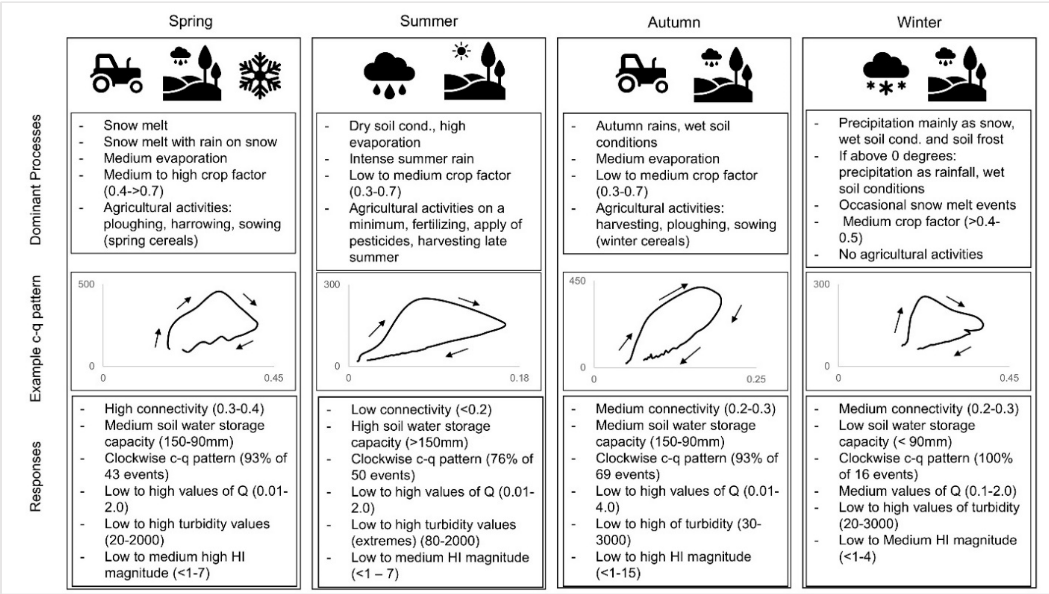

Figure 9: Conceptual model for the seasonal dominant processes and main responses based on the analysed data and showing examples for concentration-discharge hysteresis patterns

3.6 Future perspective: Agriculture, climate, and land use change

The previous sections showed how climate, hydrology and agricultural management are linked to water quality. We explored how temperature impacts the hydrology and water quality of catchment (Papers II, III, V), how hydrology is linked to water quality (Papers IV, V), and which role land use and management played for nutrient and sediment loss (Papers I, II, IV). While we have mainly focused on the changes in climate, hydrology and water quality that have already taken place, our studies also shed light on possible future changes. For the Nordic countries, the annual changes in climate and hydrology are projected to be less pronounced than seasonal ones (Hanssen-Bauer et al., 2015). In Paper IV, we showed that the largest increase in temperature was in spring and winter, whereas discharge mainly increased in autumn and winter (Papers III, V). Typical seasonal patterns (Figure 9) that we see today, such as snow melt peak in spring and inactive winter, might not appear in this form in the future. Warmer temperature in winter, for example, will affect soil frost condition and influence infiltration capacities and discharge event participation (Ala-aho et al., 2021). Further increase in temperature might affect runoff events during spring, which are often characterised by high water discharge, particularly in snow impacted catchments (Casson et al., 2019).

Changes in spring runoff might have several causes: shift of snow melt peaks earlier in the year (Pulliainen et al., 2020), less precipitation, higher temperature (Papers III, V), and consequently more evaporation (Paper V) during this period (Donnelly et al., 2017), as well as earlier start of the growing season (Paper III). In this context, we also have to consider changes in high and low flows and extreme events. Increased precipitation during autumn and more precipitation falling as rain instead of snow in winter, in combination with the increased number of melting periods and high soil moisture (reduced infiltration capacity) can cause increased high flow discharge (e.g. Skuterud, Paper V) (Blöschl et al., 2019; Meriö et al., 2019). These changes might contribute to higher nutrient and sediment concentrations and fluxes in the future, especially in seasons when the soil is not covered by plants and therefore is more exposed to erosion (Ulén et al., 2010). This calls for increasing and restoring the landscape water storage capacity (Wilson et al., 2019), as well as a change in ploughing and fertilising management, taking into account nutrient legacy, vegetation cover such as catch/cover crops or straw stubbles, buffer strips, and tile drainage systems (Bechmann, 2014; Casson et al., 2019; Liu et al., 2019).

This is also important for extreme events, since we found that maximum turbidity values highly correlated with maximum discharge (Paper IV). A higher frequency of extreme precipitation during summer is projected in the Nordic countries, which could also increase the number of discharge and nutrient peaks during the summer season (Hanssen-Bauer et al., 2015; Wiréhn, 2018). Even in summer, when agricultural fields are fully vegetated, extreme runoff events can have the same impact on e.g. total phosphorus concentration as a snowmelt event in spring (Wilson et al., 2019).

The analysis in Paper V indicated that single extreme conditions such as low average temperature and high average temperature can influence the total hydrological regime. A change in the coupling between variables can also affect subsequent years. The year 2010 had a colder average temperature compared to other years and the winter was drier than usual (Dyrrdal et al., 2013). Our wavelet coherence analysis indicated a decoupling between discharge and temperature and discharge and soil water storage capacity during 2010 for four catchments, which could be due to these cold temperatures. In 2018, northern Europe was affected by an extreme drought and extreme low-flow conditions were recorded (Bakke et al., 2020; Fennell et al., 2020). The high temperatures meant that there was a strong increase in mean temperature from 2017 to 2018 in Volbu, which might have affected the decoupled coherency between discharge and precipitation, soil water storage capacity, snow water equivalent, and evaporation. In regions affected by seasonal snow, droughts are also determined by accumulated snow volume and timing of snowmelt. If high temperatures already occur during the snowmelt season and they can lead to extreme high runoff during spring in mountainous catchments (Bakke et al., 2020). Groundwater is important to mention in this context, because it plays a crucial role in the occurrence, timing and magnitude of a hydrological drought (Bakke et al., 2020). It is thus important for the drought resilience of a catchment (Fennell et al., 2020).

To what extent climate change will lead to a change in farmer's behaviour and agricultural management is an important point in the discussion about future land use. Understanding farmers' perceptions can provide important information to agricultural policymakers. An empirical study of farmers' perceptions of climate change and their vulnerability to climatic changes in Finland and Sweden stated that agricultural policy (regulations, financial grants, subsidies, negative sanctions) may have a higher impact on farmers' behaviour than climate change itself (Juhola et al., 2017). A Canadian study showed that prices, policy, and land characteristics played a major role for crop choices (Grise and Kulshreshtha, 2016) and Mittenzwei and Øygarden (2020) illustrated how environmental politics impacts agriculture in Norway. In the long term, Zimmermann et al. (2017) predicted that technology and breeding potential will have a higher impact on farm management and yield than climate change. Agricultural policy and technology development is therefore also likely to affect bioeconomic production and, in turn, water quality.

4. CONCLUSIONS and RECOMMENDATIONS

Based on the presented studies, climate, agricultural management, hydrology, and water quality are closely linked to each other and they will likely change. The presented studies documented a change in temperature and hydrology and a close relationship between discharge and sediment loss. Further, we showed that type of land use, agricultural management, and soil conditions also play an important role in nutrient and sediment loss processes in small catchments.

Especially, cold climate regions are very sensitive to changes in climate, and therefore long-term monitoring catchment data play a key role in observing long-term changes in hydrology, water quality and related processes. It is important to sustain and maintain monitoring programmes that observe climate, agriculture and hydrology at field and catchment scales. These data can provide a framework for quantifying and evaluating sources of nutrients and sediments and can be used to assess catchment responses to climate and land use changes. Further, monitoring data can help to evaluate the effect of mitigation measures on nutrient concentrations. In addition to broader long-term monitoring data, continuous high-resolution monitoring data based on sensor technique are a powerful tool to describe and understand processes at catchment scale. They can give detailed insights into causes of nutrient and sediments losses. It is necessary to combine different resolution levels and methodologies to close the knowledge gaps. This should also be seen in the context of changing temperature and hydrology.

In the conducted studies, changes in temperature and hydrology (precipitation and discharge) could be detected best at the seasonal scale, which is also where the largest changes occurred. Discharge, turbidity, field operations, crop factor, connectivity index, and soil water storage capacity showed a strong seasonality. It is therefore recommended to analyse climate and hydrological data not only on annual basis, but seasonally as well.

Working with holistic system-based approaches is challenging, but more research at headwater catchment scales is needed. These approaches make it possible to link different pressures for nutrient and sediment loss such as climate, hydrology and agricultural management. Further, they contribute to an understanding about processes affecting the water quality at catchment scale.

In our studies, we showed that responses to climate, hydrology and land management are different from catchment to catchment. Conditions such as the location (e.g. inland or coastal), precipitation (snow or rain-dominated), catchment size, topography and soil texture determine which effect land use and climate pressures have on hydrology and water quality and which processes are predominant. Therefore, more information is needed from different locations to enable tailored land management and mitigation measures adapted to the local conditions.

It will also be important to improve the understanding of how and to what extend climate change and policy affect farmers' activities and perceptions, catchment processes and resulting water quality. If we want to gain good water quality and maintain ecosystem services related to water in the future, collaborations between researchers, politicians, land manager and farmers are crucial.

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Paper I

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Potential impacts of a future Nordic bioeconomy on surface water quality

Hannu Marttila, Ahti Lepistö, Anne Tolvanen, Marianne Bechmann, Katarina Kyllmar, Artti Juutinen, Hannah Wenng, Eva Skarbøvik, Martyn Futter, Pirkko Kortelainen, Katri Rankinen, Seppo Hellsten, Bjørn Kløve, Brian Kronvang, Øyvind Kaste, Anne Lyche Solheim, Joy Bhattacharjee, Jelena Rakovic, Heleen de Wit

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Abstract Nordic water bodies face multiple stressors due to human activities, generating diffuse loading and climate change. The 'green shift' towards a bio-based economy poses new demands and increased pressure on the environment. Bioeconomy-related pressures consist primarily of more intensive land management to maximise production of biomass. These activities can add considerable nutrient and sediment loads to receiving waters, posing a threat to ecosystem services and good ecological status of surface waters. The potential threats of climate change and the 'green shift' highlight the need for improved understanding of catchment-scale water and element fluxes. Here, we assess possible bioeconomy-induced pressures on Nordic catchments and associated impacts on water quality. We suggest measures to protect water quality under the 'green shift' and propose 'road maps' towards sustainable catchment management. We also identify knowledge gaps and highlight the importance of long-term monitoring data and good models to evaluate changes in water quality, improve understanding of bioeconomy-related impacts, support mitigation measures and maintain ecosystem services.

Keywords Bioeconomy · Land use · Surface water · Water quality

INCREASED DEMAND FOR BIOMASS IS A CHALLENGE TO SUSTAINABLE MANAGEMENT OF NORDIC SURFACE WATERS

Clean surface and coastal waters are hallmarks of the Nordic countries. These waters are valuable natural resources and essential for Nordic societies, economies and human wellbeing as they provide multiple ecosystem services. Nordic catchments have varying climates and geohydrology which influence agricultural and forest productivity. These catchments currently face multiple stressors, e.g. increasing demand for resources, increased production levels, global warming and changes in the hydrological cycle. The EU bioeconomy strategy states that more wood and crop-based biomass is needed to move towards a low-carbon and resource-efficient society in which fossil resources are replaced by renewables to mitigate climate change (European Commission 2012). This societal transformation towards a more circular bio-based economy, known as the 'green shift' from use of fossil fuels towards renewable resources, is expected to increase the demand for biomass production in the Nordic countries and elsewhere in Europe. The current understanding of the consequences, especially for water systems, is limited (Golembiewski et al. 2015). Land use practices will most likely change, the volume of biomass extracted will increase and this will likely influence water quality (Rosegrant et al. 2013) and the local hydrology. Land use changes predicted for the Nordic countries include intensified forestry (Eyvindson et al. 2018) and crop production (Jordan et al. 2007), perhaps also on marginal soils such as peatlands, which will increase the pressure on water systems.

Trade-offs between ecosystem services are inevitable, since the increased need for biomass has adverse effects on the biodiversity and provision of ecosystem services, and these effects are eventually reflected in the structure and function of freshwater ecosystems (Jordan et al. 2007). In the Nordic countries, threats to freshwater ecosystems and coastal seas include eutrophication (Bechmann and Stålnacke 2019), brownification (e.g. de Wit et al. 2016) and biodiversity loss (Riemann et al. 2016). The impacts of bioeconomic development on environmental goals are addressed by international strategies that aim at halting biodiversity loss (European Union 2011), limiting the global temperature rise (IPCC Paris Agreement), and obtaining good ecological and chemical status of all surface water bodies within the European Union (EU) and the EFTA countries (Water Framework Directive (WFD) 2000). These strategies, however, may not be compatible with increased biomass production and removal. Compromises are therefore needed when taking multiple, often controversial, objectives into account in land use planning and decision making (Juutinen et al. 2019). In natural resources planning and policy making, benefits are usually evaluated separately from each other, which overlooks their potential trade-offs. This generally leads to overexploitation of natural resources.

The WFD and many national regulations implementing the WFD aim for good ecological, and chemical status for all surface water bodies by the end of 2027. There are many concerns that river basin management and restoration actions are too slow to reach the WFD aims and that diffuse nutrient loadings, in particular, should be diminished significantly (e.g. Hering et al. 2010; Räike et al. 2019). There are increasing demands for solutions that balance land management practices and water body ecological goals, while simultaneously considering multiple uses of land, water and ecosystem services (Giri and Qiu 2016; Johansen et al. 2018).

Although we do not yet fully appreciate the possible changes in land use following a transition to the bioeconomy, some conclusions can be drawn based on projected global futures (Rakovic et al. 2020). One likely scenario is intensified land use pressures in all Nordic countries. At the same time, it must be acknowledged that Nordic countries have a great variation in land use patterns both in terms of agriculture and forestry (Table 1, Hagen et al. 2013). Furthermore, the crops produced, dominant forest tree species and soils all differ across the Nordic region. For example, Finland has about one-third of their forests on peatlands, whereas Norwegian and Swedish forests mainly are on moraine deposits and mineral soils. Nevertheless, there are also many similarities between the Fennoscandian countries, having a generally cool climate and large areas with boreal forests with rather low level of human activities, as well as thousands of rivers and lakes, which is much more than the rest of Europe. These natural characteristics create a large potential for bioeconomic development, but also for negative impacts on the many relatively pristine rivers and lakes. Denmark is very different from the other Nordic countries and more comparable to Central-European countries (e.g. Northern Germany, the Netherlands) having a milder climate, very few areas with low human activities due to a large proportion being used for agriculture, and has mainly very small lakes and many small streams.

Table 1 Proportions of land cover in Nordic countries

	Denmark	Finland	Norway	Sweden
Agriculture (%)	63.4	7.5	3.5	7.5
Forest (%)	12.9	72.9	37.4	68.7
Other (%)[a]	23.7	19.6	59.1	23.8

[a]Peatland, freshwater, mountain areas above the treeline, open uncultivated land, urban areas, open areas (in the north minor vegetation, in the south bedrock), etc

In the following, we highlight the importance of considering the water quality effects of increasing biomass extraction from Nordic catchments, focusing on Norway, Finland, Sweden and Denmark. The aim of this paper is to highlight the water quality aspects of the 'green shift' in a Nordic perspective, assess the state of the understanding, and identify knowledge gaps with focus on suitability of existing monitoring and modelling tools for Nordic landscapes.

ANTHROPOGENIC ACTIVITIES THAT IMPACT WATER QUALITY IN NORDIC CATCHMENTS

Nordic surface waters have many specific challenges that need to be considered and have been identified as posing a risk to sustaining good ecological status, in particular:

- Intensive agricultural practices causing leaching of phosphorus and nitrogen, and erosion processes especially on silty, clayey and other vulnerable soil types. Coastal areas with acid sulphate soil deposits and risk for downstream acidification. Agricultural cultivation of peatlands leading to leaching of nutrients and carbon.
- Intensification of forestry both in peatlands and on mineral soils. Peatland forestry with drainage and soil preparation, and intensification of forest harvesting (especially clear-cutting and whole-tree harvesting), leading to leaching of organic carbon and nitrogen, and loss of base cations.
- Increased pressure from increased nutrient and carbon loads on coastal and inland waters and drinking water reservoirs. Surface water and groundwater of high quality and several ecosystem services.
- Regional variations of management practices, catchment vulnerability to disturbances and expected climate change (multiple stressors), challenging predictions of land use on water quality.

In the following sections, we treat these challenges in a Nordic perspective.

The agricultural sector in Nordic countries and its impact on water quality

For centuries, Nordic countries have created climate-adapted and optimised cultivation systems for food security. Losses of suspended sediments, nitrogen and phosphorus from these systems to surface waters vary widely between catchments (Pengerud et al. 2015; Tattari et al. 2017). Environmental factors like geology and climate significantly influence the water quality and ecological status, e.g. sloping clay soils contribute high levels of suspended solids and phosphorus, while coarser soils with a high content of organic matter cause high levels of nitrogen loss (Bechmann et al. 2008). Drainage of coastal clay deposit formed in the Litorina sea stage contains sulphate that leaches as sulphuric acid resulting in low pH and release of metals (Fältmarsch et al. 2008). Production intensity is also a major factor influencing agriculture pollution and loads to receiving waters (Bechmann et al. 2008). From an agricultural perspective, societal demands for more biomass would imply intensification of production and clearing of new land for agriculture (Stehfest et al. 2010). For decades, cheap fertilisers prices have led to high use of phosphorus (P) and accumulation of P in soils. Also utilisation of marginal land areas for e.g. paludiculture may increase leaching. This adds new pressures on watercourses and potentially increases pollutant loading.

Changes in agricultural management over the past decades have led to increased intensity of production in some farming regions in the Nordic countries, while in other regions farming is becoming more extensive and agricultural land is being abandoned (Bechmann et al. 2008). These trends will probably accelerate in the future. Arable land with fertile soils in climate regions that are favourable for agricultural production will be more intensively managed. Higher productivity may increase the risk for elevated leaching rates if, e.g. crops are destroyed due to more extreme weather. Agricultural land close to riparian areas may also be used for more water retention measures such as wetlands, ponds, vegetated buffer zones, irrigation reservoirs and floodplains. This will further increase the need for efficient use of remaining agricultural land for food production.

Soil erosion and losses of particulate phosphorus are the main threats to water quality in regions with a high proportion of clay soil (Ulén et al. 2010), but also nitrogen losses from clay soils can be considerable (e.g. Tattari et al. 2017). Nitrogen losses is a severe problem for farmers and coastal waters in areas with coarser soils especially if agricultural production is intensive with high fertilisation rates. In Finland, agriculture is also conducted on peatland/organic soils, where the high organic matter content with low C/N ratios causes carbon and nitrogen leaching to water courses (Räike et al. 2019). Drained, organic soils offer a good growth substrate, but release high loads of nutrients to water courses. In recent decades, water protection measures and mitigation to reduce environmental impacts of food production have gained more attention, in part because of the EU WFD. The effects of mitigation measures under the EU WFD are difficult to assess but appear to vary widely (Stålnacke et al. 2014; Pengerud et al. 2015). The WFD 'fitness check' (EC 2019) concludes that substantial progress in water bodies' overall status is lacking, but the reason is difficult to assess because of many changes in monitoring and classification methodologies preventing a confident comparison of the two classification cycles (EEA 2018). These methodological changes include adding more eutrophication-sensitive biological quality elements like benthic algae in rivers and taking hydromorphological quality elements into account in assessment. In addition, the effect of climate on nutrient runoff is a confounding factor for assessment of mitigation measures on water quality, which illustrates the need for process-based understanding of catchment-scale processes.

Although challenges in evaluation of the extent and the efficiency of the mitigation measures implemented, clear evidence of changes in waters is shown for some areas in the Nordic countries. The strict Danish policy actions has resulted in a significant reduction in nitrogen loss from Danish agriculture (Dalgaard et al. 2014). In Sweden, nitrogen leaching has decreased in regions where mitigation measures such as catch crop, spreading of manure in spring instead of autumn and spring ploughing has been implemented to a large extent (Fölster et al. 2012). Also the agricultural advisory campaign focus on nutrients has most likely contributed to better nitrogen efficiency in these regions. In Norway the effect of mitigation measures is not so visible because of changes in climate and management at the same time (Bechmann et al. 2019; Lyche Solheim et al. 2020). The opposite also occurs, e.g. one recent study from Finnish river basins shows that the effects of water protection measures are not visible in total N and total P loads due to changes in precipitation and temperatures (Räike et al. 2019).

Sustainable crop production must include measures to minimise soil disturbance and reduce negative effects on water quality (Ulén et al. 2010). Soil compaction by farm machinery has been shown to cause decreased infiltration and increased runoff risk in agricultural land areas (Seehusen et al. 2019). Soil tillage is the main agricultural practice causing soil disturbance and increased risk of erosion and nutrient losses (Ulén et al. 2010). Tillage in autumn, as opposed to spring, leaves soil uncovered during a long period of the year when runoff occurs. However, fields without autumn tillage are a bigger source of dissolved phosphorus (Puustinen et al. 2007) as vegetation cover transport phosphate from deeper layers to the top surface. New cropping systems will be required to further decrease the nutrient leaching. Vegetation that is permanent or at least covers the soil during most of the year is here a key factor. Catch crops succeeding the main crop is effective against nitrogen leaching but the effect on leaching of phosphorus is more unclear (Aronsson et al. 2016). Careful selection of crop production systems and avoidance of bare soil layers in fields are key to achieve a successful sustainable bioeconomy in agricultural regions. In drained areas, controlled drainage systems offer ways to the sustain water table and minimise leaching, e.g. from cultivated peatlands. In general, good cropping conditions maintain growth and plant nutrient uptake limiting leaching potential. In Nordic conditions, drainage might be important to prevent water logging.

There is a risk that the political push towards a bioeconomy may cause riparian zones and other marginal lands to be more intensively utilised for fuel, fodder and food. At the same time, natural riparian zones can be highly useful in keeping soil particles, nutrients and other pollutants from entering the water bodies and thus should be protected and maintained in areas of intensive agriculture (Stutter et al. 2019). Restoring and maintaining natural vegetation in riparian zones will provide buffer zones where nutrients can infiltrate in the soil and be used by the terrestrial vegetation, and thereby reduce losses to the water bodies (Turunen et al. 2019). Riparian zones also have many important ecological functions (Tolkkinen et al. 2020).

The forestry sector in the Nordic countries and its impacts on water quality

Finland, Norway and Sweden have a strong tradition of commercial forestry and use of wood-based products. However, limited empirical data are available on the impacts of a forest-based bioeconomy on waters, particularly in the longer term in the whole Nordic region. More intensified forestry might include afforestation on new areas, densification of existing forests, fertilisation prior to harvest and a move from stem-only harvest towards whole-tree-harvest to produce biofuels that can replace fossil fuels (see, e.g. Futter et al. 2019). Further, continuous cover forestry, e.g. in Finland is becoming more popular in order to avoid harmful effects of clear cuttings. The sustainability of forest management is currently debated. Evidence of increased exports of carbon, nutrients and suspended solids to water courses following forest harvest is quite well established (e.g. Kreutzweiser et al. 2008). Many studies report temporary nutrient exports (Ahtiainen and Huttunen 1999; Joensuu et al. 2001; Finér et al. 2010; Futter et al. 2010). However, long-term effects of forestry operations on water courses are still largely unknown. Recent studies indicate considerably longer-term leaching impact from peatland-based forestry to water courses (Nieminen et al. 2017, 2018a). The effects of forest-based bioeconomy management strategies to increase biomass production and its effect on water quality at landscape scale are inadequately understood (Laudon et al. 2011). More knowledge on the impacts of a forest-based bioeconomy on waters is therefore strongly needed, including longer-term datasets and empirical evidence of the catchment and regional-scale impacts from recent shifts towards a forest-based bioeconomy.

Any intensification in forest use can generally be expected to result in increased decomposition of soil organic matter, increased runoff after harvesting and release of nutrients and carbon to waters (Laudon et al. 2011). The most pronounced effects of forestry harvest in mineral soils on surface water quality usually occur at final harvest, i.e. leaching of nitrogen and removal of base cations stored in tree biomass. Soil disturbance and erosion caused by heavy harvesting equipment on wetter soils can lead to higher dissolved organic carbon (DOC) losses and might also promote mercury methylation and runoff of methylmercury (Porvari et al. 2003; Eklof et al. 2016). Previous studies suggest an average increase of one-third in large-scale nutrient loading after forest operations in mineral soils compared with situation before operations (Kortelainen et al. 2006; Tattari et al. 2017). However, there is great local variation and the magnitude of loading is strongly related to local catchment properties and intensity of operations. Oni et al. (2015) have suggested that there are widespread and persistent landscape-scale forestry effects on water quality. The challenge in evaluation of long-term land management practices is that these practices are typically not sufficiently widespread at catchment scale to explain long-term trends in receiving larger water bodies (Kortelainen et al. 1997). Thus, monitoring at all scales from headwaters to large water bodies is needed in order to detect the element load contributions of forestry operations.

In the Nordic countries, a significant proportion of forest biomass is harvested from drained peatlands especially in Finland. In peatland forestry significant loads occur during initial drainage, maintenance operations and especially after final harvest (Kaila et al. 2014). Any future biomass harvesting from peatland forestry areas poses a potential risk to water courses and continuous cover forestry has been suggested to mitigate impacts (Nieminen et al. 2018b). Warm winters result in shorter soil frost period and loading from soft soils can be expected to be increasing after harvesting. Selective harvesting of individual trees within forestry stands maintains sufficient evapotranspiration from stands and local water table level in peat, and thereby reduces the need for drainage network maintenance. Overall, the combined effect of changing climate (temperature, precipitation), increasing peat decomposition due to drainage and fluctuating groundwater levels creates a high risk of nutrient leaching from drained peatlands (Marttila et al. 2018). Considerable area of drained peatland (Laiho et al. 2016) and peaty arable land in the northern Bothnian Bay catchment in Finland create a hot-spot area for potential future increases in nitrogen and carbon loading.

CLIMATE CHANGE IMPOSES ADDITIONAL PRESSURE AND MODIFIES LOADING PATTERNS TO NORDIC WATERS

Hydrological conditions and processes in the Nordic region are currently undergoing major changes due to amplified atmospheric and arctic oceanic warming (e.g. Jeppesen et al. 2010). The region is becoming warmer and wetter (Øygarden et al. 2014) and these trends are expected to continue in the future (Arheimer et al. 2005; Huttunen et al. 2015). Especially winters are getting warmer, and springs and autumns wetter, but also getting higher frequency of heavy rains and drought periods (Sorteberg et al. 2018). This is intensifying the hydrological system, accelerating biogeochemical processes and leaching in catchments (Mellander et al. 2018). Higher temperatures, increasing precipitation and changes in the timing and variability of heavy rain events, as well of snow cover and soil frost will all significantly affect the timing and magnitude of nutrients and particle loading from biomass production. Further changes in the timing, seasonality, variability and extreme events of precipitation and temperature are also projected. Apart from affecting the magnitude of loading, climate change will increase the periods when soils are biogeochemically active, thus creating a risk of higher leaching. For example, increased frequency and/or intensity of rain in summer and autumn may increase the risk of erosion and leaching of nutrients. Also higher mineralization of nitrogen due to higher temperature may increase leaching. All these changes in the hydrological cycle will pose challenges to conventional water protection measures and efforts in water protection conducted so far.

Climate change in combination with a focus on increased biomass production may lead to changes in agricultural and forestry management (e.g. increased use of fertiliser), and changes in land use, and therefore overall impacts on water quantity and quality (Rosegrant et al. 2013). Increasing temperature and precipitation will have a positive effect on biomass production systems but simultaneously increase the risk of nutrient and soil losses (Deelstra et al. 2011; Øygarden et al. 2014). Extreme weather events can lead to floods and/or droughts in Nordic catchments, ultimately can accelerate leaching of nutrients to water courses and downstream lakes and coastal waters. Water scarcity may become more common in the Nordic region, as seen in the extremely hot dry summer of 2018, resulting in crop failure and declining groundwater levels. Increased future precipitation during winter and spring, when soil is bare, will also lead to higher runoff and associated nutrient transport and soil losses (Arheimer et al. 2005; Deelstra et al. 2011; Øygarden et al. 2014). Increased nitrogen and phosphorus losses from agricultural sites in Nordic and Baltic countries have already been reported due to changed conditions (Deelstra et al. 2011; Pengerud et al. 2015). In agriculture, soil and nutrient losses during the vegetation-free period will be further accelerated by specific agricultural practices such as autumn ploughing due to increased rain intensity.

Boreal headwaters, lakes and coastal seas are often reported to be the recipient of high carbon and nutrient loads from land, but there are only a few published data on the trends in concentrations in coastal waters (Aksnes et al. 2009). Organic carbon concentrations in many Nordic river basins are rising and total organic carbon fluxes from some river basins to coastal waters are increasing (Fleming-Lehtinen et al. 2015; Räike et al. 2016). Elevated carbon concentrations and brownification are now being detected in all scales (de Wit et al. 2016), from small forested lakes (Vuorenmaa et al. 2006) to large-scale river basins (Lepistö et al. 2008; Räike et al. 2016) and large lakes (Forsius et al. 2017). A warming climate, changes in hydrology and decreases in acidic deposition are considered to be the major driving factors behind trends in carbon export, but are also causing an increasing trend in total nitrogen fluxes (Rankinen et al. 2016). For both forested and agricultural areas in northern parts of the Nordic countries, total nitrogen flux consists mostly of organic nitrogen, whereas at southern sites nitrate-nitrogen dominates in both small upstream catchments and large river basins (Kortelainen et al. 1997; Chen and Bechmann 2019). Overall, a considerable proportion of the nitrogen flux from boreal forest and peatland-dominated river basins may reach lakes and the sea in the form of organic nitrogen. In boreal headwater catchments, carbon and nitrogen losses are highly related to each other because of the dominance of organic nitrogen compounds in nitrogen cycling (Kortelainen et al. 2006; Lepistö et al. 2008).

More sustainable land management is needed to counteract this threat to water quality in streams, lakes and coastal waters. Climate change, nitrogen and phosphorus surplus in agricultural production and atmospheric deposition are current drivers contributing to increasing terrestrial fluxes to the coastal waters, but the bioeconomy and intensified land management is likely to become more important as more biomass is needed. Currently, Nordic assessments on bioeconomy (e.g. Lange et al. 2015) do not sufficiently include environmental impacts of the green shift on watercourses and their quality. For example, environmental impact assessment of new large bioproduct factories are focusing only on its waste receiving waters (e.g. Kile et al. 2019), not on its effects on land use with all consequences.

IMPORTANCE OF INTEGRATED DATASETS FOR EVALUATING THE CONSEQUENCES OF A NORDIC BIOECONOMY

Nordic countries have a long tradition of monitoring water quality for environmental effects of air quality (e.g. Fölster et al. 2014; De Wit et al. 2016), riverine loading of elements (Skarbøvik et al. 2014; Rankinen et al. 2016; Räike et al. 2019) and their impact on lake eutrophication, agricultural practices (Bechmann et al. 2008; Kyllmar et al. 2014) and to a lesser extent forestry practices (Ahtiainen and Huttunen 1999; Tattari et al. 2017). Effects of forestry and agricultural practices on water quality are also studied in experimental contexts (Lundekvam and Skoien 2007), resulting in complementary insights from the monitoring programmes. Systematic monitoring of forestry impacts on water quality in highly productive forested areas is limited while monitoring in catchments with undisturbed forest has a more extensive geographical coverage. Monitoring of streams and lakes in natural landscapes provides a reference to compare with monitoring of comparable types of rivers and lakes in managed landscapes. Such monitoring of reference sites are essential to answer questions arising about the new pressures to Nordic waters from intensified land use and climate change. There is also a need to incorporate new parameters (emerging pollutants, microplastic, etc.) (e.g. Kaste et al. 2018).

It is not straightforward to predict the impact of climate change and the bioeconomy on water quality for the whole Nordic region. In a European perspective, land cover and land use, geology (Fennoscandian shield with similar bedrock types) and climate show strong similarities for Finland, Sweden and Norway, while Denmark in these respects is more similar to Central-European countries further south and east. However, even within Fennoscandia, large contrasts exist between catchments in terms of landscape (vegetation, land cover, soil type, topography), management and climate (Arheimer et al. 2005). Still, most importantly, the countries are similar enough to benefit from cooperation and knowledge exchange. The form and the degree to which climate change and bioeconomic policy affect water quality will depend on catchment characteristics such as topography, soil, microclimate, land use change and sensitivity of ecosystems. Further, it is unknown how agriculture and forest management will change under various bioeconomic pathways (Rakovic et al. 2020) and how that management will adapt to climate change.

Long-term continuous datasets

Analysis of long-term datasets is one important way to evaluate and compare the consequences of various actions and measures. However, in long-term datasets the episodic impacts of certain catchment-based measures cannot easily be distinguished from changes, e.g. due to climate, which complicates their interpretation. For example, land use may have long-term influences on water quality (Nieminen et al. 2017). Transport of nutrients from diffuse sources is strongly influenced by a complex combination of temporal and spatial factors, such as fluctuating meteorological and hydrological conditions, geomorphological characteristics, crop cycles and management practices in forestry and agriculture (Palviainen et al. 2013; Kyllmar et al. 2014; Tattari et al. 2017). Spatially, a mosaic of large numbers of different land uses is typical for catchments in the Nordic regions, which can mask the effect of local activities at a larger scale (Oni et al. 2015). Temporally, land uses, and their area vary from year to year, and the impacts of a single practice may last from a couple of years up to one or more decades. Additionally, aquatic processing of nutrients changes the catchment imprint on water quality (de Wit et al. 2018). All these contributing factors make estimation of overall loading complex and challenging at the catchment scale (Haygarth et al. 2012; Bouwman et al. 2013).

Need for monitoring of small catchments

For reliable future assessments, representative datasets for the various conditions across the entire Nordic region are needed. These need to be acquired on fine time scales, so that ongoing changes and extreme events can be comprehensively detected and assessed. Monitoring data on small representative catchments, experimental plots or river basins loaded mainly by diffuse sources can provide a framework for quantifying and evaluating diffuse source loading of sediments and nutrients. Such data could be used for assessing catchment responses to different land use activities, including activities likely to increase within a bioeconomy framework. For agriculture, field experiments have given knowledge on functioning and risk for nutrient leaching in various crop cultivation systems on different soils and under different climates, which in turn has resulted in recommendations, regulations and subsidies (Bechmann et al. 2016). But knowledge on efficiency of many measures to reduce nutrient leaching is still scarce, e.g. treatment or restored wetlands and buffer zones, use of two stage ditches, liming of clay soils. In forestry, field experiments and paired-catchment studies have increased our understanding of dominant processes and given suggestions for measures. Unfortunately, there are currently insufficient empirical data available on the impacts on water quality of forestry operations used at present, such as whole-tree harvesting, removal of stumps and removal of cutting residues. Recommendation is to establish smart design for monitoring of forestry and agricultural practices, experiments and impacts on water quality. In this context, these recommendations mean using the latest monitoring technologies, existing infrastructure and long time series, combining monitoring efforts from different land use sectors and using representative sites including different risk areas.

While all catchment management activities have potentially severe and undesirable consequences at the local scale, these effects are not readily apparent at the larger landscape scale (Oni et al. 2015). Landscape type is the dominant factor in nutrient and carbon export via boreal rivers. For example, the large changes in carbon flux and nutrient concentration sometime observed in headwater catchments following final felling (Schelker et al. 2012) may be impossible to detect in larger river basins as they represent a relatively small proportion of the total land use pressure. Also, aquatic processes become increasingly important at larger spatial scales, affecting the catchment imprint on water quality. The same applies to other land uses and practices. Thus, location of the monitoring network is key to the successful estimation of leaching and loadings from various land use practices. In addition, lakes play an especially important role in nutrient and carbon cycles and retention, with e.g. more than half of all carbon exported from boreal catchments possibly being consumed in within-lake processes rather than entering the sea (Tranvik et al. 2009). This indicates a need to monitor water quality changes at all scales, in order to detect the true consequences of intensified land use activities.

Development of new modelling and monitoring tools

Understanding large-scale, complex interactions in Nordic freshwaters is challenging due to the many controlling factors across catchments, climatic conditions, geohydrological and land use practices (Laudon et al. 2011; Futter et al. 2016). Process-based conceptual models are often used to help identify the governing factors for carbon and nutrient dynamics in surface waters at varying scales (Futter et al. 2008; Ledesma et al. 2012). For example, the INCA-C model has been applied to headwater catchments in Fennoscandia (de Wit et al. 2016), to a large boreal river basin in Finland (Lepistö et al. 2014) and to large temperate catchments in Sweden (Ledesma et al. 2012). Previous modelling results obtained using the INCA-C model suggest that climate change-driven patterns in runoff, soil moisture and temperature are typically more important than temporal changes in land management in controlling surface water DOC concentrations. In the forestry sector, annual operations are carried out on only a minor percentage of the catchment area and thus it is challenging to separate catchment-scale impacts of land use activities from the impacts of climate-induced interannual variability (Oni et al. 2015). A decision-support tool for mitigating phosphorus loss from agricultural areas has been widely used by water managers to optimise implementation of mitigation measures in Norway (Drohan et al. 2019). This model was validated on long-term monitoring data for small agricultural catchments. However, in the agricultural sector, results obtained using the INCA-P model have shown that land use change is more effective than changes in agricultural practices in controlling phosphorus losses (Farkas et al. 2013). Another widely used model is the Soil & Water Assessment Tool (SWAT or SWAT+), which has been successfully applied to various land use practices in the Nordic region (e.g. Hashemi et al. 2016). Many of the Nordic countries also have their own national models that can be used to model the effects of large-scale changes in land use patterns. The results are used for reporting to EU, HELCOM and for national environmental goal assessments, but not yet to model scenarios of an increased future reliance on the bioeconomy from the water quality point of view.

Overall, future monitoring efforts should seek to include new monitoring methods and modelling tools. This would provide more information about the governing factors and processes, and also allow more accurate prediction of future scenarios. For example, sensors offer continuous monitoring of water quality that can give increased understanding of pollutant transport during extreme events, something that is more difficult to detect from infrequent grab sampling or composite sampling (e.g. Koskiaho et al. 2010; Skarbøvik and Roseth 2014). Results from different parts of the Nordic region obtained using multiple modelling tools could be combined. Availability of long-term continuous datasets and data on representative small catchments across the Nordic region would then help to focus more intensively on current and future scenarios in different perspectives. Monitoring systems for land management and water quality and quantity, in combination with hydrological and ecological modelling, could give an indication about the future situation and provide knowledge on feasible mitigation measures and adaption strategies (Giri and Qiu 2016; Couture et al. 2018).

Can integrated, knowledge-based land use planning help mitigate leaching?

Land use planning is a complicated process where multiple and often controversial objectives have to be taken into account. Awareness of the immaterial benefits humans derived from nature is increasing, so new approaches are required to incorporate impacts on various ecosystem services into land use planning (Tolvanen et al. 2013; Johansen et al. 2018). A well-known example is the conflict between efficient agricultural production and environmental goals. Furthermore, for example recent studies on drained low-productivity peatlands in Finland found strong trade-offs between biodiversity, nutrient loading to waters and greenhouse gas balances. These trade-offs are also strongly variable over time (Tolvanen et al. 2018; Juutinen et al. 2019, 2020) and imply that different targets cannot be achieved simultaneously. This means that the choice of optimal land use options requires compromises, case-specific assessments and consideration of the duration of effects in order to balance multiple conflicting objectives (Kurttila et al. 2020). For accurate evaluation of these trade-offs and consequences, data obtained through proper long-term monitoring and modelling of surface waters in a catchment perspective are essential.

Combining know-how on reducing nutrient and carbon leaching, monitoring data and modelling results in multiple land use planning would offer a powerful tool to optimise land use effects from several points of views. Trade-offs between ecosystem services and effects on water bodies cannot always be completely avoided, but they can be reduced with careful land use planning. For example, previous land use and land management optimisation studies have found that relatively high environmental benefits can be achieved with a low reduction in economic returns (Pennington et al. 2017). However, while the initial increases in environmental benefits can be inexpensive, further efforts may increase the costs considerably (Juutinen et al. 2019). Numerical multi-objective optimisation can be a useful tool in identifying cost-effective land use and land management approaches that simultaneously supply ecosystem services and economic returns at landscape or regional level (Johansen et al. 2018) with further links to water quality from different land uses. In the future we need to develop decision-support systems, where water quality monitoring and modelling are an integrated part.

FUTURE PATHWAYS AND RECOMMENDATIONS FOR A SUSTAINABLE BIOECONOMY IN TERMS OF WATER QUALITY

From a bioeconomy perspective, the pressures on water quality are related to changes in the intensity of agriculture and forestry. To what extent this affects water quality is difficult to assess, whether the pressures primarily act on a local scale, in headwaters, or on a regional scale in downstream rivers and lakes, or all the way to marine coastal ecosystems. This is partly because land use impacts generating diffuse loading interact with other anthropogenic pressures such as point-source pollution, atmospheric deposition of nitrate, hydromorphological alteration habitats and climate change. Also, aquatic processes become increasingly important at larger spatial scales, impacting the catchment imprint on water quality. In concert, multiple anthropogenic pressures—modified by aquatic processing—(potentially) threaten the ecological status of surface waters (EEA 2018). Disentangling and quantifying the cause-and-effect relationship between multiple pressures and ecological functioning is challenging, especially when addressing the regional scale (Birk et al. 2020). To understand effects of land use on water quality, we need (i) monitoring, (ii) modelling, (iii) experiments and (iv) expert judgement. Especially combining monitoring data and modelling is required to support integrated, knowledge-based land use planning.

Monitoring data from small, well-defined, data-rich and well-understood catchments have great potential to provide insights into cause–effect relationships between multiple pressures and water quality. The results of such analysis would give a good understanding of the effects of various measures and thus assist in regional- and Nordic-scale land use planning. This would in turn help tackle the future challenge of water quality under threat from the green shift in Nordic catchments. To mitigate effects of intensified land use, it is critical to have efficient monitoring programmes that enable detection of changes and selection of the most efficient countermeasures. To be able to distinguish water quality responses from local activities within the catchment and responses from external widespread stressors (e.g. deposition and climate change), an understanding of reference water quality is needed. For understanding and quantifying reference water quality, continuation of long-term monitoring of natural catchments is necessary. However, simultaneously we need smart and systematic monitoring of land use impacts. Combination of long-term reference sites with land-use-impacted catchments having comparable types of rivers and lakes (the paired-catchment approach) is recommended focusing on modern land use changes across the Nordic region. Different nature of impacts in agriculture and forestry are needed to take account as time horizon from loading perspective differs in agricultural and forestry operations and thus require a different design.

The Nordic countries have a long tradition in knowledge-based management of natural resources. However, increasing land use pressures call for new sustainable solutions for land use management. For example, to date conventional measures to control nutrient loading have focused on (i) management methods in fields or forest or (ii) 'end-of-pipe' solutions where outgoing waters are directed through various water protection measures such as settling basins. Especially end-of-pipe methods have been shown to be inefficient in many cases and it has been pointed out that the focus should be on prevention of processes leading to leaching and erosion, rather than treating water post contamination (Nieminen et al. 2018c).

The main knowledge gap in the Nordic countries related to effect of intensified land management on water quality is lack of a holistic understanding of driving processes at different scales from headwaters to lakes and to coastal waters, including the role of aquatic processing (e.g. N-retention in wetlands, P-retention in lakes, food-web interactions) for modifying the pressures and impacts on water quality. We propose the following actions for better assessment of bioeconomy-associated impacts and improvement of mitigation efforts to reduce nutrient loading to Nordic waters.

- Sustain or improve current monitoring programmes by developing a cost-efficient monitoring allowing a more systematic assessment of the impacts of forestry and agriculture on water quality, using unmanaged sites as reference ("paired-catchment approach").
- Development of monitoring and modelling tools including databases to assess temporal change in responses to single-event interventions (such as forest harvest, forest fertilisation or establishment of buffer zones).
- Extend existing monitoring programmes to include new parameters needed for modern management choices.
- Promote integration of monitoring programmes operating at different catchment scales and of different water body types (streams, rivers, lakes), with special attention for the use and development of catchment models and understanding of aquatic processing.
- Improved management and availability of national and international datasets with open-access data sharing.

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AUTHOR BIOGRAPHIES

Hannu Marttila (✉) is Assistant Professor in University of Oulu, Finland. His research focuses on hydrological processes and catchment management issues in northern landscapes with strong cross-disciplinary work across science fields.
Address: Water, Energy and Environmental Engineering Research Unit, University of Oulu, P.O. Box 4300, 90014 Oulu, Finland.
e-mail: hannu.marttila@oulu.fi

Ahti Lepistö is a Senior Research Scientist, PhD, at the Finnish Environment Institute SYKE, Finland. His research interests include impacts of climate change and forestry on nutrient fluxes, green bioeconomy, catchment hydrology and biogeochemistry, modelling, and real-time water quality monitoring.
Address: Finnish Environment Institute SYKE, Freshwater Centre, Latokartanonkaari 11, 00790 Helsinki, Finland.
e-mail: ahti.lepisto@ymparisto.fi

Anne Tolvanen is a Professor in forest ecology and the multiple use of forests at the Natural Resources Institute Finland. Her research concentrates on the reconciliation of land uses to safeguard biodiversity, and her group develops models and tools that are used in the planning and management of peatland and forest ecosystems.

Address: Natural Resources Institute Finland, University of Oulu, P.O. Box 413, 90014 Oulu, Finland.
e-mail: anne.tolvanen@luke.fi

Marianne Bechmann is a Research Professor in the Norwegian Institute of Bioeconomy Research, Norway. Her research interests include soil and water relations in agricultural areas and the effect of different management and land use on water quality.
Address: Norwegian Institute of Bioeconomy Research (NIBIO), Fredrik A. Dahls vei 20, 1430 Ås, Norway.
Address: Norwegian Institute of Bioeconomy Research (NIBIO), P.O. Box 115, 1431 Ås, Norway.
e-mail: marianne.bechmann@nibio.no

Katarina Kyllmar is a Research leader at the Swedish University of Agricultural Sciences, Department of Soil and Environment. Her research interest is in how geology, climate and agricultural production impact on water quality at the small catchment scale. This includes development of methods for monitoring and for assessment.
Address: Department of Soil and Environment, Swedish University of Agricultural Sciences, Box 7014, 75007 Uppsala, Sweden.
e-mail: katarina.kyllmar@slu.se

Artti Juutinen is a Professor in economics of multiple use forestry at the Natural Resources Institute Finland. His research interests include topics related to environmental and resource economics.
Address: Natural Resources Institute Finland, University of Oulu, P.O. Box 413, 90014 Oulu, Finland.
e-mail: artti.juutinen@luke.fi

Hannah Wenng is a PhD candidate at the faculty of Environmental Science and Natural Resource Management of the Norwegian University of Life Science. She works for the Norwegian Institute for Bioeconomy Research (NIBIO) in the BIOWATER project. Her research interests are hydrology and agriculture.
Address: Norwegian Institute of Bioeconomy Research (NIBIO), Fredrik A. Dahls vei 20, 1430 Ås, Norway.
Address: Norwegian University of Life Science, Ås, Norway.
e-mail: hannah.wenng@nibio.no

Eva Skarbøvik is Research leader for the Department of Hydrology and Water Environment at the Norwegian Institute of Bioeconomy Research (NIBIO). Her research interests include catchment hydrology, water quality and eutrophication.
Address: Norwegian Institute of Bioeconomy Research (NIBIO), Fredrik A. Dahls vei 20, 1430 Ås, Norway.
e-mail: eva.skarbovik@nibio.no

Martyn Futter is an Associate Professor in catchment-scale water quality modelling. His research focusses on how human activities affect hydrology, nutrient and contaminant cycling in production landscapes.
Address: Swedish University of Agricultural Sciences, Box 7050, 75007 Uppsala, Sweden.
e-mail: martyn.futter@slu.se

Pirkko Kortelainen is a Leading Research Scientist in Finnish Environment Institute. Her research interests include interactions between biogeochemical cycles with land use, climate and atmospheric deposition.
Address: Finnish Environment Institute, Latokartanonkaari 11, 00790 Helsinki, Finland.
e-mail: pirkko.kortelainen@ymparisto.fi

Katri Rankinen is a Senior Researcher at the Biodiversity Centre in Finnish Environment Institute. Her current research involves mapping and valuation of ecosystem services of water purification in context of changing climate and land use. Special interest is in effects of agriculture on water quality.
Address: Finnish Environment Institute, Latokartanonkaari 11, 00790 Helsinki, Finland.
e-mail: katri.rankinen@environment.fi

Seppo Hellsten is an experienced hydrobiologist and currently heading the unit of Restoration and Assessment of Finnish Environment Institute SYKE. He is in charge of Syke team of Biowater in Nordic Centre of Excellence.
Address: Finnish Environment Institute, University of Oulu, P.O. Box 413, 90014 Oulu, Finland.
e-mail: seppo.hellsten@ymparisto.fi

Bjørn Kløve is a Professor in water resources engineering at Water, Energy and Environmental Engineering research unit, University of Oulu. His research combines hydrological processes studies using hydrologic and isotopic measurements, remote sensing and numerical modelling to understand ecosystems and impacts of land use and climate change.
Address: Water, Energy and Environmental Engineering Research Unit, University of Oulu, P.O. Box 4300, 90014 Oulu, Finland.
e-mail: bjorn.klove@oulu.fi

Brian Kronvang is Professor at Department of Bioscience, Aarhus University. His research interest is in Catchment Science.
Address: Department of Bioscience, Aarhus University, Vejlsøvej 25, 8600 Silkeborg, Denmark.
e-mail: bkr@bios.au.dk

Øyvind Kaste is a Senior Research Scientist at the Norwegian Institute for Water Research and Associate Professor at the University of Agder, Norway. He holds a PhD in limnology from the University of Oslo. His research interests are assessment and modelling of element cycles in catchments, with focus on soil–water transfer and cycling of nutrients in aquatic ecosystems.
Address: Norwegian Institute for Water Research, Gaustadalléen 21, 0349 Oslo, Norway.
Address: University of Agder, Pb 422, 4604 Kristiansand, Norway.
e-mail: oka@niva.no

Anne Lyche Solheim is a limnologist working as a Senior Researcher at the Norwegian Institute for Water Research (NIVA) in Oslo, Norway. Her research interests focus on impact of nutrients and climate change on the risk for harmful algal blooms in lakes. She is a key expert for the European Commission and for the European Environment Agency doing large-scale assessments on ecological status of rivers and lakes and has been involved in many EU research projects concerning development of ecological assessment systems for the Water Framework Directive.
Address: Norwegian Institute for Water Research, Gaustadalléen 21, 0349 Oslo, Norway.
e-mail: anne.lyche.solheim@niva.no

Joy Bhattacharjee is a Doctoral student in Water, Energy and Environmental Engineering research group at University of Oulu. He is using remote sensing methods and hydrological modelling to improve understanding of processes in peatlands.
Address: Water, Energy and Environmental Engineering Research Unit, University of Oulu, P.O. Box 4300, 90014 Oulu, Finland.
e-mail: joy.bhattacharjee@oulu.fi

Jelena Rakovic is a PhD student at the Swedish University of Agricultural Sciences. Her research focuses on how landscape and biogeochemical processes influence phosphorus mobilisation and transfer in agricultural catchments.
Address: Department of Soil and Environment, Swedish University of Agricultural Sciences, Box 7014, 75007 Uppsala, Sweden.
Address: Swedish University of Agricultural Sciences, Box 7050, 75007 Uppsala, Sweden.
e-mail: jelena.rakovic@slu.se

Heleen de Wit is a Senior Research Scientist at the Norwegian Institute for Water Research in Oslo, Norway. Her research interests include climate and air pollution impacts on catchment biogeochemistry.
Address: Norwegian Institute for Water Research, Gaustadalléen 21, 0349 Oslo, Norway.
e-mail: heleen.de.wit@niva.no

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WOMEN ADVANCING RESEARCH IN HYDROLOGICAL PROCESSES

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Land-use dominates climate controls on nitrogen and phosphorus export from managed and natural Nordic headwater catchments

Heleen A. de Wit[1,2,3] | Ahti Lepistö[4] | Hannu Marttila[5] | Hannah Wenng[6,7] | Marianne Bechmann[6] | Gitte Blicher-Mathiesen[8] | Karin Eklöf[9] | Martyn N. Futter[9] | Pirkko Kortelainen[4] | Brian Kronvang[8] | Katarina Kyllmar[10] | Jelena Rakovic[10]

[1]Norwegian Institute for Water Research (NIVA), Oslo, Norway
[2]Department of Biological Sciences, University of Oslo, Oslo, Norway
[3]Centre for Biogeochemistry in the Anthropocene, University of Oslo, Oslo, Norway
[4]Finnish Environment Institute SYKE, Helsinki, Finland
[5]Water, Energy and Environmental Engineering Research Unit, University of Oulu, Oulu, Finland
[6]The Norwegian Institute of Bioeconomy Research (NIBIO), Ås, Norway
[7]Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Sciences, Ås, Norway
[8]Department of Bioscience, Aarhus University, Silkeborg, Denmark
[9]Department of Aquatic Sciences and Assessment, Swedish University of Agricultural Sciences, Uppsala, Sweden
[10]Department of Soil and Environment, Swedish University of Agricultural Sciences, Uppsala, Sweden

Correspondence
Heleen A. de Wit, Norwegian Institute for Water Research, Gaustadalléen 23, Oslo 0349, Norway.
Email: heleen.de.wit@niva.no

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Abstract

Agricultural, forestry-impacted and natural catchments are all vectors of nutrient loading in the Nordic countries. Here, we present concentrations and fluxes of total nitrogen (totN) and phosphorus (totP) from 69 Nordic headwater catchments (Denmark: 12, Finland:18, Norway:17, Sweden:22) between 2000 and 2018. Catchments span the range of Nordic climatic and environmental conditions and include natural sites and sites impacted by agricultural and forest management. Concentrations and fluxes of totN and totP were highest in agricultural catchments, intermediate in forestry-impacted and lowest in natural catchments, and were positively related %agricultural land cover and summer temperature. Summer temperature may be a proxy for terrestrial productivity, while %agricultural land cover might be a proxy for catchment nutrient inputs. A regional trend analysis showed significant declines in N concentrations and export across agricultural (-15 μg totN L^{-1} $year^{-1}$) and natural (-0.4 μg NO_3-N L^{-1} $year^{-1}$) catchments, but individual sites displayed few long-term trends in concentrations (totN: 22%, totP: 25%) or export (totN: 6%, totP: 9%). Forestry-impacted sites had a significant decline in totP (-0.1 μg P L^{-1} $year^{-1}$). A small but significant increase in totP fluxes (+0.4 kg P

km^{-2} $year^{-1}$) from agricultural catchments was found, and countries showed contrasting patterns. Trends in annual concentrations and fluxes of totP and totN could not be explained in a straightforward way by changes in runoff or climate. Explanations for the totN decline include national mitigation measures in agriculture international policy to reduced air pollution and, possibly, large-scale increases in forest growth. Mitigation to reduce phosphorus appears to be more challenging than for nitrogen. If the green shift entails intensification of agricultural and forest production, new challenges for protection of water quality will emerge possible exacerbated by climate change. Further analysis of headwater totN and totP export should include seasonal trends, aquatic nutrient species and a focus on catchment nutrient inputs.

KEYWORDS

agriculture, bioeconomy, forest, forestry, long-term trend, mitigation, monitoring, stream

1 | INTRODUCTION

Reconciliation of increasing reliance on agricultural and forestry products with water quality protection is becoming more urgent under the green growth policies that are being developed in Europe. The so-called "green shift" towards a low-carbon and resource-efficient society to mitigate climate change is expected to require wood and crop-based biomass for replacement of fossil resources by renewable energy-sources (Scarlat, Dallemand, Monforti-Ferrario, & Nita, 2015).

During the green shift, production of meat and cereals in Europe are expected to intensify—partly as consequence of income growth—with adverse effects on water quality (Rosegrant, Ringler, Zhu, Tokgoz, & Bhandary, 2013). Agricultural production in Europe is one of the main pressures identified under the Water Framework Directive (WFD) that reduces ecological status of surface and coastal waters, by increasing runoff of nitrogen and phosphorus (EEA, 2019). The WFD is implemented nationally with approaches targeted at climate, soil, hydrological conditions and agricultural production (Ulen, Bechmann, Folster, Jarvie, & Tunney, 2007). The WFD aims for good ecological, chemical and hydromorphological status by the end of 2027. However, river basin management and restoration actions could be insufficient to reach the WFD aims within 2050. In particular, diffuse nutrient loadings should be reduced significantly (Hering et al., 2010; Räike, Taskinen, & Knuuttila, 2020). National agro-environmental legislation in the Nordic countries since 1990 has led to country-specific reductions of the N and P field balances (inputs from fertilizer substracted with removal by harvest) on agricultural land. As an example, Danish regulations decreased the N and P field balance with 45% and 76% during the period 1990–2015 (Blicher-Mathiesen et al., 2020) and in Finland with 35% and 60%, respectively, during the period 1995–2013 (Aakkula & Leppänen, 2014). These country-specific reductions in field nutrient balances are expected to affect nutrient runoff from agricultural catchments although the presence of legacy nutrient stores will confound such relationships (Tattari et al., 2017).

Forest management to increase biomass for bioenergy is another pressure with potential effects on nutrient loadings to surface waters (Kreutzweiser, Hazlett, & Gunn, 2008). Increased extraction of forest biomass and intensified forestry have trade-offs with ecosystem services like biodiversity (Eyvindson, Repo, & Monkkonen, 2018) and are likely to also impact water quality (Laudon et al., 2011). Local increases of nitrogen and phosphorus concentrations in forestry-impacted catchments is well-documented (De Wit et al., 2014; Lofgren, Ring, von Bromssen, Sorensen, & Hogbom, 2009) but its impact on a wider temporal and spatial scale is less clear (Sponseller et al., 2016). In areas with intensive peatland forestry like Finland, harvesting operations in forest on organic soils are of specific concern (Marttila et al., 2018; Nieminen et al., 2018). Furthermore, intensified forestry by conducting whole tree harvesting may require application of a fertilizer to avoid reduced forest growth (Akselsson, Westling, Sverdrup, & Gundersen, 2007; Merila et al., 2014). In freshwaters, phosphorus is usually considered to be the limiting nutrient (Schindler, 1977) although more recent studies suggest a role for nitrogen as well (Bergstrom & Jansson, 2006). In marine waters, production typically is limited by nitrogen (Howarth & Marino, 2006).

Agriculture and forestry are important pillars of Nordic societies. Forestry is of particular interest to Sweden and Finland, both of which have a high percentage of productive forest and a large forestry sector (Verkerk et al., 2019). Agriculture is a dominant land use in Denmark and across the Nordic region, nutrient loadings from agriculture is a large concern for eutrophication of freshwater and marine ecosystems (Frigstad et al., 2020; Karlson, Rosenberg, & Bonsdorff, 2002). These waters are valuable natural resources and essential for Nordic societies, economies and human wellbeing as they provide multiple ecosystem services (Kronvang et al., 2008; Marttila et al., 2020; Ulen et al., 2007).

A solid understanding of processes driving catchment export of nitrogen and phosphorus is thus at the basis of predictions of effects of the green shift on water quality. In addition to agricultural and forest management, catchment export of nitrogen and phosphorus can be accelerated by extreme hydrological events (Borgesen & Olesen, 2011; Mellander et al., 2018) despite the measures and efforts made particularly in agriculture to reduce loading. Hydrological conditions are changing in the Nordic region (Oygarden et al., 2014) and are expected to continue to do so in the future (Arheimer & Lindstrom, 2015; Huttunen et al., 2015). Nutrient-runoff mitigation measures at the catchment scale (e.g., buffer zones, artificial wetlands) in a changed climate (Carstensen et al., 2020; Haygarth et al., 2012; Laudon et al., 2016) may not be sufficient for adequate protection of water quality.

Small headwater catchments without point sources of nutrients provide an ideal framework to assess land use and climate impacts on nutrient export to surface waters, because nutrient retention in small streams is of lesser importance compared with larger river basins (Weigelhofer, Ramiao, Pitzl, Bondar-Kunze, & O'Keeffe, 2018). Nitrogen deposition from air pollution is a driver of changes in nitrogen runoff in such small catchments (Vuorenmaa et al., 2018), mitigated by international policy to reduce emissions of nitrogen to the atmosphere. Long-term changes in diffuse nutrient fluxes from managed catchments are strongly influenced by a complex combination of temporal and spatial factors, such as fluctuating climatic and hydrological conditions, land cover, soil characteristics, crop cycles and land-use practices in forestry and agriculture (Bechmann et al., 2014; Kyllmar, Carlsson, Gustafson, Ulen, & Johnsson, 2006; Tattari et al., 2017; Vuorenmaa, Rekolainen, Lepisto, Kenttamies, & Kauppila, 2002). Similarly, natural catchments are governed by climatic and hydrological conditions (Vuorenmaa et al., 2018) but lack the confounding influence of management. Such catchments provide a reference that enables distinguishing between interacting pressures, that is, intensified agricultural and forestry-related land use, and climate change (Skarbovik et al., 2020). Combined records from natural and managed catchments, from a wide range of environmental gradients and under common management regimes, are therefore potentially useful for assessing water quality responses to environmental change and evaluation of mitigation measures to protect water quality.

Here, we present concentrations and export of total nitrogen (totN) and total phosphorus (totP) and other species of nitrogen and phosphorus, in 69 Nordic headwater catchments for the period 2000–2018. The catchments are representative of Nordic natural (unmanaged) and agricultural landscapes and include also forestry-impacted sites. They cover a wide range of climate, soil type, runoff and management patterns. The primary focus is on totN and totP because all study sites have full records suitable for trend analysis (10 years or more) for these parameters. We test effects of land use, climate, runoff and land cover on spatial variation and temporal trends on concentrations and fluxes of totN and totP. Because nutrient runoff is potentially sensitive to differences in national mitigation measures (Hellsten et al., 2019; Kronvang et al., 2008; Ulen et al., 2007), we analyse for patterns by country in addition to examining patterns within land-use categories across the Nordic region.

2 | MATERIALS AND METHODS

Study sites and monitoring programs Data records on water chemistry, discharge and climate were compiled for 69 small catchments in Denmark (n = 12), Finland (n = 18), Norway (n = 17) and Sweden (n = 22) for the period 2000–2018 (Figure 1, Table 1). Detailed catchment-specific information is available (Table SI-1). All catchments are included in national monitoring programs, designed to assess long-term effects of air quality, agriculture and forestry on water quality. The monitoring programs follow standardized national or international procedures for sampling and chemical analysis, including QA-QC procedures. In all countries the analytical programs have changed over time, depending on funding and monitoring priorities. All sites have records of totN and totP for at least 10 full calendar years. Shorter time series were available for some variables (see Table SI-2). All catchments were attributed to a land-use category, that is, agriculture, forestry-impacted and natural.

Discharge was measured daily, using an open channel stage-discharge relationship in Danish streams. V-notch profiles or crump weir with a stage-height relationship were used elsewhere. Water was predominantly sampled by grab sampling, except for agricultural catchments in Sweden and Norway where flow-proportional composite sampling was used (Deelstra et al., 2014; Kyllmar, Forsberg, Andersson, & Martensson, 2014b). Sampling frequency varied from weekly to every second week to monthly and was stable throughout the entire monitoring period, with some exceptions as described below. In agricultural catchments, field management is monitored on an annual basis, except in Finland where annual management data are not available from all sites (Tattari et al., 2017). In all catchments, point sources are of minimal importance for annual loading of nitrogen and phosphorus.

From Denmark, the five predominantly agricultural and seven catchments with natural vegetation belong to the National Monitoring and Assessment Program for the Aquatic and Terrestrial Environments (NOVANA) (Svendsen, Bijl, Boutrup, & Norup, 2005) and monitoring started in 1990. Water chemistry in catchments with natural vegetation was sampled every 2 weeks or every month until 2009, when the sampling programs were repeated every third year. Catchments with natural vegetation are mostly forested with extensive forest management in some while two contain <10% of extensively managed grassland areas (Supplementary Information) and are surrounded by agricultural areas of differing intensity. Farming practices in the five agricultural catchments include cereal production for intensive pig farming, intensive dairy farming areas with mixed fodder crops and cereal and sugar beet production on clay soil (Blicher-Mathiesen et al., 2020). All catchments are situated at low altitudes (8–110 m.a.s.l.). Catchment soils are mainly sand and sandy loams but one agricultural catchment is on clay soil (Svendsen et al., 2005). Subsurface drainage depends on soil texture (rare in sandy soils, common in fine-textured, especially clay soils).

For Finland, six agricultural catchments, eight forestry-impacted and four natural catchments are included (Seuna, 1983). Water discharge monitoring was initiated in 1957 and monitoring of water quality in 1962 (Vuorenmaa et al., 2002). Catchment boundaries are well-defined, and typically groundwater and surface water boundaries coincide. Most arable land in the agricultural catchments is located on graded soils, with high proportions of silt and clay except for one site (Haapajyrä) where acid sulphate soils dominate, related to post-ice age

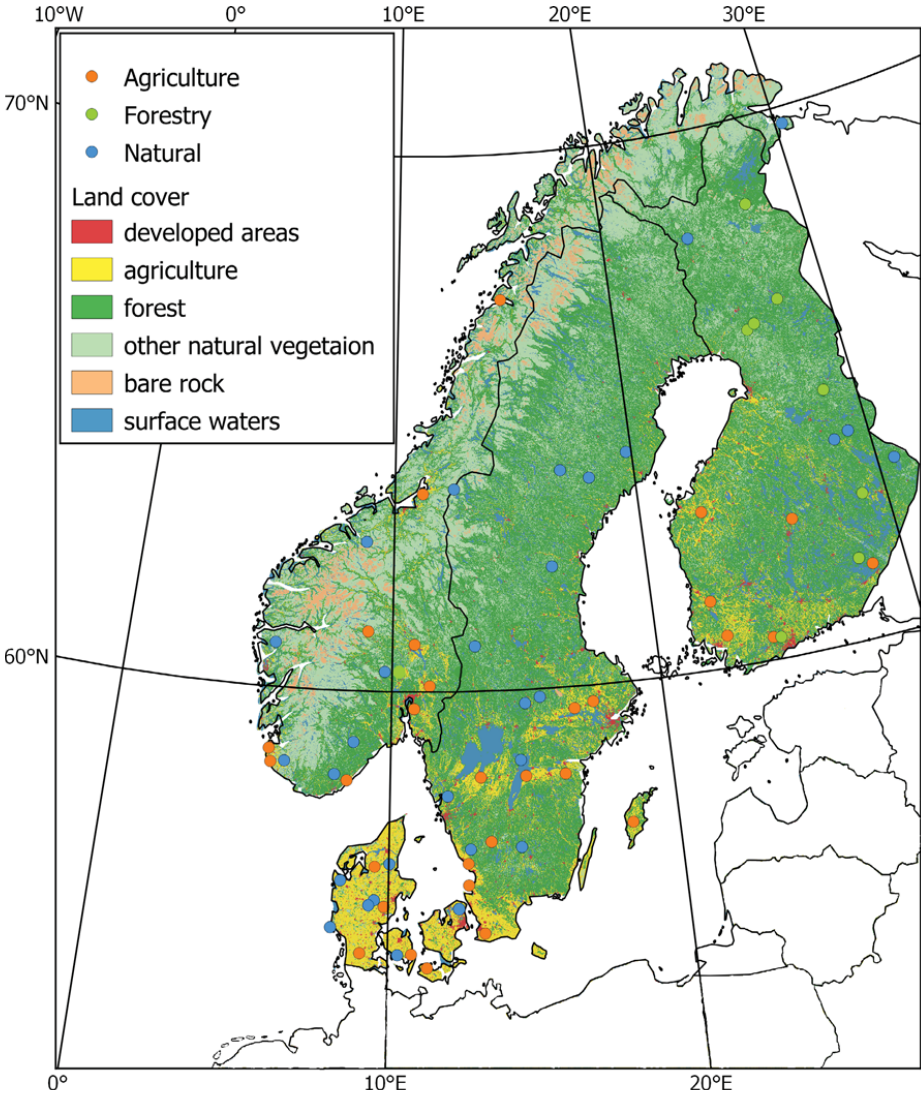

FIGURE 1 Map of study catchments in the Nordic countries. The land cover information bases on CORINE land cover information (https://land.copernicus.eu/pan-european/corine-land-cover). Colour coding refers to land use category

land uplift of marine sediments, which leach considerable amounts of sulphuric acids. Crop cultivation includes mostly cereals and root crops.

Eight small forestry-impacted catchments represent extensively managed forest land (Tattari et al., 2017; Vuorenmaa et al., 2002). The most important forestry practices (drainage, clear-cutting, soil scarification, fertilization) were undertaken in 1960–1990 (Kortelainen & Saukkonen, 1998). Soil types vary from mineral to peatland-dominated. Four Finnish natural catchments were included. These are dominated by coniferous forests and peatlands on moraine or organic soils (Ahtiainen & Huttunen, 1999; Lohila et al., 2015).

The nine Norwegian agricultural catchments are monitored under the Norwegian Agricultural Environmental Monitoring program (JOVA) (Bechmann et al., 2008). Monitoring at all but one catchment started between 1990 and 1995. The catchments represent the main farming systems in Norway; cereal production in the eastern and middle parts of the country, vegetable production in the south, intensive dairy farming in the west, and more extensive grass production in the southern mountains and in northern Norway (Wenng, Bechmann, Krogstad, & Skarbøvik, 2020). Soil texture varies from clay loam (dominated by surface runoff), loam and sand

TABLE 1 Key site characteristics, grouped by country and land use category, presented as median (minimum–maximum) values

		Denmark	Finland	Norway	Sweden	All
Agricultural	n	5	6	9	10	30
	Area (km^2)	7.5 (4.4–11)	5.7 (0.1–15)	3.1 (0.9–29)	7.8 (1.8–33)	
	Elevation (m.a.s.l)	30 (8–110)	48 (25–95)	119 (23–652)	42 (8–155)	
	Agriculture (% of area)	80 (64–87)	48 (17–100)	62 (35–88)	87 (58–93)	
	Forest (% of area)	7 (2–25)	44 (0–69)	29 (3–55)	4 (0–32)	
	Peatland (% of area)	2 (0–5)	9 (0–26)	1 (0–24)	0 (0–0)	
	MAT (°C)	10.2 (9.7–10.7)	6.2 (5.2–6.8)	6.9 (4.2–9.5)	8.5 (7.9–10.0)	
	MAP (mm)	773 (718–862)	626 (568–683)	948 (629–1,520)	619 (546–929)	
	MAQ (mm)	246 (146–550)	256 (239–343)	674 (287–1,067)	241 (150–467)	
	totN conc; flux	4,298; 1,151	2,694; 911	4,440; 3,000	4,419; 1,481	4,231; 1,450
	totP conc; flux	107; 28	90; 26	130; 151	172; 48	128; 44
Natural	n	7	4	7	12	30
	area (km^2)	4.6 (0.4–16)	1.2 (0.72–5)	2.6 (0.4–25)	1.2 (0.04–9)	
	Elevation (m.a.s.l)	53 (8–93)	183 (166–320)	521 (163–935)	322 (127–643)	
	Agriculture (% of area)	1 (0–10)	0 (0–0)	0 (0–0)	0 (0–0)	
	Forest (% of area)	90 (8–99)	72 (53–84)	20 (4–90)	81 (59–92)	
	Peatland (% of area)	0 (0–0)	28 (16–47)	6 (0–22)	14 (0–38)	
	MAT (°C)	10.0 (9.5–10.7)	3.7 (1.2–4.0)	5.1 (1.8–7.8)	5.2 (2.9–8.5)	
	MAP (mm)	824 (782–1,003)	691 (607–754)	1,203 (553–3,719)	760 (622–1,186)	
	MAQ (mm)	168 (98–218)	336 (289–376)	1,150 (436–2,299)	523 (315–946)	
	totN conc; flux	960; 117	240; 77	226; 240	318; 139	280; 139
	totP conc; flux	48; 10	7; 2	3; 4	7; 4	7; 4
Forestry	n		8	1		9
	area (km^2)		14.6 (0.7–56)	0.3		
	Elevation (m.a.s.l)		158 (41–270)	590		
	Agriculture (% of area)		0 (0–3)	0		
	Forest (% of area)		64 (38–98)	73		
	Peatland (% of area)		36 (2–59)	22		
	MAT (°C)		3.0 (0.9–6.7)	5.1		
	MAP (mm)		647 (588–754)	840		
	MAQ (mm)		389 (229–444)	877 (877–877)		
	totN conc; flux		584; 200	345; n.d.		555; 200
	totP conc; flux		22; 7	8; n.d.		20; 7

Note: Data for climate, discharge, concentrations and fluxes are given for the period 2000–2018. Concentrations and fluxes are medians of median annual values; units for totN and totP concentrations in $\mu g\ L^{-1}$; totN and totP fluxes in $kg\ km^{-2}\ year^{-1}$.
Abbreviations: MAP, mean annual precipitation; MAQ, mean annual discharge; MAT, mean annual temperature.

(subsurface drainage) to peat and sandy soils (subsurface drainage) (Bechmann, 2014).

The seven natural catchments in Norway are part of the national program for monitoring effects of long-range transported air pollution (Garmo & Skancke, 2018). Monitoring started during the early 1970s in four stations (de Wit, Hindar, & Hole, 2008), and around 1990 in three other stations. The catchments are all located on acid-sensitive bedrock and land cover varies from forest, forest interspersed with peatland, and predominantly tundra or bare rock. Catchments are hydrologically well-defined, with gneissic and granitic bedrock and soils developed on moraine/glacial till. The forestry site at Langtjern was established in 2008 (De Wit et al., 2014).

Eight of the 10 Swedish agricultural catchments are from the Swedish national agricultural monitoring program, and two are from a less intensively monitored regional program (Kyllmar et al., 2014a). The monitored catchments were established between 1988 and 1996. All catchments have a large proportion of agricultural land, most of which is tile drained. Catchments cover the main variations in climate and geological characteristics in Sweden and hence in agricultural production (Kyllmar et al., 2014b). In south-west Sweden, catchments have sandy loam soils and are characterized by intensive crop production including cereals, rape seed, potatoes and vegetables. In the southern inland highlands, where precipitation is higher and soils are coarse, grass and dairy production are typical. Swedish catchments with clay soils, mainly located in the central agricultural areas, are characterized by production of cereals and rape and a low number of animal units. In east Sweden, catchments with sandy loam soils have mixed crop production including irrigated areas with potatoes. In 2004, the sampling method changed from grab sampling to flow-proportional composite sampling and in this study only data from 2004 and onwards were used.

The 12 Swedish natural catchments were established to study long time trends in natural, undisturbed areas (Folster, Johnson, Futter, & Wilander, 2014) and consequently have not been impacted by forest management in the past four to five decades. Four catchments belong to the Integrated Monitoring of the Environmental Status in Swedish Forested Ecosystems (IM), established in the late 1980s and mid-1990s (Vuorenmaa et al., 2018). Six catchments are included the PMK5 long-term monitoring program (Folster & Wilander, 2002), one is part of the Krycklan Catchment Study (Laudon et al., 2013) and one is included in the Integrated Studies of the Effects of Liming Acidified Waters, ISELAW program (Appelberg, Lingdell, & Andren, 1995) where liming took place around 1990. Catchments are hydrologically well-defined and several of the catchments include a small lake or pond (0–13% water). All Swedish forested catchments are dominated by coniferous stands and the granitoid bedrock is covered with till-soils interspersed with mires and small lakes.

2.1 | Water chemical data and analytical methods

Common variables in all monitoring programs were totN and totP. In the natural catchments, monitoring programs also included nitrate (NO_3), ammonium (NH_4) (allowing computation of total organic N, TON) and total organic carbon (TOC). In Finnish catchments and some Danish natural catchments, dissolved reactive phosphorus (DRP) and suspended solids (SS) were included. In agricultural catchments, NO_3 was most often included in addition to DRP and SS. All monitoring programs used accredited laboratories and standardized analytical programs (Bechmann et al., 2008; Folster et al., 2014; Garmo & Skancke, 2018; Kortelainen et al., 2006; Kyllmar et al., 2014a; Pengerud et al., 2015).

2.2 | Calculation of fluxes

Element fluxes in catchments with grab sampling were calculated by linear interpolation of daily nutrient concentrations between sampling dates, multiplying daily concentrations with daily discharge to sum over a calendar year to give annual element export. In catchments with flow-proportional sampling, annual and monthly concentrations were calculated by summarizing daily fluxes over a month or a year and divided by total water discharge during the corresponding period. Daily nutrient fluxes were obtained by multiplying daily water discharge with concentrations in the corresponding weekly/ fortnightly water sample. Daily concentrations were set to be constant for the period between outtake of composite water samples, most often every second week (Wenng et al., 2020).

2.3 | Climate data

For each catchment, mean annual and summer (June, July, August) temperature and precipitation were derived from publicly available gridded datasets using area-weighted catchment averages. For Finland, Norway and Sweden, data were obtained from the Norwegian Meteorological Institute Nordic Gridded Climate Dataset, version 19.09, with a spatial resolution of 1×1 km (met.no). Data with a daily resolution, interpolated to a grid from observational data using Bayesian interpolation and scale-separation concepts, was used as input data. For Denmark, hourly timestep ERA5 data with a resolution of 0.25° (https://climate.copernicus.eu/climate-reanalysis) were used.

2.4 | Trend analysis

Annual median concentrations (totN, totP, NO_3, DRP and SS) were calculated using monthly median concentrations in all sites for the period 2000–2018 where at least 10 years of data were available. This guaranteed comparability as sampling method (grab or composite) and periods differed among countries and sites. Clear outlier data points outside normal variation (including extremes) were excluded from the median concentration calculations. Annual fluxes for totN and totP were calculated following standard national procedures. All statistical tests were run in R (version 3.5.0). For trend analyses, we used the Mann-Kendall trend test with R package

TTAinterfaceTrendAnalysis. We applied the Mann-Kendall trend test to yearly median concentrations and fluxes for the period 2000–2018 and used the Theil-Sen estimator to estimate temporal concentration trends. The Theil-Sen estimator can be applied when the data contains outliers or when data are missing (Bouza-Deaño, Ternero-Rodríguez, & Fernández-Espinosa, 2008). To transform absolute changes into relative changes, in percent per year, we multiplied Theil-Sen slopes by 100 and divided by the long-term median values. We used Regional Mann-Kendall analysis using R package rtk to study patterns in trends at country level (Norway, Finland, Sweden and Denmark) for concentrations (totN, totP, NO_3, DRP and SS) and fluxes (totP and totN).

2.5 | Statistical analysis

Partial least square regression (PLS) was used to evaluate how environmental variables explained the variance of median totN and totP concentrations as dependent variables. PLS is particularly useful, when a large set of explanatory variables is given and variables are collinear (Abdi, 2007; Wold, Sjostrom, & Eriksson, 2001). The explanatory variables used, in both the totN and totP model, were latitude, longitude, land cover categories (agriculture, forest, peatlands, shrublands and lakes), annual and summer mean temperature, annual runoff, annual precipitation and summer precipitation (Table SI-1). The strength of the PLS models was evaluated by the goodness of fit, r^2, and the goodness of prediction, Q^2, for each component. The importance of each explanatory variable was related to the variable influence on the projection (VIP). Variables with a VIP value above 1 are commonly identified as most influential when explain the variance of dependent variables. The PLS was run in R version 3.5.2 using the packages pls and plsdepot.

3 | RESULTS

3.1 | Catchment characteristics and mean water chemistry and nitrogen and phosphorus fluxes

The study sites included 30 agricultural catchments, 30 natural catchments and 9 forestry impacted catchments (8 in Finland, 1 in Norway), distributed throughout the Nordic countries (Figure 1, Table 1, Table SI-1). Catchment areas ranged between <0.5 km^2 to >25 km^2, with a tendency towards smaller-sized natural catchments. In Finland, peatlands covered on average 28% of the catchment area in natural and in forestry-impacted sites, considerably more than in Sweden (14%) and Norway (6%). Forest was the dominant land cover in natural catchments except in Norway, where mountains and shrublands dominated. The agricultural sites were generally located at lower elevations than the natural and forestry-impacted sites, except in Denmark. Agricultural sites had a warmer climate than natural and forestry-impacted sites, probably partly because of lower elevation and placement at lower latitudes with favourable climatic conditions for agriculture. East–west precipitation gradients are considerable in the Nordic countries, illustrated by the high precipitation received by the Norwegian catchments compared with Finland, while Denmark and Sweden were intermediate. Annual runoff was highest in Norway and lowest in Denmark. Low runoff in Denmark is notable because precipitation here was not markedly different from Finland and Sweden.

Median concentrations of totN and totP declined in the following order: agriculture (totN 4.2 mg L^{-1}; totP 0.14 mg L^{-1}) > forestry (totN 0.6 mg L^{-1}; totP 0.02 mg L^{-1}) > natural (totN 0.28 mg L^{-1}; totP 0.007 mg L^{-1}) (Table 1). Ranges in concentrations of totN and totP overlapped between countries, with a tendency towards highest totP in Sweden and Norway in the agricultural catchments and the lowest totP in natural Norwegian catchments (Figure 2). For totN, countries were more similar than for totP. In Denmark, ranges in totP and totN of agricultural and natural catchments were more similar than in other Nordic countries.

In all land-use categories, NH_4 made up a very small part of totN concentrations (<5%) (Table 2). By contrast, NO_3 was the dominant fraction of totN in agricultural catchments (55–85%) while in natural and forestry-impacted catchments, concentrations of NO_3 were between 1% and 17% of totN, with Denmark as a notable exception (59%). In natural and forestry-impacted catchments, the organic fraction dominated totN (77–95%). In agricultural catchments, DRP was between 24 and 38% of totP and was significantly correlated with totP (data not shown, r^2 = 0.54, p < .0001). In natural catchments, totP was significantly correlated with TOC (data not shown, r^2 = 0.76, p < .0001) suggesting that most totP was organic P. In Danish natural sites, totP concentrations were positively correlated with SS (p < .05, data not shown) and negatively with TOC (p = .053), suggesting that totP here was particle-bound rather than of organic origin. Where DRP was measured in natural catchments (14 sites), it made up 18–42% of totP, which indicates that a considerable part of totP was bio-available. The DRP fraction is traditionally thought to identify inorganic reactive fractions of P but may also include labile organic fractions (e.g., Haygarth & Sharpley, 2000). SS were correlated with totP in agricultural catchments (data not shown, r^2 = 0.38, p < .001), indicating that a considerable part of totP was particle-bound.

Median annual fluxes of totN and totP (kg km^{-2} $year^{-1}$) declined in the order agriculture (totN 1,450; totP 44) > forestry (totN 200; totP 7) > natural (totN 139; totP 4) (Table 1). Norway had the highest totN fluxes in agricultural and natural catchments, probably because of higher runoff (Figure 3). The same pattern emerged for totP fluxes in agricultural catchments, but the Danish natural catchments exported more totP than the other natural catchments despite lower runoff.

3.2 | Spatial patterns in concentrations and fluxes

We explored spatial patterns in totN and totP concentrations and fluxes in relation to land use climate and runoff. Flow-weighted and arithmetically averaged concentrations revealed similar relationships

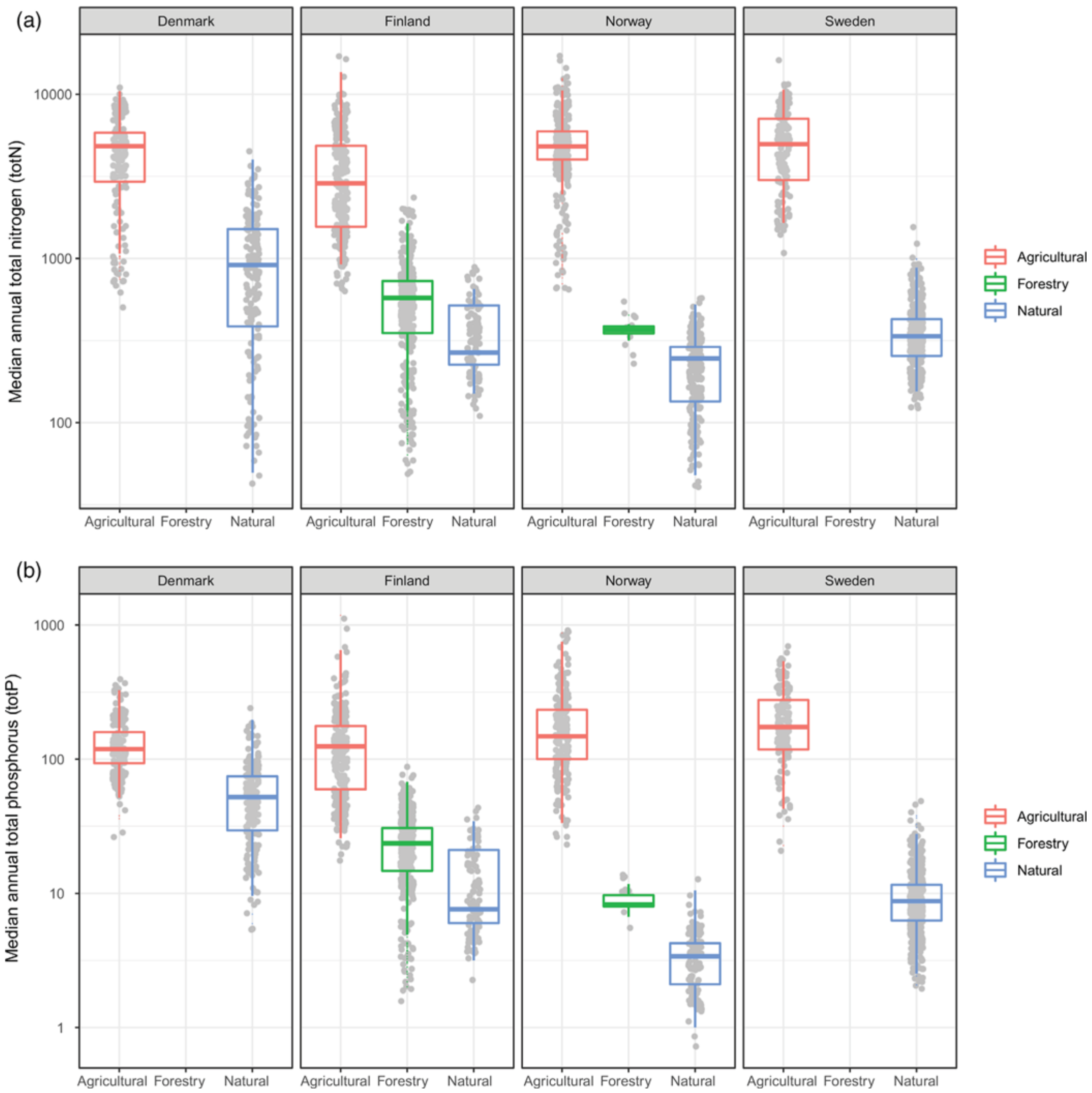

FIGURE 2 Concentration ranges for the grouped sites, for median totN and totP (μg^{-1}) calculated for annual averages for agricultural (n = 30), forestry (n = 9) and natural (n = 30) sites for the period 2000–2018

(data not shown) and we focus here on results for arithmetically averaged concentrations and fluxes.

The PLS models with annual median totN and totP concentrations as dependent variables revealed similar relationships. Only the results for totN are given here (Figure 4) while totP results are given in SI (Figure SI-1). The first two components explained 71% of the variance of totN concentrations between catchments (r^2) and the prediction ability (Q^2) was 66%. The catchment scores for each component (Figure 4a) clearly distinguished agricultural sites from natural and forestry-impacted sites. The Danish natural sites (labelled specifically because of deviations from other natural sites, see paragraph 3.1) also clustered together. The PLS model for totN included five explanatory variables with a VIP value above 1; the proportion of agricultural land cover, summer temperature and annual temperature, all of which were positively related, and forest cover and latitude, which were negatively related to totN (Figure 4b). This suggests that totN and totP concentrations were largely driven by a land-use gradient, from high percentage agriculture to high percentage forest. This land-use gradient is to a large extent also a climate gradient, with highest nutrient concentrations associated with warmer regions located in the

TABLE 2 Mean concentrations of totP, totN, TOC and suspended solids (SS), and mean fractions (in mass/mass) for DRP to totP, SS to totP, TON to totN, NO_3 to totN and NH4 tot totN, grouped by land use category and country (DEN, Denmark; FIN, Finland; NOR, Norway; SWE, Sweden), calculated from median concentrations for each site

			totP	DRP:TotP	SS:TotP	TotN	TON:TotN	NO_3:totN	NH_4:totN	TOC	SS
Category	Country	n	μg L^{-1}	g g^{-1}	g g^{-1}	μg L^{-1}	g g^{-1}	g g^{-1}	g g^{-1}	mg C L^{-1}	mg L^{-1}
AGR	DEN	5	107	0.38	0.15	4,298	0.54	0.81	0.02	n.d.	14
	FIN	6	90	0.24	0.28	2,694	0.29	0.55	0.04	13	17
	NOR	9	130	0.36	0.18	4,440	n.d.	0.77	n.d.	n.d.	11
	SWE	10	172	0.31	0.29	4,419	n.d.	0.85	0.00	9	38
FOR	FIN	8	22	0.25	0.21	584	0.77	0.14	0.02	16	4
	NOR	1	8	n.d.	n.d.	345	0.92	0.02	0.05	17	n.d.
NAT	DEN	7	48	0.40	0.10	960	0.36	0.59	0.03	15	4
	FIN	4	7	0.18	0.09	240	0.95	0.01	0.01	11	1
	NOR	7	3	n.d.	n.d.	226	0.79	0.17	0.03	3	n.d.
	SWE	12	7	0.42	0.15	318	0.90	0.05	0.03	9	1

Note: Note that full records were not available for each variable (Supplementary information, Table 2).
Abbreviations: AGR, agricultural; FOR, forestry-impacted; n, number of sites; NAT, natural; n.d., no data.

southern part of the Nordic countries. By contrast, the natural land cover types, that is, forests, peatlands, lakes and shrublands were associated with lower nutrient concentrations and were grouped together with precipitation and runoff, demonstrating that natural and more nutrient-poor catchments are located in colder and wetter regions of the Nordic countries. Thus, climate and land use are confounded which implies that identification of separate impacts of these two factors is challenging.

The PLS analysis and the correlation matrix (Figure SI-2) were consistent in identifying percentage agriculture as the most important driver of totN and totP concentrations, while %forest had the opposite effect. However, %agriculture and %forest were strongly negatively correlated. In addition, the PLS identified positive relationships between nutrient concentrations and (annual and summer) temperature and negative relationships with runoff. Using a simple linear regression analysis, we tested the explanatory power of single drivers for variation in totN and totP concentrations and fluxes within each land use category (Figure 5). Significant ($p < .05$) relationships between nutrient concentrations and summer temperature were found for the natural (totN: r^2 0.50; totP: r^2 0.50) and forestry-impacted catchments (totN: r^2 0.79; totP: r^2 0.50) (Figure 5a,b), but not for agricultural catchments. In the natural catchments, summer temperature was positively correlated with log-transformed concentrations of TON and TOC (data not shown, TON: $r^2 = 0.48$, $p < .0001$; TOC: $r^2 = 0.43$, $p < .0001$).

There were no significant correlations between annual mean runoff and fluxes of totN and totP (SI Figure 2), which surprised us because discharge is used to calculate element fluxes. Possibly, differences in seasonality of runoff and nutrient concentrations are stronger controls of the total annual fluxes than the annual runoff itself. In managed catchments, fertilizer application and remineralization of crop residues are important causes of seasonal variation in nutrient concentrations. Within each land-use category, positive relationships between runoff and fluxes of totN ($r^2 = 0.26$) and totP ($r^2 = 0.59$) were found for agricultural catchments and for fluxes of totN in natural catchments ($r^2 = 0.35$) (Figure 5c,d).

Natural catchments had less variation in soil type than agricultural catchments (SI Table 1), that is, they were dominated by moraine soils while the agricultural sites had clay, loam, peat and sandy soils. Grouping of sites by management and soil type did not result in a better explanation of factors driving N and P export (data not shown).

3.3 | Trends in concentrations and fluxes

We used annual mean flow-weighted concentrations and annual medians of measured concentrations as basis for trend estimates and found no significant differences using a pair-wise comparison (data not shown). Consistent with the other results reported, we continue with reporting trends based on the median concentrations. Absolute and relative trends in both fluxes and concentrations of totP and totN showed considerable variation between land use categories and countries (Figure 6), without the emergence of clear spatial patterns. Out of 69 sites, 22 and 25% had significant change in totN and totP concentrations, respectively. For totN concentrations, negative significant trends exceeded positive trends ($p < .05$, 4 positive, 11 negative). In addition, for totP, negative trends were more frequent than positive trends ($p < .05$, 6 positive, 11 negative). Fewer sites displayed significant changes in fluxes (totN: $p < .05$, 6%; totP: $p < .05$, 9%) and runoff ($p < .05$, 9%) The forestry-impacted sites had a relatively high number of significant trends (three and four out of nine sites had significant change in totN and totP concentrations, respectively), and the directional change of the significant totN and totP trends was consistent in each site.

Patterns of changes emerged when testing concentrations and fluxes of totN, totP, NO_3, and DRP for each land use category in a

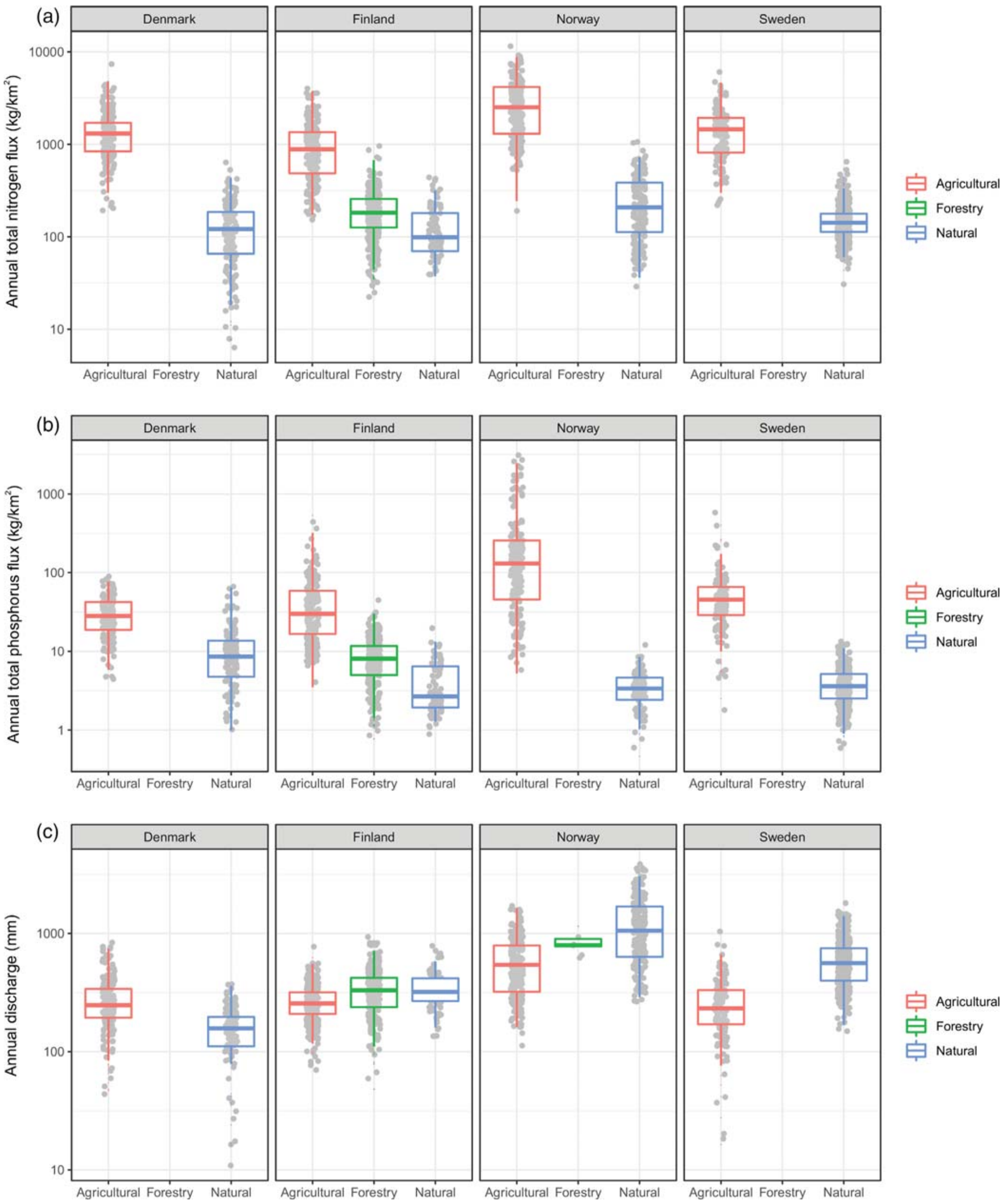

FIGURE 3 Flux and annual discharge ranges for the grouped sites, for median annual totN and totP flux (kg km^{-2}) from agricultural (n = 30), forestry (n = 9) and natural (n = 30) sites for the period 2000–2018

regional Mann-Kendall test (Table 3). The sen-slopes in Table 3 are in absolute units, in contrast to the trends in Figure 6. In agricultural sites across the Nordic countries, there was a significant ($p < .01$) downward trend in concentrations of totN (–15 μg L N $^{-1}$ year^{-1}) and a weakly significant downward trend in NO_3 ($p < .1$) (–9 μg L N $^{-1}$ year^{-1}). The natural sites show significant downward trends in

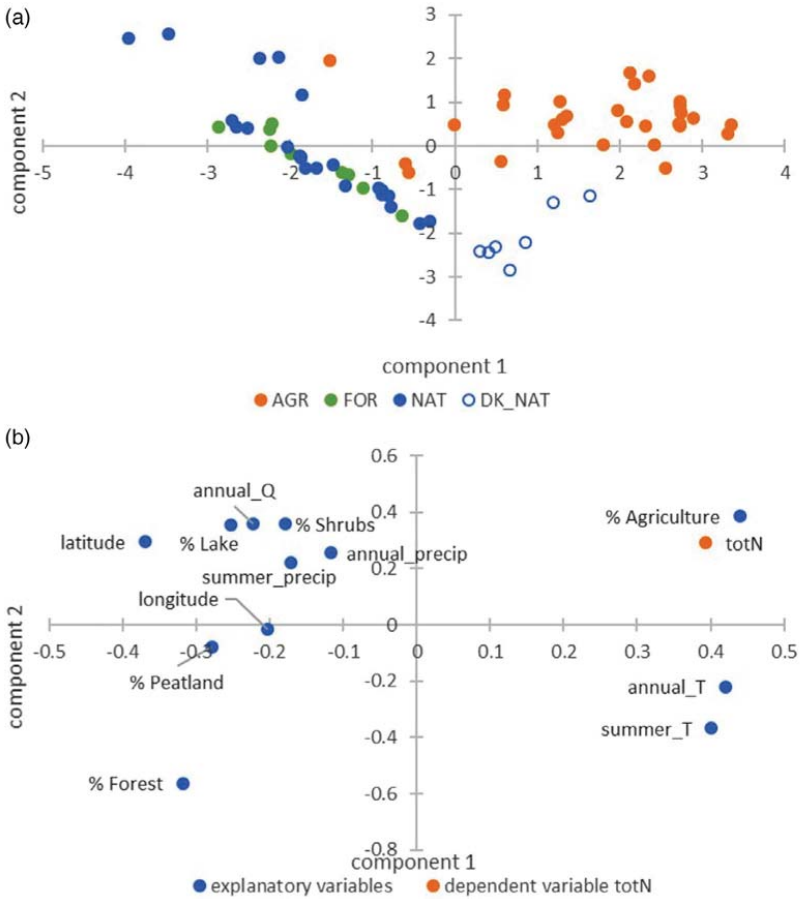

FIGURE 4 (a) Scoring of each single observation (catchments) for the two first components; (b) Loading of the explanatory variables and the dependent variable totN concentration for the first two components

concentrations of NO_3, totP and DRP. The sen-slope for NO_3 (–0.42 μg N L^{-1} $year^{-1}$) was similar to the sen-slope in totN (–0.45 μg N L^{-1} $year^{-1}$) for natural sites. Results from agricultural and natural sites suggest that most of the changes in totN were related to changes in NO_3 (Table 3).

In agricultural sites, significant downward trends in concentrations of P-species in Denmark (–0.3 μm L^{-1} $year^{-1}$ DRP) contrasted with significant upward trends in Norway and Sweden (+1.2 and +0.6 μm L^{-1} $year^{-1}$ DRP, respectively), resulting in a lack of change for all agricultural sites combined. Trends in N-species concentrations were mostly downward across all countries. In the natural sites, only Sweden had a significant downward change in totN concentrations.

With regard to fluxes, the regional M-K results (Table 4) indicated a significant decline in export of NO_3, at rates of –6.7 and –0.25 kg N km^{-2} $year^{-1}$, for agricultural and natural catchments, respectively, consistent with the trend in NO_3 concentrations but not with the trend in totN concentrations. Export of totP showed a strong positive trend (p < .05, 0.4 kg P km^{-2} $year^{-1}$) for agricultural sites despite the variations in trends strength between countries, and the contrasting results for totP concentrations. For all natural sites combined, the export of DRP declined significantly (p < .05, –0.02 kg P km^{-2} $year^{-1}$).

Thus, the regional M-K results indicated downward trends in the Nordic countries in N-species across land use categories, downward trends in concentrations of P-species in natural and forestry-impacted sites, and increases in totP export from agricultural catchments.

In a correlation matrix, we tested if the trends in concentrations and fluxes of N and P species could be related to trends in climate (temperature, precipitation) and hydrology (discharge) within each land use category but except for forestry-impacted sites, few significant correlations were found (Figure SI-3). In the forestry-impacted sites (n = 8), trends in runoff correlated negatively with trends in nutrient species, but its significance largely depended on one site and we do not regard this result as particularly robust. Thus, regional patterns of change in totN and totP concentrations for 2000 to 2018 could not be explained with simple relationships with climate and runoff.

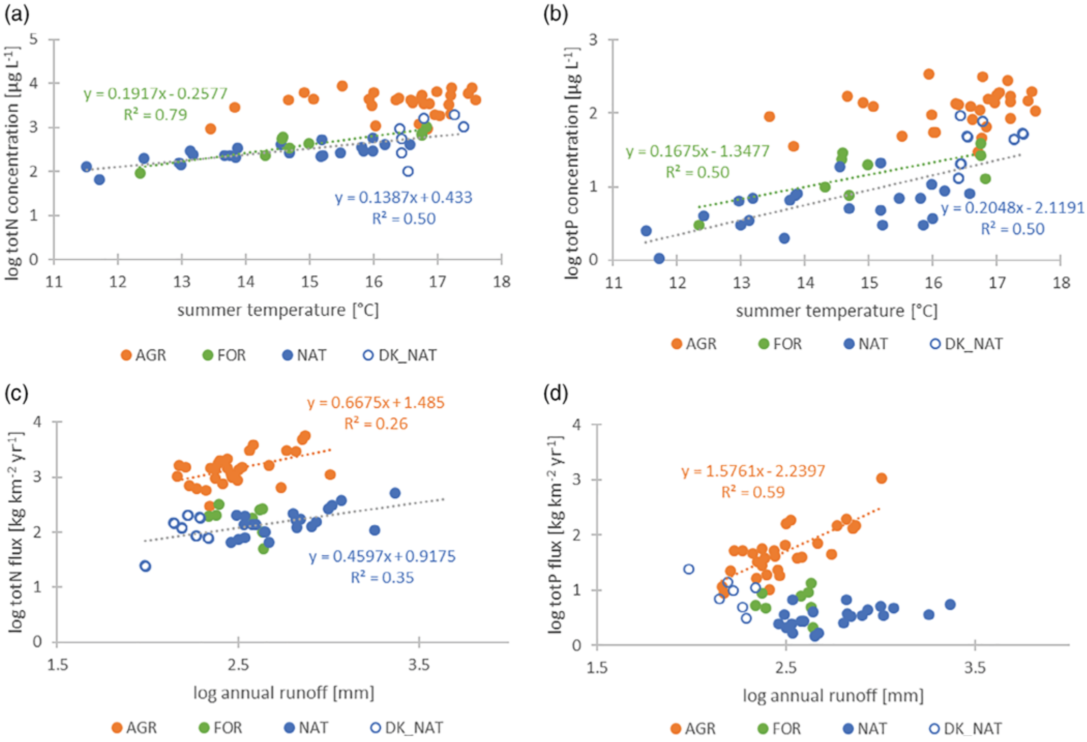

FIGURE 5 Concentrations of totN and totP (log-transformed) versus summer T (panel a, b); fluxes of totN and totP (log-transformed) versus annual runoff (log transformed) (panel c, d). Only significant regression lines for each land use category (significant slopes, $p < .05$) are shown. AGR, agricultural catchments; FOR, forestry-impacted catchments; NAT, natural catchments; DK_NAT, natural catchments in Denmark (included in the NAT regression equations)

4 | DISCUSSION

Long-term water quality and hydrological records from headwater Nordic catchments spanning large environmental and climate gradients offer a unique possibility to evaluate combined effects of land use, land cover and climate on surface water quality in managed and unmanaged landscapes. Most often, long-term assessments focus on a dominant land use, either agricultural (Blann, Anderson, Sands, & Vondracek, 2009; Pengerud et al., 2015), forestry-impacted (Kreutzweiser et al., 2008) or natural catchments (Vuorenmaa et al., 2018). Significant proportions of nutrient loadings from Nordic countries to marine recipients originate from agriculture, natural and semi-natural ecosystems (HELCOM, 2018; Lepisto, Granlund, Kortelainen, & Raike, 2006) suggesting that changes in nutrient runoff from both managed and unmanaged ecosystems is pertinent to the ecological status of receiving waters.

We found that long-term averaged nutrient concentrations and export were an order of magnitude higher from agricultural catchments compared with forestry-impacted and natural catchments, and that forestry-impacted catchment delivered significantly more nutrients than natural catchments. The high nutrient export from agricultural catchments is primarily driven by long-term surpluses of N and P, as indicated by statistics on gross nutrient balances (calculated from inputs of manure and fertilizer and removal from harvest) for agricultural land which vary roughly between 30 and 120 kg ha year^{-1} for N, and 0 to 12 kg ha year^{-1} for P in the Nordic countries after 2000 (Eurostat, 2020). In natural catchments, the main source of nutrient loading is atmospheric deposition, typically between 1 and 10 kg N ha^{-1} year^{-1} (Vuorenmaa et al., 2017) and usually retained for 90% within the catchment (Vuorenmaa et al., 2017; Watmough et al., 2005). In some agricultural catchments, losses of nitrogen may be close to a steady-state between inputs and outputs (Basu, Thompson, & Rao, 2011; Thompson, Basu, Lascurain, Aubeneau, & Rao, 2011). However, catchment characteristics such as tile drainage, topography, texture and mitigation measures to reduce nutrient runoff will control the fate of the nutrient excess, that is, runoff, groundwater or soil storage (Hellsten et al., 2019; Kronvang et al., 2005a; Kronvang, Vagstad, Behrendt, Bogestrand, & Larsen, 2007). Forest management typically consists of a mosaic of numerous treatments (harvesting, drainage, fertilization, soil tillage) with considerable

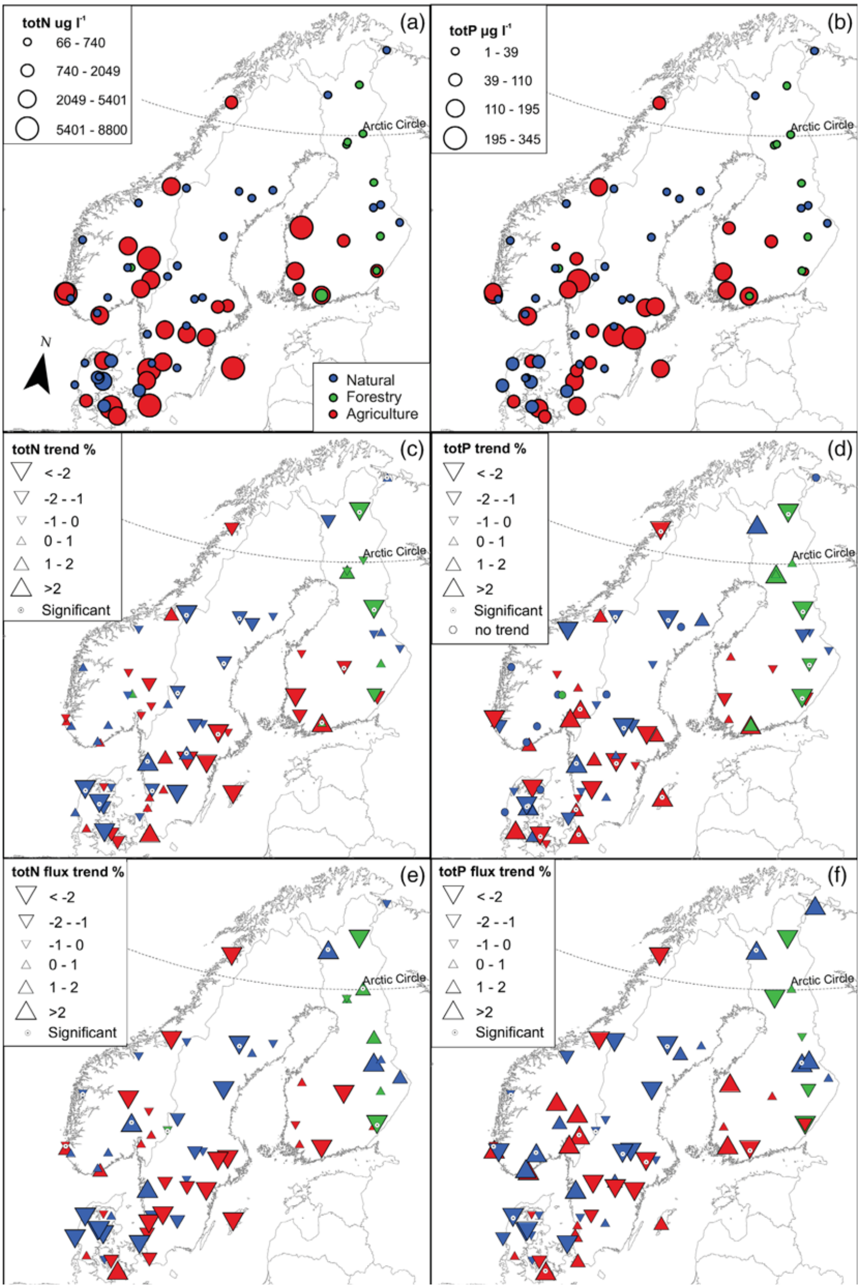

FIGURE 6 Map showing annual median concentrations of (a) totN and (b) totP, (c) trend of annual median totN concentration (% year^{-1}), (d) trend of annual median totP concentration (% year^{-1}), (e) trend of annual flux for totN (% year^{-1}) and (f) trend of annual flux for totP (% year^{-1}) for the period 2000–2018

TABLE 3 Results of regional Mann-Kendal test for concentrations of totN, NO_3 (in μg N L^{-1} $year^{-1}$), totP and DRP (in μg P L^{-1} $year^{-1}$), grouped by agricultural (AGR), Forestry-impacted (FOR), Natural NAT) sites and country

		Denmark slope	p	Finland slope	p	Norway slope	p	Sweden slope	p	All slope	p
AGR	totN	−8.9	n.s.	−22.6	*	−24.0	*	−7.1	n.s.	−15.2	**
	NO_3	−4.4	n.s.	−25.0	*	−13.9	n.s.	31.3	n.s.	−9.5	n.s.
	totP	−0.8	**	−0.3	n.s.	1.2	n.s.	1.6	n.s.	0.1	n.s.
	DRP	−0.3	***	−0.2	n.s.	0.6	*	1.2	**	0.0	n.s.
NAT	totN	−2.7	n.s.	−0.4	n.s.	0.5	n.s.	−1.8	**	−0.45	n.s.
	NO_3	−2.7	*	0.0	n.s.	−0.4	**	−0.6	***	−0.42	***
	totP	0.3	n.s.	−0.1	*	0.0	n.s.	−0.02	n.s.	−0.01	*
	DRP	−0.05	n.s.	n.d.		n.d.		−0.10	***	−0.03	***
FOR	totN	n.d.		−1.7	n.s.	n.d.		n.d.			
	NO_3	n.d.		0.3	n.s.	n.d.		n.d.			
	totP	n.d.		−0.1	*	n.d.		n.d.			
	DRP	n.d.		n.d.		n.d.		n.d.			

Note: Significance levels: *<.05, **<.01, ***<.001, n.s., *p* > .05. n.d., no data.

TABLE 4 Results of regional Mann-Kendal test for fluxes of totN, NO_3 (in kg N km^{-2} $year^{-1}$), totP and DRP in kg P km^{-2} $year^{-1}$), grouped by agricultural (AGR), Forestry-impacted (FOR), Natural NAT) site and country

		Denmark slope	p	Finland slope	p	Norway slope	p	Sweden slope	p	All slope	p
AGR	totN	0.34	n.s.	0.35	n.s.	−5.15	n.s.	−27.6	*	−8.46	n.s.
	NO_3	−7.21	n.s.	−3.23	n.s.	−2.73	n.s.	−18.1	n.s.	−6.72	*
	totP	0.13	n.s.	0.52	*	2.33	***	−0.66	n.s.	0.44	**
	DRP	0.01	n.s.	0.021	n.s.	0.507	**	−0.17	n.s.	0.055	n.s.
NAT	totN	−0.67	n.s.	1.08	n.s.	2.42	**	−0.51	n.s.	0.18	n.s.
	NO_3	−0.99	*	−0.018	n.s.	−0.17	n.s.	−0.29	***	−0.25	***
	totP	−0.16	n.s.	0.035	n.s.	0.055	*	0.00	n.s.	0.007	n.s.
	DRP	−0.02	n.s.	−0.0032	n.s.			−0.038	**	−0.022	*
FOR	totN			1.44	n.s.					1.44	n.s.
	NO_3			0.045	n.s.					0.045	n.s.
	totP			−0.044	n.s.					−0.044	n.s.
	DRP			n.d.						n.d.	

Note: Significance levels: *<.05, **<.01, ***<.001, n.s., *p* > .05. n.d., no data.

temporal and spatial variations (Ahtiainen & Huttunen, 1999; Kreutzweiser et al., 2008; Tattari et al., 2017). In forestry-impacted catchments, elevated nutrient runoff compared with natural catchments can be related both to application of fertilizer and to mobilization of soil nutrient stores.

When considering all land use categories simultaneously, we found that spatial variations in site-specific totN and totP concentrations were largely driven by a land-use gradient which partly overlapped with a climate gradient, demonstrating that climate and land use are confounded. The highest nutrient concentrations were associated with warmer, agricultural regions located in the south. Natural land cover types (i.e., forests, peatlands, lakes and shrublands) with lower nutrient concentrations were associated with cooler and wetter conditions. Agricultural land cover was the single-most powerful explanation for describing spatial variation in nutrient concentrations and can be considered as a proxy for gross nutrient balances as discussed earlier. Consistent with our study, totN and totP concentrations in Norwegian lakes, including natural and agriculturally impacted systems, were found to be positively related to terrestrial productivity and negatively to runoff (Hessen, Andersen, Larsen, Skjelkvale, & de Wit, 2009). Hessen and co-authors also highlighted nitrogen deposition as a strong driver of aquatic concentrations of N-species. This factor is likely to be most easily detectable in catchments with low nitrogen retention capacity, that is, with little soil and vegetation cover (Kaste, Austnes, & de Wit, 2020).

The positive correlations between spatial variation in totN concentrations and summer temperature in the natural and forestry-impacted catchments were mirrored by positive correlations between TON and summer temperature, and TOC and summer temperature. This suggests these correlations are a demonstration of the strong links between the element cycles of nitrogen and carbon in forested ecosystems (Mattsson, Kortelainen, & Raike, 2005). Surface water concentrations of dissolved organic matter are highest in carbon-rich catchments (Sobek, Tranvik, Prairie, Kortelainen, & Cole, 2007), which are found in Nordic regions with higher average temperatures (Callesen et al., 2003). Temperature, particularly during summer season, can be interpreted as a proxy for terrestrial productivity at least in climate where moisture is mostly not a limiting factor (Piao et al., 2011). By contrast, significant relationships between nutrient concentrations and summer temperature were not found in agricultural catchments, suggesting that combined effects of crop, management practices and soil type are stronger controls on element cycling than temperature in these systems (Bechmann et al., 2008).

Danish natural catchments had three to five times higher nutrient concentrations than other Nordic natural catchments, which could be indicative of profound differences in natural reference conditions (Skarbovik et al., 2020). The EU WFD (EC, 2000) defines reference conditions as "water bodies with no, or only very minor, anthropogenic alterations compared with conditions normally associated with undisturbed conditions". However, legacies of former land use (Hamilton, 2012) combined with lateral groundwater flow (Brunke & Gonser, 1997) in flat landscapes complicate interpretations of catchment effects on streamwaters. Geology, soils, climate and land use history in Denmark contrast with other Nordic countries (Emanuelsson, 2009). Deeper, sandy soils which predominate in the flat Danish landscape are probably associated with a relatively larger proportion of precipitation feeding groundwater, while the Fennoscandian shield is characterized by thinner soils, greater relief and more superficial hydrological pathways. Most loamy and clayey agricultural soils in Denmark are tile-drained which directs part of the precipitation surplus directly to surface waters (Møller, Børgesen, Bach, Iversen, & Moeslund, 2018). Skarbovik et al. (2020) also suggest that bank erosion may be more important in Danish than in other Nordic streams. In Norway and Sweden, agricultural soils are often tile-drained, especially clayey soils with low hydraulic conductivity that are more exposed to the risk of surface runoff. Steeper slopes in Norway also contributes to higher erosion and P export (Bechmann et al., 2008). In addition, higher temperatures and longer growing seasons make evaporative losses relatively more important in the hydrological cycle in southern parts of the Nordic countries (Kortelainen, Saukkonen, & Mattsson, 1997). The different composition of totN and totP species in agricultural and natural sites suggests a wide variation in susceptibility to hydrological and management impacts on their transport and leaching, for example, diffuse and particulate transport, and transport of nutrients in inorganic versus organic forms. Variation in soil type and texture was higher in agricultural catchments, with clay, loam, peat and sandy soils than in (semi-) natural catchments which were dominated by moraine soils.

We found a general decline in concentrations and fluxes of total nitrogen and NO_3 from agricultural and natural catchments in the Nordic region as a whole, for the period 2000–2018. These downward trends for agricultural catchments agree with the downward trends found in the gross N budget for agricultural land during the period 2000–2016, which is highest for Sweden (−27%) and lowest for Norway (−3%), with Denmark (−15%) and Finland (−14%) being in between (Eurostat, 2020). However, the reductions in both gross N budget and stream concentrations and fluxes of N were substantially higher during the 1990s in Denmark, Finland and Sweden (Hellsten et al., 2019; Windolf, Blicher-Mathiesen, Carstensen, & Kronvang, 2012). The reduction in gross N budget was driven by intensive mitigation campaigns to minimize N losses, especially in Denmark (Hansen, Thorling, Schullehner, Termansen, & Dalgaard, 2017; Kronvang et al., 2005b) and Sweden, where catch crop and spring ploughing were implemented (Folster et al., 2014). The totN load to 10 estuaries (catchments covering 35% of the Danish land area) decreased by 39% during the period 1990–2009 (Windolf et al., 2012) following mandatory national regulations on agricultural production (Kronvang et al., 2005b). Agricultural extensification in two Norwegian sites reduced totN export here, although there was little national focus on mitigation measures to reduce nitrogen losses (Hellsten et al., 2019). Earlier studies demonstrated a predominance of declines in nitrogen export from agricultural headwater catchments in Denmark and Sweden, but lack of change in Norway (Kyllmar et al., 2014a; Stålnacke et al., 2014). Changes in fertilizer application explained downward totN trends in Finnish agricultural catchments while upward trends were related to crop distribution (Tattari et al., 2017).

Declines in NO_3 concentrations in natural catchments dominated over change in totN. In natural catchments, most totN consists of organic N and the dynamics of organic N are closely linked to those of DOM, which is usually elevated during the summer and autumn (Lepisto, Kortelainen, & Mattsson, 2008) whereas NO_3 is highest during the dormant season (de Wit et al., 2008) and likely to be more strongly linked to atmospheric deposition (Vuorenmaa et al., 2018). The widespread decline in annual totN concentrations in agricultural and natural sites could not be explained by simple relationships with climate or runoff. Spatial variation in totN export was strongly related to annual runoff in agricultural catchments, however, and implies that increases in runoff could lead to increased element export (e.g., Oygarden et al., 2014). It is likely that investigations of climatic and hydrological impacts on water quality and element export would benefit from a focus on seasonal trends and/or from including a longer time period (de Wit et al., 2008; Jeppesen et al., 2009; Jeppesen et al., 2011; Wenng et al., 2020).

Given the profound contrasts in N concentrations between land use categories, and the lack of correlations between trends in N species and trends in climatic and hydrological variables, it is likely that the decline in N species is the concerted effect of various interplaying factors, including environmental policy. Other studies document long-term declines in reactive nitrogen from unmanaged and managed Nordic landscapes (Garmo et al., 2014; Rekolainen, Mitikka, Vuorenmaa, & Johansson, 2005) which are likely caused by changes in N deposition and climate-mediated changes in hydrology (de Wit et al., 2008; Kaste et al., 2020; Vuorenmaa et al., 2018). The decline in N deposition itself is related to reduced emissions to the atmosphere (Grennfelt et al., 2020). Lucas et al. (2016) suggested that increased forest growth was responsible for declining NO_3 concentrations in rivers draining natural and forestry-impacted landscapes in Northern Sweden, an area that receives relatively low levels of N deposition. Substantial increases in forest standing stock are common in Finland, Sweden and Norway (de Wit, Austnes, Hylen, & Dalsgaard, 2015; Luyssaert et al., 2010) suggesting that increased nitrogen uptake by forests may affect NO_3 leaching from forested catchments elsewhere in the Nordic region. In Chesapeake Bay, USA, a watershed with considerably higher proportion of agriculture and developed areas than the Nordic countries, declines in atmospheric N deposition were found to be the second-most important factor responsible for the decrease in N export to the bay (Ator, Garcia, Schwarz, Blomquist, & Sekellick, 2019).

Contrary to Lucas et al. (2016), Räike et al. (2020) suggest that forestry practices in Northern Finland have increased N runoff to the Baltic through increasing the area of ditched peatlands to promote forest growth, which has led to increases in organic N (Tattari et al., 2017). Forestry-impacted catchments exported on average over 40% more N than natural catchments, which suggests that forest management could substantially increase levels of totN in surface waters. Forest management-induced increases in N export from, for example, clear-cutting, soil preparation and ditching are well-documented (De Wit et al., 2014; Kreutzweiser et al., 2008; Nieminen et al., 2018), but the duration of increased nutrient export following disturbance is usually short relative to the forest rotation cycle (Sponseller et al., 2016). Furthermore, appropriate, context-sensitive (Ring et al., 2017) forest management can safeguard water quality (Sundnes et al., 2020; Sponseller et al., 2016).

Patterns of long-term change in totP concentrations and export were more varied temporally and spatially than for nitrogen; Denmark and Finland had significant declines while Sweden and Norway had significant increases in DRP, resulting in an overall neutral trend for all agricultural catchments (Kronvang, Tornbjerg, Hoffmann, Poulsen, & Windolf, 2016). To what extent climate can explain the patterns of long-term change in P export is unclear. Management of agricultural P-losses is complicated by increased precipitation intensity with subsequent increased erosion (Farkas, Beldring, Bechmann, & Deelstra, 2013) combined with a strong legacy of soil-P in the fields (Sharpley et al., 2013). Effects of mitigation of phosphorus sources might thus take several decades to document in monitoring programs (Bol et al., 2018; Mellander et al., 2018). In Norway, agricultural mitigation measures focused primarily on phosphorus, however, measures implemented to reduce totP export were changed in 2013 from general measures to measures only for high risk areas and increasing focus on production (Bechmann, Greipsland, & Falk Øgaard, 2019). Removal of subsidies to abstain from autumn tillage, followed by an increase in autumn ploughing and erosion appears to be an explanation for increases in totP export in two Norwegian catchments (Bechmann et al., 2020). Hardly any sign of significant change was found in the forestry-impacted catchments except for reduced P concentrations likely related to reductions in P fertilizing (Tattari et al., 2017). There was a small overall decline in totP for natural catchments, primarily related Finland and Sweden. Huser, Futter, Wang, and Folster (2018) suggest that the totP-decline in Swedish lakes could be a combined effect of climate change and increased uptake of phosphorus by forests, similar to the explanation provided for declining NO_3 runoff in northern Swedish rivers (Lucas et al., 2016). Increased forest growth may explain trends in Finnish natural catchments while the lack of change in totP in Norwegian natural catchments could be related to a lower proportion of forest in these catchments. The significant decline in P export from Finnish forestry-impacted catchments was, however, attributed to reduced fertilizer use.

The lack of widespread reductions in totP export is substantiated by long-term records from rivers in Finland (Räike et al., 2020) and Norway (Skarbovik, Stalnacke, Kaste, & Austnes, 2014), and from marine recipients (Frigstad et al., 2020; Kuss et al., 2020). Our study implies that mitigation of P is more challenging than for N, because of more variation in sources (Kronvang et al., 2007), complexity of hydrological pathways (Mellander et al., 2018) and delays in responses to mitigation as a consequence of legacy pools of phosphorus in soils (Bol et al., 2018; Jeppesen et al., 2009) and lake sediments (Couture et al., 2018).

Nutrient export from agricultural, forestry-impacted and natural ecosystems, in declining order of importance, is a strong control of freshwater and marine ecological status in the Nordic countries. Mitigation measure have been effective especially for reduction of nitrogen runoff, but the effect of mitigation can be counteracted by climate change (Crossman et al., 2013). If the green shift will be associated with intensification of agricultural and forest production and increased use of fertilizer, this will pose new challenges for protection of water quality (Marttila et al., 2020). Long-term monitoring records of small headwaters under varied combinations of land use, climate and land cover are valuable and necessary for assessing combined effects of stressors on water quality and nutrient cycling and retention at the landscape level. We recommend sustained funding of long-term monitoring of managed and unmanaged, natural catchments. Further analysis should consider (a) further inclusion of nutrient species (e.g., nitrate, particulate P, organic forms, and so forth) for investigation of possible contrasting responses to climate, runoff and mitigation and their impacts on aquatic ecology, (b) examine long-term patterns in seasonal variation, (c) incorporate information about nutrient inputs (including atmospheric deposition), and agricultural and forestry management.

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DATA AVAILABILITY STATEMENT

The raw data are openly available in a public repository that does not issue DOIs. The data that support the findings of this study are available from the corresponding authors upon reasonable request.

ORCID

Heleen A. de Wit https://orcid.org/0000-0001-5646-5390
Ahti Lepistö https://orcid.org/0000-0003-4021-2342
Hannu Marttila https://orcid.org/0000-0002-9744-2483
Martyn N. Futter https://orcid.org/0000-0002-9789-7138

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SUPPORTING INFORMATION

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Table SI-1: Characteristics of the 69 monitored catchments

Catchment	Cat.	Location [dec. degrees]		Size [km^2]	Avg. elevation m.a.s.l.	Land cover [%]							Dom. soil type	Basic management		Annual mean T [°C]	Annual P [$mm\ yr^{-1}$]
		Lat.	Long.			Agric	Forest	Devel.	Shrubs	Peatland	Lakes	Other		Agriculture	Forestry		
Denmark																	
Bolbro bæk,	A	55.1	9.1	7.52	30	80.8	7.0	7.3	0.0	0.9	2.4	1.6	sand	cereal/maize/ grass	managed	10.2	862
Højvads Rende	A	54.9	11.3	9.87	8	64.1	24.9	6	0	2.1	2.5	0.4	clay	cereal/sugar beet/grass	managed	10.7	773
Horndrup bæk	A	56	9.9	5.48	110	69.2	17.5	7.1	0.0	4.7	0.3	1.2	sand/ loam	cereal/grass	managed	9.7	764
Lillebæk	A	55.1	10.8	4.38	35	86.8	2.1	9.2	0.0	0.4	0.5	1.0	sand/ loam	cereal/grass	managed	10.5	718
Odderbæk	A	56.7	9.5	11.44	29	80.2	4.3	7.9	0.0	4.4	1.0	2.2	sand	cereal/maize/ potato/grass	managed	9.8	794
Følstrup	N	56	12.3	6.13	37	7	78	0	0	0	0	15	sand/ loam	n.r.	partly managed	10	782
Skærbæk	N	56.1	9.4	4.59	93	10	39	0	0	0	0	51	sand	n.r.	partly managed	9.5	834
Hestbæk	N	56.5	8.4	5.4	29	1	90	0	0	0	0	9	sand	n.r.	partly managed	10.1	940
Holstenhuus afløb	N	55.1	10.3	0.38	80	0	99	0	0	0	0	1	sand/ loam	n.r.	partly managed	10.4	787
Langslade rende	N	55.6	8.1	15.7	8	1	8	0	0	0	0	91	sand	n.r.	no manage ment	10.7	1003
Refskær bæk	N	56.8	10	2.78	53	1	96	0	0	0	0	3	sand	n.r.	partly managed	9.8	801
Rustrup Skovbæk	N	56.1	9.5	0.47	82	1	98	0	0	0	0	1	sand/ loam	n.r.	partly managed	9.6	824
Finland																	
Haapajyrä	A	62.9	22.5	6.09	25	57.4	19.6	0	0	23	0	0	clay	cereal/grass	managed	5.8	568
Hovi	A	60.4	24.4	0.12	42	100	0	0	0	0	0	0	clay	cereal		6.9	674
Latosuonoja	A	61.4	28.7	5.32	83	16.6	57.4	0	0	26	0	0	peat	cereal	managed	5.5	683

Catchment	Cat.	Location [dec. degrees]		Size [km^2]	Avg. elevation m.a.s.l.	Land cover [%]							Dom. soil type	Basic management		Annual mean T [°C]	Annual P [mm yr^{-1}]
		Lat.	Long.			Agric	Forest	Devel.	Shrubs	Peatland	Lakes	Other		Agriculture	Forestry		
Löytäneenoja	A	61.3	22.2	6.24	35	63.1	34.9	0	0	2	0	0	sand	cereals/root crops	managed	6.7	597
Ruunapuro	A	62.5	26.0	5.39	95	20.5	68.5	0	0	11	0	0	sand	cereal/grass	managed	5.2	619
Savijoki	A	60.6	22.7	15.21	54	39.1	53.9	0	0	7	0	0	clay	cereal/grass	managed	6.8	634
Huhtisuonoja	F	61.4	28.6	4.94	81	0	55	0	0	45	0	0	moraine	n.r.	managed	5.6	682
Kesselinpuro	F	62.7	29.0	21.7	95	1.3	48.7	0	0	50	0	0	peat	n.r.	managed	5.2	650
Kotioja	F	66.1	26.2	18.0	162	1	45	0	0	54	0	0	peat	n.r.	managed	2.8	644
Laanioja	F	68.4	27.4	13.6	270	0.3	97.7	0	0	2	0	0	moraine	n.r.	partly managed	0.9	588
Myllypuro	F	64.7	28.6	9.86	178	0.6	72.4	0	0	27	0	0	moraine	n.r.	managed	3.3	754
Teeressuonoja	F	60.4	24.4	0.69	41	0	87	0	0	13	0	0	moraine	n.r.	managed	6.7	680
Vähä-Askanjoki	F	66.6	27.7	15.62	155	0	83	0	0	17	0	0	moraine	n.r.	managed	2.3	603
Ylijoki	F	66.1	26.7	56.0	160	3	38	0	0	59	0	0	peat	n.r.	managed	2.8	644
Kelopuro	N	63.2	30.7	0.74	166	0	53	0	0	47	0	0	moraine	n.r.	natural	4.0	714
Liuhapuro	N	63.8	28.5	1.7	184	0	61	0	0	39	0	0	moraine	n.r.	natural	3.8	669
Lompolonjängänoja	N	68	24.2	5.14	320	0	83	0	0	17	0	0	moraine	n.r.	natural	1.2	607
Porkkavaara	N	63.9	29.6	0.72	182	0	84	0	0	16	0	0	moraine	n.r.	natural	3.7	754
Norway																	
Hotran	A	63.7	11.1	20.0	146	58	35	3	0	1	0	3	loam	cereal/grass	n.r.	6.9	948
Kolstad	A	60.9	10.8	3.08	259	68	26	6	0	0	0	0	sand/loam	cereal/grass	n.r.	5.8	629
Mørdre	A	60.1	11.4	6.8	180	65	28	3	0	4	0	0	clay	cereal	n.r.	6.6	738
Naurstad	A	67.3	14.8	1.456	48	35	29	1	0	24	11	0	peat	grass	n.r.	5.9	1220
Skas-Heigre	A	58.8	5.6	28.3	37	84	3	10	0	1	0	2	sand/loam	grass	n.r.	9.5	1318
Skuterud	A	59.7	10.8	4.489	119	62	26	2	0	10	0	0	loam	cereal	n.r.	7.4	929

Catchment	Cat.	Location [dec. degrees]		Size [km^2]	Avg. elevation m.a.s.l.	Land cover [%]							Dom. soil type	Basic management		Annual mean T [°C]	Annual P [mm yr^{-1}]
		Lat.	Long.			Agric	Forest	Devel.	Shrubs	Peatland	Lakes	Other		Agriculture	Forestry		
Time	A	58.7	5.7	1.14	68	88	0	12	0	0	0	0	sand/ loam	grass	n.r.	9.2	1485
Vasshaglona	A	58.3	8.5	0.87	23	48	30	6	0	0	0	16	sand/ loam	cereal/vegeta bles/potato	n.r.	8.6	1520
Volbu	A	61.1	9.1	1.66	652	41	55	3	0	1	0	0	sand	grass	n.r.	4.2	650
Langtjern	F	60.4	9.7	0.3	590	0	73	0	5	22	0	0	moraine	n.r.	natural, 30% harvested Jan. 2009	5.2	840
ω Birkenes	N	58.4	8.2	0.41	228	0	90	0	3	7	0	0	moraine	n.r.	natural, ~5% harvested in 1986	7.8	1713
Dalelva	N	69.7	30.4	3.2	163	0	20	0	61	4	15	0	moraine	n.r.	natural	1.8	553
Kårvatn	N	62.8	8.9	25	935	0	18	0	76	2	4	0	moraine	n.r.	natural	4.1	1203
Langtjern	N	60.4	9.7	4.8	590	0	68	0	5	22	5	0	moraine	n.r.	natural	5.1	840
Øygardsbekken	N	58.6	6.1	2.55	590	0	4	0	83	6	7	0	moraine	n.r.	natural	6.8	2763
Storgama	N	59.1	8.7	0.6	589	0	11	0	59	22	8	0	moraine	n.r.	natural	4.7	1192
Svartetjern	N	60.8	5.6	0.57	452	0	68	0	18	0	14	0	moraine	n.r.	natural	6.1	3719
Sweden																	
SE-C6	A	59.7 *	17.4	33.06	28	61	32	0	0	0	0	7	clay	cereal	n.r.	8.1	546
SE-E21	A	58.4	14.8	16.32	110	90	4	0	0	0	0	6	loam	cereal	n.r.	8.4	584
SE-E23	A	58.4	16.2	7	60	62	0	0	0	0	0	38	clay	cereal/grass	n.r.	8.4	628
SE-F26	A	57.2	13.5	1.82	155	73	10	0	0	0	0	17	sand/ loam	grass	n.r.	8	904
SE-I28	A	57.4	18.4	4.77	36	86	11	0	0	0	0	3	loam	cereal/grass/p otato	n.r.	9	603

Catchment	Cat.	Location [dec. degrees]		Size [km^2]	Avg. elevation m.a.s.l.	Land cover [%]							Dom. soil type	Basic management		Annual mean T [°C]	Annual P [$mm\ yr^{-1}$]
		Lat.	Long.			Agric	Forest	Devel.	Shrubs	Peatland	Lakes	Other		Agriculture	Forestry		
SE-M36	A	56.4	12.7	7.89	35	87	4	0	0	0	0	9	loam	cereal/grass/potato	n.r.	9.6	855
SE-M42	A	55.5	13.2	8.24	48	93	1	0	0	0	0	6	loam	cereal	n.r.	10	692
SE-N34	A	56.8	12.7	13.93	25	87	5	0	0	0	0	8	loam	cereal/grass/potato	n.r.	10	929
SE-O18	A	58.4	13.2	7.66	72	92	2	0	0	0	0	6	clay	cereal	n.r.	8.6	611
SE-U8	A	59.6	16.7	6	8	58	0	0	0	0	0	42	clay	cereal/grass	n.r.	7.9	588
Gårdsjön	N	58.1	12	0.037	127	0	90.5	0	4.5	0	0	5	moraine	n.r.	not managed the last 20 years	8	1107
Aneboda	N	57.1	14.5	0.189	225	0	82.1	0	0	14.2	0	3.7	moraine	n.r.	semi-natural	7.8	758
Gammtratten	N	63.8	18.1	0.45	365	0	82.6	0	0	13.9	0	3.5	moraine	n.r.	semi-natural	3.3	780
Höjdabäcken	N	64	16.9	4.849	540.2	0	69.9	0	0	16.8	13.3	0	moraine	n.r.	natural	2.9	627
Kindla	N	59.8	14.9	0.204	470	0	68.8	0	0	23.9	0	7.3	moraine	n.r.	semi-natural	6.1	759
Laxbäcken	N	59.8	15.4	9.057	277.6	0	86.9	0	0	13	0.1	0	moraine	n.r.	natural	6.7	815
Lill-Fämtan	N	60.8	13.1	5.957	643.5	0	90.6	0	0	5.2	2.5	1.6	moraine	n.r.	natural	4.3	762
Lilltjärnsbäcken	N	63.8	12	0.632	463	0	79.3	0	0	9.8	10.9	0	moraine	n.r.	natural	3.9	1080
Lommabäcken nedre	N	58.7	14.6	1.056	184	0	92.1	0	0	3.8	4.1	0	moraine	n.r.	natural	8.1	697
Pipbäcken	N	57.1	12.8	1.351	137.2	0	59.4	0	0	38.1	2.5	0	moraine	n.r.	natural	8.5	1186
Stormyrbäcken	N	62.3	16.3	3.457	436.4	0	66.7	0	0	29.5	3.7	0	moraine	n.r.	natural	3.8	721
Svartberget	N	64.2	19.8	1.957	278.4	0	77.9	0	0	19.8	2.3	0	moraine	n.r.	natural	3.7	622

*For the Swedish agricultural catchments exact locations are not publicly available

Table SI-2: Details on the monitoring programs for 69catchments

Catchment	Start monitoring of		Additional monitoring	Water sampling method (grab, grab sampling; fl-prop, flow-proportional)	Time resolution (w, weekly; 2w, fortnightly; m, monthly)	Additional information on catchment	Reference
	TotN	TotP					
Denmark							
Bolbro bæk,	1990	1990	NH_4, DRP	grab	2w	irrigation	1)*
Højvads Rende	1990	1990	NH_4, DRP	grab	2w		-“-
Horndrup bæk	1990	1990	NO_3, NH_4, DRP	grab	2w		-“-
Lillebæk	1990	1990	NH_4, DRP	grab	2w		-“-
Odderbæk	1990	1990	NO_3, NH_4, DRP	grab	2w	Irrigation	-“-
Følstrup	1990	1990	NO_3, NH_4, DRP	grab	2w to m		2)
Skærbæk	1990	1990	NO_3, NH_4, DRP	grab	2w to m		-“-
Hestbæk	1990	1990	NO_3, NH_4, DRP	grab	2w to m	extensive forest management	-“-
Holstenhuus afløb	1990	1992	NO_3, NH_4, DRP	grab	2w to m	extensive forest management	-“-
Langslade rende	1990	1990	NO_3, NH_4, DRP	grab	2w to m	part of military training area	-“-
Refskær bæk	1993	1993	NO_3, NH_4, DRP	grab	2w to m		-“-
Rustrup Skovbæk	1991	1991	NO_3, NH_4, DRP	grab	2w to m		-“-
Finland							
Haapajyrä	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		3), 4)
Hovi	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		-“-
Latosuonoja	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		-“-
Löytäneenoja	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		-“-
Ruunapuro	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		-“-
Savijoki	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		-“-
Huhtisuonoja	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		3), 4), 5), 6)
Kesselinpuro	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		-“-
Kotioja	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		6)
Laanioja	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		3), 4)
Myllypuro	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		3), 4), 5), 6)
Teeressuonoja	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		-“-
Vähä-Askanjoki	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		
Ylijoki	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		6)

Catchment	Start monitoring of		Additional monitoring	Water sampling method (grab, grab sampling; fl-prop, flow-proportional)	Time resolution (w, weekly; 2w, fortnightly; m, monthly)	Additional information on catchment	Reference
	TotN	TotP					
Kelopuro	1988	1992	NO_3, NH_4, TON, DRP	grab	2w to m		
Liuhapuro	1981	1992	NO_3, NH_4, TON, DRP	grab	2w to m		7)
Lompolonjänganoja	2007	1992	NO_3, NH_4, TON, DRP	grab	2w to m		8)
Porkkavaara	1992	1992	NO_3, NH_4, TON, DRP	grab	2w to m		7)
Norway							
Hotran	1992	1992	NO_3, DRP	fl-prop	2w		9)
Kolstad	1991	1992	NO_3, DRP	fl-prop	2w		-“-
Mørdre	1992	1992	NO_3, DRP	fl-prop	2w		-“-
Naurstad	1994	1992	NO_3, DRP	fl-prop	2w		-“-
Skas-Heigre	1995	1992	NO_3, DRP	fl-prop	2w		-“-
Skuterud	1993	1992	NO_3, DRP	fl-prop	2w		-“-
Time	1995	1992	NO_3, DRP	fl-prop	2w		-“-
Vasshaglona	1998	1992	NO_3, DRP	fl-prop	2w		-“-
Volbu	1993	1992	NO_3, DRP	fl-prop	2w		-“-
Langtjern	2008	1992	NO_3, NH_4, TON	grab	w to m		10)
Birkenes	1988	1992	NO_3, NH_4, TON	grab	w		11)
Dalelva	1989	1992	NO_3, NH_4, TON	grab	w		-“-
Kårvatn	1988	1992	NO_3, NH_4, TON	grab	w		-“-
Langtjern	1988	1992	NO_3, NH_4, TON,	grab	w		-“-
Øygardsbekken	1993	1992	NO_3, NH_4, TON	grab	2w		-“-
Storgama	1988	1992	NO_3, NH_4, TON	grab	w		-“-
Svartetjern	1994- 2009	1992- 2005	NO_3, NH_4, TON	grab	w		-“-
Sweden							
SE-C6	2004	2004	NO_3, NH_4, DRP	fl-prop	2w		
SE-E21	2004	2004	NO_3, NH_4, DRP	fl-prop	2w		
SE-E23	2007	2007	NO_3, NH_4, DRP	fl-prop	2w		
SE-F26	2005	2005	NO_3, NH_4, DRP	fl-prop	2w		
SE-I28	2005	2005	NO_3, NH_4, DRP	fl-prop	2w		
SE-M36	2004	2004	NO_3, NH_4, DRP	fl-prop	2w		12)
SE-M42	2006	2006	NO_3, NH_4, DRP	fl-prop	2w		13)

Catchment	Start monitoring of		Additional monitoring	Water sampling method (grab, grab sampling; fl-prop, flow-proportional)	Time resolution (w, weekly; 2w, fortnightly; m, monthly)	Additional information on catchment	Reference
	TotN	TotP					
SE-N34	2004	2004	NO_3, NH_4, DRP	fl-prop	2w		14).
SE-O18	2004	2004	NO_3, NH_4, DRP	fl-prop	2w		
SE-U8	2007	2007	NO_3, NH_4, DRP	fl-prop	2w		
Gårdsjön	1988	1992	NO_3, NH_4	grab	m		
Aneboda	1996	1992	NO_3, NH_4, DRP	grab	2w		15)
Gammtratten	1998	1992	NO_3, NH_4, DRP	grab	2w		16)
Höjdabäcken	1987	1992	NO_3, NH_4	grab	m		
Kindla	1994	1992	NO_3, NH_4, DRP	grab	2w to m		
Laxbäcken	1989	1992	NO_3, NH_4	grab	m		
Lill-Fämtan	1986	1992	NO_3, NH_4	grab	m		
Lilltjärnsbäcken	1987	1992	NO_3, NH_4	grab	m		
Lommabäcken nedre	1987	1992	NO_3, NH_4	grab	m		
Pipbäcken	1987	1992	NO_3, NH_4	grab	2w		
Stormyrbäcken	1988	1992	NO_3, NH_4,	grab	m		
Svartberget	1986	1992	NO_3, NH_4	grab	m		

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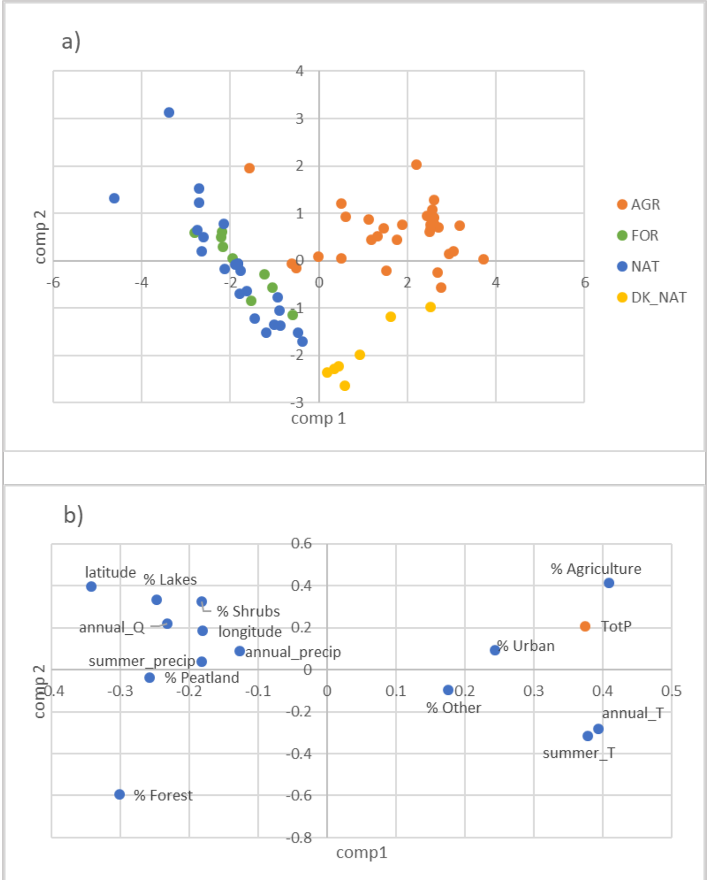


Figure SI-1 a) Similarities between the catchments; b) Similarities between the explanatory variables (blue dots) and their relation to the dependent variable total phosphorus (orange dot)

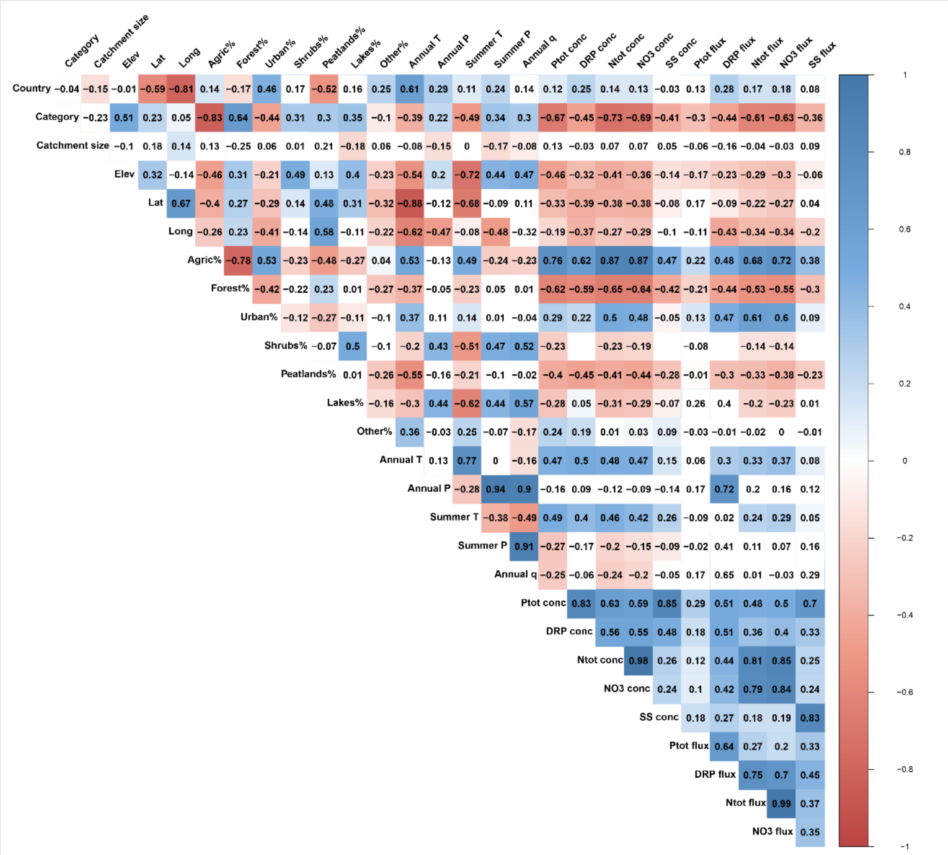
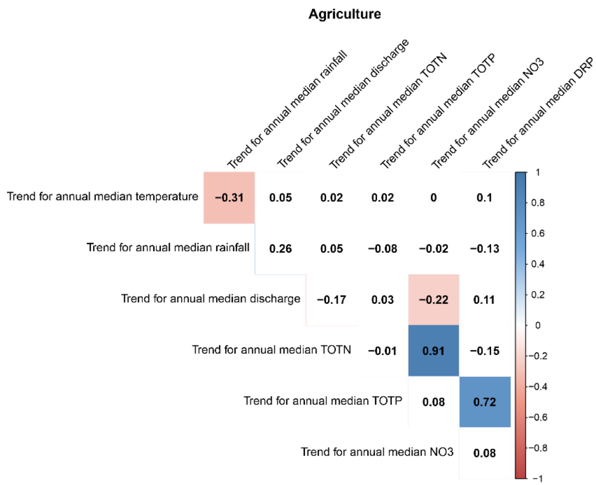
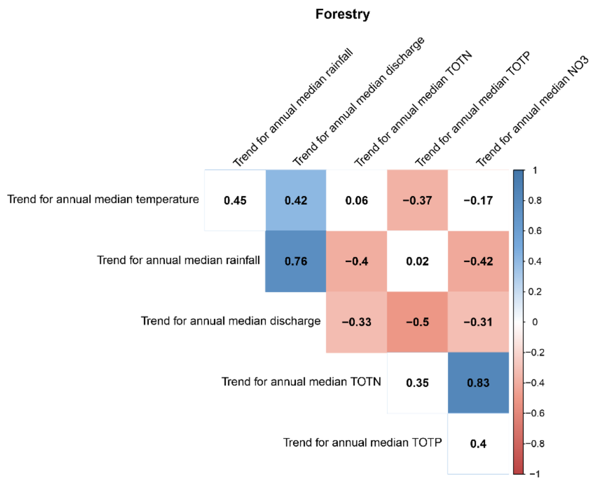


Figure SI-2 Correlation matrix (Pearson, significance level p<0.1) for site median concentrations and site-averaged fluxes of nutrients, climate variables, discharge and land cover percentages in study catchments (n=69). P =precipitation, T= air temperature, q = specific discharge.





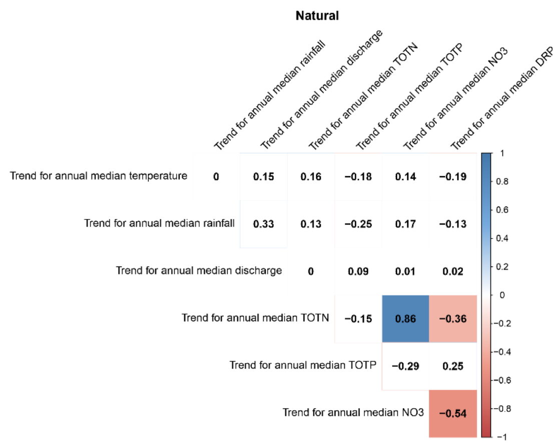


Figure SI-3 Correlation matrix (Pearson, significance level $p<0.1$) for trends in annual mean temperature, precipitation and discharge, and trends in concentrations of totN, totP, NO_3 and DRP, for land use categories agriculture (top left), forestry (top right) and natural catchments (bottom right).

Paper III

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Climate effects on land management and stream nitrogen concentrations in small agricultural catchments in Norway

Hannah Wenng, Marianne Bechmann, Tore Krogstad, Eva Skarbøvik

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Abstract Land use and climate change can impact water quality in agricultural catchments. The objectives were to assess long-term monitoring data to quantify changes to the thermal growing season length, investigate farmer adaptations to this and examine these and other factors in relation to total nitrogen and nitrate water concentrations. Data (1991–2017) from seven small Norwegian agricultural catchments were analysed using Mann–Kendall Trend Tests, Pearson correlation and a linear mixed model. The growing season length increased significantly in four of seven catchments. In catchments with cereal production, the increased growing season length corresponded to a reduction in nitrogen concentrations, but there was no such relationship in grassland catchments. In one cereal catchment, a significant correlation was found between the start of sowing and start of the thermal growing season. Understanding the role of the growing season and other factors can provide additional insight into processes and land use choices taking place in agricultural catchments.

Keywords Agricultural management · Climate change · Growing season · Nitrogen leaching · Water quality

INTRODUCTION

The agricultural sector is under pressure to respond to energy and food security challenges and to reduce greenhouse gas emissions. At the same time, the threat of climate change and an increasing demand on bioeconomic products may intensify the pressure on agricultural production (Rosegrant et al. 2013). Furthermore, agricultural production is one of the main sources of elevated nutrient concentrations in water bodies both in Norway and globally (Ulén et al. 2007; Giri and Qiu 2016). The changing climate affects agricultural production systems and also hydrology, and thereby influences nutrient and soil losses (Deelstra et al. 2011; Giri and Qiu 2016).

The Intergovernmental Panel on Climate Change (IPCC) developed different Representative Concentration Pathways (RCP) for climate change research. If the RCP 4.5 (intermediate emissions) is assumed for Norway, the annual average temperature is expected to rise by approximately 2.7 °C (calculated for the period 1971–2000 to 2071–2100), with the greatest change in Northern Norway (Hanssen-Bauer et al. 2015). Moreover, higher temperatures can lead to a longer thermal growing season, here defined as the period when the mean temperature exceeds 5 °C (Ruosteenoja et al. 2011). In Norway, the RCP 4.5 scenario projects an extension of the thermal growing season by one to two months (Hanssen-Bauer et al. 2015). Previously, Jeong et al. (2011) showed an increase of the vegetative growing season (phenology) for the temperate zone in the Northern Hemisphere during the period 1982–2008. Consequently, this may imply earlier timing of agricultural management in spring (e.g. seedbed preparation, sowing), the introduction of new crop varieties adapted to a longer growing season and higher yields (He et al. 2018; Wiréhn 2018). However, it is still unknown if a prolonged thermal growing season has or will have an impact on water quality. Øygarden et al. (2014) and Wiréhn (2018) suggested that a prolonged thermal growing season can reduce the risk of nitrogen (N) leaching due to better utilisation of nutrients and a longer period with vegetation cover. Nevertheless, uncertainties exist since it is not known how agricultural management may adapt to climate change, including the potential for increased N application due to expectations of higher yields. Furthermore, it is uncertain how soil mineral N will change due to higher temperatures (He et al. 2018).

The connection between climate change, growing season length and agricultural production has been discussed by a number of researchers, for example, Børgesen and Olesen (2011); Ruosteenoja et al. (2011), Øygarden et al. (2014) for Northern European Countries and He et al. (2018), Morgounov et al. (2018) for North America. Most of these studies applied a model-based approach and did not use monitoring data that enables a retro-perspective view on this topic.

Therefore, the aim of the present study was to investigate three objectives to determine whether:

(1) Climate change has already affected the length of the thermal growing season in the monitored catchments investigated
(2) Farmers have adapted their sowing and harvesting dates to this change
(3) A prolonged thermal growing season has affected N leaching to streams

The analysis was based on 27 years (1991–2017) of monitoring data from seven small Norwegian agricultural catchments. The data were statistically analysed, using Mann–Kendall Trend Test, Pearson correlation and a linear mixed model.

MATERIALS AND METHODS

Study sites

Data were used from seven small agricultural catchments (87 to 680 ha), covering different regions of Norway (Fig. 1). The catchments belong to the long-term Norwegian Agriculture Environmental Monitoring Programme (JOVA), which has been run by the Norwegian Institute of Bioeconomy Research since 1991. The widespread network, with monitoring stations located at the outlet of each catchment, made it possible to represent different Norwegian climate zones, soils, topography and elevation, and therefore also different agricultural production systems such as cereal, grass and vegetable production (Tables 1 and 2).

The catchments represent the main agricultural production systems of their specific region: extensive grass production in the north and in the mountains (Naurstad and Volbu); intensive dairy production in western Norway (Time); a mix of dairy and cereal production in inland southern Norway (Kolstad); cereal production in the south-eastern part of the country (Skuterud, Mørdre); and vegetable and cereal production in southern Norway (Vasshaglona) (Fig. 1). The cereal production areas are found in regions where there is relatively little precipitation during the harvest period (Bechmann 2014). The production systems are reflected in fertiliser input and water quality. For example, Time and Vasshaglona show a high fertiliser input and high TN concentrations in the streams due to intensive use of grassland for meat and dairy production and intensive vegetable production, respectively. All catchments have a widespread drainage system. The climatic variation can be seen in the runoff and in the thermal growing season length (Table 2).

Monitoring data

The analysis was based on 27 years of observation data on hydrology, N concentrations and agricultural management. The earliest time series started in 1991 and ended in 2017 (Table 1). Water level was measured continuously at catchment outlet streams, using a pressure transducer combined with a Campbell data logger, and converted to discharge (flow) at standard weirs. The data logger controlled the rate of automatic water-sampling and these sub-samples were combined as composite samples on a volume proportional (flow-weighted) basis and collected every 14th day (Deelstra et al. 2013). Annual and monthly flow-weighted concentrations were calculated by summarising daily loss over a month or a year and divided by total runoff during the corresponding period. Daily loss was calculated as daily runoff multiplied by N concentrations in the corresponding fortnightly water sample. This study used the annual period from 1st May to 1st May (agro-hydrological year) to account for the time lags between agricultural management and weather impacts in the catchment. In this way, the thermal growing season of one calendar year will relate to N concentrations the following autumn, winter and spring. The analytical method used to determine TN and NO_3-N concentrations involved oxidative digestion with peroxydisulfate, which is a colorimetric method (Norwegian Standard ISO 11905-1:1997). Since the 1990 s, information about farm management has been collected on a yearly basis for each individual field. Farmers have provided information about crop type, sowing and harvesting dates, type and date of tillage, yield, amount of applied fertiliser (mineral and manure), type and number of animals, and amount and date of applied pesticides (Bechmann 2014). Data on temperature and precipitation were recorded by local weather stations located in or close to the catchments. The thermal growing season length was calculated based on daily average temperature. The start of the thermal growing season was defined as the day on which the daily average temperature remained higher than 5 °C after seven days, and the end was defined as the day when the daily average temperature had been lower than 5 °C after seven days (Carter 1998; Hanssen-Bauer et al. 2015). The actual agricultural growing season for cereal crops was defined as the period between sowing

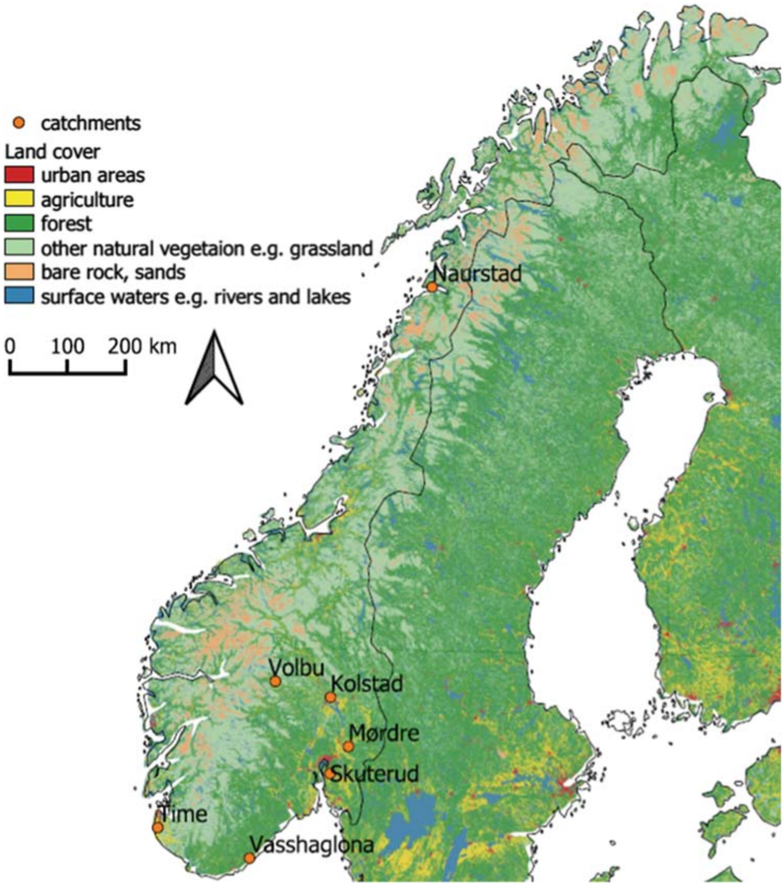

Fig. 1 Location of the seven monitored JOVA catchments in Norway. Land use data: CORINE land cover (https://land.copernicus.eu)

(first day) and harvesting (last day) of crops, which reflects the farmers' actual management of the field (Waha et al. 2012). We used both the first day of sowing and the day when 50% of the area was sown to correlate it with thermal growing season length. Nitrogen balances were based on the agricultural management data, calculated as applied N in fertiliser and manure, minus N removed by yield (the latter was based on farmers' estimates of yield and standard values for N content in the product) (Bechmann 2014).

Statistical analysis

The following statistical tests were performed: Mann–Kendall Trend Test, Pearson correlation and a linear mixed effects model.

The Mann–Kendall non-parametric trend test can account for the non-normality of hydrological data (Yue et al. 2002). The test was applied to see if there were long-term changes for the following parameters: thermal and actual agricultural growing season length, flow-weighted TN and NO_3-N concentrations, N input, N balance, yield, harvest and sow dates, stream discharge, precipitation and temperature. The Mann–Kendall tests were based on monthly and annual data, using calendar years and agro-hydrological years.

The linear mixed effects model provides a technique for analysing the water quality data on the basis of non-probabilistic sampling (Lessels and Bishop 2013; Giri and Qiu 2016). The model was not used as a prediction tool, but to help explain processes. The linear mixed effects model considered both fixed effects and random effects on the response variables TN and NO_3-N concentrations. We chose N concentrations and not fluxes, because concentrations are less dependent on runoff, and may therefore be

Table 1 Main characteristics of the monitored JOVA catchments

Catchment	Total area (ha)	Agricultural land use (%)	Main crops	Soil texture	Elevation range (m.a.s.l.)	30-year normal T (°C)	Monitoring period
Skuterud	450	62	Cereals	Silty clay, loam, silty loam	91–146	5.3	1994–2017
Mørdre	680	65	Cereals	Silt, silty clay, loam	130–230	4.0	1992–2017
Kolstad	310	68	Cereals	Loam, loamy sand	200–318	3.6	1991–2017
Time	97	88	Grass	Loamy sand, organic	35–100	7.2	1996–2017
Naurstad	146	42	Grass	Peat soil	4–91	4.5	1994–2017
Vasshaglona	87	48	Vegetables, potatoes, cereals	Sand, loam	5–40	6.9	1998–2017
Volbu	166	43	Grass	Silty sand, silty loam	440–863	1.6	1994–2017

Table 2 For the monitoring period: annual mean temperature (T) in °C, annual sum of precipitation (P) in mm, mean thermal growing season length in days per year, annual (1st May to 1st May) flow-weighted TN and NO_3-N concentrations in mg l^{-1}, annual N fertiliser input in kg ha^{-1} and annual (1st May to 1st May) mean N balance (surplus) in kg ha^{-1}

Catchment	T (°C)*	P (mm)*	Growing season length (days)*	TN (mg l^{-1})	NO_3-N (mg l^{-1})	Fertiliser input (kg $ha^{-1)}$*	N balance (kg ha^{-1})*
Skuterud	6.6+	824	200+++	5.8	4.5	163	6.0
Mørdre	6.1++	709	184+	5.0	3.6	126	5.3−
Kolstad	4.9++	734	172	10.9	9.3	159	6.5
Time	8.3	1282+	243+++	6.5	4.6	375	10.3+++
Naurstad	5.5+++	1278	179+	1.1	0.4	104−	2.9−
Vasshaglona	8.4	1459	230	5.8	4.5	188	8.81
Volbu	3.1	613++	155	3.2	2.4	105−	2.8−

*Significant levels: +/– $0.05 > p > 0.01$; ++/– $0.01 > p > 0.005$; +++/—$0.005 > p$; and trend direction is marked with + for upward and − for downward

better suited to identify other effects such as thermal growing season length, and variables such as temperature, discharge and or agricultural practices (Bechmann 2014). The fixed effects consider global effects, whereas the random effects consider the individuality of each catchment. Furthermore, linear mixed effects models can deal with dependency in observations and different spatial and temporal scales. Monitoring is based on repeated measurements on the same individual, in our case the stations in the chosen catchments. The statistical design is a parallel group design. The intention was to go beyond the chosen catchments and give more general assessments. The model, which was performed with R version 3.5.2, is described below:

- Linear Mixed Model (LMM) describes log TN and log NO_3-N as a function of growing season length, fertiliser input, N balance, discharge and temperature. It was applied to study whether the thermal growing season, fertiliser input, N balance, discharge and temperature (representing climate), has an impact on the TN and NO_3-N concentrations in the streams for all catchments.

Precipitation was omitted from the LMM on the assumption that it provides the same information as the discharge variable (Øygarden et al. 2014). Years with incomplete observations for all variables were taken out of the analysis. In total, there were 158 observations over a period of 16–27 years for all catchments. The water quality concentrations of TN and NO_3-N were log-transformed to a normal distribution. The LMM was applied to three types of datasets: (1) the aggregated dataset; (2) the data in four catchments with cereal production (96 observations); and (3) data in three catchments with grass production (62 observations). Pearson correlation was applied to view the catchments individually. The statistical significance level was set at 5% and a (non-significant) tendency to change at 5–10% following the method by Skarbøvik et al. (2014).

RESULTS AND DISCUSSION

Change in the thermal growing season length

The Mann–Kendall Trend Test of the aggregated data for all seven catchments showed a significant increase of the thermal growing season length with an average change of 0.66 days per year. When analysing the catchments separately, four of seven showed a significant increasing trend in thermal growing season (Fig. 2a): Skuterud, Mørdre, Naurstad and Time (Table 2). The three remaining catchments Kolstad, Volbu and Vasshaglona showed no significant trends.

The Mann–Kendall Trend Test showed that four catchments had significant increases of the annual mean temperature (Table 2) and in addition the catchment Time indicated to increase ($p > 0.09$). The Mann–Kendall test of the seasonal changes of mean air temperature showed that six out of seven catchments had a significant increase in monthly mean temperature either in March, April or May, and three out of seven catchments saw a significant increase in the average monthly air temperature during autumn (September). This increase in spring and autumn temperatures was also shown for the periods 1985 to 2014 and 1971 to 2000 by Hanssen-Bauer et al. (2015).

Warmer spring temperatures accelerates the phenological development of plants (Menzel et al. 2006; Jeong et al. 2011) and a change in thermal growing season may affect the actual agricultural growing season and management (Børgesen and Olesen 2011; Ruosteenoja et al. 2011; He et al. 2018). This would mean earlier sowing and, if no change in plant varieties occur, earlier harvesting of spring cereals. A possible shift in the varieties of cereals used to those better adapted to a longer growing season and with higher yield potential could result in later harvesting (Seehusen et al. 2015; He et al. 2018). Further, with shifting the sowing date earlier in the year and with simultaneous increased CO_2 concentrations and precipitation an increase of yield could be expected as He et al. (2018) simulated for a Canadian region. For Skuterud, Mørdre and Kolstad, which are cereal production catchments, long-term changes for the first day of sowing and last day of harvesting were analysed. No significant changes over time could be found. In Skuterud there was a significant Pearson correlation (coeff. 0.63) between start of the thermal growing season and the day when 50% of the area is sown (Fig. 3). Considering the case, when at least one farmer had started to sow, there was a significant Pearson correlation with the coefficients 0.62 for Skuterud and 0.42 for Mørdre. Kolstad showed no significance (coeff. 0.18). Here, the extreme conditions show what is possible and that there are farmers which will likely change their sowing date of spring cereals in accordance with changes in spring temperatures due to interannual climate variability. It provides a scenario of farmers' adapting their sowing activities to a changing growing season over time. Other authors have found a weak relationship between spring temperature and farmers' sowing dates due to e.g. the number of frost days (van Oort et al. 2012).

Moreover a prolonged thermal growing season will not always lead to earlier sowing, because other factors also play a role in the farmers' decision-making processes. Kolberg et al. (2019), for example, found that the most limiting factor for early plant development in Norway is soil moisture, because of its impact on soil strength, trafficability and aeration. Riley (2016) argued that soil water content is the main factor in Norwegian farmers' decision to sow or harvest. Soil moisture was also found to be an important factor for agricultural sites in the Canadian prairies (Bootsma and De Jong 1988). More precipitation in spring and autumn is expected, which will affect the workability of the soil at the time the cereals are sown in Norway (Kolberg et al. 2019). Soil type, weather forecasts, available working days, workforce and machinery also play a role in the decision-making process (Waha et al. 2012; Kolberg et al. 2019). Farmers choose suitable cropping periods to optimise production on the basis of these factors (Waha et al. 2012). The current length of the growing season is limited by low temperatures, soil moisture in spring and autumn and the availability of solar radiation in northern countries. These factors also limit the productivity of crops (Olesen and Bindi 2002; Seehusen et al. 2015). Here, the trend for the annual average cereal yields (including spring and winter wheat, oat and barley) was analysed for Skuterud, Mørdre, and Kolstad. The Mørdre and Kolstad catchments indicated an upward tendency in cereal yields ($p = 0.08$, $p = 0.1$). He et al. (2012) saw a large potential for increasing yields of spring wheat in Canada due to earlier seeding dates, driven by increase in temperature and increase in precipitation during important growth stages. However, this is in contradiction with Seehusen et al. (2015), who argued that the trend in Norway is rather a stagnation in cereal yields due to poor physical soil conditions and poor drainage systems, reinforced by weather conditions. Other limiting factors for the yield can be warmer temperatures and less precipitation during the growing season (He et al. 2018).

Trends in water discharge, TN and NO_3-N concentrations

For the Nordic countries, an increase of annual precipitation is predicted (Hanssen-Bauer et al. 2015; Wiréhn 2018), hence a consideration of the potential for changes in stream discharge. Two out of seven catchments showed a tendency in increasing annual water discharge ($0.07 < p <$

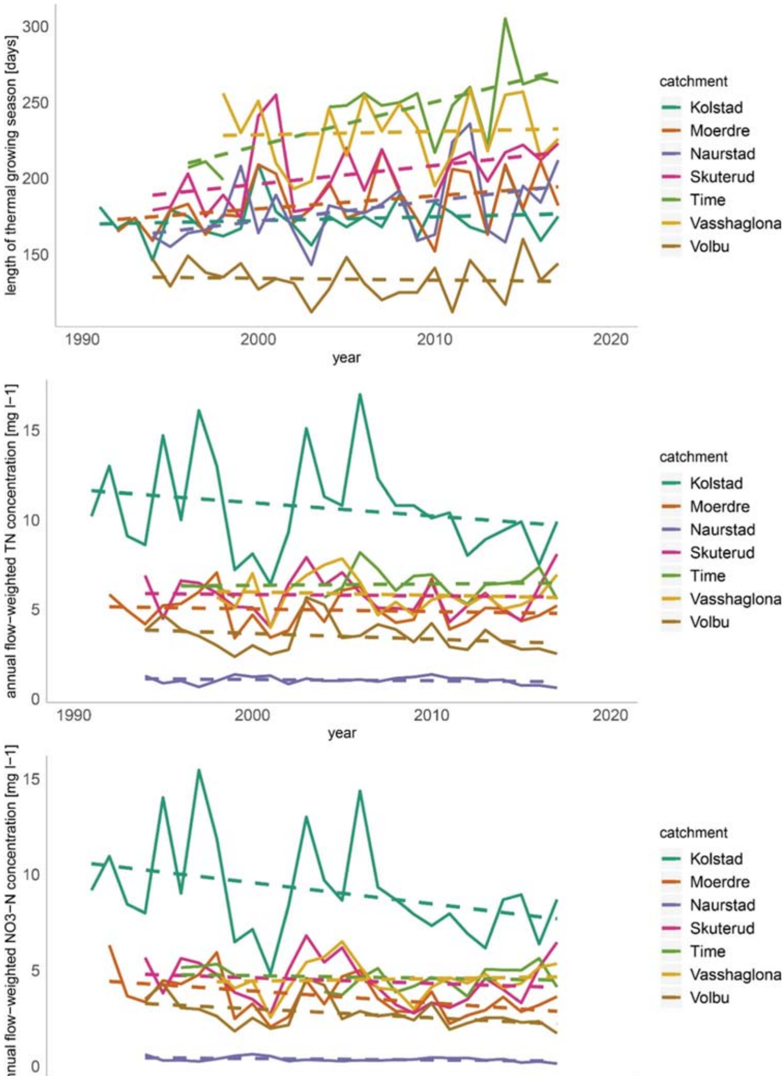

Fig. 2 Change in thermal growing season length (**a**), annual flow-weighted TN concentration (**b**), and annual flow-weighted NO_3-N concentration (**c**) for the seven analysed catchments. The dashed lines illustrate the linear long-term changes and are not related to statistical significance

0.1). Skuterud had a significant upward trend. In terms of the annual TN concentrations no significant trend could be found. For the annual NO_3 -N concentrations, no significant trends could be found, and only Kolstad indicated a downward trend ($p > 0.08$). It might be considered, however, that interannual changes might weaken signals for significant trends (Table 2, Fig. 2b, c).

The explanation for the changes in N concentrations in these small catchments may differ from catchment to catchment. For Mørdre and Volbu, the N balance decreased significantly during the monitoring period until 2017, which contributes to the decrease in N concentrations (Valkama et al. 2013). In Time, there was an increase in application of mineral fertiliser and the N balance also

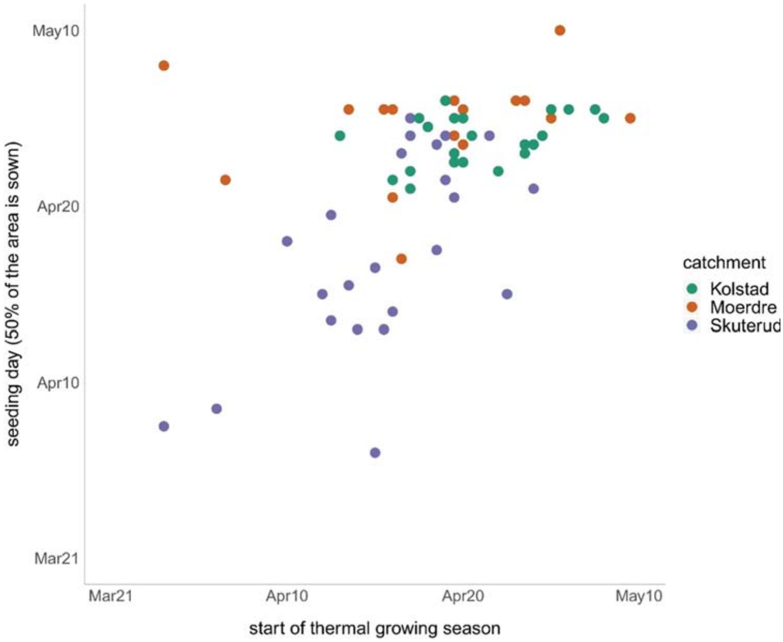

Fig. 3 Correlation between the first day of sowing of spring cereals and the start of the thermal growing season. Pearson correlation: Skuterud 0.63

showed a significant upward trend (Table 2). In Kolstad, an increase in grassland and decrease in cereal area can be expected to contribute to a decrease in nitrogen concentration. In addition, increasing discharge often leads to a dilution of N concentrations. Such a dilution effect for NO_3-N has been shown by Bieroza et al. (2018) based on a high-frequency dataset from an agriculturally dominated catchment in the UK.

Trends in agricultural management

The Mann–Kendall analysis on fertiliser input revealed significant upward trends for the total input as well as for mineral fertiliser. The analysis of total fertiliser input for each single catchment indicates an upward trend for Kolstad and Time ($p < 0.1$). Significant downward trends in total fertiliser input and mineral N application could be observed in Naurstad and Volbu (Table 2). This is probably due to the increasingly extensive grass and animal production i.e. less animals per ha and intensity of management.

For manure application, Kolstad and Vasshaglona showed a significant upward trend. In Kolstad, there is an ongoing change from cereal production combined with animal husbandry, to more animal husbandry and grass production. The significant upward trends in manure application in Vasshaglona can be linked to a probable intensified production of vegetable and potato and less cereal production (e.g. Bechmann et al. 2008). Correspondingly, an intensification of the production in the Time catchment (dairy and grass production) is a probable reason for the significant upward trend in the application of mineral fertiliser in this catchment. Changes in mineral N application reflect changes in cropping systems, whereas the change of N application in the form of manure reflects changes in dairy, meat and grass production (Zimmermann et al. 2017).

Effect of thermal growing season, climate and nitrogen input on nitrogen concentrations

The results of LMM applied on the aggregated data show a significant relationship between thermal growing season length and TN and NO_3-N concentrations in the streams (Table 3). Furthermore, for cereal production systems (4 catchments), the thermal growing season length played a significant role in reducing TN and NO_3-N concentrations (Table 3). Five out of seven catchments showed a negative Pearson correlation between TN concentrations and growing season length (Tab 4). However, Skuterud and

Table 3 Results of the linear mixed effects model. The significance level is 5%, and the slope gives the direction (negative is downward, positive is upward) and the magnitude of the relationship, the bold fonts depict significant *p* values

Dataset	Fixed effects	Constituent	Growing season	Total N fertiliser input	Discharge	Average air temperature	N balance
All catchments	Slope	TN	− 0.002	< 0.001	<− 0.001	0.01	0.02
		NO_3-N	− 0.003	0.001	<− 0.001	0.03	0.02
	p value	TN	**0.002**	0.3	**< 0.001**	0.5	**0.05**
		NO_3-N	**0.014**	0.3	**0.03**	0.2	**0.04**
Cereal production systems	Slope	TN	− 0.004	0.001	<− 0.001	0.03	0.02
		NO_3-N	− 0.006	< 0.001	<− 0.001	0.05	0.03
	p value	TN	**<0.001**	0.3	**0.003**	0.1	**0.01**
		NO_3-N	**<0.0014**	0.6	**< 0.001**	**0.01**	**0.001**
Grass production systems	Slope	TN	<0.001	< 0.001	<− 0.001	− 0.01	0.004
		NO_3-N	<0.001	0.002	< 0.001	0.005	− 0.003
	p value	TN	0.8	0.5	0.2	0.7	0.8
		NO_3-N	0.7	0.3	0.9	0.9	0.9

Table 4 Pearson correlation coefficient between total nitrogen and different variables for each catchment

	TN–growing season length	TN–precipitation	TN–discharge	TN–temperature	TN–N balance
Kolstad (cereal, grass)	− 0.2	− 0.4*	− 0.4*	0.1	0.3
Mørdre (cereal)	− 0.5**	− 0.6**	− 0.5**	− 0.07	− 0.09
Naurstad (grass)	0.2	− 0.3	− 0.5*	− 0.2	0.4
Skuterud (cereal)	− 0.5*	− 0.4*	− 0.6**	− 0.02	0.2
Time (grass)	0.3	− 0.1	0.1	0.5	0.04
Vasshaglona (cereal, vegetables)	− 0.2	− 0.3	− 0.4	− 0.03	0.2
Volbu (grass)	− 0.2	− 0.3	− 0.1	− 0.2	0.06

*Significant levels: *0.05 > p > 0.01; **0.01 > p > 0.005; ***0.005 > p

Mørdre (cereal catchments) showed a significant negative correlation between TN concentrations and growing season length (Table 4). The grass production systems behave differently since the growing season length had no significant effect on the TN and NO_3-N concentration in the streams (Tables 3, 4).

Additionally, there could be co-variances with the specific catchment properties, such as climate, soil type and intensity of the agricultural production. With only a few catchments in each group, there may be some inherent variables that explain the variation in N concentration between catchments. This can be seen, for instance, in the Time catchment, where the high intensity in grass production corresponds to high N concentrations, compared to the extensive production systems in Naurstad and Volbu (Fig. 4). Furthermore, differences in soil type may affect N concentrations. Soils dominated by coarse texture as in Kolstad are prone to higher soil percolation rates and hence, tend to have higher N concentrations compared to soils dominated by surface runoff which can be found in Skuterud and Mørdre (Table 2) (Bechmann 2014).

The results of the LMM applied to the aggregated data showed also that both the N balance and water discharge play a significant role in regulating nitrogen concentrations (Table 3). Water discharge affects N concentrations in stream water, e.g. by dilution of the concentration during high water discharges (Bechmann 2014, Bieroza et al. 2018). This offers an explanation to the negative slope and correlation in Tables 3 and 4, respectively. In the cereal catchments, discharge showed a significant dilution effect (Tables 3, 4).

The N balance is an indicator of how much N is available in the agricultural soils for leaching (Valkama et al. 2013). When the N balance is positive, there is a risk of more N being leached (Cherry et al. 2008; Valkama et al. 2013). Our results show that N balance has a significant effect in increasing TN and NO_3-N concentrations for the aggregated data and for the cereal catchments (Table 3). In a study of 14 Nordic time series, Bechmann et al. (2014)

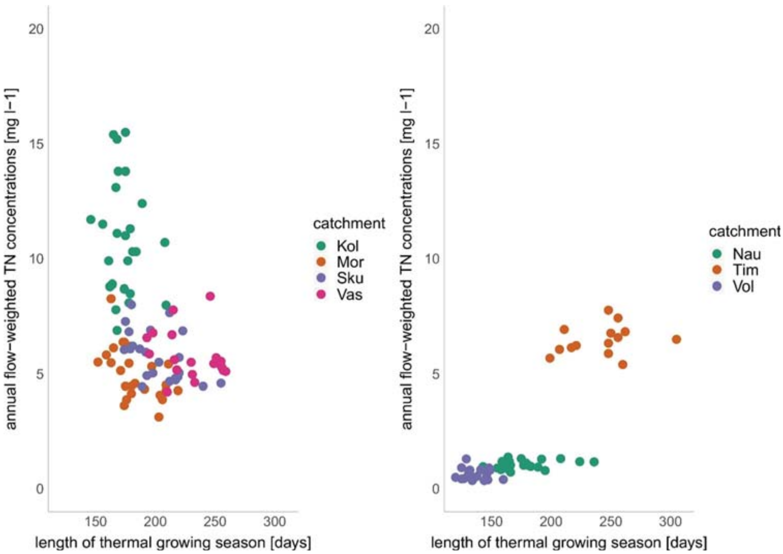

Fig. 4 Scatterplot between TN concentration and growing season length for cereal (left) and grass (right) production systems

also showed a positive significant correlation between N balance and N concentrations.TN and NO_3-N concentration in the streams increased in line with total fertiliser input in both grass and cereal dominated catchments, although not statistically significant. That means in real terms as fertiliser would increase, so too would TN and NO_3-N increase in the catchment stream.

Warmer temperatures increase the turnover rate of organic matter, which supports mineralisation of N and might cause an additional risk of N leaching (Patil et al. 2010; Børgesen and Olesen 2011; He et al. 2018). The results of the LMM showed a positive slope for temperature, although not significant. A constraint in terms of the positive effect of growing season length is the availability of light. Even if the spring and autumn gets warmer, and the risk of late spring and early autumn frosts decreases, the availability of light still determines plant development and growth in northern countries (Olesen and Bindi 2002). Although the impact of climate change will positively affect agricultural productivity in northern countries by increasing the resource use efficiency of crops, the negative impacts should not be neglected (Olesen and Bindi 2002; He et al. 2018). Intensification and other land use changes could lead to an increased demand for fertiliser to gain higher yields (Zimmermann et al. 2017), and therefore increasing the risk of N leaching as He et al. (2018) simulated for a Canadian region. Additionally, a warmer climate and prolonged thermal growing season can make regions located further north and at higher altitudes suitable for cereal production (Ruosteenoja et al. 2011; Seehusen et al. 2015), which might also lead to an increased area under agricultural land use.

At the same time parts of northern countries, such as the regions where the Vasshaglona catchment is located, will be under an increased risk of summer droughts (Trnka et al. 2011). This limits the ability of plants to take up nitrogen if no irrigation is available, thereby increasing the risk of N leaching and a decrease in yield (He et al. 2018).

The analysis indicates that not all farmers have adapted their management to a change in the thermal growing season. Therefore, further studies are needed to look at triggering factors and turning points that apply to changes in farmers' behaviour and agricultural management. Understanding farmers' perceptions can provide important information to agricultural policy makers. Juhola et al. (2017) undertook an empirical study on farmers' perceptions of climate change and their vulnerability in Finland and Sweden. Among several positive effects, the prolonged growing season was mentioned by the interviewed farmers and advisors, because it provides a chance to cultivate new crop varieties and could result in higher yields (Juhola et al. 2017). Nevertheless, agricultural policy may have a higher impact on farmers' behaviour than climate change (Juhola et al. 2017). Grise and Kulshreshtha (2016) showed for a Canadian region that prices, policy and land characteristics played a major role for crop choices. In the long term, Zimmermann et al. (2017) predicted that technology and breeding potential will have a higher impact on farm management and yield than climate change. Agricultural policy and technology development could therefore also affect bioeconomic production and, in turn, water quality.

CONCLUSIONS

In this study, the relationships between climate (thermal growing season), land management (farmers' activities) and nitrogen concentrations were investigated in seven small agricultural catchments across Norway. The results can be summarised as follows:

- For the first objective, the study found that climate change has affected the length of the thermal growing season, there was an increase in the thermal growing season length in four of the seven catchments, located in different parts of Norway; the south-east (Skuterud, Mørdre), the south-west (Time) and the north (Naurstad).
- Considering objective (2), that farmers have adapted their sowing and harvesting dates to this change, the results were not definite. In two of the south-eastern catchments with cereal production, there was a significant correlation between the start of the growing season and the first day of sowing spring cereals (when at least one farmer had sown), which may indicate that farmers have adapted their agricultural management to changes in the spring temperature. No catchment showed a significant long-term change in sowing dates (considering the first day) for spring cereals, probably because of factors such as soil moisture and trafficability.
- For objective (3), the analysis found that a prolonged thermal growing season has affected N leaching to streams differently for cereal and grass dominated catchments. There was a negative correlation between N concentrations and the length of the growing season in catchments with cereal production, whereas the effect of a prolonged growing season on water quality seems to be limited for catchments with grassland, possibly because of increased fertiliser input, changes in precipitation, temperature, discharge patterns and permanent vegetation cover.

For the future bioeconomy, it will be important to improve understanding of how policy and climate change affect farmers' activities, catchment processes and resulting water quality. Hence, there is a continued requirement for long-term data-series on water quality, thermal growing season, agricultural management and land use change. In this context, it would also be desirable to define a growing season not only based on temperature, but also on soil moisture or the number of precipitation days before sowing. This would provide a more satisfactory link between this concept and actual agricultural practices. Although the future cannot be absolutely predicted, two main factors may change the agricultural landscape, viz. climate change and a transition to a bioeconomy. The former may affect the growing season and farmers' choices and opportunities, the latter may change the need for biomass and agricultural products. Hence, both changes may affect runoff and losses of nutrients to agricultural streams and enhance eutrophication processes in water systems. Preparedness is important and in addition to modelling, the continuation of long time-series data gathering is imperative.

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AUTHOR BIOGRAPHIES

Hannah Wenng (✉) is a PhD candidate at the faculty of Environmental Science and Natural Resource Management of the Norwegian University of Life Science. She works for the Norwegian Institute for Bioeconomy Research in the BIOWATER project. Her research interests are hydrology and agriculture.
Address: Norwegian Institute for Bioeconomy Research (NIBIO), Norwegian University of Life Science (NMBU), Fredrik A. Dahls vei 20, 1430 Ås, Norway.
e-mail: hannah.wenng@nibio.no

Marianne Bechmann is a Research Professor at the Norwegian Institute for Bioeconomy Research. Her research interests include catchment science, agricultural management in relation to sediment and nutrient runoff.
Address: Norwegian Institute for Bioeconomy Research (NIBIO), Norwegian University of Life Science (NMBU), Fredrik A. Dahls vei 20, 1430 Ås, Norway.
e-mail: marianne.bechmann@nibio.no

Tore Krogstad is a Professor at the faculty of Environmental Science and Natural Resource Management of the Norwegian University of Life Science. His research interests include soil and water chemistry, soil fertility and soil chemical analysis related to plant nutrition, nutrient runoff and eutrophication.
Address: Faculty of Environmental Science and Natural Resource Management, Norwegian University of Life Science – NMBU, Fougnerbakken 3, 1432 Ås, Norway.
e-mail: tore.krogstad@nmbu.no

Eva Skarbøvik (PhD) is Head of Department at the Division of Environment and Natural Resources, Norwegian Institute of Bioeconomy Research (NIBIO). Her research interests include catchment hydrology, water quality and eutrophication.
Address: Norwegian Institute for Bioeconomy Research (NIBIO), Norwegian University of Life Science (NMBU), Fredrik A. Dahls vei 20, 1430 Ås, Norway.
e-mail: eva.skarbovik@nibio.no

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Sediment transport dynamics in small agricultural catchments in a cold climate: A case study from Norway

Hannah Wenng [a,b,*], Robert Barneveld [a], Marianne Bechmann [a], Hannu Marttila [c], Tore Krogstad [b], Eva Skarbøvik [a]

[a] The Norwegian Institute of Bioeconomy Research (NIBIO), P.O. Box 115, 1431 Ås, Norway
[b] Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Science (NMBU), P.O. Box 5003 NMBU, 1432 Ås, Norway
[c] Water, Energy and Environmental Engineering Research Unit, University of Oulu, P.O. Box 8000, FI-90014 University of Oulu, Finland

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ABSTRACT

Increased nutrient and soil losses from agricultural areas into water bodies constitute a global problem. Phosphorus is one of the main nutrients causing eutrophication in surface waters. In arable land, phosphorus losses are closely linked to sediment losses. Therefore, a better understanding of the sediment-runoff processes in agricultural areas is a key to reduce the eutrophication impacts and to implement mitigation measures. The objectives of this study were to identify dominant sediment runoff processes in cultivated grain-dominated catchments in a cold climate. We assessed continuous high-resolution turbidity data, temporal and spatial catchment properties and agricultural management data to describe and get a better understanding of the cause-relationship of sediment transfer in two small agricultural dominated catchments in southern Norway. The concentration-discharge pattern, index of connectivity and agricultural activities were considered with the wider aim to establish a link between field and catchment scale. The results showed that the dominant concentration-discharge pattern was a clockwise concentration-discharge (c-q) hysteresis in both catchments indicating that areas close to or in the stream gave the highest contribution to turbidity. The main driver for turbidity was discharge, though soil water storage capacity, rain intensity and former discharge events also played a role. Intensity of soil tillage and index of connectivity (likelihood of water and particles to be transported to the stream) impacted the c-q hysteresis index. Little vegetation cover and high intensity of soil tillage led to a high hysteresis index, which indicates a quick increase in turbidity following increased discharge. Other links between agricultural management and in stream data were difficult to interpret. The findings of this study provide information about discharge, field operations and vegetational status as drivers for turbidity and about the spatial distribution of sediment sources in two agricultural catchments in a cold climate. The understanding of sediment runoff processes is important, when implementing management actions to combat agricultural emissions to water most efficiently.

1. Introduction

Elevated nutrient and particle concentrations in water bodies as a result of transport from agricultural sites constitute a global problem, leading to deterioration in their ecological status (Bechmann et al., 2008; Giri and Qiu, 2016; Ulén et al., 2007). Phosphorus is one of the main nutrients that cause eutrophication in surface waters and reduces the functioning of a healthy aquatic ecosystem (Álvarez et al., 2017; Schoumans et al., 2014). Areas with marine clay soil, as found in Scandinavia, naturally show a relative high total phosphorus content that is increased by fertilization (Krogstad and Øgaard, 2008). The aim of the European Water Framework Directive (EU, 2000) and other international agreements is to avoid high nutrient loads and control the impact of agriculture and other land use influences on water bodies. Here, the monitoring of small scale catchments can play a key role, because their water quality impacts larger lake and river systems (Bol et al., 2018; Brendel et al., 2019). Typically, the loss of P from agricultural fields is closely associated with particle loss (Ballantine et al.,

* Corresponding author at: The Norwegian Institute of Bioeconomy Research (NIBIO), P.O. Box 115, 1431 Ås, Norway.
E-mail addresses: hannah.wenng@nibio.no (H. Wenng), robert.barneveld@nibio.no (R. Barneveld), marianne.bechmann@nibio.no (M. Bechmann), hannu.marttila@oulu.fi (H. Marttila), tore.krogstad@nmbu.no (T. Krogstad), eva.skarbovik@nibio.no (E. Skarbøvik).

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2009b), which is one reason why it is necessary to monitor suspended sediments (SS) and particle-bound P. Insight into the causes, quantities, and dynamics that characterize phosphorus and suspended sediment fluxes from agriculture is important if effective and efficient measures are to be devised. Sediment monitoring has traditionally been undertaken by grab sampling, continuous sampling with large time lags, and composite sampling on a volume-proportional (flow-weighted) basis. Time-proportional (incl. grab) sampling with low resolution may over time lead to inaccurate estimates of maximum and average concentrations, and it will also fail to detect variation in concentrations. (Leigh et al., 2019; Skarbøvik and Roseth, 2015; Stutter et al., 2017). Provided that the number of subsamples is sufficient, flow-proportional composite sampling will yield more accurate estimates of averages, but the variation will be concealed (Cassidy et al., 2018; Leigh et al., 2019; Villa et al., 2019).

Sensor techniques can show continuous concentrations and therefore provide detailed insight into transport dynamics and the highly variable concentration patterns of particles in streams (Lannergård et al., 2019; Skarbøvik and Roseth, 2015). In particular, continuous high-frequency measuring of turbidity is a useful tool and a surrogate that can be used to detect changes in SS and particle-associated P (Gippel, 1995; Kämäri et al., 2020; Marttila et al., 2013). More frequent data collection may reduce errors in load calculations, as it can capture concentrations during all peak events (Skarbøvik et al., 2012; Valkama and Ruth, 2017). Many different studies have used high-frequency data as a source for process understanding and for estimating nutrients and SS (for example Bieroza and Heathwaite, 2015; Dupas et al., 2015; Fovet et al., 2018; Kämäri et al., 2020; Lannergård et al., 2019; Minella et al., 2008). However, processes have been studied less in sloping landscapes in high latitude climates like Norway (Liu et al., 2019). Cold climate regions are defined by an average air temperature above 10 °C in their warmest month and under 0 °C in their coldest months (Peel et al., 2007). These temperatures, especially in winter, often make it difficult to use sensors the whole year round, and an option for heating is therefore useful (Valkama and Ruth, 2017).

One possible tool for analyzing particle export and discharge is the concentration-discharge (c-q) hysteresis that occurs whenever there is a difference in the relative timing of particle export and discharge during a runoff event (Evans and Davies, 1998). A c-q-approach is important in small catchments (<10 km^2) because small headwater streams are more sensitive to SS and P from local sources than are large catchments. Headwater catchments can provide detailed insight into c-q processes (Bol et al., 2018; Lefrançois et al., 2007). Characteristics such as land use, topography, and annual precipitation patterns (e.g. dry summer, wet autumn) create challenging conditions for mitigating erosion processes. It is particularly challenging to identify, describe and understand the non-point P sources, and sediment and P dynamics at the catchment scale because of spatial heterogeneity and temporal variability (Bol et al., 2018; Haygarth et al., 2012). In addition, the seasonal changes in agricultural management (field operations) and their dependence on precipitation and temperature must be taken into account when dealing with soil and nutrient losses from agricultural catchments (Bieroza and Heathwaite, 2015; Øygarden, 2000). More information is also needed from different locations, as each catchment is unique in its complexity, land-use pressures, catchment size, and predominant processes (Buck et al., 2004; Haygarth et al., 2012; Kämäri et al., 2020). In this context, high-frequency water quantity and quality data analysis, combined with spatial analysis of land use at catchment and field scale, is a powerful tool for understanding dominant transport processes in the terrestrial phase, and for producing better information for management purposes (Barneveld et al., 2019; Keesstra et al., 2019).

We aim to investigate sediment runoff processes in small agricultural catchments in southern Norway that differ in terms of their topography and soil. We analyze high-resolution sensor data on turbidity, combined with spatial and temporal catchment properties and agricultural management factors. The objectives of this research are:

1. To identify the relative importance of near-stream, in-stream and field sources of sediments and particle-bound P.
2. To quantify the (relative) importance of climatic and agronomic drivers that play a role in sediment and particle-bound P loss at catchment scale with respect to seasonality.
3. To establish a causative correlation between agricultural management and turbidity responses in the stream.

The overall aim of this study is to contribute to a better understanding of dominant sediment runoff processes in agricultural headwater catchments with respect to timing and quantity in cold climates.

2. Method and materials

2.1. Study sites

Our case study areas were two small agricultural catchments located in the southeast of Norway (Fig. 1). The Skuterud and Mørdre catchments are part of the Norwegian Agricultural Environmental Monitoring Programme (JOVA) and have been monitored for water quality since the early 1990's. Both catchments are dominated by cereal production, and the soils are tile drained.

Skuterud has a total area of 450 ha and an elevation between 91 and 146 m above sea level. with an average slope gradient of 5.9% (Barneveld et al., 2019) (Table 1). Sixty-two percent of the area is agricultural, of which 80% is under cereal production. The growing season is about 202 days (Wenng et al., 2020). The soils originate from marine deposits, and the main soil textures of the arable land are silty clay, loam, and silty loam (24% sand, 48% silt, 27% clay) (Kværnø and Øygarden, 2006). Skuterud has warm summers (mean temperature 15.6 °C), and winters (mean temperature −2.6 °C) with unreliable snowfall. The annual precipitation is 824 mm and the annual mean temperature is 6.6 °C (Table 1, Wenng et al., 2020).

Mørdre has a total area of 680 ha with an elevation between 130 and 230 m above sea level. (Table 1). Here, 65% of the area is used for agricultural production, of which cereals comprise about 80%. The growing season is about 194 days (Wenng et al., 2020). Mørdre is characterized by ravines, whereas the thalwegs of secondary ravines were artificially levelled in the 1960's to create more suitable land for agricultural production (Barneveld et al., 2019). The average slope in Mørdre is 14.5%. The main soil textures of the arable land are silt, silty clay, and loam (16% sand, 58% silt, 26% clay) (Kværnø and Øygarden, 2006). Mørdre is characterized by a continental climate with warm summers (mean temperature 14.7 °C) and cold winters (mean temperature −4.5 °C). It has higher snow reliability because it is located upcountry and further north (50 km from Skuterud) (Fig. 1). The annual precipitation is 709 mm and the annual mean temperature is 6.1 °C (Wenng et al., 2020).

2.2. Monitoring data

High-resolution turbidity sensors were installed in the outlets of the two catchments. Turbidity was measured every 15 min by the multiparameter sensor MPS-D8 (SEBA Hydrometrie). The detection limit of the sensor was 3210 Nephelometric Turbidity Units (NTUs). For Skuterud, there were two observation periods: the first comprising the years 2015 and 2016, and the second from mid-August 2018 until the end of 2019. In Mørdre, turbidity was measured from mid-August 2018 until the end of 2019. For the monitoring period 2018–2019, the sensors were equipped with a heat wire (Skuterud) and a heat lamp (Mørdre) to prevent the water from freezing, thereby ensuring winter operation. Water level and discharge were monitored continuously using a pressure transducer combined with a Campbell data logger and v-notch dam at the outlet of the catchments. Precipitation was recorded at hourly intervals at local weather stations located in or close to the catchments. In addition, event-based hourly water samples were taken using an ISCO

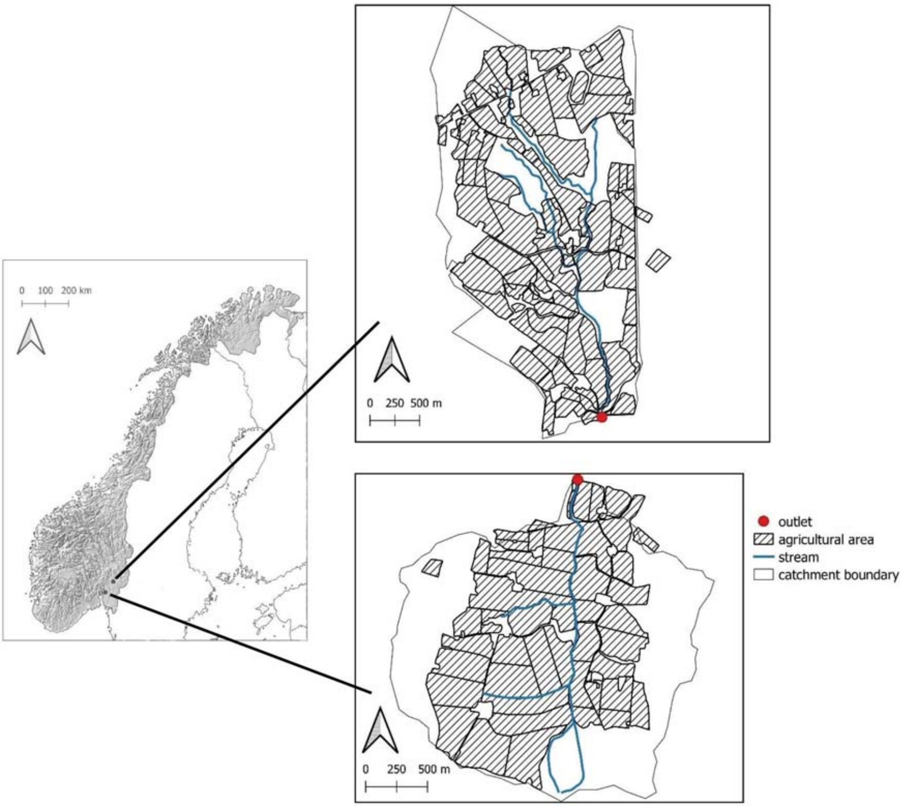

Fig. 1. Locations of the study catchments Mørdre (upper) and Skuterud (bottom) in southeast Norway. The main monitoring station is at the same location as the outlet.

Table 1
Overview of the catchment properties: total area in hectares, land use, main crops, soil texture, elevation, slope, annual mean temperature and precipitation.

Catchment	Total area [ha]	Agricultural land use [%]	Main crops	Soil texture	Elevation range [m.a.s.l.]	Slope [%]	Ann. mean T [°C]	Ann. P [mm]
Skuterud	450	62	cereals	Silty clay, loam, silty loam	91–146	5.9	6.6	824
Mørdre	680	65	cereals	Silt, silty clay, loam	130–230	14.5	6.1	709

portable sampler (Teledyne) to construct calibration curves between turbidity and SS, and between turbidity and total phosphorus (TP). The sampler was usually set up before a rain or snow melting period began, and 24 water samples (500 ml) were taken at hourly intervals for each event. These water samples were analyzed for TP concentration, SS concentration, electrical conductivity (EC), and turbidity in the laboratory. Total phosphorus concentration was determined by oxidative digestion with potassium peroxydisulfate, which is a colorimetric method (Norwegian Standard ISO 11905-1:1997). Suspended sediment concentration was analyzed by filtrating the sample using a glass fiber filter with a pore size of 1.2 μm (Whatman GF-C) and weighing it after one hour of drying at 105 °C. Although this method is standard, it slightly underestimates the SS concentrations, because clay particles are by definition <2 μm and some of the fine particles will pass through the filter pores until they clog. Turbidity measured in NTU was analyzed using the turbidimeter model 2100AN from Hach. Nine events with 221 single water samples were sampled and analyzed for Skuterud, while seven events with 195 single water samples were sampled and analyzed for Mørdre. The high-frequency turbidity data were aggregated from 15-min values to hourly values to correspond to hourly water discharge values.

The JOVA monitoring program also collects land management data. Farmers provide information about crop type, sowing and harvesting dates, the type and date of tillage, yield, fertilizer application date and amount of applied fertilizer (mineral and organic), the type and number of animals, and amount and date of applied pesticides (Bechmann, 2014; Wenng et al., 2020). In our analysis, we linked stream processes to agricultural management data, focusing especially on i) fertilization application and ii) the date and timing of field operations such as sowing, plowing, harrowing, and harvesting.

For information on soil water characteristics, the water storage capacity of the soil was downloaded from the Norwegian data platform (SeNorge.no, 2020) http://www.senorge.no/, an open portal run by the Norwegian Water Resources and Energy Directorate (NVE), the

Norwegian Meteorological Institute (MET), and the Norwegian Mapping Authority. They provide daily data on snow, water, weather, and climate dating back to 1957. These hydrological variables are calculated using the Gridded Water Balance model (GWB) (Beldring et al., 2003).

2.3. Total phosphorus and suspended sediment concentrations and fluxes

A linear relationship between turbidity (hourly sensor data) and TP and SS, respectively, was established from the hourly event-based water samples (Eqs. 1–4). The goodness and significance of the fit were evaluated within a linear regression and the coefficient of determination (R^2). Next, hourly TP and SS concentrations (mg l^{-1}) and fluxes (mg ha^{-1}) for the whole monitoring period 2015–2019 were calculated for each catchment based on Eqs. (1–4).

The SS and TP concentrations of Skuterud and Mørdre were calculated based on:

$$\text{Skuterud: SS concentration} = 0.45{*}\text{TURB} + (-5{\cdot}1) \tag{1}$$

$$\text{TP concentration} = 0.0009{*}\text{TURB} + 0.09 \tag{2}$$

$$\text{Mørdre: SS concentration} = 0.39{*}\text{TURB} + (-\,2{\cdot}82) \tag{3}$$

$$\text{TP concentration} = 0.0005{*}\text{TURB} + 2{\cdot}81 \tag{4}$$

2.4. Hysteresis index for turbidity and water discharge

We used a concentration (turbidity) discharge (c-q) hysteresis analysis to analyze processes and sediment sources in the study catchments. Before conducting the hysteresis index analysis, the high-frequency data were checked for outliers and possible measurements errors. All turbidity values above the sensor detection limit (3210 NTU) were deleted, since we assumed that, when these high values occurred in more than one time step in a row, the sensor was most probably blocked by particles or organic matter. Missing values were due to technical problems with the sensor. In total, 4% of the data points were excluded from the analysis.

The start of an event was defined as the onset of precipitation, while the end was defined when precipitation stopped and the discharge was close or similar to that at the start of the event. For each precipitation event, c-q data were plotted and classified into (i) clockwise (cw), (ii) anticlockwise (ac), (iii) eight-shaped (es), or (iv) no hysteresis when an unclear pattern was observed. A clockwise c-q pattern occurs when the peak concentration comes before the peak discharge, whereas, in an anticlockwise c-q pattern, the peak concentration comes after the peak discharge (Williams, 1989). A total of 142 events were identified for Skuterud and 95 events for Mørdre (Table 2). For each hysteresis event, the hysteresis index (HI) created by Lawler et al. (2006) was calculated to classify the events in terms of magnitude and direction and to make them comparable to each other. Subsequently, the Q_{mid} (at 50% of the flow range, Lawler et al., 2006), turbidity for Q_{mid} at the rising limb ($TURB_{RL}$), and turbidity for Q_{mid} at the falling limb ($TURB_{FL}$) were calculated. The HI was determined for the clockwise c-q pattern, where $TURB_{RL} > TURB_{FL}$.

$$HI = (TURB_{RL}/TURB_{FL}) - 1 \tag{5}$$

for the anticlockwise c-q pattern, where $TURB_{RL} < TURB_{FL}$.

$$HI = (-1/(TURB_{RL}/TURB_{FL})) + 1 \tag{6}$$

HI thereby represents both the magnitude of the event and its hysteretic behavior (a positive sign stands for clockwise and a negative sign for anticlockwise) (Lawler et al., 2006). In addition to the HI, we calculated the rise in the discharge and turbidity within the first hour of the event and the increase in the discharge and turbidity at the steepest point of the rising limb to get an indication of how quickly the systems

Table 2
Characteristics of the events for Skuterud (Sku) and Mørdre (Mør) with number and types of patterns, average, minimum and maximum discharge (Q) values, average, maximum and minimum turbidity, mean and maximum hysteresis index (HI), average rain intensity, water storage capacity, mean and median crop factor and the mean normalized connectivity index and the timing of the Q peak.

	No. of events	No. and types of pattern	Q [$m^3 s^{-1}$]			Turbidity [NTU]			HI [-]		Rain intensity [mm h^{-1}]	Water storage capacity of soil [mm]				Crop factor [-]	Connectivity index [-]	Timing Qmax [h]
			Min	Mean	Max	Min	Mean	Max	Mean	Max	Mean	Max	Mean	Max	Mean	Median	Mean	Mean
Sku	142	97 cw, 9 ac, 11 es, 25 no pattern	0.07	0.2	0.45	29	91	339	1.94	14.9	0.47	25	120	194	0.51	0.50	0.68	12
Mør	95	63 cw, 1 ac, 1 es, 31 no pattern	0.11	0.25	0.47	93	292	904	2.23	7.3	0.3	12	79	168	0.50	0.46	0.39	15

reacted.

2.5. Crop factor and hydrological connectivity index

A crop factor (C, dimensionless) was calculated for the years 2015, 2016, 2018, and 2019 for each agricultural unit in the catchment (Barneveld et al., 2019). The crop factor represents the protection of vegetation against particle loss. A value of 1 represents no vegetation combined with autumn tillage, while a value of 0.01 represents fully developed crop vegetation in the fields (following Barneveld et al., 2019). It gives an indication of the impact of agricultural activities and crop growth on particulate sediment transport through surface and subsurface pathways. Daily C factors were calculated for each field. Each field operation was assigned initial and final C values. The C values are then allowed to develop over time, depending on their operation. If the operation is sowing or planting, C values decrease with assumed vegetative growth and according to the daily temperature. All other operations are followed by a gradual decrease in the C value over time. Changes in field operations and vegetation cover during an agricultural year will also impact the hydrological and sediment connectivity of water and particles to the stream. We calculated a connectivity index based on the procedure in Borselli et al. (2008). The Borselli index of connectivity (IC, dimensionless) expresses the spatially distributed probability that water and sediments will be transported from a location to a predefined sink. The index has an upstream and a downstream component. The upstream component consists of the contributing area and its average value for slope steepness and a weighting factor that describes the soil surface's ability to convey matter. The downstream component is the length of the path to the sink, divided by steepness and the weighting factor. In this study, the C factor values were used as the weighting factor for the index of connectivity. This combination of IC and C is expected to represent the seasonal effect of agronomic activity on the catchment's connectivity. We also calculated a version including the tile drains, but it did not produce any different results for the IC at catchment scale.

2.6. Statistical analysis

Two datasets, the event dataset (the event-based hourly water grab sampling data) and the hourly sensor dataset formed from previously described data, served as the basis for the statistical analysis. The event dataset consisted of information about the events' mean event turbidity ($TURB_{mean}$), maximum and minimum event turbidity ($TURB_{max}$, $TURB_{min}$), sum of precipitation, rain intensity, HI, and TP and SS concentration and fluxes, the mean event discharge (Q_{mean}), maximum and minimum event discharge (Q_{max}, Q_{min}), event length in hours, crop factor (C), and connectivity index (IC), water storage capacity of the soil (wsc), and the hourly increase in discharge and turbidity at the beginning and at the steepest point of the rising limb during the specific events. The hourly dataset (Fig. 2) contained the total hourly turbidity data and the corresponding calculated TP and SS concentrations and fluxes for the whole monitoring period (2015–2019). Analyses of variance (Kruskal–Wallis) and post-hoc tests (Wilcoxon-Mann-Whitney) were carried out to compare the characteristics (runoff and water quality) of the two catchments and to determine the seasonal differences. When comparing the two catchments, the monitoring data from Skuterud for 2015 and 2016 were excluded to ensure the same timeframe for both sites. When analyzing the catchment data individually, the years 2015 and 2016 were included for Skuterud. First, a Spearman correlation was used to link the single process parameters to each other. Second, multivariate regressions were compiled to consider the intercorrelation between the explanatory variables. The dependent variables were Q_{mean}, Q_{max}, $TURB_{mean}$, and $TURB_{max}$. Explanatory variables were event Q_{mean} and Q_{max} (for turbidity), total precipitation per event, rain intensity per event, water storage capacity, crop factor, and index of connectivity. Seasons used in this study were defined as winter (December–February), spring (March–May), summer (June–August), and autumn (September–November). A 95% confidence interval and 5% significance level were set throughout the statistical analysis, which was carried out in R version 3.5.2.

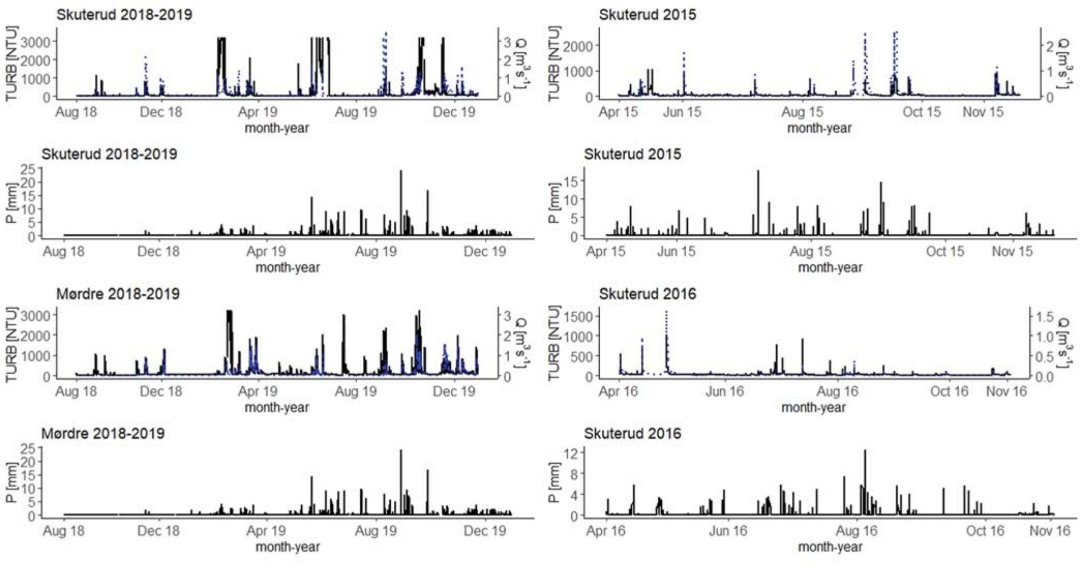

Fig. 2. Time series (hourly data measured by the sensor) of turbidity (TURB), discharge (Q, marked in dashed blue) and precipitation (P) for the periods 2015, 2016, 2018–2019 for the Skuterud catchment and 2018–2019 for the Mørdre catchment. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. Results

3.1. Phosphorus and suspended sediment concentrations related to turbidity

The results of the linear regressions between turbidity and TP and SS, respectively, showed that turbidity is a good proxy for concentrations of both TP and SS in the two studied catchments. In total, five data points of 221 turned out to be outliers for the Skuterud catchment and were excluded (Fig. 3). Here, a large discrepancy between laboratory values and what was measured in the field led to the assumption that there were errors in the measurements for these five data points in either the laboratory or the field. In Mørdre, one outlier was detected and excluded for the same reason as in Skuterud.

For Skuterud, a good fit was found between SS concentration and turbidity, with a significant R^2 of 0.75, and a significant positive correlation between TP and turbidity ($R^2 = 0.63$) (Fig. 3a, b). For Mørdre (Fig. 3), the linear regression showed a significant relationship between concentration of SS and turbidity, and TP and turbidity (Fig. 3c, d R^2 is 0.85 and 0.65, respectively).

3.2. Seasonal differences

Runoff was highest during autumn 2019 for both catchments, in Skuterud, 44%, and in Mørdre, 41% of the annual runoff. Spring and winter runoff also play an important role in the yearly runoff. In Skuterud, 30% of the runoff occurred during the winter and 18% in the spring. In Mørdre in 2019, runoff during spring and winter constituted 28% and 25% of annual runoff. Summer plays a minor role due to less rainfall. These patterns were found throughout the monitoring period (Fig. 4). The datasets resulted in significant seasonal differences ($p = 0.0$) in discharge, with autumn being the dominant season in Skuterud and spring the dominant season in Mørdre (Fig. 4).

In Skuterud in 2019, the SS loads were highest in autumn and winter, with 53% and 32% of the total annual load, respectively. Turbidity showed a similar pattern. Spring and summer 2019 accounted for 7% and 8% of the annual SS load. The distribution is the same for the whole dataset (Fig. 4). In Mørdre, 43% of the annual SS load in 2019 occurred in the autumn and 26% in winter and spring. Turbidity followed a similar pattern (Fig. 4). Both autumn and winter play a major role in particle loss in Skuterud and Mørdre (Fig. 4). Spring seems to be slightly more dominant in Mørdre than in Skuterud when both discharge and turbidity are considered.

All seasons in both catchments were dominated by a clockwise HI

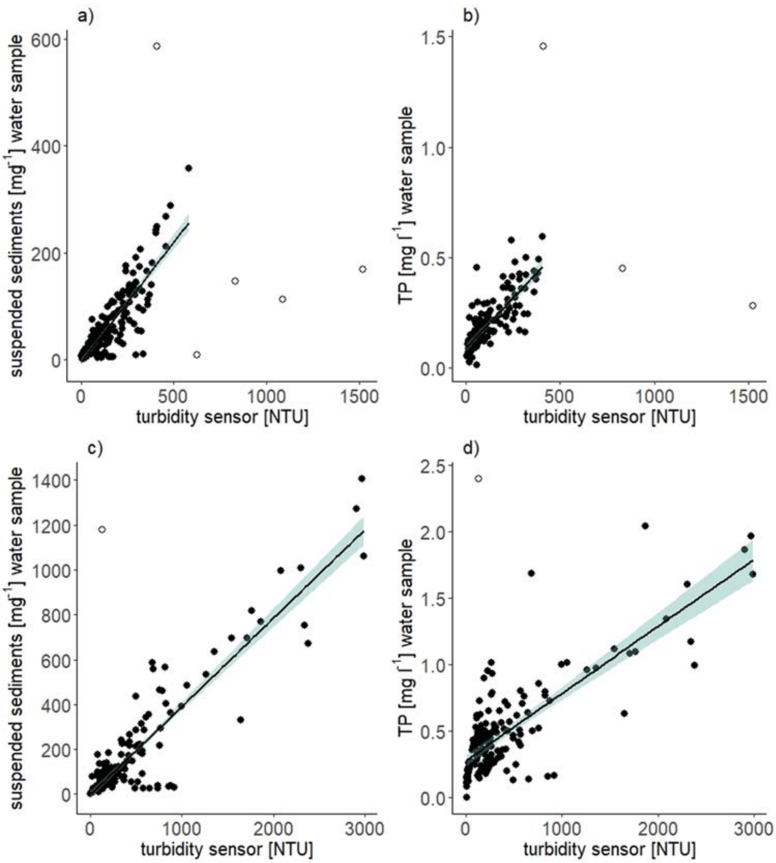

Fig. 3. Relation between suspended sediments and total phosphorus from the hourly water samples and turbidity measured by the sensor for Skuterud a), b) and Mørdre c), d). The unfilled data points were outliers and taken out from the analysis. Please note the different axis scales.

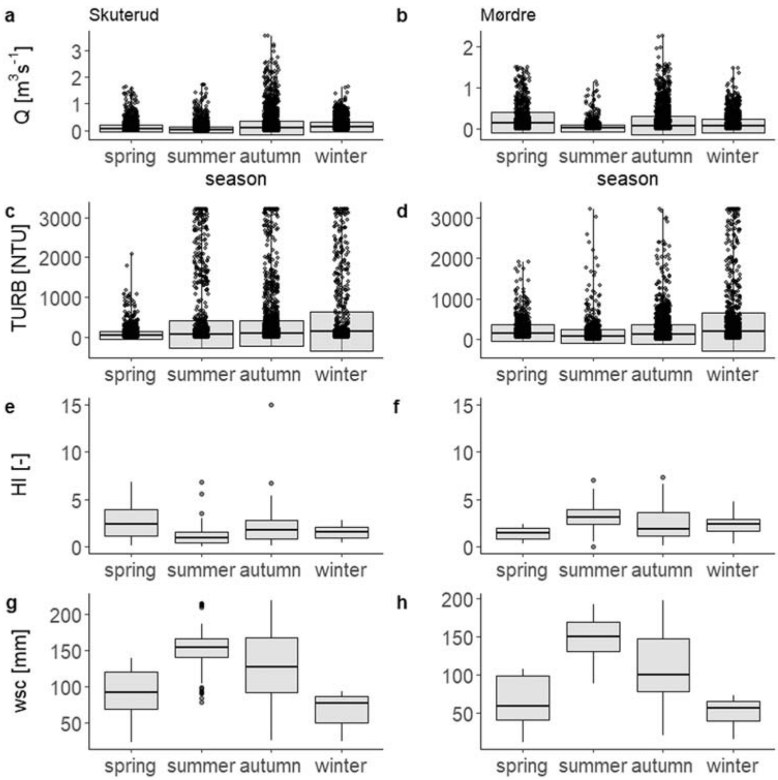

Fig. 4. Boxplots across the seasons for Skuterud (left column, period 2015, 2016, 2018–2019) and Mørdre (right column, period 2018–2019); a), b) hourly runoff data; c), d) hourly turbidity data; e), f) hysteresis index (HI); g), h) average daily soil water storage capacity (wsc).

(turbidity-water discharge pattern and its magnitude). The magnitude was higher in spring and autumn than in summer (Fig. 4), which means that both discharge and turbidity are higher in autumn and spring than in summer. For Mørdre, the tendency towards a corresponding seasonal difference in HI between spring and summer ($p = 0.061$), with the highest magnitude in summer (Fig. 4), might be due to a shorter

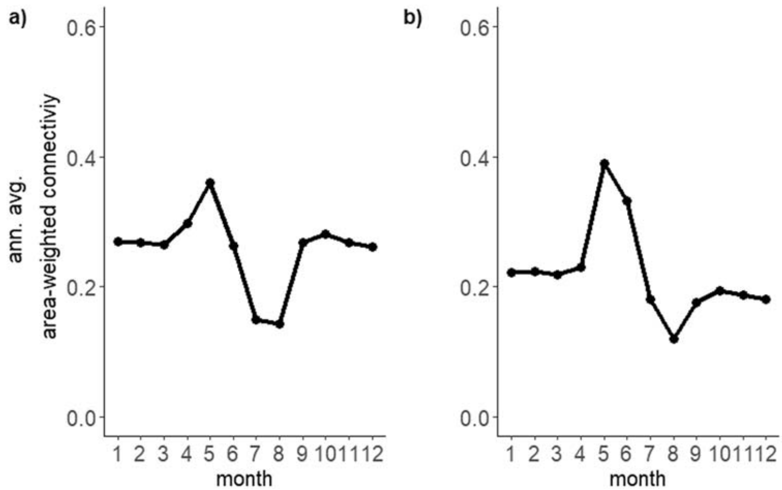

Fig. 5. Normalized average monthly area-weighted index of connectivity over the whole JOVA monitoring period (1990–2019) for Skuterud a) and Mørdre b).

monitoring period and therefore few data for spring.

Other variables, such as the water storage capacity of the soil and the connectivity index, also showed seasonal variations (Figs. 4, 5). Water storage capacity (Fig. 4) showed a clear seasonal pattern, with the lowest storage capacity in winter (wet conditions, frozen soil) and highest in summer (dry conditions). Annual average, area-weighted connectivity calculated for the whole JOVA monitoring period (1990–2019) also showed a seasonal pattern (Fig. 5). The index of connectivity is highest during May and during autumn, followed by winter, due to a low crop factor when fields are only covered with sparse vegetation and when a lot of field operations are taking place, such as ploughing, seedbed preparation, and sowing. The highest crop factor, and hence lowest connectivity, was in summer. During May, autumn and winter, the soil surface conditions are more conducive to particle transport, and the probability of water or particles being transported to the channel is higher in these seasons than in summer conditions. Here, the index of connectivity was lowest when fully developed vegetation cover was found on the fields (Fig. 5).

3.3. Runoff and turbidity

As noted above, the c-q patterns of the events were dominated by clockwise hysteresis (positive HI), despite the differences in topography and soil characteristics (Table 2), meaning that turbidity in general peaked before the discharge peak. Significant differences between the two catchments could be seen for the mean turbidity values and for maximum turbidity during the events ($p = 0.0$), with higher values for Mørdre than for Skuterud (Table 2). The analysis of hourly turbidity for the whole period showed a similar picture, with higher turbidity for Mørdre than for Skuterud (Fig. 2). Neither mean nor maximum event discharge (Table 2), nor the average hourly discharge, varied between the catchments. The calculated HI for each event did not differ significantly between the two catchments, although Mørdre had a higher average HI value, meaning that the events had a larger magnitude.

There was a significant positive relationship between discharge and turbidity in both catchments, which is not only valid for the single events (Table 3), but also for the hourly sensor data (Skuterud $R^2 = 0.76$, Mørdre $R^2 = 0.75$, data not shown). Thus, turbidity increases with increasing discharge, as do TP and SS concentrations and fluxes.

Skuterud was found to have a significantly higher median crop factor than Mørdre (Table 2). This is due to more autumn tillage in Skuterud than in Mørdre. A comparison of the connectivity index resulted in significantly higher connectivity in Skuterud than in Mørdre, which fits with the result that, in Mørdre, the events lasted longer and the discharge peak took longer to appear after the event began (Table 2).

The relative importance resulting from the multivariate regression showed that, in both catchments, precipitation and water storage capacity largely explained the variation in event Q_{mean} (Table 4). Soil water storage capacity plays a major role for Q_{mean} in both catchments, because it determines the baseflow. Connectivity played a minor role in both catchments. The maximum event Q_{max} showed a similar pattern as the event Q_{mean} in Skuterud and in Mørdre (Table 4). The Q_{max} was the main explanatory variable for mean event $TURB_{mean}$ and maximum event $TURB_{max}$ in both catchments (Table 5). Hence, Q_{max} has the energy to transport the particles.

Table 3
Significant correlations (in bolt) between event parameters mean and maximum discharge (Q_{mean}, Q_{max} [$m^3 s^{-1}$]), mean turbidity ($TURB_{mean}$ [NTU]), rain intensity [mm hr^{-1}], water storage capacity [mm], crop factor [-] and connectivity index [-].

	Skuterud			Mørdre		
	Q_{mean}	$TURB_{mean}$	HI	Q_{mean}	$TURB_{mean}$	HI
Q_{mean}		**0.66**	**0.54**		**0.53**	0.21
Q_{max}		**0.81**	**0.64**		**0.69**	**0.33**
Rain intensity	**0.28**	**0.4**	0.14	**0.26**	**0.63**	0.21
Water storage capacity	**-0.71**	**-0.44**	**-0.25**	**-0.7**	-0.18	0.13
Crop factor	0.11	-0.03	**0.33**	**-0.24**	-0.06	**0.28**
Connectivity index	**0.2**	0.001	**0.4**	-0.28	-0.1	**0.28**

3.4. Rain intensity, water storage capacity of the soil, crop factor, and connectivity

Rain intensity showed a significant positive correlation with mean event turbidity for Skuterud ($R^2 = 0.40$) and Mørdre ($R^2 = 0.63$) (Table 3). The result of the multivariate regression showed that rain intensity explains 21% of the mean event $TURB_{mean}$ in Skuterud and 36% in Mørdre (Table 5). Furthermore, the water storage capacity of the soil correlated with mean event Q_{mean} and mean event $TURB_{mean}$. The storage capacity showed a significant negative correlation with discharge in both catchments, which means that higher storage capacity can result in less discharge (Table 3). The same explanatory power was shown in the multivariate regression (Table 4). The event $TURB_{mean}$ had a significant negative correlation with water storage capacity in Skuterud; hence, the less available storage capacity, the more surface runoff and more particle transport (Table 3). In Mørdre, the correlation was also negative, but not significant (Table 3). The multivariate regression showed that the water storage capacity of the soil explained 4–13% of the variation in mean and maximum event turbidity for Skuterud and Mørdre (Table 5).

The crop factor (combined field activity and crop cover) correlated significantly positively with the HI in Skuterud ($R^2 = 0.33$) and Mørdre ($R^2 = 0.28$) (Table 3). This means that little vegetation cover combined with soil tillage lead to a higher HI. Moreover, the connectivity index correlated significantly positively with the HI index for Skuterud ($R^2 = 0.4$) and Mørdre ($R^2 = 0.28$) (Table 3). The additional information on distance from field to stream and the upstream area contribution did not add to the explanation of HI in Mørdre.

Any further direct linkage between the crop factor and index of connectivity with other parameters such as discharge and $TURB_{mean}$ was limited (Table 3). Although the connectivity index correlated significantly positively with mean event Q_{mean} ($R^2 = 0.2$) in Skuterud, such a pattern was not seen in Mørdre, probably due to a smaller dataset. No significant correlation was found between Q_{max} and crop factor and index of connectivity in either catchment.

The results of the multivariate regression showed that connectivity only contributed a little to explaining the variation in Q_{mean}, Q_{max} (Table 4), $TURB_{mean}$, and $TURB_{max}$ (Table 5) in Skuterud and Mørdre. The crop factor did not improve the multivariate regression. Furthermore, there was no correlation between the connectivity index and the timing of the turbidity peak, nor between the connectivity index and the steepness of the increase in discharge and turbidity at the beginning of an event and the steepest point of the rising limb of hysteresis (data not shown).

3.5. Pre-event conditions

Previous runoff events determine the moisture content of the soil and the availability of particles from both surrounding fields and channel to be eroded and transported. We calculated a ratio between the Q_{max} of the previous event and the next event ($Q_{max\text{-}j}/Q_{max}$) and correlated it with maximum turbidity of the latter event (Fig. 6). It turned out that high ratios (pre-event runoff peak > event peak) were linked to rather small turbidity values at the event peak (Fig. 6). This indicates that large pre-events flush most of the easily available stored particles, and that less sediment will be available in following events. Small ratios (pre-event peak < event peak) are linked to high turbidity values (Fig. 6). Hence, small pre-events leave more material that can be transported in the next event.

Table 4
Multivariate regression for event mean (Q_{mean} [$m^3 s^{-1}$]) and maximum (Q_{max} [$m^3 s^{-1}$]) discharge, showing the total explanation of the model and the partial explanation of sum of precipitation [mm], water storage capacity [mm] and connectivity index [-]. *Significant effect

	Skuterud				Mørdre			
	Total 46% p = 0.0	Q_{mean}	Total 48% p = 0.0	Q_{max}	Total 46% p = 0.0	Q_{mean}	Total 56% p = 0.0	Q_{max}
Explanatory variables								
Sum precipitation		41%*		66%*		23%*		53%*
Water storage capacity		57%*		32%*		65%*		41%*
Connectivity index		2%		1%		11%		6%

Table 5
Multivariate regression for mean ($TURB_{mean}$) and maximum ($TURB_{max}$) event turbidity. Numbers show how much of the variation is explained with all variables and how much each variable explains (*significant effect).

	Skuterud				Mørdre			
	Total 66% p = 0.0	$TURB_{mean}$	Total 30% p = 0.0	$TURB_{max}$	Total 64% p = 0.0	$TURB_{mean}$	Total 51% p = 0.0	$TURB_{max}$
Explanatory variables								
Qmax		65%*		79%*		59%*		71%*
Rain intensity		21% (p = 0.09)		13%		36%*		16%
Water storage capacity		13%*		4%		4%		12%*
Connectivity index		1%		5%		1%		2%

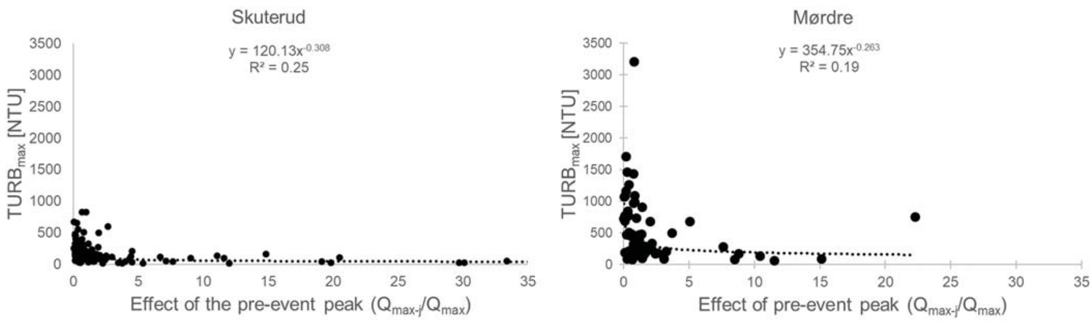

Fig. 6. Relationship of ratio between $Q_{max\text{-}j}$ of the previous event and the next event Q_{max} ($Q_{max\text{-}j}/Q_{max}$) and maximum event turbidity ($TURB_{max}$) for Skuterud and Mørdre.

4. Discussion

4.1. Concentration – discharge pattern

The dominant c-q pattern in both catchments was clockwise (Fig. 7). This fast transport of SS and TP is typical of small-scale catchments (Heidel, 1956). Other studies have also found that a clockwise c-q pattern for SS and TP dominates in agricultural headwater catchments (Keesstra et al., 2019; Outram et al., 2016; Rose et al., 2018). Furthermore, catchments dominated by clay soils, characterized by a preferential flow through macropores and tile drains and by overland flow, lead to a fast response of SS and TP (Bieroza et al., 2019; Ulén et al., 2018). Both catchments are tile-drained, which may explain the dominance of the clockwise c-q pattern. On average, Mørdre had higher mean turbidity values in the events and over the whole monitoring period (hourly sensor dataset) (Fig. 2), which can be explained by higher erodibility due to steeper channel slopes and hilly topography. According to Barneveld et al. (2019), gully erosion contributes to 66% of the total soil loss in Mørdre and to only half as much in Skuterud. Moreover, channel bed dynamics, stream bank erosion, and remobilization of particles may also be impacts that are important in Mørdre, where the main channel is wider (5–10 m) and has longer slopes than in Skuterud (<5 m channel width). In addition, meandering is more active in Mørdre than in Skuterud (Barneveld et al., 2019).

In our study sites, the good fit between turbidity, SS, and TP shows that turbidity can be used as a substitute for SS and TP. This is consistent with previous observations, including Norwegian, Swedish, and Finnish agricultural catchments (Kämäri et al., 2020; Sandström et al., 2020; Skarbøvik and Roseth, 2015; Villa et al., 2019). Phosphorus is mainly bound to soil particles (Walling et al., 1997) and it is especially positively correlated with small particles such as clay, which have a larger relative surface area (Ballantine et al., 2009b; Kleinman et al., 2011; Sandström et al., 2020). Skuterud and Mørdre both have soils with a high clay and silt content, which influences the SS and TP concentrations in the stream.

The relationship between TP concentration and turbidity shows a larger slope in Skuterud than in Mørdre, which means that, with the same level of turbidity, Skuterud has higher TP concentrations than Mørdre (Fig. 3). This is consistent with the results from the annual TP loss analysis, which show higher TP concentrations in Skuterud than in Mørdre. This was also found by Bechmann et al. (2008). Furthermore, the TP–turbidity relationships show that, even when turbidity is zero,

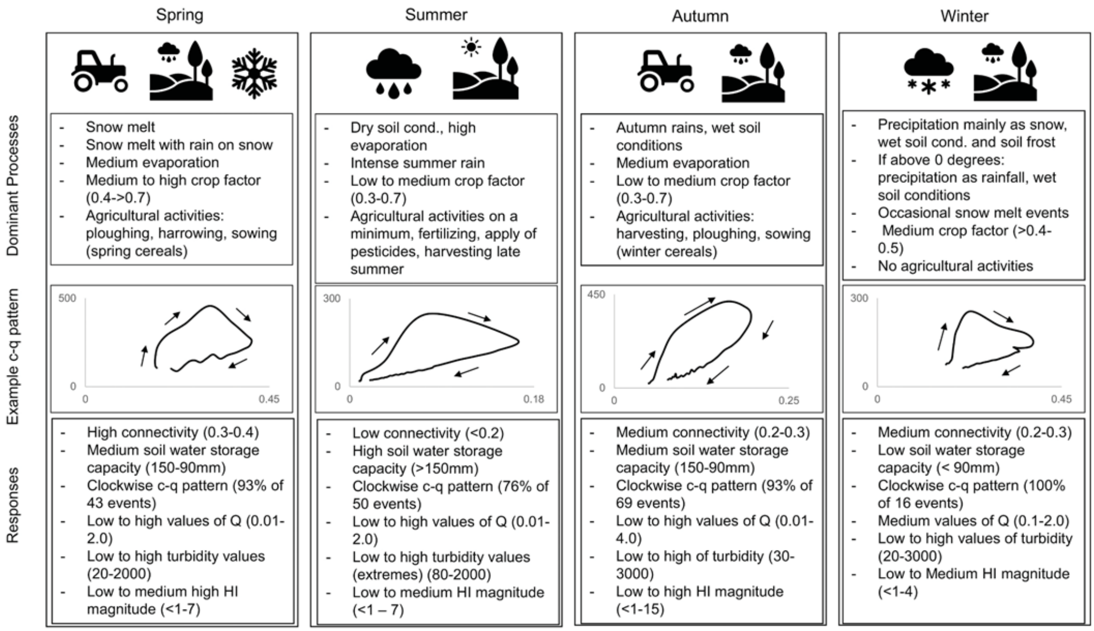

Fig. 7. Conceptual model for the seasonal dominant processes and main responses based on the analyzed data and showing examples for a concentration-discharge hysteresis patterns.

there is still P transport that is not particle-bound. Withers et al. (2012) showed that the contribution from scattered dwellings in Mørdre was 51 kg P yr^{-1}, whereas in Skuterud it was only 7.4 kg P yr^{-1}. This must be taken into account if the P concentration in the suspended sediments is to be estimated. Especially in the case of low turbidity, the TP will overestimate the content of P in soil particles. However, the value of high-frequency turbidity data is that they contribute to understanding runoff processes of SS and TP, and turbidity is a reliable proxy for SS and TP during high runoff events.

4.2. Future perspective: climate change

Our results show that discharge is the main driver of turbidity (explains more than 50% of the variation), and hence also of SS and TP, in our sites (Table 5). We observed that rain intensity influenced the average event turbidity values (Tables 3, 5). This is important because the number of intense local rain events in the Nordic countries is expected to increase (Hanssen-Bauer et al., 2015), which entails a risk of higher turbidity values in agricultural streams.

For Norway, the change in the total annual discharge is predicted to be small, whereas seasonal changes are expected to be high (Hanssen-Bauer et al., 2015). Moreover, it is assumed that winter discharge will increase, that winters will be warmer, and that water runoff will decrease in summer. Skuterud and Mørdre showed an increase in the mean annual temperature, while Skuterud also showed an increase in annual discharge during the period 1994–2017 (Wenng et al., 2020). These changes might contribute to higher sediment concentrations and sediment fluxes in the future (Fig. 7), especially in seasons when the soil is not covered by plants and therefore more exposed to erosion (Ulén et al., 2010). Autumn ploughing will leave the soil bare during this period of higher erosion risk. This is also important for extreme events, because the maximum turbidity values are highly correlated with maximum discharge. The winter of 2019 contributed to rather high turbidity values (Skuterud 27% and Mørdre 35% of annual turbidity) due to mild conditions with relatively more rain than snow compared to the long-term average. At lower temperatures, decreasing soil hydraulic conductivity weakens the ability of soil to transport water and leads to increased surface runoff and particle loss (Gao and Shao, 2015; Wu et al., 2018). Spring and autumn have been known as seasons for soil loss in the Nordic countries (Deelstra, 2015), due to snow melt periods combined with rain early in the year and wet periods after harvesting in autumn. The winter season also plays an important role in particle and nutrient runoff in the Nordic countries, alternating between freezing and thawing and, consequently, snowmelt (Øygarden, 2000). There is still a high risk of soil loss in the spring season in Mørdre (Figs. 2, 4), where the average snowfall is higher than in Skuterud due to differences in climate regions. However, even today, winters can contribute to severe erosion and sediment transport events if there is no permanent snow cover (Øygarden, 2003; Skøien et al., 2012). The data showed that, in winter and spring, the water storage capacity of the soil was very low (Fig. 4), due to frozen or wet conditions. This means that the capacity of the soil to take up water is very limited in these seasons. Hence, stubble, cover crops, and no autumn tillage play an even more important role in protecting freshwater systems in agricultural areas during the relatively long non-growing season in the north (Liu et al., 2019; Skøien et al., 2012). High levels of turbidity can also occur during rainstorms in summer (Skuterud; Fig. 4), even though the fields have a fully developed vegetation cover. A Canadian study also found peaks in discharge linked to high TP concentrations during summer (Casson et al., 2019). However, although turbidity and concentrations of SS may be high during summer, discharge is low, and therefore the total loss of particles is low compared to other seasons (Fig. 7). A higher frequency of extreme precipitation during summer is predicted in the Nordic countries, which could also increase the number of discharge and nutrient peaks during the summer season (Hanssen-Bauer et al., 2015; Wiréhn, 2018). Factors controlling turbidity differ with the seasons (Fig. 7), as reflected in, for example, the seasonality of temperature, water storage capacity of the soil, the annual average connectivity, and the crop factor (Figs. 4, 5).

Lefrançois et al. (2007) found seasonal variation in SS due to the evolution of sediment supply and deposited and stored sediment during a hydrological year. Although we have no direct measurements from our study sites, we could expect similar behavior with stored sediments (Ballantine et al., 2009b). This is consistent with the suggestion by Casson et al. (2019) that drivers of P dynamics also vary by season, as do patterns of nutrient loss (Liu et al., 2019).

4.3. Linking field activities and the index of connectivity to turbidity response

In this study, the crop factor could be directly linked to the HI, and, hence, to a combination of discharge and turbidity. Both the vegetation and agricultural management (tilled, not tilled etc.) have an impact on water runoff and particle (and therefore TP) loss. A well-developed vegetation cover affects the runoff through interception, better infiltration, and soil protection (Blankenberg and Skarbøvik, 2020; Stutter et al., 2019), whereas soil cultivation can lead to loose material being available for erosion (Bechmann et al., 2008; Ulén et al., 2007). A correlation was also seen between the index of connectivity and the HI. Bracken et al. (2013) also showed that connectivity plays an important role in runoff processes. However, we found that the connectivity index only had limited explanatory power for the mean event discharge and turbidity. The difficulties in linking the connectivity index to discharge and turbidity could be due to catchment size. The catchments are small, and the distances from field to (higher order) stream are relatively short compared to distances in larger catchments, which may explain why the distance from field to stream is of less consequence in small catchments.

On field scale, the effects of field operations and vegetation cover can clearly be seen (Skøien et al., 2012). At catchment scale, there is a heterogeneity of field operations. Not all farmers perform the same operations at the same time on their fields. Hence, a signal from single-field operation is difficult to detect directly in the channel. Other internal catchment variabilities may also play a role, such as micro-topography and heterogeneity in vegetation development (Luo et al., 2018). Direct detection of the impact of field operation is often also a matter of timing in combination with precipitation. Water and particles are not always transported to the stream or outlet during one and the same event (Ballantine et al., 2009a, 2009b). They may be temporarily stored in fields, buffer zones, or upper stream channel systems before finally being transported to the stream outlet. Nevertheless, some studies show that, for example, autumn tillage influences particle loss and water quality (Farkas et al., 2013; Rankinen et al., 2015).

Moreover, Haygarth et al. (2012) suggest that, if the impact on a stream can hardly be seen, this might be due to the sampling frequency. Even with high-frequency data, however, not all single sources, processes, and pathways can be documented due to the complexity on the catchment scale and the influence of variation in time and space on runoff generation. It is indeed difficult to observe management practices in stream data, since nutrient transfer in agricultural catchments is not just caused by a single process (management), but by several processes which are not always active. Nevertheless, small headwater catchments provide the conditions required to observe this link (e.g., Kyllmar et al., 2006 and as shown here with the crop factor, the connectivity index and HI). Water quality concerns about sediments and P apply on the catchment scale rather than on farm or individual field scale (Sharpley et al., 2009). Small catchments can enable us to discover these links and to better explain and understand dominant processes during different seasons with different management options, and make it possible to take a more integrative approach to cover the complexity of processes (Bol et al., 2018). They are a key influence on the environmental state and nutrient levels of larger lakes and catchments, and are therefore of great importance, especially when they are well monitored (Bol et al., 2018). These issues are also important for farmers and land managers, when it comes to the question of which mitigation measures to choose and where to locate them in the catchment.

5. Conclusion

Studying high-resolution data from two agricultural catchments has led to the following conclusions:

1. The clockwise c-q pattern was dominant in both catchments (although they differ in topography and soil type), which suggests particles eroded from banks and channels and particles that are quickly transported from fields. The catchment (Mørdre) with the highest turbidity also had the highest HI. This indicates that the sediment sources were closer to the stream in this catchment and of importance to the particle loss.
2. We found that the main driver of turbidity was discharge and variation in it. However, in the field, it was noted that soil water storage capacity influenced discharge and turbidity, while increased rain intensity led to higher in-stream turbidity values. Furthermore, turbidity was shown to depend on previous discharge events, with lower turbidity than normal occurring after a high pre-event peak, probably because the amount of readily available soil and sediment material had been depleted.

   Autumn and spring were the dominant seasons for discharge, due to autumn rainfall, snowmelt and rainfall periods in spring. Spring, autumn, and winter were important to turbidity, in spring and autumn due to high field activities, such as ploughing, in combination with rainfall. High turbidity during winter was due to non-permanent snow cover and rain.
3. Agricultural management (crop factor) and the index of connectivity influenced the c-q hysteresis index. A high crop factor (little vegetation cover and high soil tillage) and a high index of connectivity resulted in a large hysteresis index, indicating large event-triggered sediment transport. No other direct connections were detected between agricultural management and response in the streams.

Linking drivers directly to a response in the stream is challenging due to the nature of the catchments. Catchment heterogeneity and complexity buffers the effect of a direct response. Moreover, hydrological drivers have a dominating influence on discharge and turbidity, masking the effects of other factors in the catchment. High-resolution turbidity data are valuable for describing and understanding processes at catchment scale, but are also somewhat limited. The findings in this study provides information about drivers of turbidity, and therefore of soil, sediment, and phosphorus losses from agricultural catchments. They also offers insights that can help with the selection of the most appropriate mitigation measures in different seasons. This insight into processes should also be applicable in other cold-climate regions with comparable conditions. Moreover, our study demonstrates a method for analyzing high-frequency datasets that could be followed up by studies in regions with different soil, climate, and hydrological conditions, hence improving the planning of site-specific and seasonally adapted environmental mitigation measures.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Paper V

Hydrology under change? Long-term and seasonal changes in small agricultural catchments in Norway

Short title: **Long-term and seasonal changes in small agricultural catchments in Norway**

(80 words)

Authors: Hannah Wenng [a,b*], Danny Croghan [c], Marianne Bechmann [a], Hannu Marttila [c]

[a] The Norwegian Institute of Bioeconomy Research (NIBIO), P.O. Box 115, 1431 Ås, Norway.

[b] Faculty of Environmental Sciences and Natural Resource Management, Norwegian University of Life Science (NMBU), P.O. Box 5003 NMBU, 1432 Ås, Norway

[c] Water, Energy and Environmental Engineering Research Unit, University of Oulu, P.O. Box 8000, FI-90014 University of Oulu, Finland

*Corresponding author

Hannah Wenng: hannah.wenng@nibio.no

Danny Croghan: danny.croghan@oulu.fi

Marianne Bechmann: marianne.bechmann@nibio.no

Hannu Marttila: hannu.marttila@oulu.fi

Abstract:

In agricultural catchments, hydrological processes are highly linked to particle and nutrient loss and can lead to a degradation of the ecological status of the water. Global warming and land use changes affect the hydrological regime, especially in cold regions' catchments. In this study, we analysed 22-26 years of long-term hydrological monitoring data from seven small agricultural catchments in Norway. We applied a Mann-Kendall-trend and wavelet coherence analysis to detect long-term changes and to picture the coupling between runoff, climate, and water sources. The trend analysis showed a significant increase in the annual and seasonal mean air temperature. In all sites, hydrological changes were more difficult to detect. Discharge increased mainly in autumn and winter for some of the catchments. The wavelet coherence exhibits a clear coupling between discharge and precipitation, snow water equivalent, and soil water storage capacity. Further, we detected the different hydrological regimes of rain and snow dominated catchments. The catchments responded differently to changes due to their location and inherent characteristics. Our results highlight the importance of studying local long-term and seasonal changes in hydrological regimes to understand the effect of climate. This knowledge can then be implemented to site-specific management plans.

Keywords: climate change, cold climate, coherence, trends, water management

Highlights:

- Analysis of long-term hydrological monitoring data of 22-26 years
- Novel combination of Mann-Kendall trend and wavelet coherence analysis
- Clear trends in air temperature but not in hydrological regimes
- Discharge showed a stronger link to precipitation than to temperature

- Snowmelt and rainfall dominated catchments had different responses to climate change

Introduction

Preserving water availability and quality is one of the main challenges facing societies globally. In catchments with high agricultural activity, hydrological processes are highly linked to particle and nutrient loss which if uncontrolled can cause degradation of the ecological status of water bodies (Bechmann, 2014; Wenng et al., 2021). Hydrology in agricultural catchments is special because it is not only impacted by natural processes, but also by anthropogenic activities such as deforestation, vegetation shifts, annual soil cultivation practices, channel modification and artificial drainage (Wagena et al., 2018).

In addition, changing climate conditions may influence the hydrological behaviour of a catchment such through altering runoff generation (Arheimer and Lindström, 2015; Vormoor et al., 2015) which therefore also affects the nutrient leaching. Particularly, cold climate regions (defined as average air temperature above 10°C in their warmest month and under 0°C in their coldest months (Peel et al., 2007)) are noticeable affected by climate change (Aygün et al., 2020). According to future climate scenarios, the conditions in the Northern Hemisphere will be warmer and wetter and changes will be disproportionately greater than the global average (Aygün et al., 2020; Hanssen-Bauer et al., 2015; He et al., 2018; Laudon et al., 2017). In Norway, the annual median temperature is predicted to increase by 2.7 °C, the median annual precipitation is expected to increase by 8% (intermediate emissions (RCP 4.5), 1991-2000 to 2071-2100) with the biggest temperature change in northern parts of Norway (+4.0 °C for RCP 4.5) (Hanssen-Bauer et al., 2015).

The change in median annual discharge is predicted to be relatively small with an increase of 3% (RCP 4.5, 1991-2000 to 2071-2100), whereas seasonal changes are bigger, due to severe seasonal changes in precipitation and temperature (Donnelly et al., 2017; Hanssen-Bauer et al.,

2015). In winter the discharge is predicted to increase, whereas in summer it will decrease (Hanssen-Bauer et al., 2015). Earlier studies like Wilson et al. (2010) showed already that there was a clear positive trend in winter discharge for the period 1941-2005 in Norway and showed a tendency to more severe summer droughts.
Transition in precipitation from snow to rain will also affect the hydrological regime (Meriö et al., 2019). Precipitation as snow (storage) does usually not immediately create runoff, however when temperature rises again, the snowmelt contributes to runoff (Meriö et al., 2019). Frozen soil is another aspect of cold climate hydrology, separating water fluxes between subsurface and surface can restrict the complete infiltration of water during snowmelt and rain periods (Ala-aho et al., 2021). In the future hydrological processes in winters will be more dynamic due to changes in land-water connectivity and will transform the traditional runoff patterns into a more unpredictable temporal distribution of runoff (Tattari et al., 2017). A changing climate impacts also the flood behaviour in Northern Europe in both ways, increasing and decreasing river floods were observed by Blöschl et al. (2019). In agricultural catchments where nutrient loss and hydrology are strongly linked (Bechmann, 2014; Deelstra et al., 2014), these changes have a strong effect on nutrient loss and the control and mitigation measures that are required (Liu et al., 2019; Tattari et al., 2017).

Long-term monitoring of catchments plays a key role for observing baseline and long-term changes in hydrological processes (Brendel et al., 2019; Laudon et al., 2017). Monitoring at the catchment scale of a multitude of hydrological variables, combined with analysis of long-term and seasonal changes provide us an insight into multiple parameters and variables such as land use, temperature, runoff, precipitation and links between variables which are important for land, water, and nutrient management (Brendel et al., 2019). In cold climates in particular, there remains a lack of understanding of how soils, vegetation and water runoff interact and influence nutrient loss. (Liu et al., 2019). Further, hydrology and nutrient transport differs from the warmer region, because precipitation can occur as rain, snow and rain on snow and is highly affected by climate warming (Laudon et al., 2017; Liu et al., 2019). Therefore, it is not only crucial to study changes of single variables over time like e.g., discharge, but the coupling between discharge and climate variables and water sources. It is important to understand hydrological and climate characteristics and their interactions and how they influence nutrient loss to adapt and develop new agricultural management practices and mitigation measures if needed (Liu et al., 2019; Wagena et al., 2018).

In this study we analysed long-term hydrological and climate data (22-26 years) from seven small Norwegian agricultural catchments. Our main motivation was to:

1) to identify long-term annual and seasonal trends in hydrology (discharge, high and low flows, soil water) and climate (precipitation, temperature, evapotranspiration, snow) in small agricultural catchments in Norway
2) to identify causes for variations in discharge and discuss its impact on agricultural practices and water protection

Study area and data

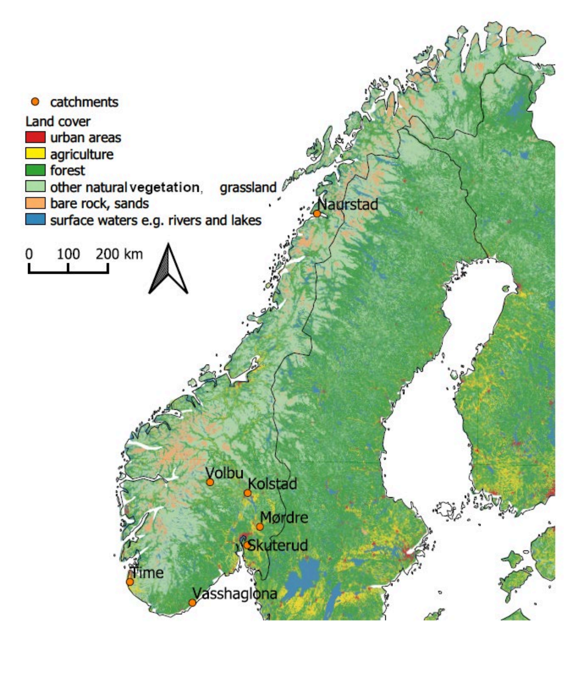

Figure 1: Locations of the studied catchments in Norway. Land use data: CORINE land cover (https://land.copernicus.eu).

Seven small agricultural catchments (87 to 680 ha, Table 1), covering different regions of Norway (Figure 1) were used in this study. The catchments are in the long-term Norwegian Agriculture Environmental Monitoring Programme (JOVA), which has been maintained by the Norwegian Institute of Bioeconomy Research since 1992 (Bechmann, 2014). These catchments were chosen because they give the longest continuous measurements on hydrology and land use. Monitoring stations were located at the outlet of each catchment, and all catchments are tile drained. The widespread network made it possible to represent different soil textures, elevations, climate conditions, and therefore also different agricultural production systems such as cereal, grass and vegetable production (Table 1). The hydrological-climatological areas represented by the catchments are (Table 1): two types of continental climate, one with no dry seasons (Kolstad and Mørdre) and one with relatively warm and dry summers and cold winters (Volbu), coastal climate in the south (Vasshaglona, Time) and north (Naurstad) with relatively high precipitation compared to the other catchments; and one catchment (Skuterud) characterized between coastal and continental climate with relative unstable and wet winters and warm summers (Table 1). Further, the presented catchments can be grouped into snow dominated (Kolstad, Mørdre, Volbu), where runoff is determined by snowmelt and rain dominated catchments (Skuterud, Naurstad, Time, Vasshaglona), where the runoff is determined by rain.

Table 1: Catchment and climate characteristics

Catchment	Total area (km^2)	Agr. land use (%)	Dominant soil texture	Elevation (m.a.s.l.)	Monitoring period mean annual T (°C)	Monitoring period mean annual P (mm)	Monitoring period mean annual Q (mm)	Climate	Monitoring period
Kolstad (Kol)	0.68	68	Loam, loamy sand	200-318	4.5	705	379	Continental climate, without dry seasons	1994-2020
Mørdre (Mor)	6.80	65	Silt, silty clay, loam	130-230	5.3	732	318	Continental climate, without dry seasons	1994-2020
Naurstad (Nau)	1.46	42	Peat soil	4-91	5.5	1264	1083	Coastal climate	1994-2020
Skuterud (Sku)	4.50	62	Silty clay, loam, silty loam	91-146	6.2	767	568	Unstable winters, warm summer	1994-2020
Time (Tim)	0.97	88	Loamy sand, organic	35-100	8.4	1322	804	Coastal climate, mild winters, high precipitation	1996-2020
Vasshaglona (Vas)	0.87	48	Sand, loam	5-40	8.4	1497	1095	Coastal climate, mild winters, high precipitation	1998-2020
Volbu (Vol)	1.66	43	Silty sand, silty loam	440-863	3.3	644	294	Continental climate, relative warm and dry summers, cold winters	1994-2020

Monitoring Data

The analysis was based on 22-26 years of hydrological observations for each catchment (Table 1). The earliest dataset started in 1994 and the latest for Vasshaglona in 1998. Water level was measured continuously at the catchment outlet, using a pressure transducer combined with a Campbell data logger, and converted to discharge (flow) at standard weirs (Deelstra et al., 2014). Water discharge (Q) was aggregated to daily values. Daily temperature (T) and precipitation (P) were taken from weather stations, located in the catchments or close by. Effective precipitation (EP) was calculated as total precipitation minus total evapotranspiration. The daily discharge data was used to calculate flow indices such as baseflow index (BFI), high flows, and low flows using the River Analysis Package (RAP, version 3.0.8; Marsh et al., 2003). The BFI describes the proportion of baseflow of the total runoff measured at the catchment outlet (Deelstra et al., 2014). The RAP used the method described by Nathan and McMahon, (1990) to calculate the BFI. They applied a method based upon a recursive digital filter. It was calculated with a recession coefficient of 0.975. To calculate the high flows, we defined the 10th and 25th (Q10, Q25) percentiles from the flow duration curve, whereas low flows were defined as the 90th and 75th percentiles of the flow duration curve (Q90, Q75). According to Wilson *et al.*, 2010, thresholds range between the 10th and 30th percentile are reasonable for perennial streams. We also calculated normalized water runoff seasonality by dividing the total seasonal runoff (Qs) with total annual runoff (Qa).

$$\text{Seasonality in Q} = \frac{Qs}{Qa} \qquad (1)$$

This gives an idea how much the different seasons contribute to the total annual runoff. Seasons were defined as winter: December – February; spring: March – May; summer: June – August; and autumn: September – November.

Model data

We added to our analysis information on daily evapotranspiration (ET), daily soil water storage capacity (SWC) (the sub-surface storage capacity in mm compared to a simulated maximum, using the HBV-model) and daily snow water equivalent (SWE). The meteorological input to the gridded hydrological model is determined by an interpolation procedure, but the hydrological variables were calculated by the Gridded Water Balance model (GWB) (Beldring et al., 2003), a spatially distributed version of the HBV hydrological model (Lindström et al., 1997). Grids are generated by interpolating between measurement stations, using triangular irregular networks (Vormoor and Skaugen, 2013). Evapotranspiration is estimated with a temperature index method by HBV model (Lindström et al., 1997) and snow data is calculated based on precipitation and temperature by the snow map model (Saloranta, 2012). All the datasets are available from the Norwegian data platform http://www.senorge.no/, an open portal run by the Norwegian Water Resources and Energy Directorate (NVE), the Norwegian Meteorological Institute (MET), and the Norwegian Mapping Authority. These data were also used for gap filling, which was required for further processing such as indices calculation and wavelet coherence analysis. Single time step gaps were filled with linear interpolation, whereas gaps of several times steps in a row were filled with data calculated by the Gridded Water Balance model.

Methods

Trend analysis

Statistical tests and trend analyses were run in R (version 3.5.2). For the trend analysis, we applied the rank-based non-parametric Mann-Kendall trend test to assess the significance of a trend (Bouza-Deaño et al., 2008). Here, we used the R package "*TTAinterfaceTrendAnalysis*" (Devreker and Lefebvre, 2020). We applied the trend test to mean monthly values to calculate the annual and seasonal trends of Q, precipitation, temperature, ET, SWC, SWE, BFI, low flow, and high flow. We used the Theil-Sen slope to estimate the slope of the changes in the hydrological and climate data (Sen, 1968; Theil, 1950). It determines for each sample point the median of the slope of the crossing lines (median between ranks). The Theil-Sen estimator can be applied when the data contains outliers or when data is missing (Bouza-Deaño et al., 2008). It is a robust non-parametric estimate of the slope.

Wavelet coherence analysis

We used wavelet coherences to identify correlations between the flow time series and predictor variables. The wavelet analysis was conducted in R version 4.0. with the R package "*biwavelet*".
This method was applied to identify trends and periods and to explore the coupling between discharge and the different climate variables such as precipitation, temperature, ET, SWE, SWC.

Wavelets decompose time series into time dependent spectral series which is calculated by applying the wavelet to the time series as a bandpass filter (Grinsted et al., 2004). The decomposition of the time series into power spectra enables the features of a time series to be localised into time and frequency. This decomposition shows the dominant periodicities of variability and how these dominant periods vary in time (Torrence and Compo, 1998). The wavelet transforms therefore allow examination of time series features at different time scales. This allows broad scale features from time series to be identified at long time scales, and fine scale features from time series to be identified at short time scales (Carey et al., 2013). In this study, we used the Morlet wavelet function. The Morlet wavelet is commonly used within hydrological studies as it is able to provide a good balance between the localisation of frequency and time, thus allowing time-dependent phase and amplitude changes to be observed (Carey et al., 2013; Torrence and Compo, 1998). The Morlet wavelet can be described as follows:

$$\varphi_0(\eta) = \pi^{-\frac{1}{4}} e^{\omega_0 \eta} e^{-\frac{1}{4} n^2} \qquad (2)$$

where φ_0 (η) is the wavelet function, ω_0 is the dimensionless frequency, i is the imaginary unit, and η is dimensionless time (Grinsted et al., 2004).

The wavelet coherence then shows the correlation and coupling between two wavelet power spectra. The wavelet coherence thus functions as a correlation coefficient between two wavelet transformed time series. The coherence relates spectra to the two original time series by identifying at what areas in both time and frequency two time series show synchronicity. Hhigh coherence between time series can be used to infer details about the hydro-meteorological processes controlling the relationship at different periodicities (Carey *et al.*, 2013). The wavelet coherence can be described for two time series that have been wavelet transformed into $W_i^x(s)$ and $W_i^y(s)$ as (Torrence and Compo, 1998):

$$R_n^2 = \frac{|s\left(s^{-1}W_i^{XY}(s)\right)|^2}{s\left(s^{-1}\left|W_i^X(s)\right|^2\right)\cdot s\left(s^{-1}\left|W_i^y(s)\right|^2\right)} \quad (3)$$

Where R_n^2 represents the coherence, W_i^X and W_i^y represent the wavelet transforms for time series X and Y, and S is a smoothing parameter that is dependent on the type of wavelet used and defined by:

$$S(W) = S_{scale}\left(S_{time} \cdot W_n(s)\right) \quad (4)$$

Where for the smoothing of a wavelet $S(W)$, S_{scale} smooths the scale axis, and S_{time} smooths the time axis (Carey et al., 2013).

Coherence values are returned ranging between 0 – 1. Values of 0 indicate no correlation, while 1 would indicate perfect correlation. The wavelet coherences in this study are presented as a heat map showing the wavelet coherences across the time series, and as a table to show the short-term coherence (< 30 days). Each coherence plot features arrows. The arrows and their direction indicate that the phase of the relationship (directionality of relationship) between discharge and other variables. Right pointing arrows indicate that the two variables are in phase (moving in the same direction, positively correlated), left ones indicate the variables are out of phase (moving in opposite directions, negative correlated). Down pointing arrows indicate that the first variable is leading, whereas up pointing indicates that the second variable leads which means the variables are not directly or immediately responding to each other.

To accurately perform wavelet transformations, continuous time series are required. Resultantly, the catchment Time was excluded from the analysis because there is a gap in the discharge data from 1999-2003, due to problems with the monitoring station.

Results

Long-term annual and seasonal trends

During the monitoring period, air temperature increased significantly in all catchments (sen-slope 0.05 to 0.1), except for Vasshaglona (Table 2). The seasonal analysis showed that temperature increased in all seasons, with the largest increase in spring (sen-slope 0.05-0.14) for all catchment, and in the winter period (sen-slope 0.05 to 0.17) for five catchments, only Naurstad showed a tendency in winter. Vasshaglona did not show any seasonal trend. Volbu was the catchment with the highest increase in air temperature in spring and winter (sen-slope 0.14 and 0.17) (Table 2). Annual ET, as expected, followed the long-term pattern of air temperature. Vasshaglona and Naurstad showed no significant annual trends for ET (Table 2).

Annual precipitation only showed a significant long-term increasing trend in Volbu (sen-slope 0.02), while Naurstad showed a tendency to increased annual precipitation (Table 2). The seasonal analysis showed a significant increase in summer (sen-slope 0.03) and winter precipitation (sen-slope 0.03) in Volbu (Table 2).

For the monitoring period Kolstad, Skuterud, Vasshaglona, and Volbu (four out of seven) were the catchments, that showed a significant increase in mean discharge (sen-slope 0.01 to 0.02) due to a significant increase either in autumn or/and in winter (Table 2). The seasonality of the discharge showed that summer contributes the lowest (9 % to 16 %) to the total annual discharge in all catchments (Figure 2). In Vasshaglona the difference between seasons, especially summer to the other seasons was smaller (average difference 0.13). In the rain dominated catchments such as Skuterud, Naurstad, Time and Vasshaglona, autumn (~30%) and winter (30 % to 40 %) are the main seasons for runoff (Figure 2). In snow dominated catchments such as Kolstad, Mørdre and Volbu winter is a relatively inactive hydrological season and spring contributes 40-50% to the yearly discharge due to snowmelt episodes (Figure 2). Mørdre has had more hydrologically active winters lately because more precipitation fell as rain instead. This could be shown by a significantly decreasing SWE in winter for Mørdre (Table 2). The discharge might increase or decrease in the seasons as we could show that discharge increased significantly in autumn in Skuterud (sen-slope 0.05) and Volbu (sen-slope 0.02) and in contrast discharge decreased significantly in autumn in Time (sen-slope 0.09, Table 2). In Kolstad, Vasshaglona and Volbu discharge increased significantly in winter (sen-slope 0.01 to 0.09).

The annual BFI increased significantly in Volbu (sen-slope <0.01, Table 2), where winter was responsible for this change (Table 2). In Mørdre, Time and Vasshaglona, the annual BFI significantly decreased (sen-slope <-0.01 to -0.01). Mørdre showed a significant decrease in spring, summer, and autumn (sen-slope -0.01 to <-0.01), Time showed a significant decrease in spring (sen-slope -0.02), summer (-0.01) and winter (<-0.01), and Vasshaglona showed a significant decrease in summer (sen-slope -0.01), which generally refers to drier conditions. The low flows of 90^{th} percentile showed a significant positive annual trend for Skuterud and Kolstad and a negative trend for Time (Table 2). For the high flows of the 10^{th} and 25^{th} percentile, Time showed a significant decrease (sen-slopes -0.15, -0.09), whereas Skuterud (sen-slope 0.1, 0.06) and Vasshaglona (0.12, 0.8) showed a significant increase (Table 2, Table SI-1). The seasonal analysis of Skuterud and Vasshaglona showed a significant increase for the high flows in autumn and winter respectively, which is also supported by a significant increase in maximum discharge in autumn in these catchments (Table SI-1). This refers to even higher discharge during high flow periods (extremes) (Table 2, Table SI-1). In contrast, in Time and Volbu, low flow during summer significantly decreased and in Naurstad and Time, winter low flows became more extreme, according to the 90^{th} percentile (Table 2). Vasshaglona was the only catchment that did not show any significant trends in low flows (Table 2, Table SI-1). The trend analysis on the annual frequency of high flows (10th percentile) only resulted in one significant trend: Skuterud (rain dominated), which showed an increasing trend in the annual numbers of high flow events.

The annual mean SWC increased significantly in Naurstad (sen-slope 0.61, Table 2), hence more water could be stored. Volbu showed a significant decrease in annual, mainly autumn and winter, SWC (sen-slope -0.73), hence less water could be stored.

Annual changes in SWE were difficult to detect. However, Mørdre, Naurstad, Skuterud and Time showed a significant decrease in SWE in winter (Table 2). In Volbu a significant and large increase in the winter seasons (sen-slope 2.01) was found.

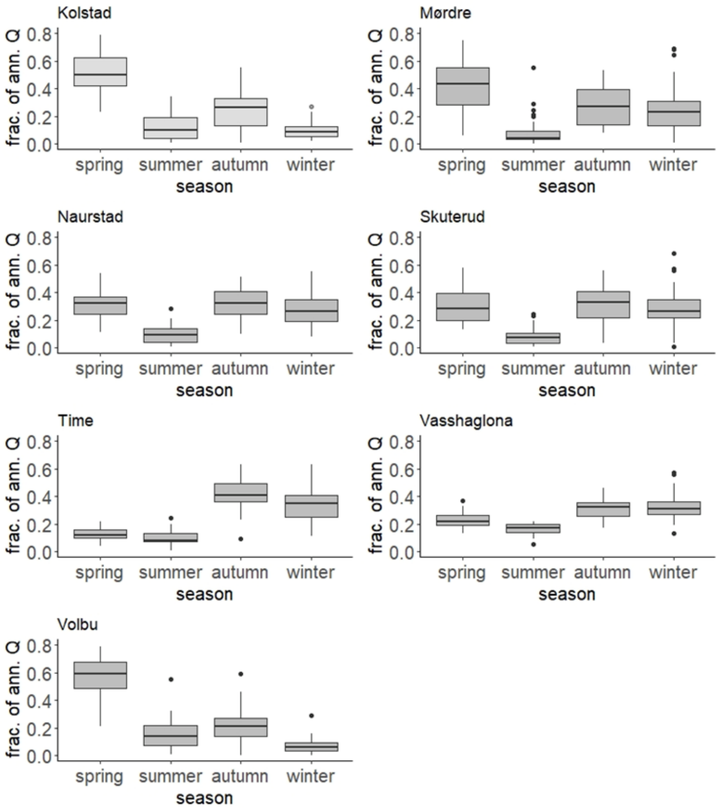

Figure 2: Seasonality of the discharge in study sites: contribution of seasonal discharge to the total annual discharge for the monitoring periods.

Table 2: Sen-slopes of annual and seasonal trends of discharge (Q), baseflow index (BFI), low flow (LF), high flow peaks (HF), precipitation (P), temperature (T), soil water storage capacity (SWC), evapotranspiration (ET) and snow water equivalent (SWE), Green: significant trend ($p<0.05$), yellow: tendency ($0.05<p<0.1$); minus indicates a negative trend, plus indicates a positive trend

	Qmean [mm]	BFI [-]	LF90 [mm]	HF10 [mm]	P [mm]	T [°C]	SWC [mm]	SWE [mm]	ET [mm]
KOL									
annual	0.01	<0.01	<0.01	0.01	<-0.01	0.07	-0.17	0	<0.01
spring	0.01	0	<0.01	-0.03	-0.01	0.09	0.12	0	0.01
summer	<0.01	0.01	<0.01	-0.03	-0.01	0.05	-0.22		0.01
autumn	0.02	<-0.01	<0.01	0.05	0	0.04	-0.46	0	0.01
winter	0.01	<0.01	<0.01	-0.01	<0.01	0.09	-0.18	-0.49	0
MOR									
annual	<-0.01	<-0.01	0	0.04	<0.01	0.07	-0.22	0	0.01
spring	-0.02	-0.01	0	0.08	-0.02	0.09	0.22	0	0.01
summer	<-0.01	<-0.01		0.07	0.01	0.04	-0.07		0.01
autumn	0.01	-0.01	0	0.04	<0.01	0.06	-0.28	0	0.01
winter	<0.01	<0.01		-0.04	0.01	0.13	-0.75	-0.58	<0.01
NAU									
annual	-0.01	<0.01	0	-0.1	0.02	0.06	0.61	0	<0.01
spring	-0.02	<-0.01	<-0.01	-0.08	0.031	0.07	0.4	0	0.01
summer	<-0.01	0	0	-0.02	0.03	0.05	0.63		-0.01
autumn	-0.03	<0.01	<-0.01	-0.23	0.02	0.06	1.16	0	0.01
winter	0.01	<-0.01	<-0.01	0.05	0.01	0.06	0.39	-0.98	<0.01
SKU									
annual	0.01	<-0.01	<0.01	0.1	-0.01	0.05	-0.29	0	0.01
spring	-0.01	<-0.01	0	<0.01	-0.02	0.07	0.01	0	0.01
summer	0.01	<-0.01	<0.01	0.09	-0.01	0.03	-0.36		0.02
autumn	0.05	<-0.001	<-0.01	0.19	<0.01	0.05	-0.58	0	0.01
winter	0.02	0.01	<0.01	0.01	<0.01	0.08	-0.44	-0.51	<0.01
TIM									
annual	<-0.01	-0.01	<-0.01	-0.15	0	0.05	-0.02	0	0.01
spring	<-0.01	-0.02	0	-0.05	<-0.01	0.05	0.07	0	0.01
summer	0.01	-0.01	<-0.01	-0.23	<0.01	0.04	-0.04		0.01
autumn	-0.09	-0.00	<-0.01	-0.08	-0.01	0.03	-0.03	0	0.01
winter	0.03	<-0.01	<-0.01	-0.17	-0.02	0.08	-0.23	-0.09	0.01
VAS									
annual	0.02	<-0.01	<0.01	0.01	0.01	0.01	-0.02	0	0.01
spring	0.03	<-0.01	<-0.01	0.24	-0.04	0.02	0.03	0	0.01
summer	-0.01	-0.01	<-0.01	-0.26	-0.03	0.01	0.5		<0.01
autumn	0.04	-0.01	<0.01	0.17	0.03	0.01	-0.33	0	0.01
winter	0.09	-0.00	<-0.01	0.11	0.09	0.04	-0.45	0.04	<0.01
VOL									
annual	0.01	<0.01	-0	0.02	0.02	0.11	-0.73	0	<0.01
spring	<0.01	<0.01	-0	-0.03	0.01	0.14	-0.58	0	<0.01
summer	<-0.01	<0.01	<-0.01	<-0.01	0.03	0.06	-0.38		0.01
autumn	0.02	<0.01	<0.01	<0.01	0.03	0.10	-0.88	0	0.01
winter	0.01	0.01	0	-0.19	0.03	0.17	-1.33	2.01	<0.01

Long-term annual and seasonal coherence

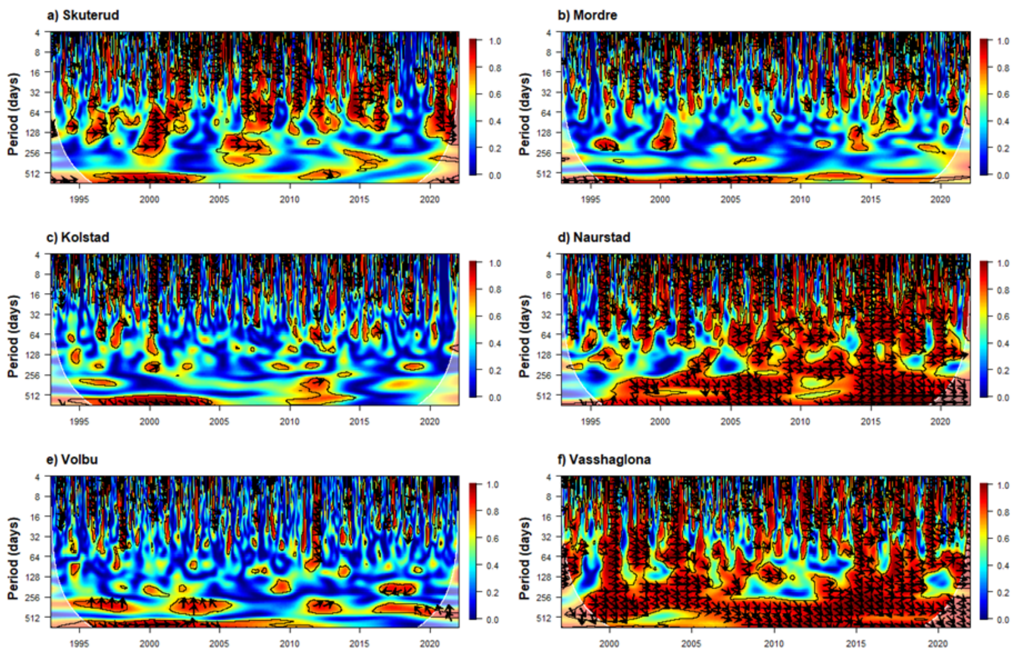

Figure 3: Wavelet coherence between discharge and precipitation for 24-26 years of data. Colours indicate the strength of the relationship, with red to orange areas within the black lines significant at 95% level.

Figure 3 shows the coherence over time between discharge and precipitation. The coherences shown within the black lines are significant. There is a clear difference between the rain dominated catchments Naurstad, Vasshaglona (coastal catchments) and to some degree, Skuterud with a strong coherency (red colour) and the snow-dominated catchments (inland catchments) with less coherence (blue colour) such as Kolstad, Volbu and Mørdre. They show a weak coherency in the short term (~30 days) and at the annual time scale (> 256 days). These catchments are also the ones with the lowest total precipitation compared to the other catchments (Figure SI-1). The rain dominated catchments show a coupling of runoff and precipitation in the short-term period (< 30 days) and the coupling gets even stronger closer to the annual period (< 256 days). When considering the average wavelet power for each period (dominant periodicity) it turned out that the dominant cycle for precipitation is a smaller periodicity (days, weeks). That reflects the seasonal behaviour of precipitation (Figure 2, SI-22). All rain dominated catchments showed that discharge and precipitation are in phase (right pointed arrow) which suggests a rapid runoff generation. Further, Kolstad and Volbu, the most inland sites, showed a small coherence during spring (0.37, 0.32) and winter (0.29, 0. 23) compared to the other catchments (Table 3, Figure 3, Figure-SI-3). The appearance of snowfall in the spring and winter months in the inland area led to the decoupling of discharge and precipitation.

Volbu (inland site) showed a long-term decline in the coherence between discharge and precipitation (Figure SI-5). However, an increasing long-term trend of the coherence is apparent with the most northern site, Naurstad (coastal site) (Figure SI-5). Nevertheless, this trend has declined in recent years.

Table 3: Mean wavelet coherence by seasons at less than 30-day periodicity for flow against temperature, precipitation, soil water storage capacity, snow water equivalent and evapotranspiration (Mean ± SD)

	T	P	SWC	SWE	ET
KOL					
spring	0.26 ± 0.11	0.37 ± 0.19	0.48 ± 0.16	0.36 ± 0.15	0.37 ± 0.13
summer	0.26 ± 0.09	0.57 ± 0.14	0.57 ± 0.13	0.11 ± 0.08	0.31 ± 0.09
autumn	0.30 ± 0.10	0.61 ± 0.18	0.66 ± 0.14	0.21 ± 0.16	0.34 ± 0.11
winter	0.26 ± 0.10	0.29 ± 0.16	0.44 ± 0.17	0.28 ± 0.11	0.44 ± 0.15
MOR					
spring	0.28 ± 0.11	0.46 ± 0.21	0.59 ± 0.15	0.38 ± 0.19	0.35 ± 0.13
summer	0.25 ± 0.10	0.53 ± 0.16	0.50 ± 0.16	0.12 ± 0.11	0.29 ± 0.10
autumn	0.31 ± 0.10	0.64 ± 0.16	0.65 ± 0.16	0.18 ± 0.14	0.35 ± 0.13
winter	0.31 ± 0.11	0.42 ± 0.19	0.59 ± 0.15	0.36 ± 0.14	0.50 ± 0.15
NAU					
spring	0.34 ± 0.10	0.54 ± 0.20	0.54 ± 0.14	0.33 ± 0.15	0.42 ± 0.15
summer	0.27 ± 0.11	0.60 ± 0.19	0.57 ± 0.18	0.10 ± 0.08	0.27 ± 0.11
autumn	0.32 ± 0.10	0.69 ± 0.14	0.67 ± 0.11	0.19 ± 0.16	0.35 ± 0.09
winter	0.36 ± 0.12	0.58 ± 0.18	0.55 ± 0.16	0.38 ± 0.14	0.48 ± 0.13
SKU					
spring	0.29 ± 0.11	0.50 ± 0.18	0.60 ± 0.16	0.37 ± 0.19	0.34 ± 0.13
summer	0.27 ± 0.08	0.51 ± 0.17	0.54 ± 0.15	0.10 ± 0.08	0.32 ± 0.11
autumn	0.30 ± 0.10	0.63 ± 0.21	0.67 ± 0.15	0.14 ± 0.12	0.35 ± 0.12
winter	0.32 ± 0.11	0.49 ± 0.22	0.65 ± 0.16	0.33 ± 0.14	0.47 ± 0.15
VAS					
spring	0.28 ± 0.10	0.53 ± 0.18	0.61 ± 0.16	0.26 ± 0.16	0.28 ± 0.11
summer	0.29 ± 0.09	0.64 ± 0.14	0.61 ± 0.14	0.07 ± 0.05	0.37 ± 0.10
autumn	0.30 ± 0.09	0.69 ± 0.21	0.68 ± 0.16	0.10 ± 0.10	0.35 ± 0.10
winter	0.32 ± 0.11	0.52 ± 0.20	0.68 ± 0.14	0.31 ± 0.16	0.39 ± 0.14
VOL					
spring	0.32 ± 0.15	0.32 ± 0.16	0.50 ± 0.15	0.40 ± 0.16	0.38 ± 0.12
summer	0.25 ± 0.10	0.50 ± 0.19	0.52 ± 0.18	0.14 ± 0.11	0.28 ± 0.10
autumn	0.29 ± 0.10	0.53 ± 0.18	0.61 ± 0.17	0.19 ± 0.13	0.34 ± 0.11
winter	0.28 ± 0.11	0.23 ± 0.10	0.43 ± 0.17	0.29 ± 0.12	0.37 ± 0.16

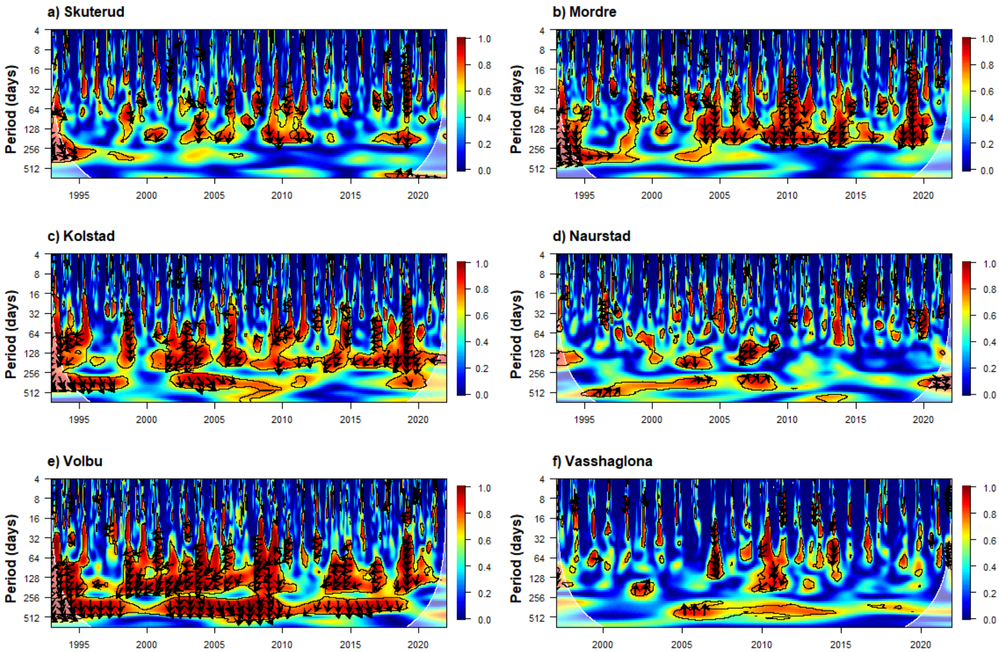

Figure 4: Wavelet coherence between discharge and snow water equivalent for 24-26 years of data. The coherence within the black lines is significant.

The impact of snow in the catchments can also be seen in the coherence between discharge and SWE (Table 3, Figure 4), where Kolstad (0.36), Mørdre (0.38) and Volbu (0.40) exhibit the strongest coherence in spring. The coupling is strongest after a six-month periodicity (> 128 days). The average wavelet power (dominant periodicity) was highest on six months to a yearly cycle for all catchments (Figure SI-23). The boxplots showed a seasonal trend in the data at all sites with low coherence in summer and autumn (Figure SI-11). Interestingly, Volbu showed a strong coherency in seasonal periods, but also on an annual scale. This suggests that Volbu´s annual runoff basically depends on meltwater. Considering the long-term trend of the coherence between discharge and SWE (Figure SI-11), Kolstad, Naurstad and Vasshaglona were quite stable (Figure SI-13). Whereas Mørdre and Skuterud exhibited a decreasing trend, that might be due to changes in the snow regime. Both showed a significant declining trend in SWE in winter (Table 2). Volbu also showed a decreasing trend in coherence with a particular drop in the last years (2017-2019).

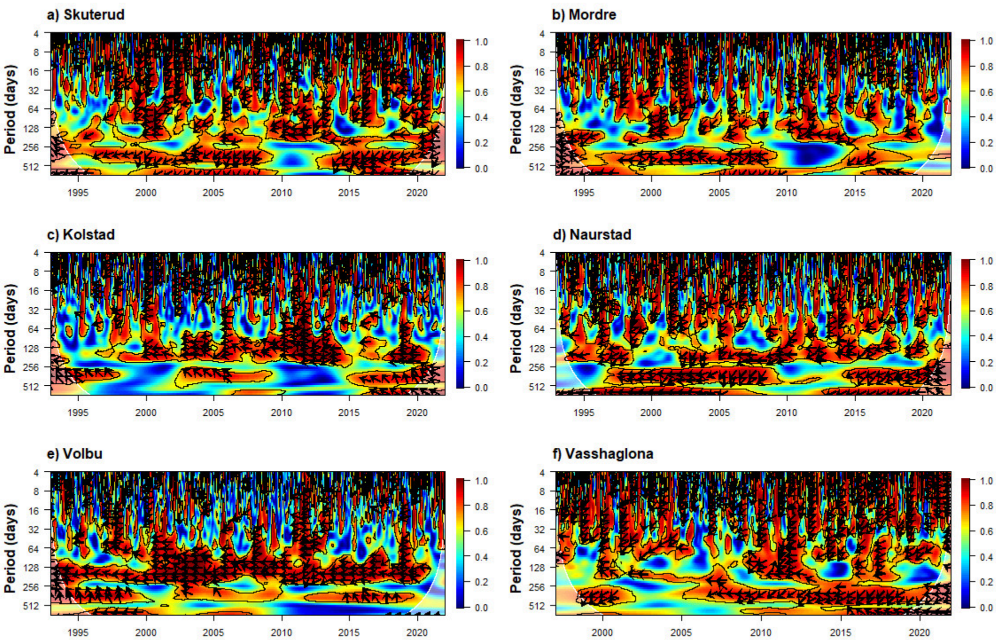

Figure 5: Wavelet coherence between discharge and soil water storage capacity for 24-26 years of data. The coherence within the black lines is significant.

Discharge and SWC are strongly connected to each other (Figure 5). The relationship is anti-phase (left point arrow, negative correlated), meaning small storage capacity results in higher discharge. The wavelet coherence analysis indicates that coupling between discharge and SWC is already apparent at short term period (< 30 days) and gets even clearer at a six month period (> 128 days) (Figure 5). The average wavelet power (dominant periodicity) was highest on six months to a yearly cycle for all catchments (Figure SI-24). The coherence was strongest in autumn for all catchments (0.61 to 0.68, Table 3). Volbu and Kolstad showed the lowest coherence in winter (0.43 and 0.44) compared to the other sites (Table 3, Figure SI-7), likely due to snow impact and frozen soil. No short-term (< 30 days) trend in coherence between discharge and SWC was detected, but in the long-term trend, this relationship for Volbu has been decreasing and particularly rapidly in the recent years and to some extent also in Mørdre (Figure 5b, e, Figure SI-9). A gap occurred in the coupling between discharge and SWC in 2010 at periodicity of 256 days, which was particularly strong in Skuterud, Mørdre and Kolstad and partly Naurstad and Volbu, but not in Vasshaglona (Figure 5).

Although temperature increased in six of seven catchments and in most of the seasons (Table 2), the coherence between discharge and temperature was low (Table 3, Figure SI-14) in contrast to precipitation or SWC. The same occurred for ET (Table 3, Figure SI-18). Discharge and temperature showed similar seasonal cycles in most of the sites. Further, we could not detect any short-term trend of coherence between discharge and temperature, while no long-term trend was exhibited. Only Volbu indicated a seasonal decoupling between discharge and temperature in the long term (right-pointing arrows). This might be due to the inland location of the catchment and Volbu showed the highest temperature increase and an increase in precipitation which might affect the hydrological regime.

Discussion

Long-term annual and seasonal changes

We found that mean air temperature showed clearly increased long-term and seasonal changes (all seasons) in all catchments, except Vasshaglona. Vasshaglona has a mild climate compared to the other catchments and changes were lower in this region (+ 0.44 °C) compared to other regions during the period 1985-2014 (Hanssen-Bauer et al., 2015). Considering long-term prediction for this area, they are projected to be smaller (+ 2.2 °C) there than in other Norwegian regions like Finnmark (+ 4.5 °C) (Hanssen-Bauer et al., 2015). Trends might therefore not be significant in Vasshaglona. Winter was the season with the biggest change compared to the other seasons in all catchments. In the short-term (1985-2014) Hanssen-Bauer et al. (2015) found that the biggest increase was in autumn (+ 0.6°C) on a national average. In addition, the projection made for Norway (Hanssen-Bauer et al., 2015) showed an increase of 3.3 °C in winter median temperature by 2100 which is the biggest expected change. Evapotranspiration showed a similar pattern to temperature and is projected to increase significantly in Fennoscandia (Donnelly et al., 2017). An increase in ET over time was also shown by our data for five of the seven catchments. However, ET used here was calculated based on a temperature index which might caused a similar pattern to temperature. Moreover, ET does not only depend on temperature, humidity, wind and CO_2 air concentrations play also a role and might impacted the results (Snyder et al., 2011). In the hydrological data, trends were not easily detectable, and a spatial pattern was difficult to draw. Precipitation increased in recent years (1985-2014) in Norway and is projected to increase further in Norway and Northern Europe in all seasons (Donnelly et al., 2017; Hanssen-Bauer et al., 2015). In our study, most of the catchments did not show any significant trends in precipitation. The mountainous catchment, Volbu, showed an increase in precipitation in summer and winter. Hanssen-Bauer *et al.* (2015) projected for the Volbu-area (inland Norway) an increase of the total annual precipitation of 13% which is one of the highest regional increases. In general, changes in precipitation are more difficult to detect, because they are not only dependent on temperature, but on atmospheric circulations (Bailey et al., 2021; Irannezhad et al., 2014; Wilson et al., 2010). In addition, measurement errors for precipitation as snow might also play role due to underestimation of 20 to 50% due to e.g., wind and wetting losses (Rasmussen et al., 2012). Further, the dataset used in this study is 22-26 year which might be too short to detect trends in precipitation. Some publications suggest that hydrological time series should at least cover 40 years (Whitfield et al., 2012).

The catchments have different seasonal patterns in runoff, depending on location and whether they are snow or rain dominated. Therefore, changes in temperature and precipitation cause differing responses. Increased precipitation during autumn and more precipitation falling as rain instead of snow in winter, in combination with the increased number of intermediate snowmelt periods in winter and high soil moisture (reduced infiltration capacity) can cause increased high flow discharge (e.g. Skuterud) (Blöschl et al., 2019; Meriö et al., 2019). Increases in precipitation have been observed in south and west Norway (Blöschl et al., 2019) and in nearby countries such as the United Kingdom as the cause for changes in flood discharge extremes (Blöschl et al., 2019).

Snow dominated inland catchments (Kolstad and Volbu) showed an increase in winter discharge, which might be due to higher temperature which leads to reductions in snowfall and increase in rainfall, and an increased number of thaw-melt periods. An increase in winter runoff for Scandinavia was also found by other studies (Donnelly et al., 2017; Wilson et al., 2010). Hanssen-Bauer *et al.*(2015) projected a relative change in winter runoff of 26% (period 1971-2000 to 2071-2100, RCP 4.5) Seasonal snow cover and snowfall are in some catchments (Kolstad, Mørdre, Volbu) an important part of the water cycle (in Norway 30% of the annual P falls as snow) and the runoff is dominated by meltwater (e.g., Volbu). Changes in climate will affect snow and soil frost conditions, influencing infiltration capacities and discharge event participation (Ala-aho et al., 2021). The mountainous catchment (Volbu) was the only catchment where SWE increased, despite increasing winter temperature. Regional differences in snow accumulation were also found on a larger scale such as a decreasing trend of SWE in the Baltic and an increasing trend in the prairies in North America (Pulliainen et al., 2020). Skaugen *et al.* (2012) found that stations in southern Norway above 850 m.a.s.l. still accumulate snow in winter, despite increased temperatures. Volbu covers elevation levels from 440 to 863 m.a.s.l. and accumulates snow, which agrees with the findings by Skaugen et al. (2012). The increased amount of snow in Volbu may be due to higher temperatures which can transport more air moisture and hence can result in more snow, especially in northern Fennoscandia and mountains areas (Pulliainen et al., 2020). This pattern might also explain the long-term decline in coherence between discharge and precipitation in this catchment because precipitation is stored as snow and water is released first during melting periods.

Spring often has increased discharge compared to other seasons. In particular, in the snowmelt-dominated catchments (here e.g., Kolstad and Volbu), spring snowmelt is usually the biggest hydrological event of the year (Casson et al., 2019). In the future, this might continue to change as we observed that four of seven catchments had tendency to decreased spring runoff (not significant). Hansen-Bauer *et al.* (2015) did not predict a decrease in spring runoff for Norway, but that might not count for single regions. Nevertheless, decreasing spring runoff might have several causes: snow melts occurring in winter, lower precipitation, and higher temperature and hence more ET during this period (Donnelly et al., 2017) and extreme dry years such as 2018 might have an effect as well (Bakke et al., 2020). This has also an effect on the low flow conditions in the upcoming seasons like summer. The possible causes for decrease in summer low flow in Volbu can be the decrease in spring runoff which affects the summer discharge (Meriö et al., 2019). The significant decrease in autumn discharge and in annual low flows in Time might refer to the higher temperature and therefore increased ET. This result fits the projected hotspots of decreased low flow in Norwegian south-west coastal areas shown by Donnelly et al. (2017).

Coupling between discharge, climate, and water sources.

Catchments in cold climates are expected to react more sensitive and rapidly to global warming and human activities than catchments in the temperate zone (Bakke et al., 2020; Laudon et al., 2017). Presenting an understanding of variability and coupling over time is important and provides an insight into how sensitive catchments are to climate change (Carey et al., 2013). The missing link between temperature and discharge in the seven Norwegian catchments may be explained by the opposite effect of temperature due to its impact on ET, snowfall-to-rain transition, and snowmelt (Blöschl et al., 2019), meaning effecting runoff indirectly and differently. Further, other factors like land use, soil type and precipitation patterns might have a stronger effect on runoff.

Generally, discharge and precipitation are closely linked to each other. The reason for a close relationship and a short lag-time between precipitation and discharge in the presented catchments are the small catchment size, relatively low ET, and a limited storage capacity of the soil due to wet conditions. Tile drainage systems in the study areas cause a fast response of runoff to precipitation for short term and annual periods (Wenng et al., 2021). That soil water storage capacity impacts the actual runoff could be shown by a high coherence. The link between runoff and SWC is important and determines how fast precipitation is translated to runoff (Carey et al., 2013; Wenng et al., 2021). Snow water equivalent is also closely related to runoff and the coherency is determined by a seasonal anti-phase pattern. That means, catchments that are impacted by snow have a disconnection from terrestrial pathways to stream during winter as water is stored in the snowpack and will first be active in spring (Carey et al., 2013). This could clearly be seen in inland and mountainous catchments and these processes are highly impacted by climate change (Blöschl et al., 2019; Meriö et al., 2019; Vormoor et al., 2016).

Volbu, the mountainous inland catchment exhibit more marked changes compared to all other catchments. Volbu had the biggest temperature increase, increasing precipitation, and had the greatest dependency on snow, hence the highest discharge occurs in spring during snowmelt. This gives us a hint of how mountainous inland catchment might behave in the future. As the hydrology of mountainous catchments is very snow dependent, changes in winter temperature above 0 °C not only impact the storage of water, the shift in the snowmelt peak, and subsequent seasons but also the entire hydrological regime (Meriö et al., 2019).

Further, our analysis indicated that single extreme conditions such as colder average temperature and high average temperatures can influence the total hydrological regime and have a tail to the following years. The year 2010 had a colder average temperature compared to others years and the winter was drier than usual (Dyrrdal et al., 2013). The decoupling between discharge and temperature, and discharge and SWC in the year 2010 for four catchments (Skuterud, Kolstad, Naurstad, Volbu) could be due to the cold temperatures observed in the year 2010. Further, the drier winters might led to larger storage capacity of water in the soil. In the year 2018, Northern Europe was affected by an extreme drought and extreme low-flow conditions were recorded (Bakke et al., 2020; Fennell et al., 2020). A strong increase in mean temperature from 2017 (mean T 3.1 °C) to the year 2018 (mean T 6.6 °C) in Volbu was observed which might have affected the decoupled coherency between discharge and precipitation, SWC, SWE, and ET in the recent years. In regions affected by seasonal snow, droughts are also determined by accumulated snow volume and timing of snowmelt. High temperatures occurring already in the snowmelt season can lead to extreme high runoff during spring in mountainous catchments (Bakke et al., 2020). The catchment in northern Norway (Naurstad) also indicated a change in the precipitation regime during 2018 and 2019, when total precipitation was smaller than in the years before related to a high-pressure systems centred over the Norwegian Sea (Bakke et al., 2020). This led to a weakening of the coupling between runoff and precipitation. Groundwater is important to mention in this context, because it plays a crucial role in the occurrence, timing and magnitude of a hydrological drought (Bakke et al., 2020). Due to regional shallow groundwater (Deelstra et al., 2014), Vasshaglona showed the smallest seasonal difference in discharge of the seven catchments. Further, it did not show any significant trends in low flows, assuming it has quite stable conditions also during dry periods. Groundwater is important for drought resilience of a catchment (Fennell et al., 2020).

Implications for agriculture and hydrology

Climate change affects not only the hydrological regime but also water quality as hydrology and nutrient loss are strongly linked in agricultural catchments (Liu et al., 2019; Wagena et al., 2018). Farmers and catchment managers in the presented Norwegian agricultural catchments and in the Nordic region will have to deal with increased discharge in autumn and winter and drier conditions in summer, including extreme high runoff and low runoff conditions and changes in snow accumulation and ET. Further, in agricultural catchments hydrological pathways are impacted by human activities due to cultivation activities and artificial drainage systems. Tile drainage is in favour of subsurface runoff (Bechmann and Bøe, 2021; Kværnø, 2013). Soil tillage and harrowing affects the soil surface and determines how much water can infiltrate. Moreover, heavy field activities in autumn such as harvesting and ploughing and bare soil in winter expose the land to erosion and runoff, hence to nutrient loss. This requires on the one hand increasing and restoring water storage in the landscape (Wilson et al., 2019) and on the other hand different ploughing and fertilising management plans, taking into account nutrient legacy, vegetation covers such as catch/cover crops or straw stubbles, and buffer stripes (Bechmann, 2014; Casson et al., 2019; Liu et al., 2019). Even in summer, when agricultural fields are fully vegetated, extreme runoff events can have the same impact on e.g. total phosphorus concentration, as a snowmelt event in spring (Wilson et al., 2019). In addition, warm and dry conditions can lead to a mineralisation of nitrogen and limit the ability to take up nutrients that are then available for runoff in autumn (Wenng et al., 2020). Further, dry conditions in summer can have a severe effect on water availability for plants which might make watering necessary. For all regions in Norway a decrease in summer runoff is projected (Hanssen-Bauer et al., 2015). Spring runoff events in snow dominated catchments often account for large nutrient export (Casson et al., 2019), this might change under future climate due to less pronounced snow melt events (Pulliainen et al., 2020) and an earlier start of the growing season due to warmer spring temperatures (Wenng et al., 2020). In our study, we show that there is not an overall pattern, the Norwegian agricultural catchments show individual patterns and high spatial variation. This requires changes to current site specific water and nutrient management plans to gain and maintain good ecological status of the catchments' water and ecosystem (Liu et al., 2019).

Conclusion

In this study, we presented long-term and seasonal trends of 22-26 years of hydrological data. We used strong analytical methods in our study, namely a Mann-Kendell trend and a wavelet coherence analysis. We analysed long-term monitoring data and showed changes in Norwegian hydrology of small agricultural catchments. We showed a significant increase in annual and seasonal air temperature. Annual changes in hydrology were more difficult to detect, seasonal differences were much more apparent. Precipitation turned out to show almost no trends in these agricultural catchments. Increasing trends in discharge are exhibited mainly in winter and autumn. We showed that there were numerous differences in the hydrological regime of rain and snow dominant catchments which influence the coherency between discharge and precipitation. Specifically: discharge is not directly linked to temperature, whereas precipitation, soil water storage capacity, and snow water equivalent showed a strong coherence and affect the variability in the runoff. This is especially apparent in agricultural catchments in a cold climate, where runoff shows strong seasonality. This seasonality changes, especially in winter which might no longer be a hydrological inactive season. Changes in winter hydrology are also relevant for subsequent seasons. Understanding these changes in hydrology and their effects on nutrient export is of great importance for cold climate regions as they are severely and disproportionately impacted by increased temperature. We showed the individuality of each catchment which implies that site-specific water and nutrient management solutions are needed.

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Supplementary Information

for Wenng et al. Hydrology under change? Long-term seasonal changes in small agricultural catchments in Norway

Figure SI-1: The given variability between the catchments shown in total annual precipitation (Ann. P), Total effective precipitation (Ann. Effect. P), average annual temperature (Avr. ann. T), total annual evaporation (ET), average annual soil water storage capacity (Avr. ann. SWC), total annual Q (Ann. Q), baseflow index (BFI), high flows and low flows.

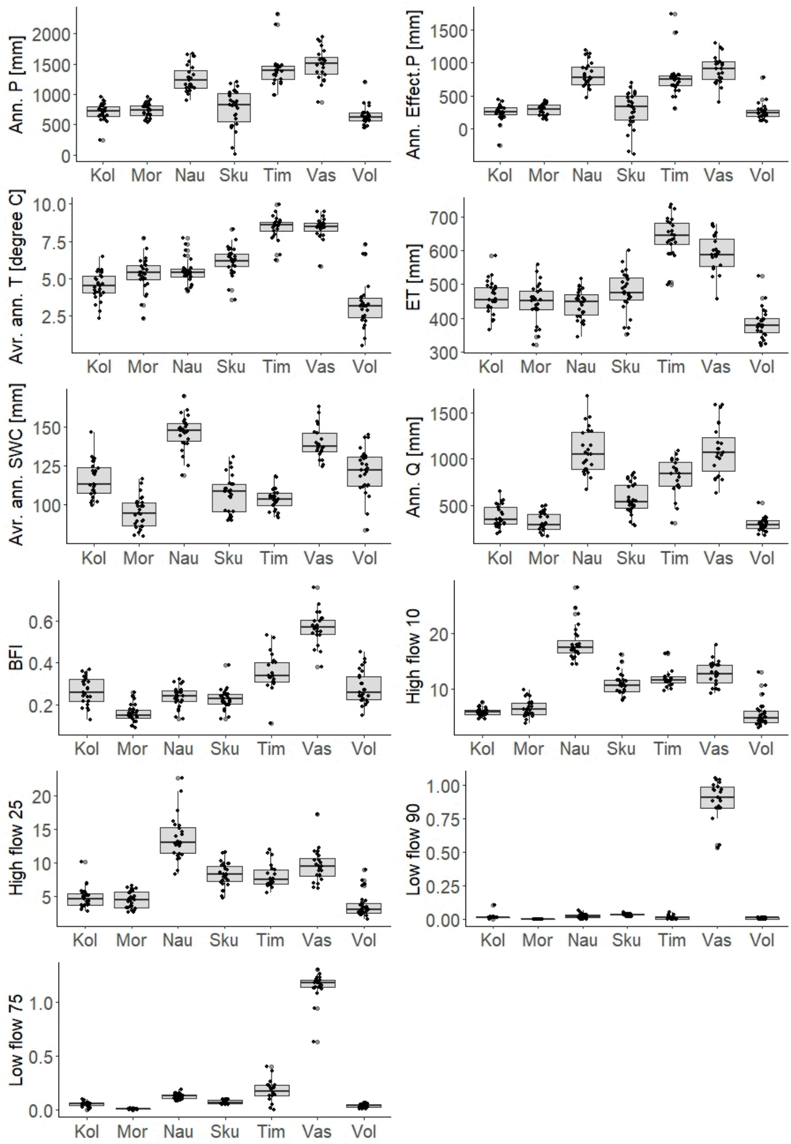

Table SI-1: Sen-slopes of the average annual trends of mean discharge (Q), median discharge (Qmed), maximum discharge (Qmax) baseflow index (BFI), low flow (Q90, 75), high flow (Q10, 25), total precipitation (P), mean temperature (T), mean soil water storage capacity (SWC), mean evaporation (ET), mean snow water equivalent (SWE), Green: significant trend ($p<0.05$), yellow: tendency ($0.05<p<0.1$); minus indicates negative trend, plus indicates positive trend

	Q [mm]	Qmed [mm]	Qmax [mm]	BFI [-]	LF90 [mm]	LF75 [mm]	HF10 [mm]	HF25 [mm]	P [mm]	T [°]	SWC [mm]	SWE [mm]	ET [mm]	EP [mm]
KOL														
annual	0.005	0.004	0.011	0.002	<0.001	<0.001	0.008	-0.004	0	0.07	-0.17	0	0.003	-0.01
spring	0.007	0.003	0.001	0.0004	0.001	0.0001	-0.03	-0.03	-0.01	0.088	0.12	0	0.01	-0.02
summer	0.002	0.002	0.0004	0.006	0.001	0.0001	-0.03	-0.003	-0.01	0.05	-0.22		0.013	-0.01
autumn	0.02	0.01	0.049	-0.003	0.0006	0.0006	0.05	0.05	0.001	0.04	-0.46	0	0.009	-0.003
winter	0.005	0.004	0.007	0.001	0.0007	0.0007	-0.01	-0.01	0.004	0.09	-0.18	-0.49	0.0004	-0.0001
MOR														
annual	-0.001	-0.001	0.007	-0.003	0	0	0.04	0.027	0.003	0.07	-0.22	0	0	-0.001
spring	-0.016	-0.009	-0.05	-0.006	0	-0.0004	0.082	0.0023	-0.015	0.085	0.22	0	0.013	-0.03
summer	-0.001	0	-0.003	-0.004		0.0006	0.07	0.05	0.011	0.036	-0.07		0.013	0.005
autumn	0.007	0.001	0.11	-0.006	0	0	0.04	0.097	0.003	0.061	-0.28	0	0.01	-0.006
winter	0.004	0.0002	0.022	0.001		0.0003	-0.042	-0.028	0.01	0.13	-0.75	-0.58	0.001	0.01
NAU														
annual	-0.01	0	-0.03	<0.001	0	<0.001	-0.1	-0.1	0.02	0.06	0.61	0	0.003	0
spring	-0.02	-0.005	-0.073	-0.0012	-0.002	-0.0012	-0.08	-0.143	0.031	0.065	0.4	0	0.013	0.01
summer	-0.002	0	0.01	0.0003	0	0.0006	-0.02	-0.11	0.026	0.054	0.63		-0.009	0.04
autumn	-0.03	-0.002	-0.33	0.003	-0.001	-0.002	-0.23	-0.1	0.024	0.061	1.16	0	0.007	0.01
winter	0.009	0.003	0.14	-0.001	-0.003	0.001	0.049	0.0079	0.008	0.061	0.39	-0.98	0.003	0.005
SKU														
annual	0.008	0.003	0.08	-0.001	0.001	0.001	0.1	0.064	-0.01	0.053	-0.29	0	0.008	0
spring	-0.013	-0.005	-0.05	-0.003	0.0002	0.003	0.004	0.0015	-0.02	0.067	0.011	0	0.013	-0.04
summer	0.005	0.002	0.056	-0.003	0.001	0.001	0.09	0.02	-0.01	0.03	-0.36		0.016	-0.02
autumn	0.05	0.011	0.33	-0.003	-0.0001	-0.007	0.19	0.254	0.002	0.045	-0.58	0	0.01	0.0001
winter	0.02	0.01	0.152	0.006	0.002	0.0023	0.005	0.013	0.001	0.084	-0.44	-0.51	0.002	-0.004
TIM														
annual	-0.003	-0.001	-0.02	-0.008	-0.002	-0.005	-0.15	-0.09	-0.005	0.05	-0.09	0	0.01	-0.03
spring	-0.002	-0.005	0.04	-0.02	0	-0.009	-0.05	0.005	-0.001	0.052	0.07	0	0.01	-0.03
summer	0.005	0.0007	0.016	-0.01	<-0.001	-0.01	-0.23	-0.15	0.004	0.037	-0.036		0.01	-0.03
autumn	-0.09	-0.036	-0.3	-0.001	<-0.001	-0.005	-0.08	-0.19	-0.005	0.032	-0.03	0	0.011	-0.02
winter	0.03	0.04	0.006	-0.004	-0.002	-0.011	-0.17	-0.017	-0.02	0.083	-0.23	-0.09	0.011	-0.09
VAS														
annual	0.024	0.01	0.09	-0.004	0.001	-0.001	0.12	0.8	<0.001	0.014	-0.02	0	0.005	0
spring	0.025	0.015	0.074	-0.002	-0.006	-0.003	0.24	0.029	-0.037	0.023	0.034	0	0.007	-0.04
summer	-0.009	-0.009	-0.023	-0.007	-0.003	-0.003	-0.26	-0.008	-0.026	0.01	0.5		0.002	-0.01
autumn	0.04	0.018	0.22	-0.008	0.005	-0.003	0.17	0.08	0.03	0.009	-0.33	0	0.008	0.01
winter	0.09	0.06	0.32	-0.0003	-0.003	0.009	0.11	0.255	0.088	0.035	-0.45	0.04	0.001	0.09
VOL														
annual	0.005	0.005	0.09	0.004	<-0.001	<0.001	0.015	0.011	0.023	0.11	-0.73	0	0.002	0
spring	0.003	0.002	-0.019	0.004	-0.0002	0.0005	-0.031	0.0015	0.01	0.14	-0.58	0	0.003	0.0008
summer	-0.001	0.0002	-0.006	0.002	<-0.001	0	-0.003	-0.008	0.033	0.057	-0.38		0.008	0.03
autumn	0.017	0.012	0.04	0.001	0.0004	0.002	0.002	0.009	0.028	0.1	-0.88	0	0.006	0.02
winter	0.005	0.005	0.01	0.005	0	0.0002	-0.191	-0.041	0.03	0.17	-1.33	2.01	<0.001	0.02

Flow vs Precipitation

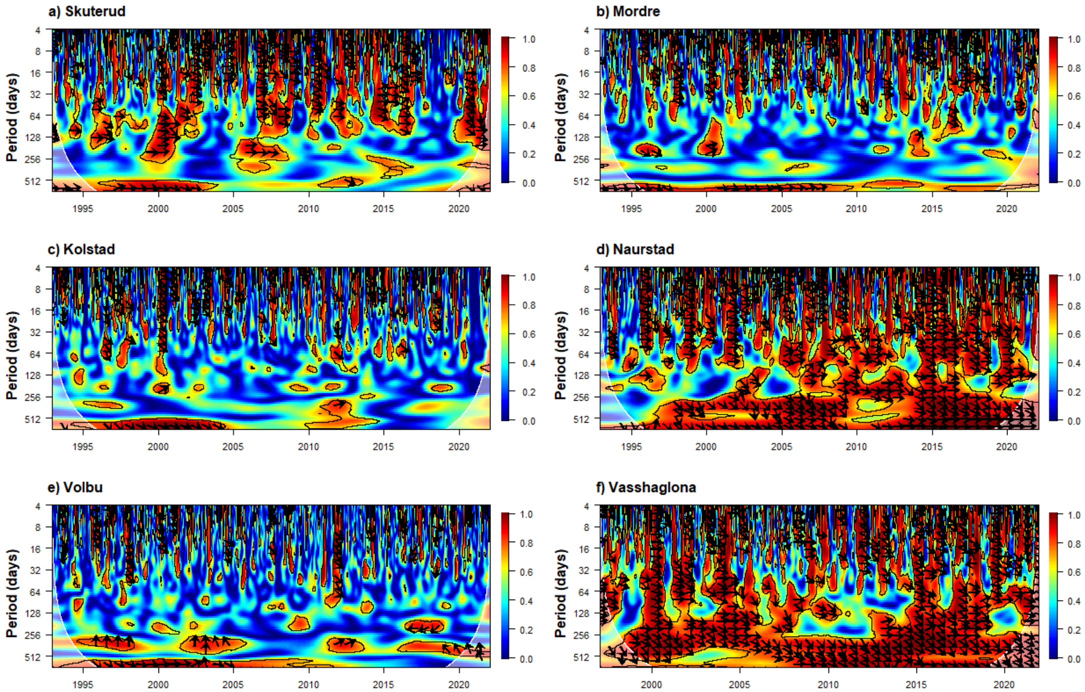

Figure SI-2: Coherence between flow and precipitation

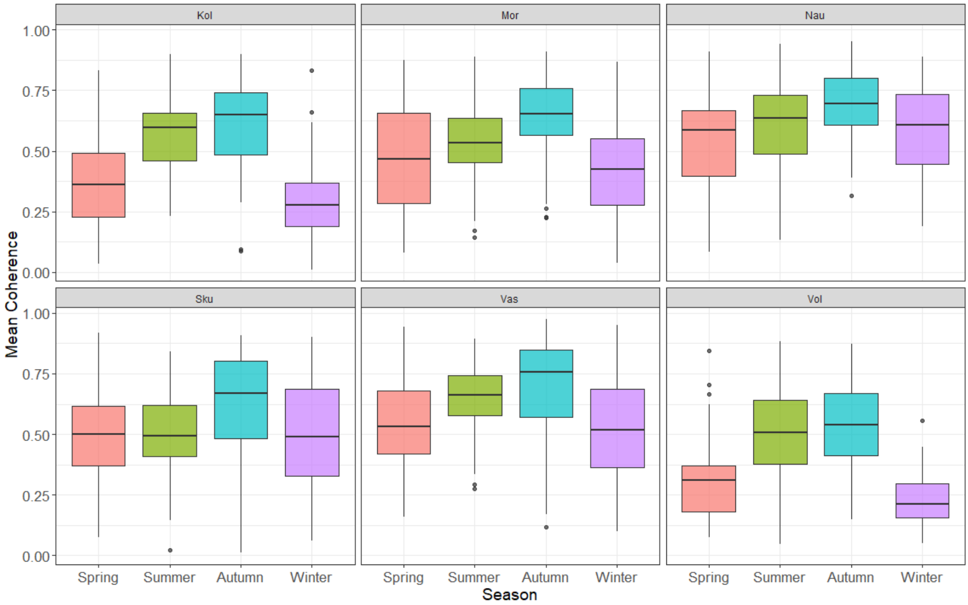

Figure SI-3: Boxplots of wavelet coherence for seasons for short term period

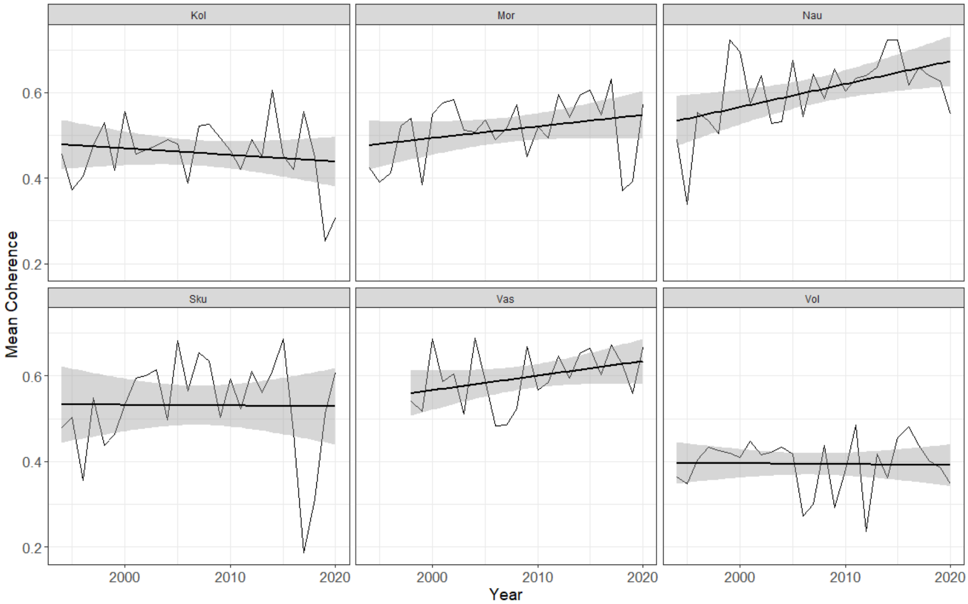

Figure SI-4: Time series for average coherency for short term periods

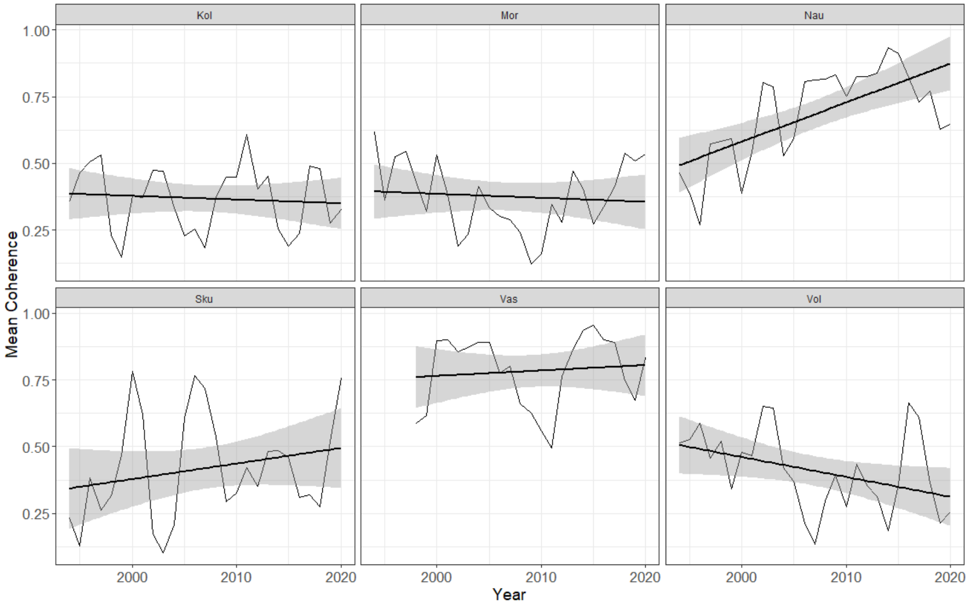

Figure SI-5: Time series for average coherency for long term periods

Flow vs Soil water storage capacity

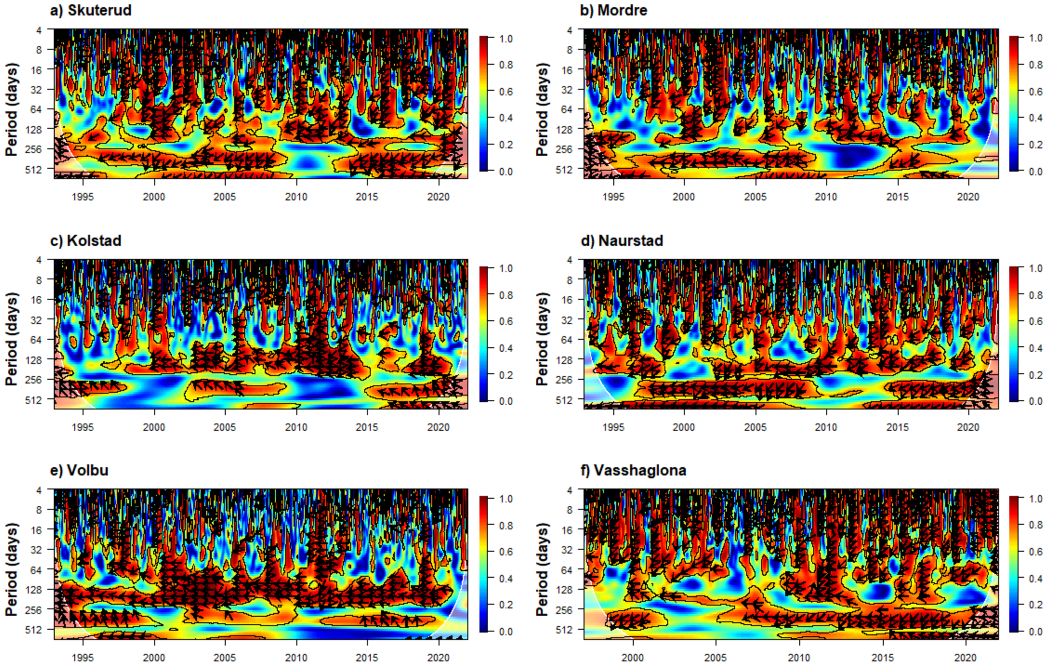

Figure SI-6: Coherence between flow and soil water storage capacity

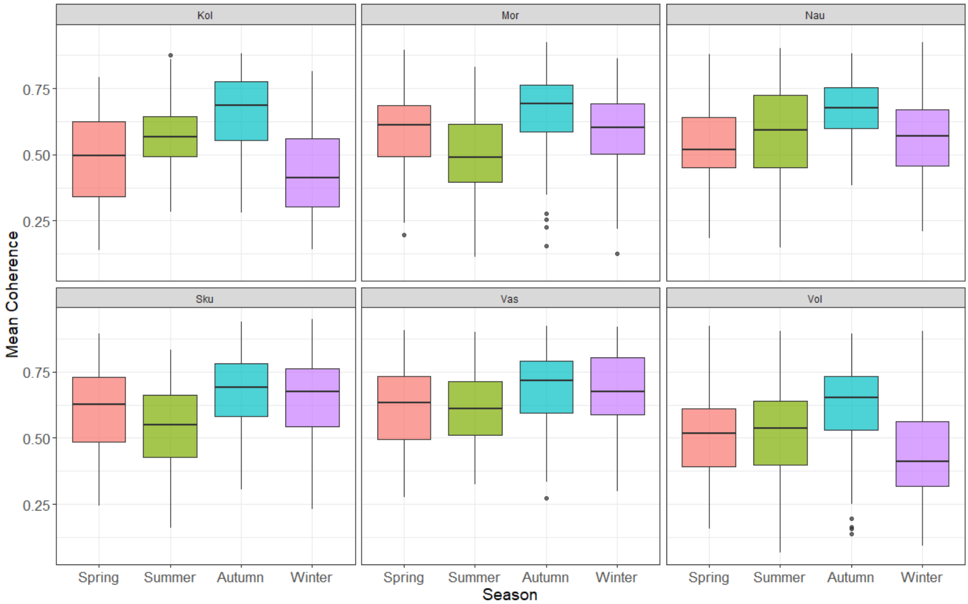

Figure SI-7: Boxplots of wavelet coherence for seasons for short term period

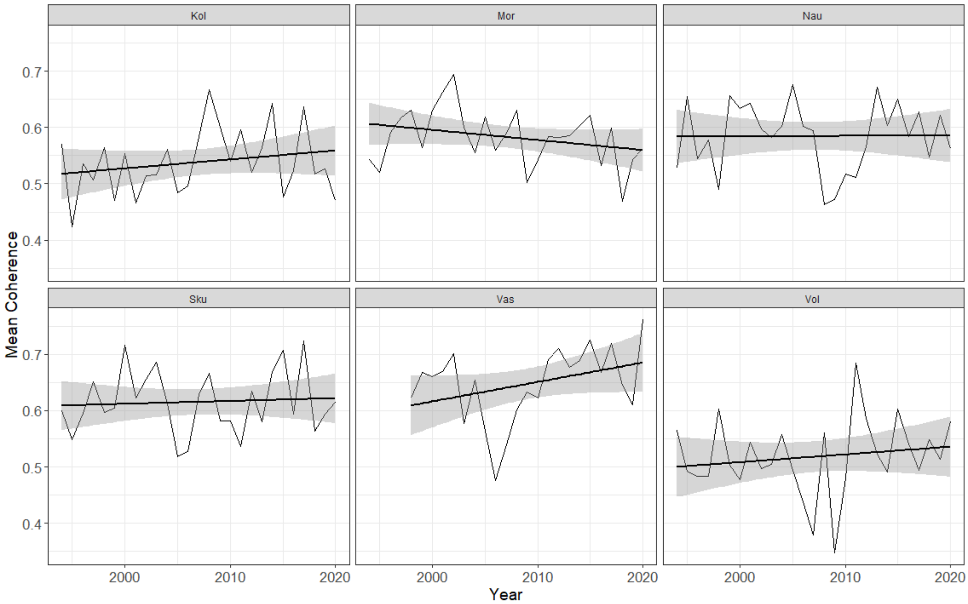

Figure SI-8: Time series for average coherency for short term periods

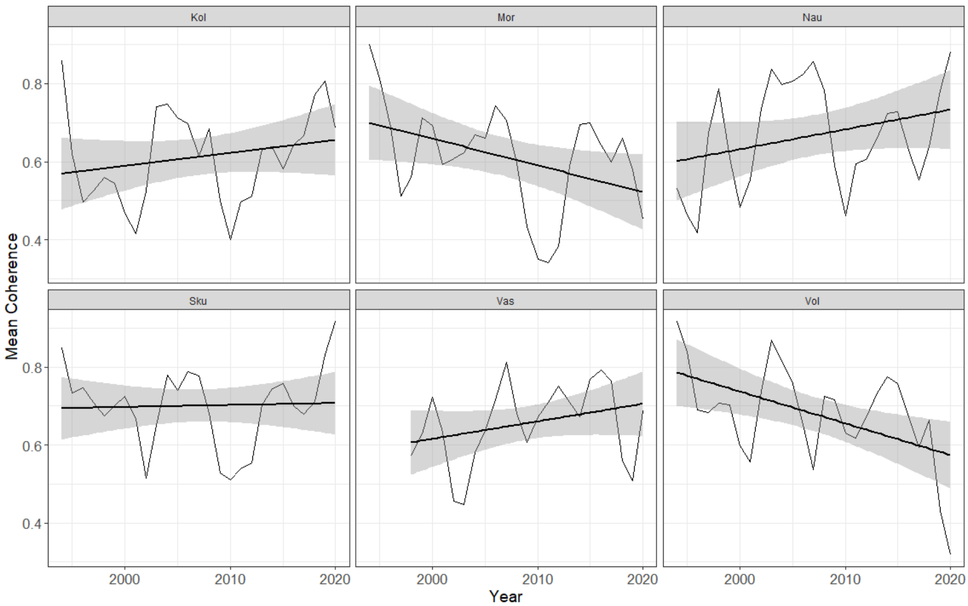

Figure SI-9: Time series for average coherency for long term periods

Flow vs Snow Water Equivalent

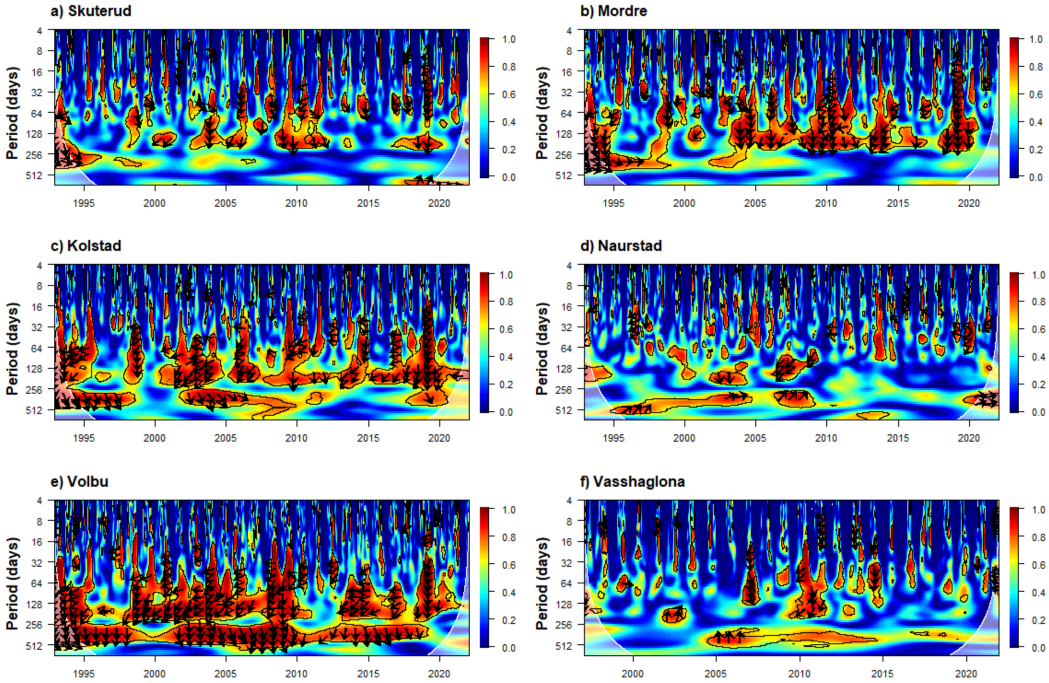

Figure SI-10: Coherence between flow and snow water equivalent

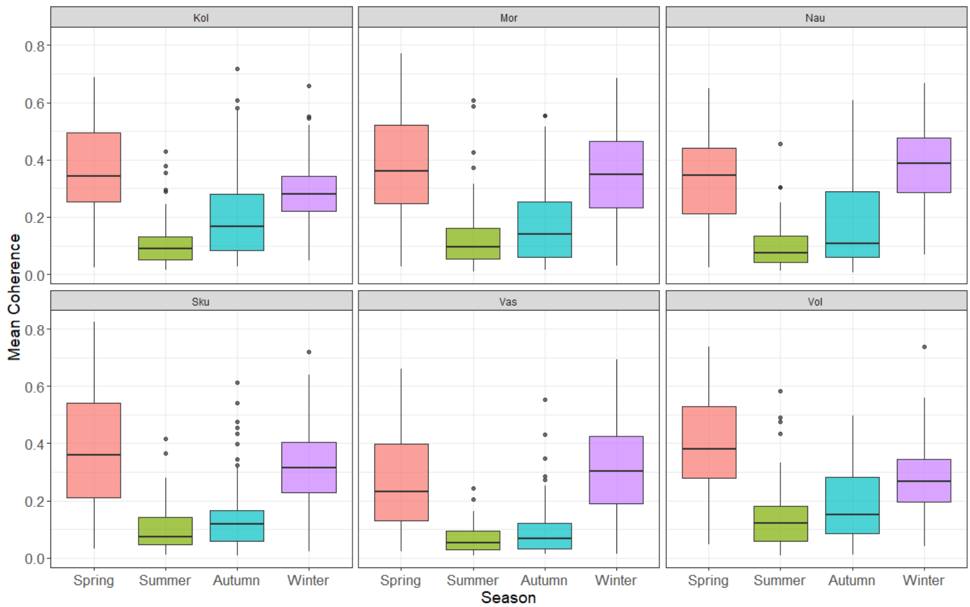

Figure SI-11: Boxplots for wavelet coherency for seasons for short-term period

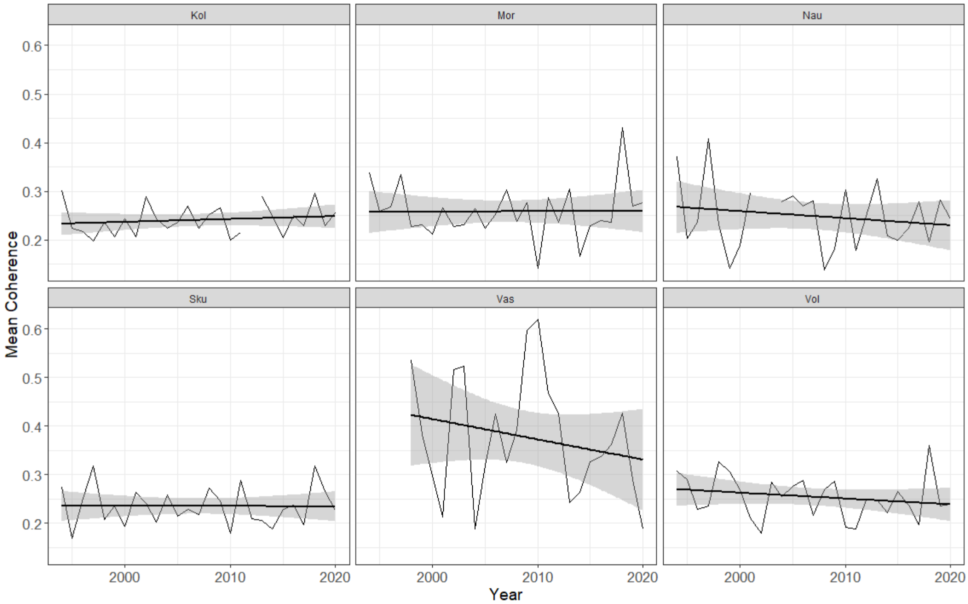

Figure SI-12: Time series for average coherency for short term periods

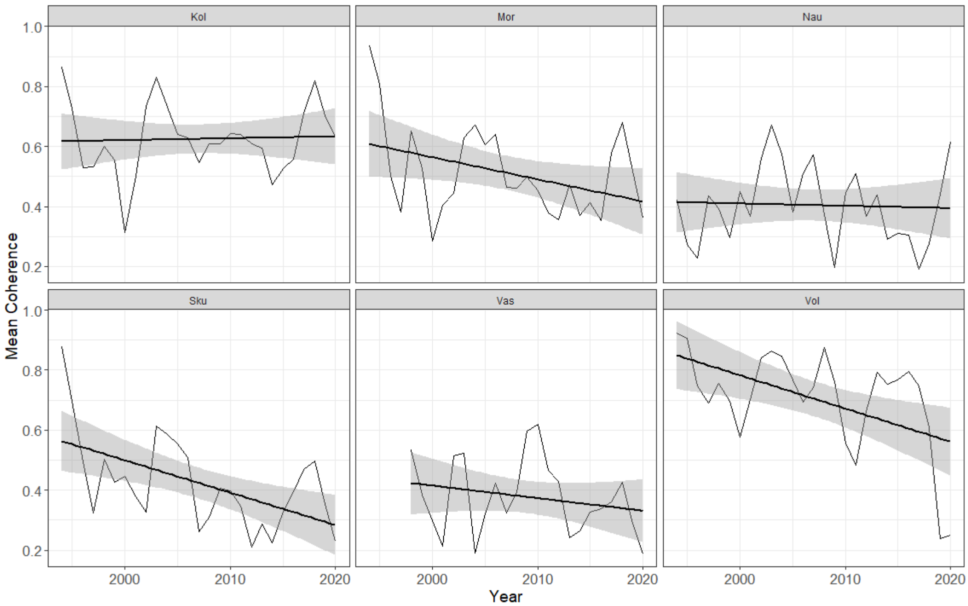

Figure SI-13: Time series for average coherency for long term periods

Flow vs Temperature

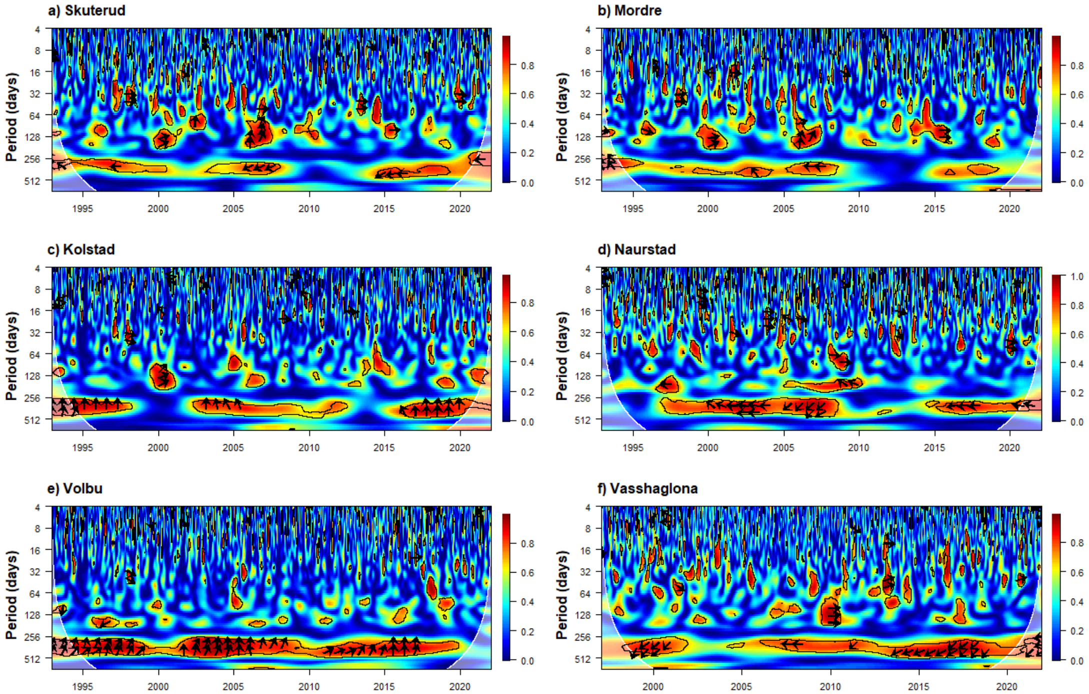

Figure SI-14: Coherence between flow and temperature

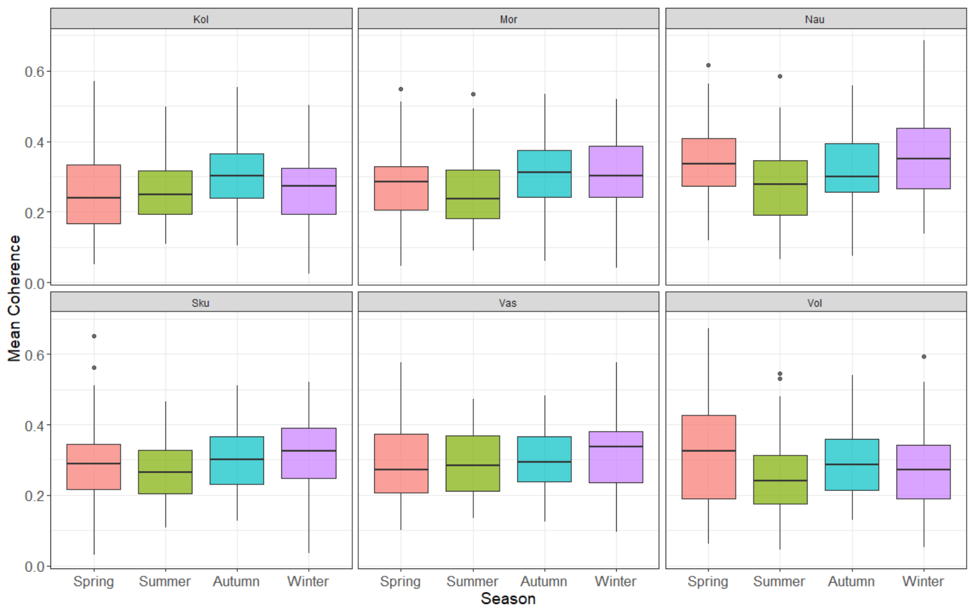

Figure SI-15: Boxplots for wavelet coherency for seasons for short-term period

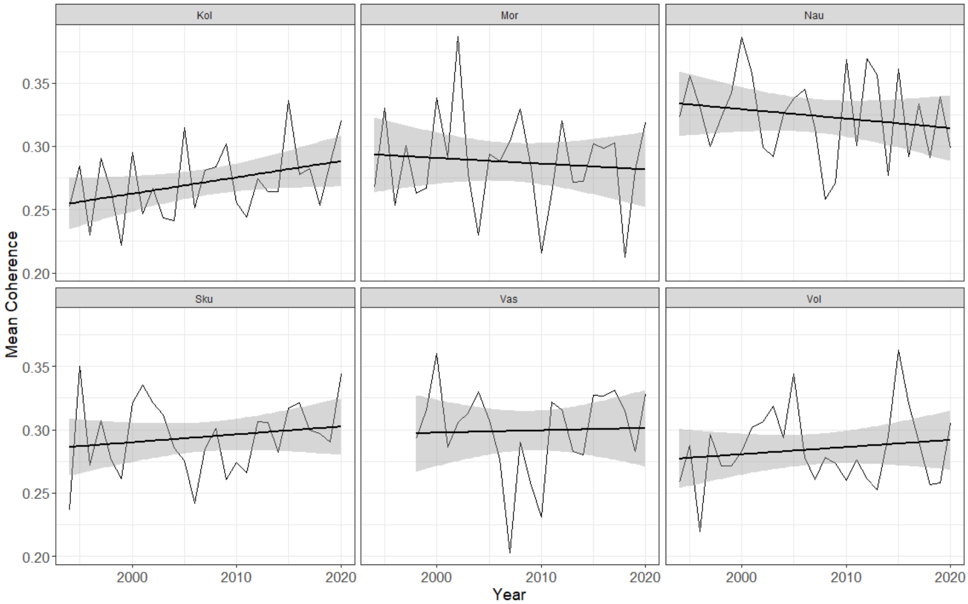

Figure SI-16: Time series for average coherency for short term periods

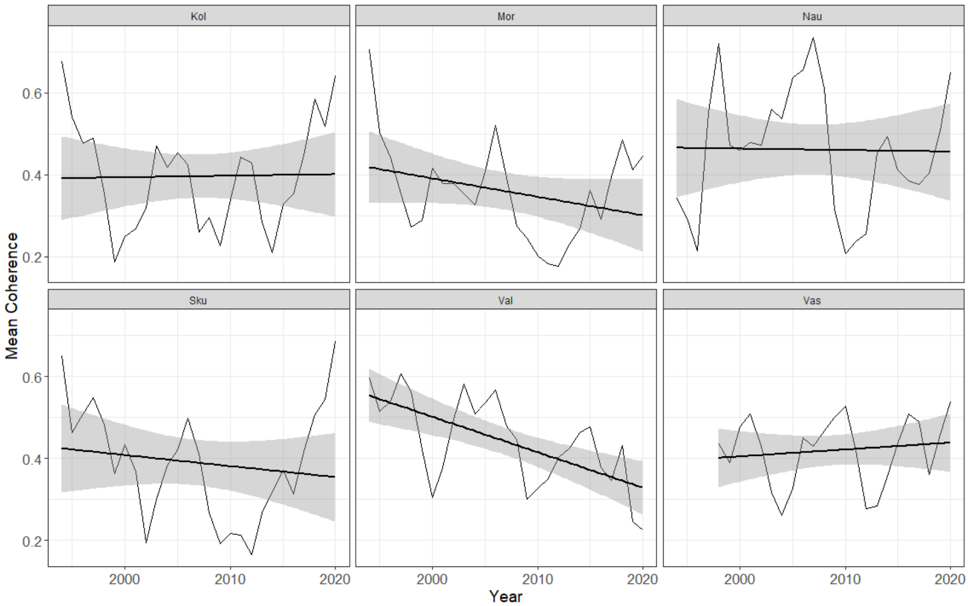

Figure SI-17: Time series for average coherency for long term periods

Flow vs Evaporation

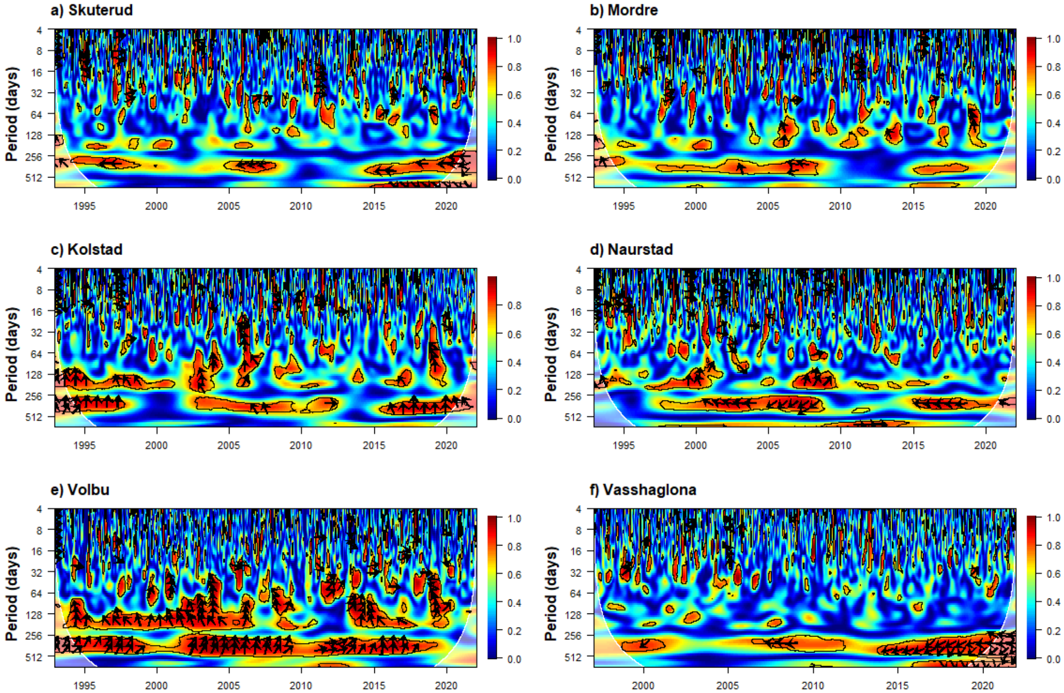

Figure SI-18: Coherence between flow and evaporation

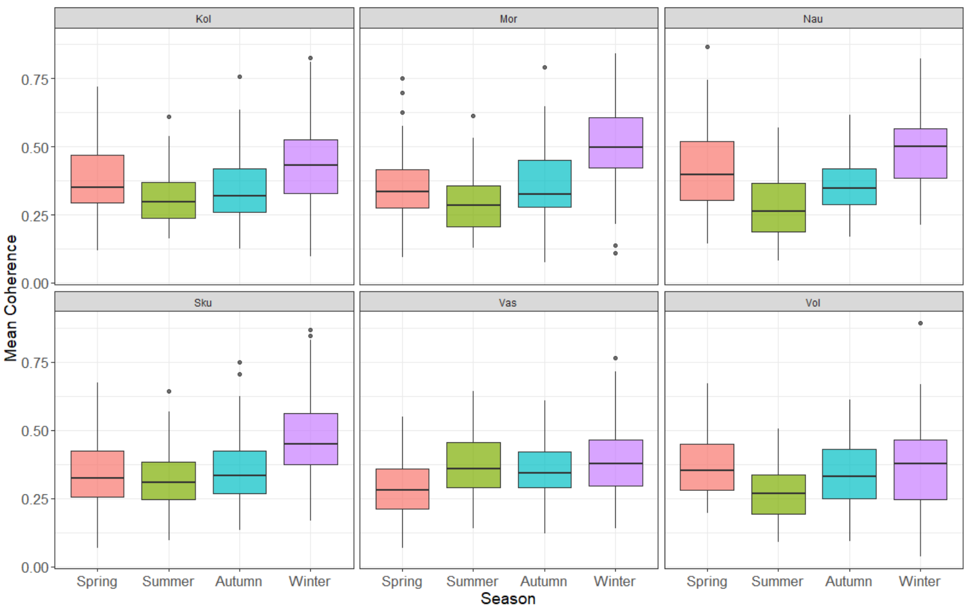

Figure SI-19: Boxplots for wavelet coherency for seasons for short-term period

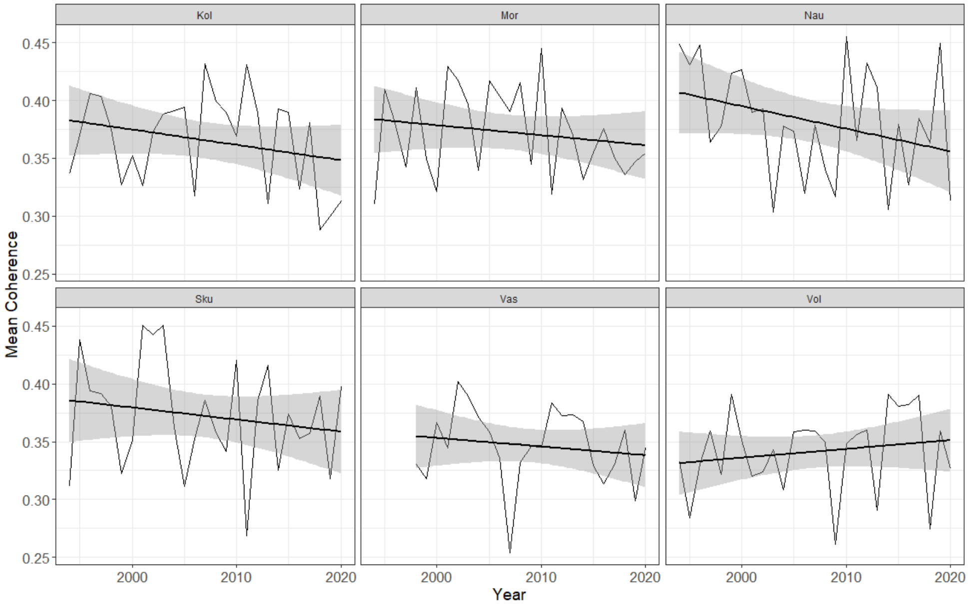

Figure SI-20: Time series for average coherency for short term periods

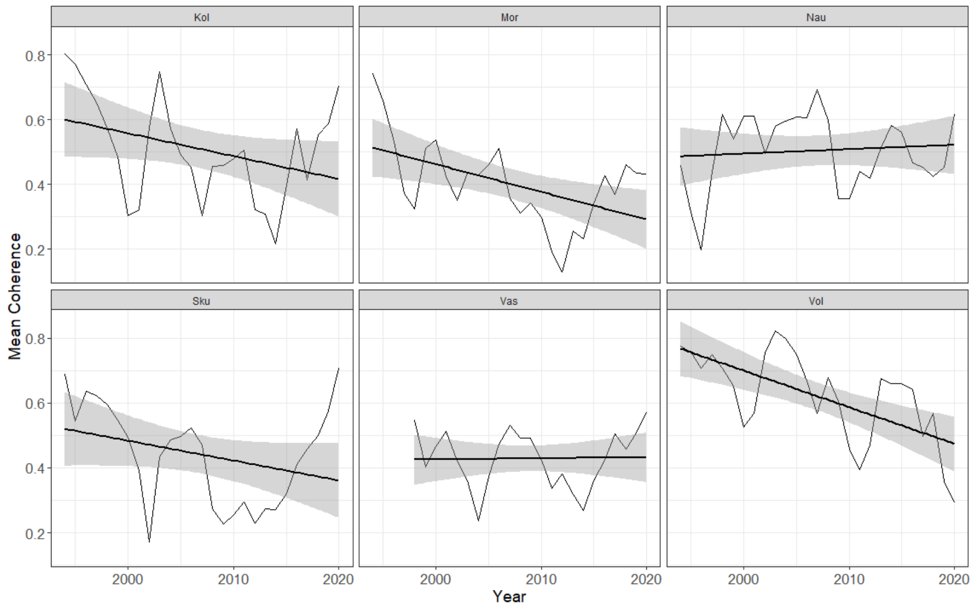

Figure SI-21: Time series for average coherency for long term periods

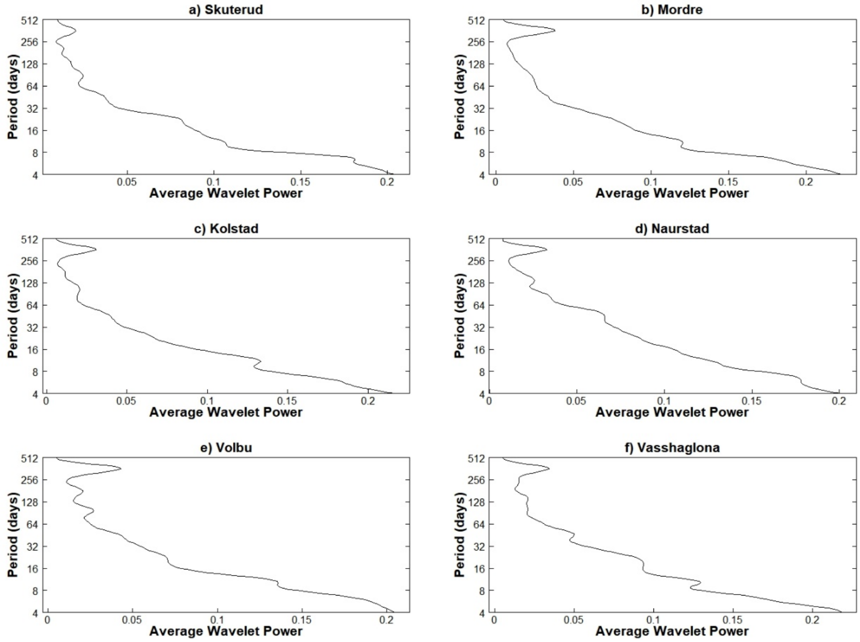

Figure SI-22: Average wavelet power for each period, showing the dominant periodicity for precipitation

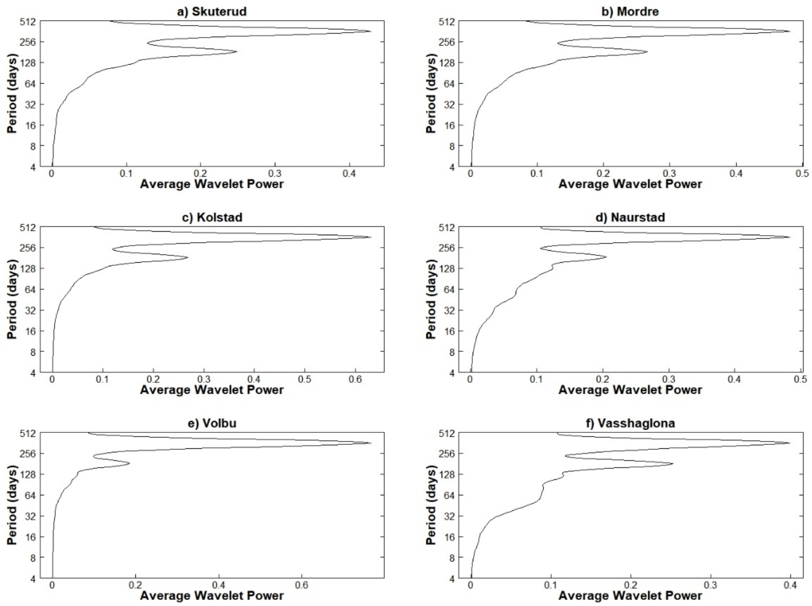

Figure SI-23: Average wavelet power for each period, showing the dominant periodicity for snow water equivalent

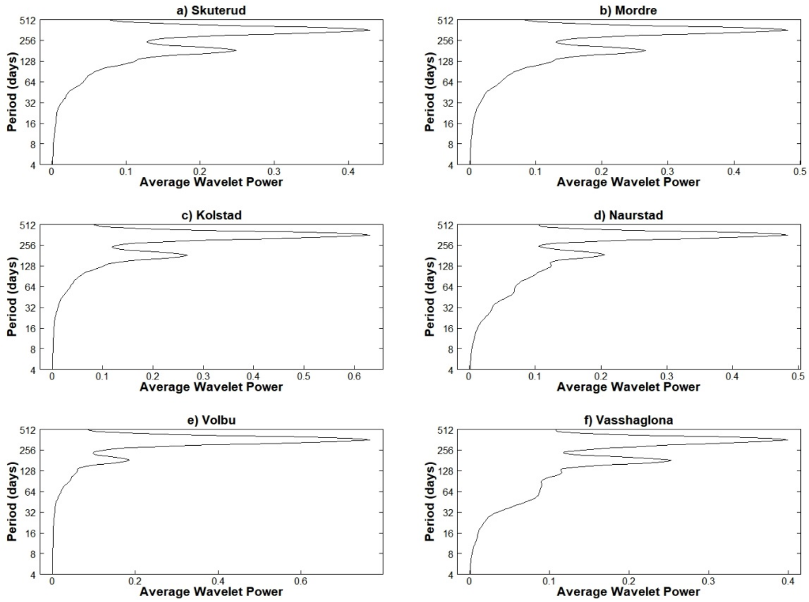

Figure SI-24: Average wavelet power for each period, showing the dominant periodicity for soil water storage capacity.

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NIBIO
NORWEGIAN INSTITUTE OF BIOECONOMY RESEARCH

Postboks 115
NO-1431 Ås, Norway
https://www.nibio.no/en

Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no

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