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

Philosophiae Doctor (PhD)
Thesis 2021:77

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

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

Philosophiae Doctor (PhD) Thesis

Hannah Tabea Wenng

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

Ås (2021)

Thesis number 2021:77
ISSN 1894-6402
ISBN 978-82-575-1853-0

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

ACKNOWLEDGEMENTS

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:

To my supervisors: Tore Krogstad for always have an open door and answering my questions. Hannu Marttila for coming with input, since the day we met, even though you were not my supervisor right from the start. Eva Skarbøvik for being my very supportive group leader and for having always an open ear for my thoughts. Marianne Bechmann who became a friend, thanks for the dinners and the lively discussions about environment, society and agriculture together with Børre.

To my co-authors: Heleen De Wit, Robert Barneveld, and Danny Croghan. Thank you for fruitful and smooth collaborations!

To my colleagues from the BIOWATER project: thanks for the nice and inspiring come-togethers at our project meetings.

To my colleagues from NIBIO: Special thanks to Geir who helped me with the installation of the sensors. To Dominika who helped me with fieldwork in Mørdre. To Csilla, Anne, and Sia for asking "how are you" and nice talks. To Ewa for the IT service and the nice chats. To Maria for your positive attitude. To Johannes for your stories from Africa and Robert for helping me in Skuterud, discussing research and cycling, and for your critical mindset which I very much appreciate.

To my friends from the Andelslandbruk Dysterjordet in Ås. Working on the field and having soil between my fingers was the perfect distraction from my research work and to get grounded.

To my friends and neighbours in Granheimlia. Special thanks to Liv-Unni and Finn-Olav who helped me from the day, when I moved into their downstairs apartment. To Katrin, Karl and Lotte for their friendship and patience. Thank you, Lotte for inviting me to your world.

To my friends spread all over Europe and the world (Japan) who keep in touch with me, although we are 1000s of kilometres apart. Special thanks to Svea who visited me almost every year in Norway. I am very thankful for our weekly phone calls, film sessions and adventures in nature. To Eva, my wine and cheese friend. Your energy is incredible! To Charlotte who just calls me, which is always a nice surprise. To Lukas, Sabine and Silke who send me signs of life from Germany and Vienna. To Joachim for your mental support, photos from the seaside and our discussions on research, life, and books. To my pen friends Debbie, Maria, Julia, and Aya who make sure that my letterbox does not run dry.

To my friends in Norway with whom I spent my time outside of the institute. Special thanks to Mari, Marya and Joris for walks and talks. To the board game group. To Ane for the training and talks before Corona. To Ana for swimming in cold water, enjoying Drøbak and your spontaneity. To Kirstine for hikes, coffees in Oslo and talks about PhD and life. Special thanks also to Sarah for your honesty and that you are always there when needed! To Irmelin, Johanna and Ross, thank you for being the way you are!

To my family, who supports me in all my decisions, and who taught me to be curious, open, to love mountains and nature and that discussions about politics and society is common sense. Special thanks to the strongest women I have ever met in my life: my mom and my granny who taught me to see the beauty in the small and ordinary things.

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*]

CONTENTS

SYNOPSIS

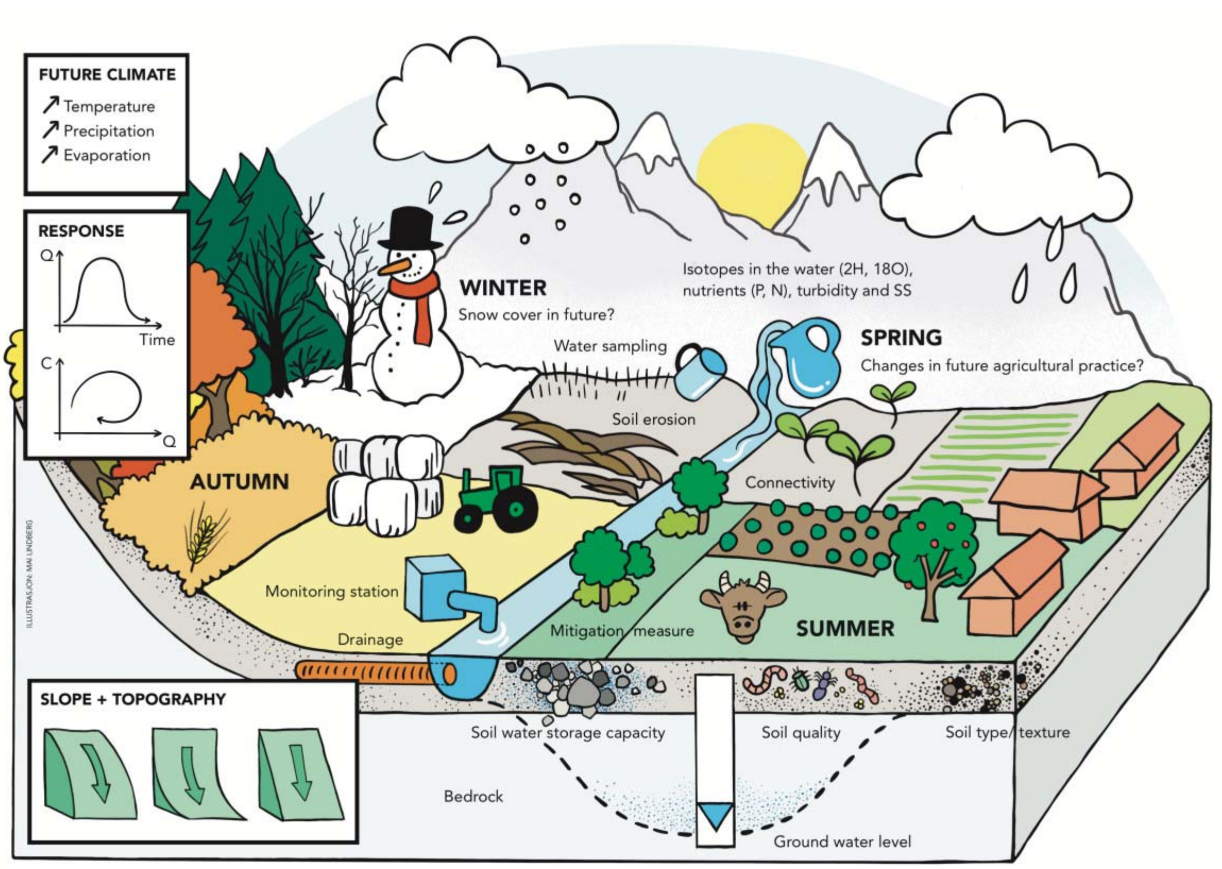

Figure 1: Catchment scale processes and their drivers during different seasons

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.

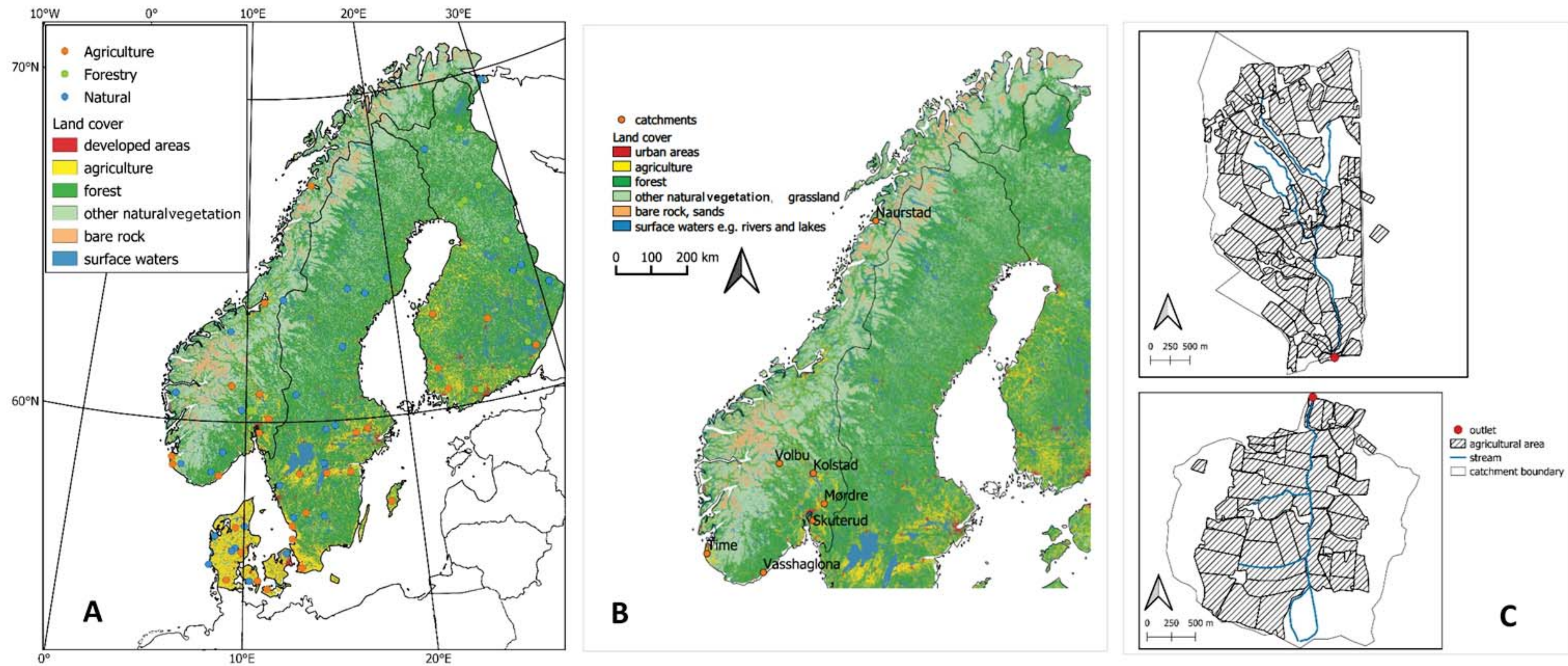

Figure 2: Location of the different catchments studied in this work. Map A: Paper II; map B: Papers III and V; map C: Paper IV.

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.

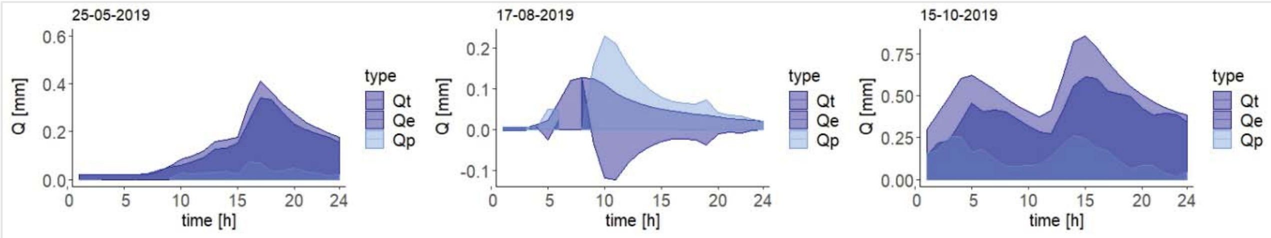

Figure 4: Hydrograph separation for three different runoff events in spring, summer, and autumn for the catchment Skuterud. Qp: pre-event water (baseflow); Qe: event water (precipitation) and Qt: runoff at time t. This figure is not shown in any of the papers.

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).

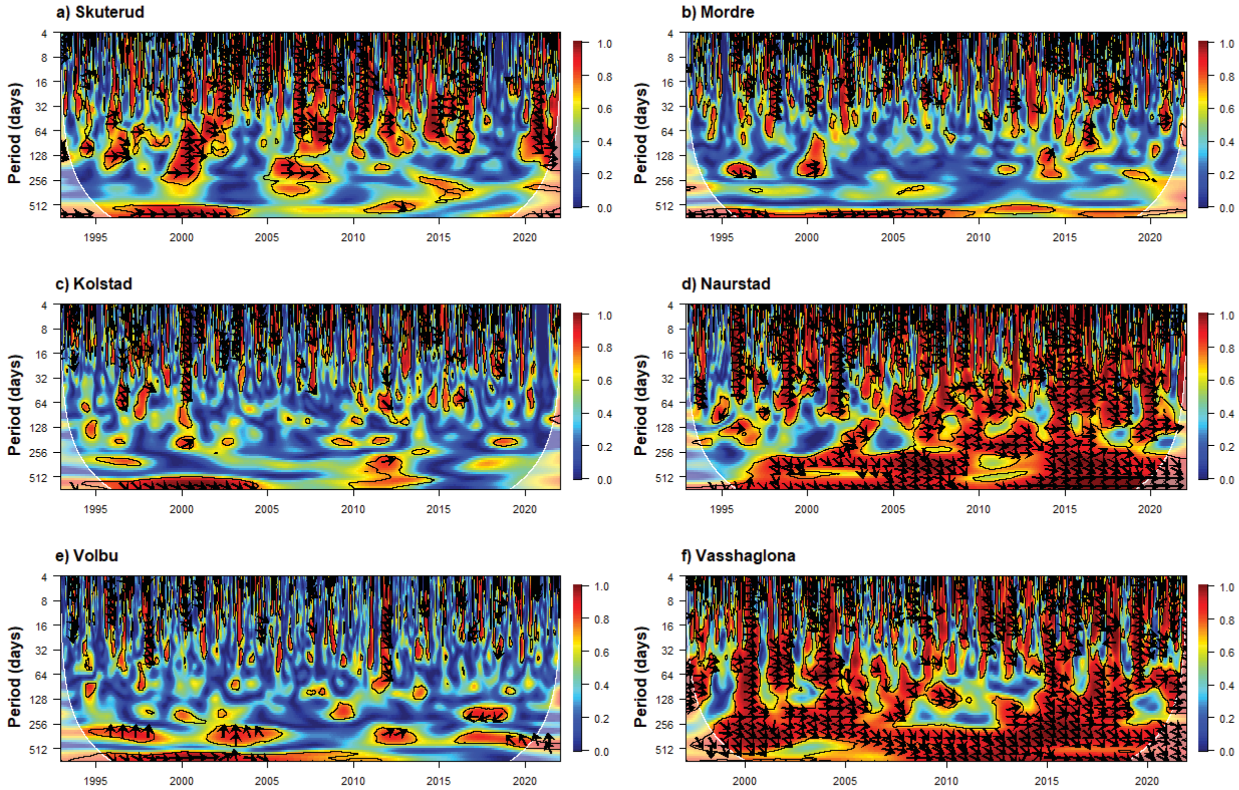

Figure 5: Wavelet coherence between discharge and precipitation for a 24-26 year period (x-axis). Periodicity of the coherence pattern is shown on the y-axis Colours indicate the strength of the relationship with red (1) to blue (0). Areas within black lines indicating 95 % significance level. A detailed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

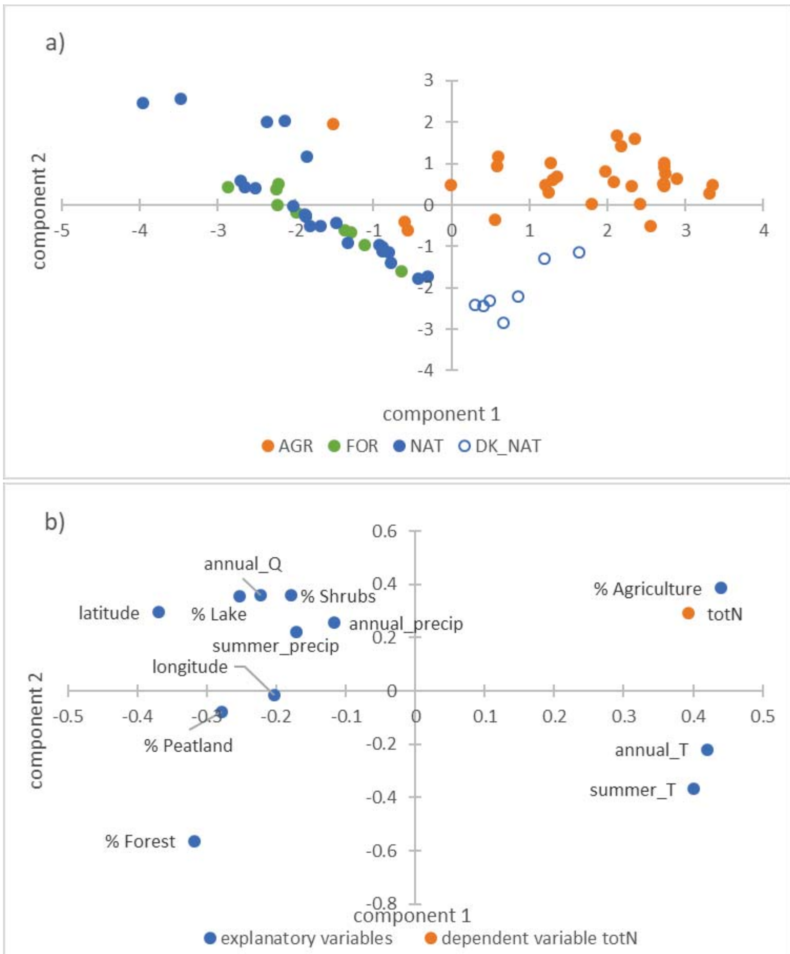

Figure: 6: a) Scoring of each single observation (catchments) for the two first components; b) Loading for the explanatory variables and the dependent variable of total nitrogen (totN).

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).

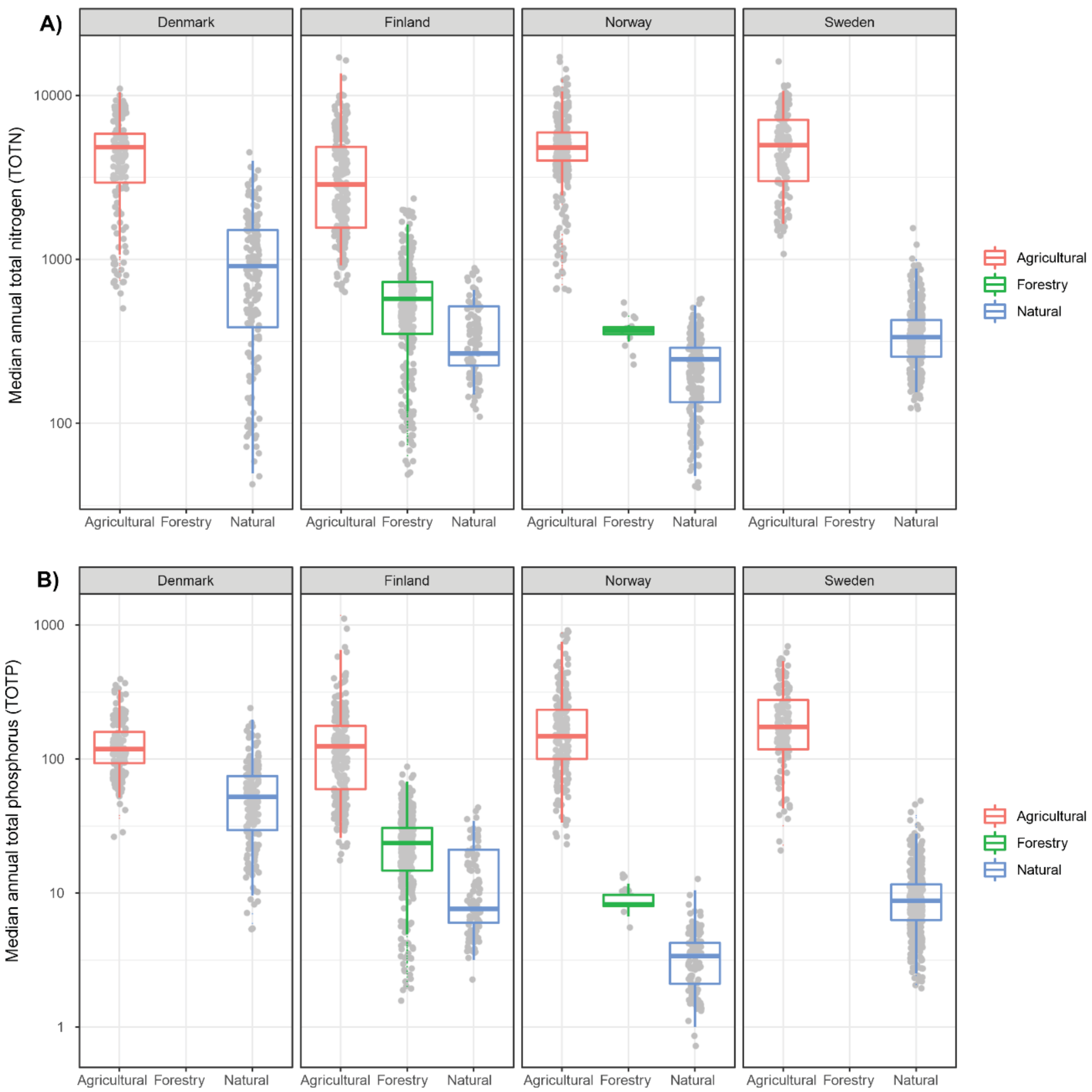

Figure 7: Concentration ranges for the grouped sites for median total Nitrogen and phosphorus, calculated for annual averages for three different land use types during 2000-2018.

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).

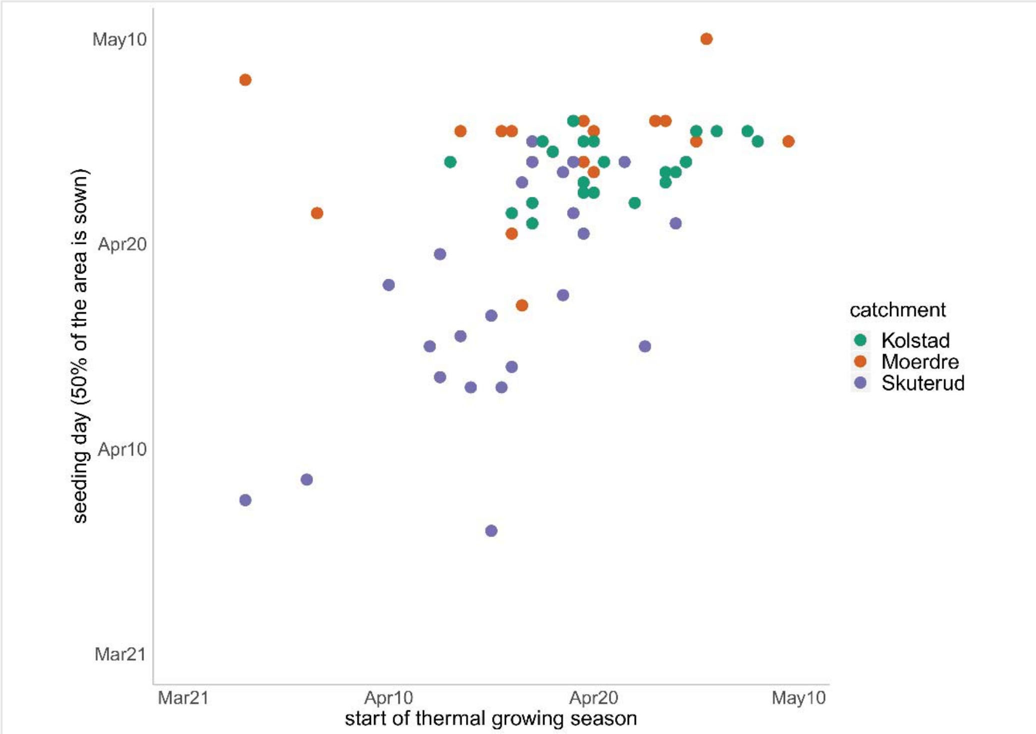

Figure 8: Pearson correlation between the first day of sowing of spring cereals and the start of the thermal growing season. R^2 for Skuterud 0.63.

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.

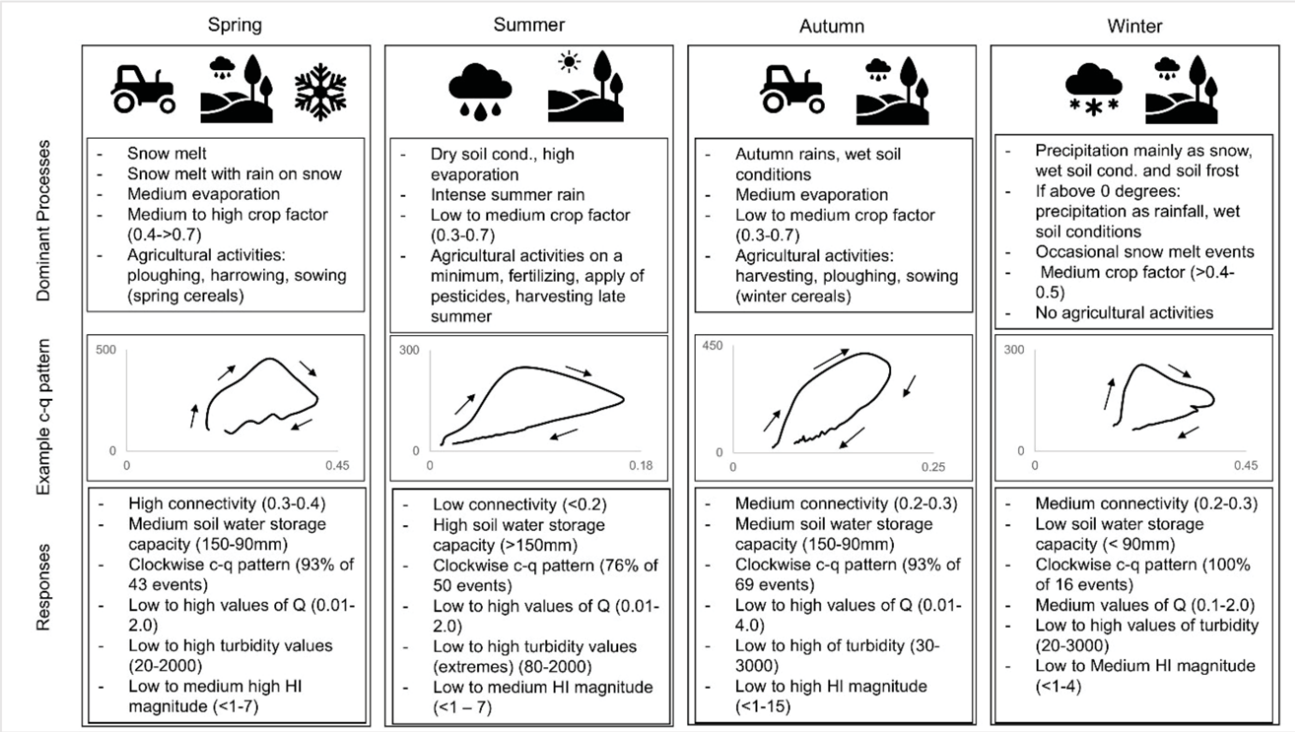

Figure 9: Conceptual model for the seasonal dominant processes and main responses based on the analysed data and showing examples for concentration-discharge hysteresis patterns

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.

5. REFERENCES

Abdi, H., 2007. Partial Least Squares Regression, PLS- Regression, in: Salkind, N.J. (Ed.), Encyclopedia of Measurement and Statistics. Sage, Thousand Oaks, California. https://doi.org/https://dx.doi.org/10.4135/9781412952644

Ala-aho, P., Autio, A., Bhattacharjee, J., Isokangas, E., Kujala, K., Marttila, H., Menberu, M., Meriö, L.-J., Postila, H., Rauhala, A., Ronkanen, A.-K., Rossi, P.M., Saari, M., Torabi Haghighi, A., Kløve, B., 2021. What conditions favor the influence of seasonally frozen ground on hydrological partitioning? A systematic review. Environ. Res. Lett. 16, 8441. https://doi.org/10.1088/1748-9326/abe82c

Bakke, S.J., Ionita, M., Tallaksen, L.M., 2020. The 2018 northern European hydrological drought and its drivers in a historical perspective. Hydrol. Earth Syst. Sci. 24, 5621–5653. https://doi.org/10.5194/hess-24-5621-2020

Ballantine, D., Walling, D.E., Leeks, G.J.L., 2009. Mobilisation and transport of sediment-associated phosphorus by surface runoff. Water. Air. Soil Pollut. 196, 311–320. https://doi.org/10.1007/s11270-008-9778-9

Barneveld, R.J., van der Zee, S.E.A.T.M., Greipsland, I., Kværnø, S.H., Stolte, J., 2019. Prioritising areas for soil conservation measures in small agricultural catchments in Norway, using a connectivity index. Geoderma 340, 325–336. https://doi.org/10.1016/j.geoderma.2019.01.017

Bechmann, M., 2014. Long-term monitoring of nitrogen in surface and subsurface runoff from small agricultural dominated catchments in Norway. Agric. Ecosyst. Environ. 198, 13–24. https://doi.org/10.1016/j.agee.2014.05.010

Bechmann, M., Blicher-Mathiesen, G., Kyllmar, K., Iital, A., Lagzdins, A., Salo, T., 2014. Nitrogen application, balances and their effect on water quality in small catchments in the Nordic-Baltic countries. Agric. Ecosyst. Environ. 198, 104–113. https://doi.org/10.1016/j.agee.2014.04.004

Bechmann, M., Deelstra, J., Stålnacke, P., Eggestad, H.O., Øygarden, L., Pengerud, A., 2008. Monitoring catchment scale agricultural pollution in Norway: policy instruments, implementation of mitigation methods and trends in nutrient and sediment losses. Environ. Sci. Policy 11, 102–114. https://doi.org/10.1016/j.envsci.2007.10.005

Bechmann, M., Stålnacke, P., 2019. Agricultural Nitrogen and Phosphorus Pollution in Surface Waters. https://doi.org/10.1093/acrefore/9780199389414.013.266

Bechmann, M., Stenrød, M., Kværnø, S.H., 2021. Erosjon og tap av næringsstoffer og plantevernmidler fra jordbruksdominerte nedbærfelt-Sammendragsrapport fra Program for jord-og vannovervåking i landbruket (JOVA) for 1992-2019. Ås, Norway (in Norwegian).

Bechmann, M.E., Bøe, F., 2021. Soil Tillage and Crop Growth Effects on Surface and Subsurface Runoff, Loss of Soil, Phosphorus and Nitrogen in a Cold Climate. Land 10, 1–15. https://doi.org/10.3390/land10010077

Bieroza, M., Bergström, L., Ulén, B., Djodjic, F., Tonderski, K., Heeb, A., Svensson, J., Malgeryd, J., 2019. Hydrologic Extremes and Legacy Sources Can Override Efforts to Mitigate Nutrient and Sediment Losses at the Catchment Scale. J. Environ. Qual. 48, 1314–1324. https://doi.org/10.2134/jeq2019.02.0063

Bieroza, M.Z., Heathwaite, A.L., 2015. Seasonal variation in phosphorus concentration-discharge hysteresis inferred from high-frequency in situ monitoring. J. Hydrol. 524, 333–347. https://doi.org/10.1016/j.jhydrol.2015.02.036

Bieroza, M.Z., Heathwaite, A.L., Bechmann, M., Kyllmar, K., Jordan, P., 2018. The concentration-discharge slope as a tool for water quality management. Sci. Total Environ. 630, 738–749. https://doi.org/10.1016/j.scitotenv.2018.02.256

Blankenberg, A.G.B., Skarbøvik, E., 2020. Phosphorus retention, erosion protection and farmers' perceptions of riparian buffer zones with grass and natural vegetation: Case studies from South-Eastern Norway. Ambio 49, 1838–1849. https://doi.org/10.1007/s13280-020-01361-5

Blöschl, G., Hall, J., Viglione, A., Perdigão, R.A.P., Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G.T., Bilibashi, A., Boháč, M., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G.B., Claps, P., Frolova, N., Ganora, D., Gorbachova, L., Gül, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T.R., Kohnová, S., Koskela, J.J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Salinas, J.L., Sauquet, E., Šraj, M., Szolgay, J., Volpi, E., Wilson, D., Zaimi, K., Živković, N., 2019. Changing climate both increases and decreases European river floods. Nature 573, 108–111. https://doi.org/10.1038/s41586-019-1495-6

Bol, R., Gruau, G., Mellander, P.E., Dupas, R., Bechmann, M., Skarbøvik, E., Bieroza, M., Djodjic, F., Glendell, M., Jordan, P., Van der Grift, B., Rode, M., Smolders, E., Verbeeck, M., Gu, S., Klumpp, E., Pohle, I., Fresne, M., Gascuel-Odoux, C., 2018. Challenges of reducing phosphorus based water eutrophication in the agricultural landscapes of Northwest Europe. Front. Mar. Sci. 5, 1–16. https://doi.org/10.3389/fmars.2018.00276

Børgesen, C.D., Olesen, J.E., 2011. A probabilistic assessment of climate change impacts on yield and nitrogen leaching from winter wheat in Denmark. Nat. Hazards Earth Syst. Sci. 11, 2541–2553. https://doi.org/10.5194/nhess-11-2541-2011

Bouza-Deaño, R., Ternero-Rodríguez, M., Fernández-Espinosa, A.J., 2008. Trend study and assessment of surface water quality in the Ebro River (Spain). J. Hydrol. 361, 227–239. https://doi.org/10.1016/j.jhydrol.2008.07.048

Brendel, C.E., Soupir, M.L., Long, L.A.M., Helmers, M.J., Ikenberry, C.D., Kaleita, A.L., 2019. Catchment-scale Phosphorus Export through Surface and Drainage Pathways. J. Environ. Qual. 48, 117–126. https://doi.org/10.2134/jeq2018.07.0265

Buck, O., Niyogi, D.K., Townsend, C.R., 2004. Scale-dependence of land use effects on water quality of streams in agricultural catchments. Environ. Pollut. 130, 287–299. https://doi.org/10.1016/j.envpol.2003.10.018

Bugge, M.M., Hansen, T., Klitkou, A., 2016. What is the bioeconomy? A review of the literature. Sustain. 8, 1–22. https://doi.org/10.3390/su8070691

Carey, S.K., Tetzlaff, D., Buttle, J., Laudon, H., McDonnell, J., McGuire, K., Seibert, J., Soulsby, C., Shanley, J., 2013. Use of color maps and wavelet coherence to discern seasonal and interannual climate influences on streamflow variability in northern catchments. Water Resour. Res. 49, 6194–6207. https://doi.org/10.1002/wrcr.20469

Carter, T.R., 1998. Changes in the thermal growing season in Nordic countries during the past century and prospects for the future. Agric. Food Sci. 7, 161–179. https://doi.org/10.23986/afsci.72857

Casson, N.J., Wilson, H.F., Higgins, S.M., 2019. Hydrological and Seasonal Controls of Phosphorus in Northern Great Plains Agricultural Streams. J. Environ. Qual. 48, 978–

987. https://doi.org/10.2134/jeq2018.07.0281

Cherry, K.A., Shepherd, M., Withers, P.J.A., Mooney, S.J., 2008. Assessing the effectiveness of actions to mitigate nutrient loss from agriculture: A review of methods. Sci. Total Environ. 406, 1–23. https://doi.org/10.1016/j.scitotenv.2008.07.015

Deelstra, J., Stenrød, M., Bechmann, M., Eggestad, H.O., 2013. Discharge measurement and water sampling, in: Bechmann, M., Deelstra, J. (Eds.), Agriculture and Environment - Long Term Monitoring in Norway. Akademika Forlag, Trondheim, pp. 83–104.

Devreker, D., Lefebvre, A., 2020. Temporal Trend Analysis Graphical Interface.

Donnelly, C., Greuell, W., Andersson, J., Gerten, D., Pisacane, G., Roudier, P., Ludwig, F., 2017. Impacts of climate change on European hydrology at 1.5, 2 and 3 degrees mean global warming above preindustrial level. Clim. Change 143, 13–26. https://doi.org/10.1007/s10584-017-1971-7

Dyrrdal, A.V., Saloranta, T., Skaugen, T., Stranden, H.B., 2013. Changes in snow depth in Norway during the period 1961-2010. Hydrol. Res. 44, 169–179. https://doi.org/10.2166/nh.2012.064

EU, 2000. Water framework directive. Directive 2000/60/EC of the European Parliament and the council of 23 October 2000 establishing a framework for community action in the field of water policy.

European Commission, 2011. Bio-based economy for Europe: state of play and future potential - Part 1, Biotechnology, Agriculture and Food. https://doi.org/10.2777/67383

Eurostat, 2020. Eurostat [WWW Document]. URL http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=t2020_rn310&lang=en (accessed 6.11.21).

Eyvindson, K., Hartikainen, M., Miettinen, K., Kangas, A., 2018. Integrating risk management tools for regional forest planning: an interactive multiobjective value-at-risk approach. Can. J. For. Res. 48, 766–773. https://doi.org/10.1139/cjfr-2017-0365

Fennell, J., Geris, J., Wilkinson, M.E., Daalmans, R., Soulsby, C., 2020. Lessons from the 2018 drought for management of local water supplies in upland areas: A tracer-based assessment. Hydrol. Process. 34, 4190–4210. https://doi.org/10.1002/hyp.13867

Giri, S., Qiu, Z., 2016. Understanding the relationship of land uses and water quality in Twenty First Century: A review. J. Environ. Manage. 173, 41–48. https://doi.org/10.1016/j.jenvman.2016.02.029

Grise, J., Kulshreshtha, S., 2016. Farmers' Choice of Crops in Canadian Prairies under Climate Change: An Econometric Analysis. J. Earth Sci. Clim. Change 07. https://doi.org/10.4172/2157-7617.1000332

Halliday, S.J., Wade, A.J., Skeffington, R.A., Neal, C., Reynolds, B., Rowland, P., Neal, M., Norris, D., 2012. An analysis of long-term trends, seasonality and short-term dynamics in water quality data from Plynlimon, Wales. Sci. Total Environ. 434, 186–200. https://doi.org/10.1016/j.scitotenv.2011.10.052

Hansen, L., Bjørkhaug, H., 2017. Visions and expectations for the Norwegian bioeconomy. Sustain. 9. https://doi.org/10.3390/su9030341

Hanssen-Bauer, I., Førland, E.J., Haddeland, I., Hisdal, H., Mayer, S., Nesje, A., Nilsen, J.E.., Sandven, S., Sandø, A., Sorteberg, A., Ådlandsvik, B., 2015. Climate in Norway 2100 - a knowledge base for climate adaption. Trondheim (in Norwegian, English summary).

Haygarth, P.M., Page, T.J.C., Beven, K.J.. ., Freer, J., Joynes, A., Butler, P., Wood, G.. . A.. ., Owens, P.N.. ., 2012. Scaling up the phosphorus signal from soil hillslopes to headwater catchments. Freshw. Biol. 57, 7–25. https://doi.org/10.1111/j.1365-2427.2012.02748.x

He, W., Yang, J.Y., Qian, B., Drury, C.F., Hoogenboom, G., He, P., Lapen, D., Zhou, W., 2018. Climate change impacts on crop yield, soil water balance and nitrate leaching in the semiarid and humid regions of Canada. PLoS One 13, 1–19. https://doi.org/10.1371/journal.pone.0207370

Heidel, S.G., 1956. The progressive lag of sediment concentration with flood waves. Eos, Trans. Am. Geophys. Union 37, 56–66. https://doi.org/10.1029/TR037i001p00056

Jeong, S.J., Ho, C.H., Gim, H.J., Brown, M.E., 2011. Phenology shifts at start vs. end of growing season in temperate vegetation over the Northern Hemisphere for the period 1982-2008. Glob. Chang. Biol. 17, 2385–2399. https://doi.org/10.1111/j.1365-2486.2011.02397.x

Jordan, N., Boody, G., Broussard, W., Glover, J.D., Keeney, D., Mccown, B.H., Mcisaac, G., Muller, M., Murray, H., Neal, J., Pansing, C., Turner, R.E., Warner, K., Wyse, D., 2007.

Sustainable devolopment of the agricultural bioeconomy. Science (80-.). 316, 1570–1571. https://doi.org/10.1126/science.1141700

Juhola, S., Klein, N., Käyhkö, J., Schmid Neset, T.S., 2017. Climate change transformations in Nordic agriculture? J. Rural Stud. 51, 28–36. https://doi.org/10.1016/j.jrurstud.2017.01.013

Kämäri, M., Tarvainen, M., Kotamäki, N., Tattari, S., 2020. High-frequency measured turbidity as a surrogate for phosphorus in boreal zone rivers: appropriate options and critical situations. Environ. Monit. Assess. 192. https://doi.org/10.1007/s10661-020-08335-w

Klaus, J., McDonnell, J.J.J., 2013. Hydrograph separation using stable isotopes: Review and evaluation. J. Hydrol. 505, 47–64. https://doi.org/10.1016/J.JHYDROL.2013.09.006

Kleinman, P.J.A., Sharpley, A.N., McDowell, R.W., Flaten, D.N., Buda, A.R., Tao, L., Bergstrom, L., Zhu, Q., 2011. Managing agricultural phosphorus for water quality protection: Principles for progress. Plant Soil 349, 169–182. https://doi.org/10.1007/s11104-011-0832-9

Kolberg, D., Persson, T., Mangerud, K., Riley, H., 2019. Impact of projected climate change on workability, attainable yield, profitability and farm mechanization in Norwegian spring cereals. Soil Tillage Res. 185, 122–138.

Kyllmar, K., Bechmann, M., Deelstra, J., Iital, A., Blicher-Mathiesen, G., Jansons, V., Koskiaho, J., Povilaitis, A., Bechmann, M., Deelstra, J., Iital, A., Blicher-Mathiesen, G., Jansons, V., Koskiaho, J., Povilaitis, A., 2014. Long-term monitoring of nutrient losses from agricultural catchments in the Nordic–Baltic region – A discussion of methods, uncertainties and future needs. Agric. Ecosyst. Environ. 198, 4–12. https://doi.org/10.1016/J.AGEE.2014.07.005

Laudon, H., Tetzlaff, D., Soulsby, C., Carey, S., Seibert, J., Buttle, J., Shanley, J., Mcdonnell, J.J., Mcguire, K., 2013. Change in winter climate will affect dissolved organic carbon and water fluxes in mid-to-high latitude catchments. Hydrol. Process. 27, 700–709. https://doi.org/10.1002/hyp.9686

Lawler, D.M., Petts, G.E., Foster, I.D.L., Harper, S., 2006. Turbidity dynamics during spring storm events in an urban headwater river system: The Upper Tame, West Midlands, UK.

Sci. Total Environ. 360, 109–126. https://doi.org/10.1016/j.scitotenv.2005.08.032

Lefrançois, J., Grimaldi, C., Gascuel-Odoux, C., Gilliet, N., 2007. Suspended sediment and discharge relationships to identify bank degradation as a main sediment source on small agricultural catchments. Hydrol. Process. 21, 2923–2933. https://doi.org/10.1002/hyp.6509

Lessels, J.S., Bishop, T.F.A.A., 2013. Estimating water quality using linear mixed models with stream discharge and turbidity. J. Hydrol. 498, 13–22. https://doi.org/10.1016/j.jhydrol.2013.06.006

Liu, J., Baulch, H.M., Macrae, M.L., Wilson, H.F., Elliott, J.A., Bergström, L., Glenn, A.J., Vadas, P.A., 2019. Agricultural water quality in cold climates: Processes, drivers, management options, and research needs. J. Environ. Qual. 48, 792–802. https://doi.org/10.2134/jeq2019.05.0220

Marsh, N.A., Stewardson, M.J., Kennard, M.J., 2003. River Analysis Package. Cooperative Research Center for Catchment Hydrology, Monash University Melbourne. Melbourne, Australia (Available: https://toolkit.ewater.org.au/).

McMillan, H., 2019. Linking hydrologic signatures to hydrologic processes: A Review. Hydrol. Process. 0–2. https://doi.org/10.1002/hyp.13632

Mellander, P.E., Jordan, P., Bechmann, M., Fovet, O., Shore, M.M., McDonald, N.T., Gascuel-Odoux, C., 2018. Integrated climate-chemical indicators of diffuse pollution from land to water. Sci. Rep. 8, 1–10. https://doi.org/10.1038/s41598-018-19143-1

Mellander, P.E., Jordan, P., Shore, M., Melland, A.R., Shortle, G., 2015. Flow paths and phosphorus transfer pathways in two agricultural streams with contrasting flow controls. Hydrol. Process. 29, 3504–3518. https://doi.org/10.1002/hyp.10415

Menzel, A., Sparks, T.H., Estrella, N., Koch, E., Aaasa, A., Ahas, R., Alm-Kübler, K., Bissolli, P., Braslavská, O., Briede, A., Chmielewski, F.M., Crepinsek, Z., Curnel, Y., Dahl, Å., Defila, C., Donnelly, A., Filella, Y., Jatczak, K., Måge, F., Mestre, A., Nordli, Ø., Peñuelas, J., Pirinen, P., Remišová, V., Scheifinger, H., Striz, M., Susnik, A., Van Vliet, A.J.H., Wielgolaski, F.E., Zach, S., Zust, A., 2006. European phenological response to climate change matches the warming pattern. Glob. Chang. Biol. 12, 1969–1976. https://doi.org/10.1111/j.1365-2486.2006.01193.x

Meriö, L.J., Ala-aho, P., Linjama, J., Hjort, J., Kløve, B., Marttila, H., 2019. Snow to Precipitation Ratio Controls Catchment Storage and Summer Flows in Boreal Headwater Catchments. Water Resour. Res. 55, 4096–4109. https://doi.org/10.1029/2018WR023031

Mittenzwei, K., Øygarden, L., 2020. The Increasing Impact of Environmental Policies on Agriculture: Perspective From Norway. J. Appl. Bus. Econ. 22, 72–81. https://doi.org/https://doi.org/10.33423/jabe.v22i6.3076

Nordic Council of Ministers, 2017. Nordic Bioeconomy. 25 Cases for Sustainable Change. https://doi.org/10.6027/ANP2016-782

Olesen, J.E., Bindi, M., 2002. Consequences of climate change for European agricultural productivity, land use and policy. Eur. J. Agron. 16, 239–262. https://doi.org/10.1016/S1161-0301(02)00004-7

Olesen, J.E., Carter, T.R., Díaz-Ambrona, C.., Fronzek, S., Heidmann, T., Hickler, T., Holt, T., Minguez, M.I., Morales, P., Palutikof, J.., Quemada, M., Ruiz-Ramos, M., Rubæk, G.H., Sau, F., Smith, B., Sykes, M.., 2007. Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models. Clim. Change 81, 123–143. https://doi.org/10.1007/s10584-006-9216-1

Øygarden, L., 2000. Soil erosion in small agricultural catchments, south easter Norway. Doctor Scientiarum Theses. Agricultural Uniersity of Norway.

Øygarden, L., Deelstra, J., Lagzdins, A., Bechmann, M., Greipsland, I., Kyllmar, K., Povilaitis, A., Iital, A., 2014. Climate change and the potential effects on runoff and nitrogen losses in the Nordic-Baltic region. Agric. Ecosyst. Environ. 198, 114–126. https://doi.org/10.1016/j.agee.2014.06.025

Patil, R.H., Laegdsmand, M., Olesen, J.E., Porter, J.R., 2010. Effect of soil warming and rainfall patterns on soil N cycling in Northern Europe. Agric. Ecosyst. Environ. 139, 195–205. https://doi.org/10.1016/j.agee.2010.08.002

Ponte, S., 2009. From fishery to fork: Food safety and sustainability in the 'virtual' knowledge-based bio-economy (KBBE). Sci. Cult. (Lond). 18, 483–495. https://doi.org/10.1080/09505430902873983

Pulliainen, J., Luojus, K., Derksen, C., Mudryk, L., Lemmetyinen, J., Salminen, M., Ikonen, J., Takala, M., Cohen, J., Smolander, T., Norberg, J., 2020. Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. Nature 581, 294–298. https://doi.org/10.1038/s41586-020-2258-0

Reynolds, W.D., Schoenau, J. j., Drury, C.F., 2014. Scientific and Practical Benefits of Long-term Field Studies. Can. J. Soil Sci. 94, 253–254. https://doi.org/10.4141/CJSS-2014-501

Riley, H., 2016. Tillage timeliness for spring cereals in Norway. Apelsvoll, Norway (in Norwegian).

Rosegrant, M.W., Ringler, C., Zhu, T., Tokgoz, S., Bhandary, P., 2013. Water and food in the bioeconomy: Challenges and opportunities for development. Agric. Econ. 44, 139–150. https://doi.org/10.1111/agec.12058

Ruosteenoja, K., Räisänen, J., Pirinen, P., 2011. Projected changes in thermal seasons and the growing season in Finland. Int. J. Climatol. 31, 1473–1487. https://doi.org/10.1002/joc.2171

Sandström, S., Futter, M.N., Kyllmar, K., Bishop, K., O'Connell, D.W., Djodjic, F., 2020. Particulate phosphorus and suspended solids losses from small agricultural catchments: Links to stream and catchment characteristics. Sci. Total Environ. 711. https://doi.org/10.1016/j.scitotenv.2019.134616

Seehusen, T., Waalen, W., Hoel, B., Uhlen, A.K., Persson, T., Strand, E., 2015. Cultivation - Climate Change - effects of climate change and need for adaption - Norwegian grain production. Apelsvoll, Norway (in Norwegian).

Sen, P.K., 1968. Estimates of the Regression Coefficient Based on Kendall's Tau. J. Am. Stat. Assoc. 63, 1379–1389. https://doi.org/10.1080/01621459.1968.10480934

Sheppard, A.W., Gillespie, I., Hirsch, M., Begley, C., 2011. Biosecurity and sustainability within the growing global bioeconomy. Curr. Opin. Environ. Sustain. 3, 4–10. https://doi.org/https://doi.org/10.1016/j.cosust.2010.12.011

Sherriff, S.C., Rowan, J.S., Fenton, O., Jordan, P., Melland, A.R., Mellander, P.E., Huallacháin, D., 2016. Storm Event Suspended Sediment-Discharge Hysteresis and Controls in Agricultural Watersheds: Implications for Watershed Scale Sediment

Management. Environ. Sci. Technol. 50, 1769–1778. https://doi.org/10.1021/acs.est.5b04573

Skarbøvik, E., Aroviita, J., Fölster, J., Solheim, A.L., Kyllmar, K., Rankinen, K., Kronvang, B., 2020a. Comparing nutrient reference concentrations in Nordic countries with focus on lowland rivers. Ambio 49, 1771–1783. https://doi.org/10.1007/s13280-020-01370-4

Skarbøvik, E., Jordan, P., Lepistö, A., Kronvang, B., Stutter, M.I., Vermaat, J.E., 2020b. Catchment effects of a future Nordic bioeconomy: From land use to water resources. Ambio 49, 1697–1709. https://doi.org/10.1007/s13280-020-01391-z

Skarbøvik, E., Roseth, R., 2015. Use of sensor data for turbidity, pH and conductivity as an alternative to conventional water quality monitoring in four Norwegian case studies. Acta Agric. Scand. Sect. B Soil Plant Sci. 65, 63–73. https://doi.org/10.1080/09064710.2014.966751

Skarbøvik, E., Stålnacke, P., Bogen, J., Bønsnes, T.E., 2012. Impact of sampling frequency on mean concentrations and estimated loads of suspended sediment in a Norwegian river: Implications for water management. Sci. Total Environ. 433, 462–471. https://doi.org/10.1016/j.scitotenv.2012.06.072

Stehfest, E., Ros, J., Bouwman, L., 2010. Indirect effects of biofuels : intensification of agricultural production. Bilthoven.

Stets, E.G., Kelly, V.J., Crawford, C.G., 2015. Regional and Temporal Differences in Nitrate Trends Discerned from Long-Term Water Quality Monitoring Data. J. Am. Water Resour. Assoc. 51, 1394–1407. https://doi.org/10.1111/1752-1688.12321

Stutter, M., Dawson, J.J.C., Glendell, M., Napier, F., Potts, J.M., Sample, J., Vinten, A., Watson, H., 2017. Evaluating the use of in-situ turbidity measurements to quantify fluvial sediment and phosphorus concentrations and fluxes in agricultural streams. Sci. Total Environ. 607–608, 391–402. https://doi.org/10.1016/j.scitotenv.2017.07.013

Stutter, M., Kronvang, B., Ó hUallacháin, D., Rozemeijer, J., 2019. Current Insights into the Effectiveness of Riparian Management, Attainment of Multiple Benefits, and Potential Technical Enhancements. J. Environ. Qual. 48, 236–247. https://doi.org/10.2134/jeq2019.01.0020

Stutter, M.I., Langan, S.J., Cooper, R.J., 2008. Spatial contributions of diffuse inputs and within-channel processes to the form of stream water phosphorus over storm events. J. Hydrol. 350, 203–214. https://doi.org/10.1016/j.jhydrol.2007.10.045

Tattari, S., Koskiaho, J., Kosunen, M., Lepistö, A., Linjama, J., Puustinen, M., 2017. Nutrient loads from agricultural and forested areas in Finland from 1981 up to 2010—can the efficiency of undertaken water protection measures seen? Environ. Monit. Assess. 189. https://doi.org/10.1007/s10661-017-5791-z

Tetzlaff, D., Buttle, J., Carey, S.K., Mcguire, K., Laudon, H., Soulsby, C., 2015. Tracer-based assessment of flow paths, storage and runoff generation in northern catchments: A review. Hydrol. Process. 29, 3475–3490. https://doi.org/10.1002/hyp.10412

Tetzlaff, D., Soulsby, C., Carey, S.K., McNamara, J.P., Laudon, H., Soulsby, C., 2017. The essential value of long-term experimental data for hydrology and water management. Water Resour. Res. 53, 2598–2604. https://doi.org/10.1002/2017WR020838

Theil, H., 1950. A rank-invaraiint method of linear and polynomial regression analysis I and II. Proc. K. Ned. Akad. Wet. Ser. A Math. Sci. Dordr.

Torrence, C., Compo, G.P., 1998. A Practical Guide to Wavelet Analysis. Bull. Am. Meteorol. Soc. 79, 61–78. https://doi.org/10.1175/1520-0477(1998)079<0061:APGTWA>2.0.CO;2

Trnka, M., Olesen, J.., Kersbaun, K.C., Skjelvåg, A.O., Eitzinger, J., Seguin, B., Peltonen-Sainio, P., Rötter, R., Iglesias, A., Orlandini, S., Dubrovský, M., Hlavinka, P., Balek, J., Eckersten, H., Cloppet, E., Calanca, P., Gobin, A., Vucetic, V., Nejedlik, P., Kumar, S., Lalic, B., Mestre, A., Rossi, F., Kozyra, J., Alexandrov, V., Semerádová, D., Zalud, Z., 2011. Agroclimatic conditions in Europe under climate change. Glob. Chang. Biol. 17, 2298–2318. https://doi.org/10.1111/j.1365-2486.2011.02396.x

Tsegaw, A., Pontoppidan, M., Kristvik, E., Alfredsen, K., Muthanna, T., 2019. Hydrological impacts of climate change on small ungauged catchments-results from a GCM-RCM-hydrologic model chain. Nat. Hazards Earth Syst. Sci. Discuss. 1–56. https://doi.org/10.5194/nhess-2019-359

Ulén, B., Aronsson, H., Bechmann, M., Krogstad, T., Øygarden, L., Stenberg, M., 2010. Soil tillage methods to control phosphorus loss and potential side-effects: a Scandinavian review. Soil Use Manag. 26, 94–107.

Ulén, B., Bechmann, M., Fölster, J., Jarvie, H.P., Tunney, H., 2007. Agriculture as a phosphorus source for eutrophication in the north-west European countries, Norway, Sweden, United Kingdom and Ireland: A review. Soil Use Manag. 23, 5–15. https://doi.org/10.1111/j.1475-2743.2007.00115.x

Ulén, B., Larsbo, M., Koestel, J., Hellner, Q., Blomberg, M., Geranmayeh, P., 2018. Assessing strategies to mitigate phosphorus leaching from drained clay soils. Ambio 47, 114–123. https://doi.org/10.1007/s13280-017-0991-x

Valkama, E., Salo, T., Esala, M., Turtola, E., 2013. Nitrogen balances and yields of spring cereals as affected by nitrogen fertilization in northern conditions: A meta-analysis. Agric. Ecosyst. Environ. 164, 1–13. https://doi.org/10.1016/j.agee.2012.09.010

Valkama, P., Ruth, O., 2017. Impact of calculation method, sampling frequency and Hysteresis on suspended solids and total phosphorus load estimations in cold climate. Hydrol. Res. 48, 1594–1610. https://doi.org/10.2166/nh.2017.199

Villa, A., Fölster, J., Kyllmar, K., 2019. Determining suspended solids and total phosphorus from turbidity: comparison of high-frequency sampling with conventional monitoring methods. Environ. Monit. Assess. 191. https://doi.org/10.1007/s10661-019-7775-7

Vuorenmaa, J., Augustaitis, A., Beudert, B., Clarke, N., Wit, H.A. d., Dirnböck, T., Frey, J., Forsius, M., Indriksone, I., Kleemola, S., Kobler, J., Krám, P., Lindroos, A.J., Lundin, L., Ruoho-Airola, T., Ukonmaanaho, L., Váňa, M., 2017. Long-term sulphate and inorganic nitrogen mass balance budgets in European ICP Integrated Monitoring catchments (1990–2012). Ecol. Indic. 76, 15–29. https://doi.org/10.1016/j.ecolind.2016.12.040

Walling, D.E., Webb, B.W., Russell, M.A., 1997. Sediment-associated nutrient transport in UK rivers. IAHS-AISH Publ. 243, 69–81.

Weigelhofer, G., Ramião, J.P., Pitzl, B., Bondar-Kunze, E., O'Keeffe, J., 2018. Decoupled water-sediment interactions restrict the phosphorus buffer mechanism in agricultural streams. Sci. Total Environ. 628–629, 44–52. https://doi.org/10.1016/j.scitotenv.2018.02.030

Welch, H.L., Green, C.T., Rebich, R.A., Barlow, J.R.B.B., Hicks, M.B., 2010. Unintended consequences of biofuels production: the effects of large-scale crop conversion on water quality and quantity. Open-File Rep. 2010-1229. U.S. Dep. Inter. U.S. Geol. Surv. Reston, Virginia 1–6.

Williams, G.P., 1989. Sediment concentration versus water discharge during single hydrologic events in rivers. J. Hydrol. 111, 89–106. https://doi.org/10.1016/0022-1694(89)90254-0

Wilson, D., Hisdal, H., Lawrence, D., 2010. Has streamflow changed in the Nordic countries? - Recent trends and comparisons to hydrological projections. J. Hydrol. 394, 334–346. https://doi.org/10.1016/j.jhydrol.2010.09.010

Wilson, H.F., Casson, N.J., Glenn, A.J., Badiou, P., Boychuk, L., 2019. Landscape Controls on Nutrient Export during Snowmelt and an Extreme Rainfall Runoff Event in Northern Agricultural Watersheds. J. Environ. Qual. 48, 841–849. https://doi.org/10.2134/jeq2018.07.0278

Wiréhn, L., 2018. Nordic agriculture under climate change: A systematic review of challenges, opportunities and adaptation strategies for crop production. Land use policy 77, 63–74. https://doi.org/10.1016/j.landusepol.2018.04.059

Withers, P.J.A., Neal, C., Jarvie, H.P., Doody, D.G., 2014. Agriculture and eutrophication: Where do we go from here? Sustain. 6, 5853–5875. https://doi.org/10.3390/su6095853

Yue, S., Pilon, P., Cavadias, G., 2002. Power of the Mann-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. J. Hydrol. 259, 254–271. https://doi.org/10.1016/S0022-1694(01)00594-7

Zimmermann, A., Webber, H., Zhao, G., Ewert, F., Kros, J., Wolf, J., Britz, W., de Vries, W., 2017. Climate change impacts on crop yields, land use and environment in response to crop sowing dates and thermal time requirements. Agric. Syst. 157, 81–92. https://doi.org/10.1016/j.agsy.2017.07.007

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: 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: 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: 107484. 13 pp.
DOI: 10.1016/j.agee.2021.107484

Paper V
Wenng, H., Croghan, D., Bechmann, M. & Marttila, H. Hydrology under change? Longterm and seasonal changes in small agricultural catchment in Norway. (Under revision)

ISBN: 978-82-575-1853-0
ISSN: 1894-6402

NIBIO
NORWEGIAN INSTITUTE OF
BIOECONOMY RESEARCH

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

NMBU
Norwegian University
of Life Sciences

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

111922 / ANDVORDGRAFISK.NO