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A case study of Lake Bolmen, Sweden

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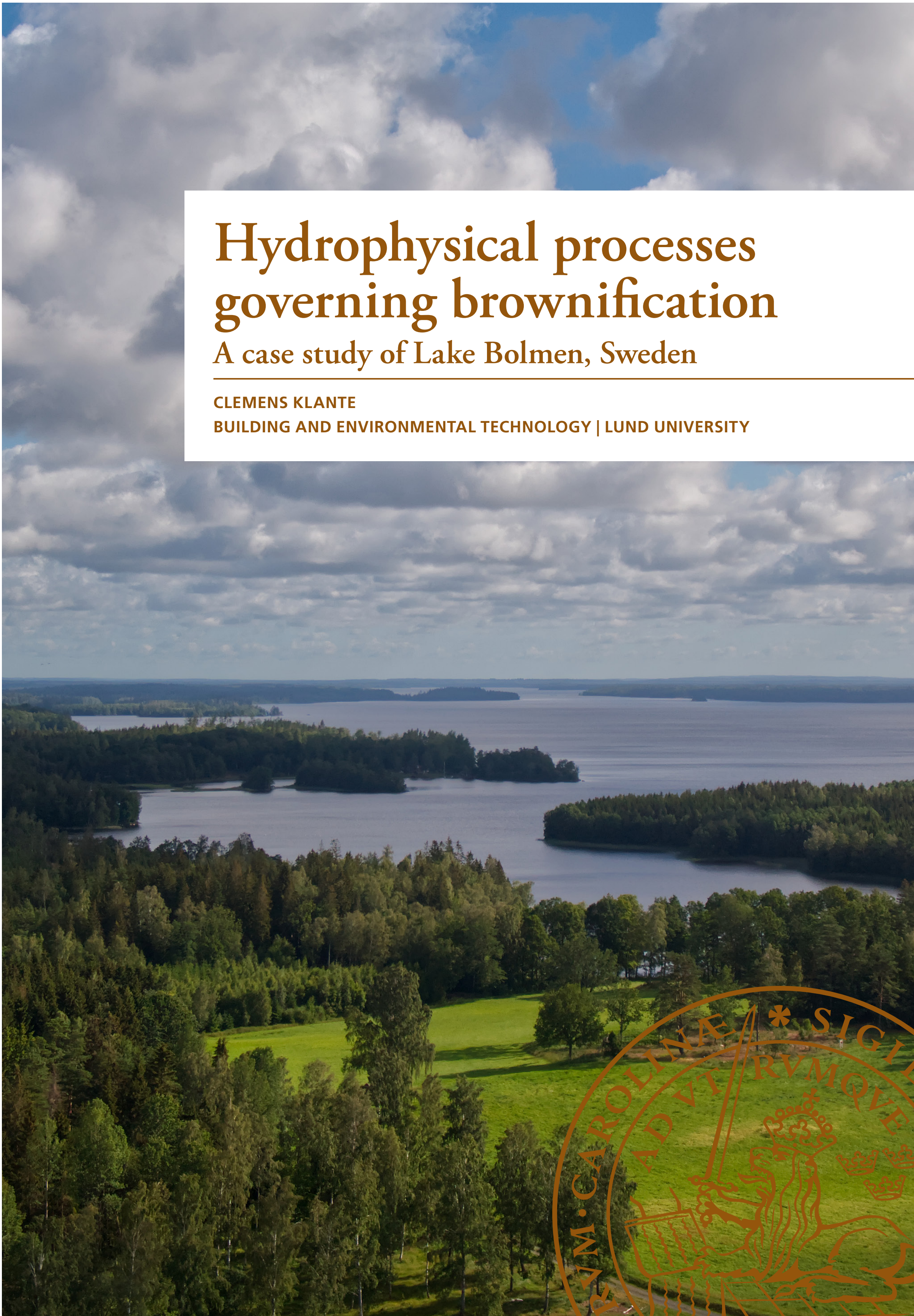

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A case study of Lake Bolmen, Sweden

by Clemens Klante

LUND UNIVERSITY

DOCTORAL DISSERTATION
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Abstract
Access to water of good quality and quantity has become more challenging because of a changing climate, as well as an increase in the use of natural resources, which has lead to altered water chemistry. One of these changes is known as brownification, resulting from a higher organic matter content causing a yellow-brown color of surface waters. Brownification has a manifold of side effects for the ecosystem, but also requires more efforts at drinking water treatment plants to remediate the discoloring of the water. Substantial research has been carried out to increase the understanding and knowledge of the complex process of brownification, in many cases focusing on the biological aspects. The significance of water movement as described in hydrology and hydrodynamics for the process of brownification, including the generation and transport of organic matter content, has been less investigated. With rising energy prices, higher demands on limiting the CO_2 emissions, and requirements for increased resilience of vulnerable infrastructure, such as drinking water treatment plants, the demand to better understand the physical processes governing brownification has grown.

This thesis investigates links between increased levels of organic matter and catchment hydrology using Lake Bolmen in south Sweden as a case study. Moreover, internal hydrodynamic processes of the lake were analyzed and related to the process of brownification. This was achieved by compiling existing data on catchment and lake properties, but also through additional field measurements. Hydrological balances and hydrodynamic modeling were employed to understand the system and to simulate the effects of climate change on brownification and to analyze possible management strategies and measures. Altered precipitation patterns, and related increases in surface runoff, have proven to be a main driver for seasonal and long-term change in brownification. Also, significant modifications in land use during the last centuries are an important driver. The application of a surface wave model indicated that resuspension influences the water color in a lake, possibly becoming an increasing problem in the future with less ice cover due to climate change. A validated box model describing the transport patterns in the lake, was used to simulate different scenarios and their impact on the brownification. These scenarios included changes in the climate forcing and different mitigation measures applied in the catchment or in the lake. Currently existing knowledge regarding measures to prevent further increase of organic matter, and resulting yellow-brown water, were critically reviewed and analyzed in the context of field studies of wetlands.

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A doctoral thesis at a university in Sweden takes either the form of a single, cohesive research study (monograph) or a summary of research papers (compilation thesis), which the doctoral student has written alone or together with one or several other author(s).

In the latter case the thesis consists of two parts. An introductory text puts the research work into context and summarizes the main points of the papers. Then, the research publications themselves are reproduced, together with a description of the individual contributions of the authors. The research papers may either have been already published or are manuscripts at various stages (in press, submitted, or in draft).

Cover illustration front: Photo of Lake Bolmen with Bolmsö Island in the background (Credits: Clemens Klante)

Cover illustration back: Photo of Kafjorden with Lake Bolmen in the background (Credits: Clemens Klante)

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MADE IN SWEDEN

Now the earth was formless and empty,
darkness was over the surface of the deep,
and the Spirit of God was hovering over the waters.
(Genesis 1:2)

Contents

Acknowledgements

Striving for a PhD can be compared with a long-distance hike in the Swedish mountains. There are those days which are perfect and the conditions for the hike could not be better. But then there are also those days where the weather is miserable and both rain and wind is blowing directly in ones face all the time. Navigation and following the right path are hard during these days, but in the end one is thankful for pushing through until the shelter for the night comes into view. The journey of my PhD was no different and would not have been possible without the support, encouragement and sometimes necessary gentle reminders that things go well if just done. I would, therefore like to take the opportunity to thank all the people that accompanied me on this hike.

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Popular science summary

' Water is the most critical resource issue of our lifetime and our children's lifetime. The health of our waters is the principal measure of how we live on the land.'

(Luna Leopold)

Water is the most valuable and at the same time most vulnerable resource on earth. It determines life at small and large scale. As we have only access to 0.25 % of the water on earth in an easy manner, taking good care of it should be a matter of great importance, for our own and our children's sake. The 0.25 % of water available for human use is plenty for the world's population and each person may have about 8 million liters of water for themselves. However, the natural distribution is not equal and in many parts of the world water is not always accessible. Over the past centuries and still ongoing today, a non-sustainable use of earth's water resources and inappropriate extraction have negatively affected availability and quality.

The increasing content of degraded plant material generated and transported into the water, also called natural organic matter (NOM), has become a major problem in the northern areas of the world. NOM discolors the water in rivers and lakes, making it brown; this is why the process of increasing content of NOM is known as brownification. Observed increase in brownification is mainly a result of land use changes, long-term effects of industrialization, and a changing climate.

The browner the water in a lake or river is, the less inviting it is for recreational purposes or for use as a source of water supply. Drinking water companies face the challenge of removing the increasing amount of NOM from the water in order to distribute a clean and safe water to the consumer. This results in higher treatment efforts, increased waste production, and more CO_2 emissions. Browner water also impacts the ecosystem. It can lead to higher surface temperatures, less sunlight in deeper areas of a lake, and changes in the fish population.

This thesis aims to understand the sources, pathways, and movement of brown water in Lake Bolmen, Sweden's twelfth largest lake, focusing on the physical processes. Lake Bolmen is the primary water source for about 10 % of Sweden's inhabitants. However, with an increasing demand and demographic growth this number is likely to increase.

Therefore, the lake catchment and its hydrology were studied and related to the phenomena of brownification. Mathematical models were used to investigate the prevailing currents and wave climate of the lake, to provide insights into the pathways and patterns of NOM transport. In order to streamline water quality monitoring, the potential benefits of utilizing advancements in satellite-based measurements and computational modeling were also investigated.

The study showed that hydrologic balances and modeling can help to simulate climate change impacts and analyze management strategies. The implementation of mitigating measures need well thought-out planning and execution to sustain good quality water.

Populärvetenskaplig sammanfattning

> *"Vatten är den mest kritiska resursfrågan under vår livstid och våra barns livstid. Hälsan hos våra vatten är det främsta måttet på hur vi lever på landet."*
> (Luna Leopold)

Vatten är den mest värdefulla och samtidigt den mest sårbara resursen på jorden. Det bestämmer livet i liten och stor skala. Eftersom vi bara har tillgång till 0,25 % av vattnet på jorden på ett enkelt sätt bör det vara mycket viktigt att ta väl hand om det, för vår egen och våra barns skull. De 0,25 % av vattnet som är tillgängligt för mänskligt bruk är gott om vatten för världens befolkning och varje person kan ha cirka 8 miljoner liter vatten för sig själv. Den naturliga fördelningen är dock inte jämn och i många delar av världen finns det inte alltid tillgång till vatten. Under de senaste århundradena och än i dag har en icke hållbar användning av jordens vattenresurser och olämplig utvinning påverkat tillgången och kvaliteten negativt.

Den ökande mängden naturligt organiskt material (NOM) har blivit ett stort problem i de norra delarna av världen. NOM är en blandning av ämnen från nedbrytningsprodukter från växter, djur och organismer. NOM missfärgar vattnet i floder och sjöar och gör det brunt; därför kallas processen med ökande innehåll av NOM för brunifiering. Den observerade ökningen av brunifiering är huvudsakligen ett resultat av förändringar i markanvändningen, långsiktiga effekter av industrialiseringen och ett förändrat klimat.

Ju brunare vattnet i en sjö eller flod är, desto mindre inbjudande är det för rekreationsändamål eller som vattenförsörjningskälla. Dricksvattenföretagen står inför utmaningen att avlägsna den ökande mängden NOM från vattnet för att kunna distribuera rent och säkert vatten till konsumenterna. Detta resulterar i större reningsinsatser, ökad avfallsproduktion och större koldioxidutsläpp. Brunare vatten påverkar också ekosystemet. Det kan leda till högre yttemperaturer, mindre solljus i djupare delar av en sjö och förändringar i fiskpopulationen.

Denna avhandling syftar till att förstå källor, vägar och rörelser av brunt vatten i sjön Bolmen, Sveriges tolfte största sjö, med fokus på de fysiskaliska processerna. Sjön Bolmen är den primära vattenkällan för cirka 10 % av Sveriges invånare. Med en ökande efterfrågan och demografisk tillväxt kommer denna siffra sannolikt att öka.

Därför studerades sjöns avrinningsområde och dess hydrologi och relaterades till fenomenet brunifiering. Matematiska modeller användes för att undersöka de förhärskande strömmarna och vågklimatet i sjön, för att ge insikter om vägar och mönster för NOM-transporten. För att effektivisera övervakningen av vattenkvaliteten undersöktes också de potentiella fördelarna med att utnyttja framsteg inom satellitbaserade mätningar och beräkningsmodellering.

Studien visade att hydrologiska balanser och modellering kan bidra till att simulera effekterna av klimatförändringarna och analysera förvaltningsstrategier. Genomförandet av begränsande åtgärder kräver genomtänkt planering och genomförande för att upprätthålla en god vattenkvalitet.

Populärwissenschaftliche Zusammenfassung

> *"Wasser ist die entscheidendste Ressource unseres Lebens und des Lebens unserer Kinder. Die Gesundheit unserer Gewässer ist der wichtigste Maßstab dafür, wie wir auf dem Land leben."*
>
> (Luna Leopold)

Wasser ist die wertvollste und zugleich sensibelste Ressource der Erde. Es bestimmt das Leben im Kleinen und im Großen. Da wir nur zu 0,25 % des Wassers auf der Erde einfachen Zugang haben, sollte es für uns und unsere Kinder selbstverständlich sein, sorgsam damit umzugehen. Die 0,25 % des Wassers, die für den menschlichen Gebrauch zur Verfügung stehen, sind ausreichend für die Weltbevölkerung, und jeder Mensch kann etwa 8 Millionen Liter Wasser für sich selbst haben. Jedoch ist die natürliche Verteilung nicht gleichmäßig, und in vielen Teilen der Welt ist Wasser nicht immer zugänglich. In den vergangenen Jahrhunderten und auch heute noch haben sich eine nicht nachhaltige Nutzung der Wasserressourcen der Erde und eine unangemessene Entnahme negativ auf die Verfügbarkeit und Qualität ausgewirkt.
Der zunehmende Anteil von natürlichem organischem Material (NOM) ist in den nördlichen Gebieten der Welt zu einem großen Problem geworden. NOM ist ein Stoffgemisch aus den Zersetzungsprodukten von Pflanzen, Tieren und Organismen. NOM verfärbt das Wasser in Flüssen und Seen und macht es braun, daher wird der Anstieg an NOM als Verbraunung bezeichnet. Die beobachtete Zunahme der Verbraunung ist vor allem eine Folge der veränderten Landnutzung, der langfristigen Auswirkungen der Industrialisierung und des Klimawandels.
Je brauner das Wasser eines Sees oder Flusses ist, desto weniger einladend ist es für Erholungszwecke oder für die Nutzung als Trinkwasserquelle. Trinkwasserversorger stehen vor der Herausforderung, die zunehmende Menge an NOM aus dem Wasser zu entfernen, um ein sauberes und sicheres Wasser an die Verbraucher zu verteilen. Dies führt zu einem höheren Aufbereitungsaufwand, einer höheren Abfallproduktion und mehr CO_2-Emissionen. Brauneres Wasser wirkt sich auch auf das Ökosystem aus. Es kann zu höheren Oberflächentemperaturen, weniger Sonnenlicht in tieferen Bereichen eines Sees und Veränderungen im Fischbestand führen.
Ziel dieser Arbeit ist es, die Quellen, Wege und Bewegungen des braunen Wassers im Bolmen-See, dem zwölftgrößten See Schwedens, zu verstehen, wobei der Schwerpunkt auf den physikalischen Prozessen liegt. Der Bolmen-See ist die Hauptwasserquelle für etwa 10 % der Einwohner Schwedens. Angesichts der steigenden Nachfrage und des Bevölkerungswachstums wird sich diese Zahl jedoch wahrscheinlich erhöhen.
Das Einzugsgebiet des Sees und seine Hydrologie wurden untersucht und mit den Phänomenen der Verbraunung in Verbindung gebracht. Mit mathematischen Modellen wurden die vorherrschenden Strömungen und das Wellenklima des Sees analysiert, um Einblicke in die Wege und Muster des NOM-Transports zu erhalten. Um die Überwachung der Was-

serqualität zu erleichtern, wurden auch die potenziellen Vorteile der Nutzung von Fortschritten bei satellitengestützten Messungen und Computermodellen untersucht.
Die Studie zeigt, dass hydrologische Bilanzen und Modellierungen helfen können, die Auswirkungen des Klimawandels zu simulieren und Bewirtschaftungsstrategien zu analysieren.
Die Umsetzung von Gegenmaßnahmen erfordern eine gut durchdachte Planung und Ausführung, um eine gute Wasserqualität zu erhalten.

Abstract

Access to water of good quality and quantity has become more challenging because of a changing climate, as well as an increase in the use of natural resources, which has lead to altered water chemistry. One of these changes is known as brownification, resulting from a higher organic matter content causing a yellow-brown color of surface waters. Brownification has a manifold of side effects for the ecosystem, but also requires more efforts at drinking water treatment plants to remediate the discoloring of the water. Substantial research has been carried out to increase the understanding and knowledge of the complex process of brownification, in many cases focusing on the biological aspects. The significance of water movement as described in hydrology and hydrodynamics for the process of brownification, including the generation and transport of organic matter content, has been less investigated. With rising energy prices, higher demands on limiting the CO_2 emissions, and requirements for increased resilience of vulnerable infrastructure, such as drinking water treatment plants, the demand to better understand the physical processes governing brownification has grown.

This thesis investigates links between increased levels of organic matter and catchment hydrology using Lake Bolmen in south Sweden as a case study. Moreover, internal hydrodynamic processes of the lake were analyzed and related to the process of brownification. This was achieved by compiling existing data on catchment and lake properties, but also through additional field measurements. Hydrological balances and hydrodynamic modeling were employed to understand the system and to simulate the effects of climate change on brownification and to analyze possible management strategies and measures. Altered precipitation patterns, and related increases in surface runoff, have proven to be a main driver for seasonal and long-term change in brownification. Also, significant modifications in land use during the last centuries are an important driver. The application of a surface wave model indicated that resuspension influences the water color in a lake, possibly becoming an increasing problem in the future with less ice cover due to climate change. A validated box model describing the transport patterns in the lake, was used to simulate different scenarios and their impact on the brownification. These scenarios included changes in the climate forcing and different mitigation measures applied in the catchment or in the lake. Currently existing knowledge regarding measures to prevent further increase of organic matter, and resulting yellow-brown water, were critically reviewed and analyzed in the context of field studies of wetlands.

List of publications

This thesis is based on the following publications, referred to by their Roman numerals:

Appended Papers

I **Brownification in Lake Bolmen, Sweden, and its relationship to natural and human-induced changes**
C. Klante, M. Larson, K. M. Persson
Journal of Hydrology: Regional Studies (2021)

II **Understanding short-term organic matter fluctuations to optimize drinking water treatment**
C. Klante, K. Hägg, M. Larson
Water Practice and Technology (2022)

III **Effects of ice cover on wave driven resuspesion in a boreal lake**
C. Klante, M. Larson
submitted to: Limnology and Oceanography (2023)

IV **Simulating Long-Term Changes in Color in Lake Bolmen, Sweden, using a Box-Model Approach**
C. Klante, M. Larson, K. M. Persson
submitted to: Journal of Hydrology: Regional Studies (2023)

V **Remote sensing data driven Modeling of water color for a browning Lake**
C. Klante, H. S. Hosseini, H. Hashemi, M. Larson, K. M. Persson, R. Berndtsson
submitted to: Journal of Hydrology (2023)

VI **Wetlands as a potential multi-functioning tool to mitigating eutrophication and brownification**
A. Borgström, L.-A. Hansson, **C. Klante**, J. Sjöstedt
submitted to: Ecological Applications (2023)

Author's contribution

Names of the authors are abbreviated by their initials. It is given that all of the co-authors have read the manuscript and provided valuable feedback on it. The first author was the corresponding author for each of the published papers.

I CK conceptualized the work, curated data, conducted the data analysis and prepared the initial manuscript together with ML. Reviewing and editing was done by ML and KMP.

II CK and ML conceptualized the work. CK collected all the data and performed the data preparation and analysis. The initial manuscript was written by CK and reviewed and edited by ML and KH.

III The work was conceptualized by CK and ML. Data collection, fields measurements and data preparation and analysis have been performed by CK. The SWAN wave model has been created, calibrated and validated by CK. ML performed the calculations for shear stress. The initial manuscript was written by CK.

IV The idea and methodology was conceptualized by ML and CK. ML did the modeling. CK collected and prepared the data. KMP helped to construct source and sink term for the model. ML and CK wrote the initial draft.

V CK and HH conceptualized the the idea with input from KMP and ML. CK collected and compiled the water quality and physical catchment data. HH was responsible for collecting the remote sensed data and creating the model. CK and HH wrote the initial manuscript.

VI AB, LAH, and JS conceived the ideas and designed methodology. AB and JS collected the data and measured the water samples. AB analyzed the data with input from LAH and JS. CK performed catchment analysis of the wetlands. AB led the writing of the manuscript.

Conference Abstracts

The relationship between brownification and governing physical processes in Lake Bolmen, Sweden
C. Klante, M. Larson, K. M. Persson
7th IWA specialist conference on NOM, Tokyo, Japan (2019)

Dependence of browning in Lake Bolmen, Sweden, on physical processes including land use
C. Klante, M. Larson
XXXI Nordic Hydrological Conference, Tallinn, Estonia (2022)

Abbrevations

A254 absorbance of light at 254 nm wavelength

ANN artificial neural network

DOC dissolved organic carbon

DOM dissolved organic matter

ECMWF European Center for Medium-Range Weather Forecasts

EVI enhanced vegetation index

LWC Lagans water council

MLR multiple linear regression

NOM natural organic matter

NSE Nash–Sutcliffe model efficiency coefficient

OM organic matter

PBDE polybrominated diphenyl ethers

PCC Pearson correlation coefficient

PET potential evapotranspiration

POC particulate organic carbon

POM particulate organic matter

RMSE root-mean-square error

RS remote sensing

SMHI Swedish Meteorological and Hydrological Institute

SWAN simulating waves nearshore

TN total nitrogen

TOC total organic carbon

TP total phosphorous

UV ultraviolet

WTP water treatment plant

WW Water Works

Hydrophysical processes governing brownification: A case study of Lake Bolmen, Sweden

1 Introduction

Water is the most precious inorganic compound on earth, which constitutes the cornerstone of all life. As a resource it is fundamental for human survival at the most basic level, but also at higher levels such as in agriculture and industry. Having access to water of good quality has significant impacts on the health, well-being, and the ability to develop, and is considered as a human right by the United Nations (Morris 2019, UN Water 2023). In the first world it is taken for granted to have access to water, but often it is not asked at what cost. The access to a clean and resilient source water is not self-evident and due to an ever-increasing demand it poses a challenge all around the world.

Deteriorating source water quality, mainly caused by human influence on earth and climate change, has become an increasing challenge for drinking water production. The quantity of good quality source water decreases, seemingly at rapid speeds, and more efforts are necessary to produce drinking water of good quality. Surface waters in the northern hemisphere have been influenced through historic changes in land use, industrialization, and climate, resulting among other things in increased loads of natural organic matter (NOM). A part of this NOM reflects the light in a way so that the water appears yellow-brownish to the human eye, therefore the process is also called brownification (or browning). This does not only pose challenges for drinking water production, but also for the ecosystem. Predicted precipitation increase and higher annual temperature are expected to increase the NOM loads in the future, and with an ever increasing water demand, good quality source water may get scarcer for future generations.

1.1 Background

Sydvatten AB is sourcing, cleaning, and distributing potable water for almost one million inhabitants in southern Sweden. Sydvatten AB is the regional water supply utility in south Sweden and operates two water treatment plants (WTPs), Ringsjö Water Works (WW) (surface water) and Vomb WW (artificial recharged groundwater) (Figure 1) producing annually an average of 2500 l/s. Vomb WW produces approximately 1100 l/s and Ringsjö WW 1400 l/s (Sydvatten AB 2021*b*).

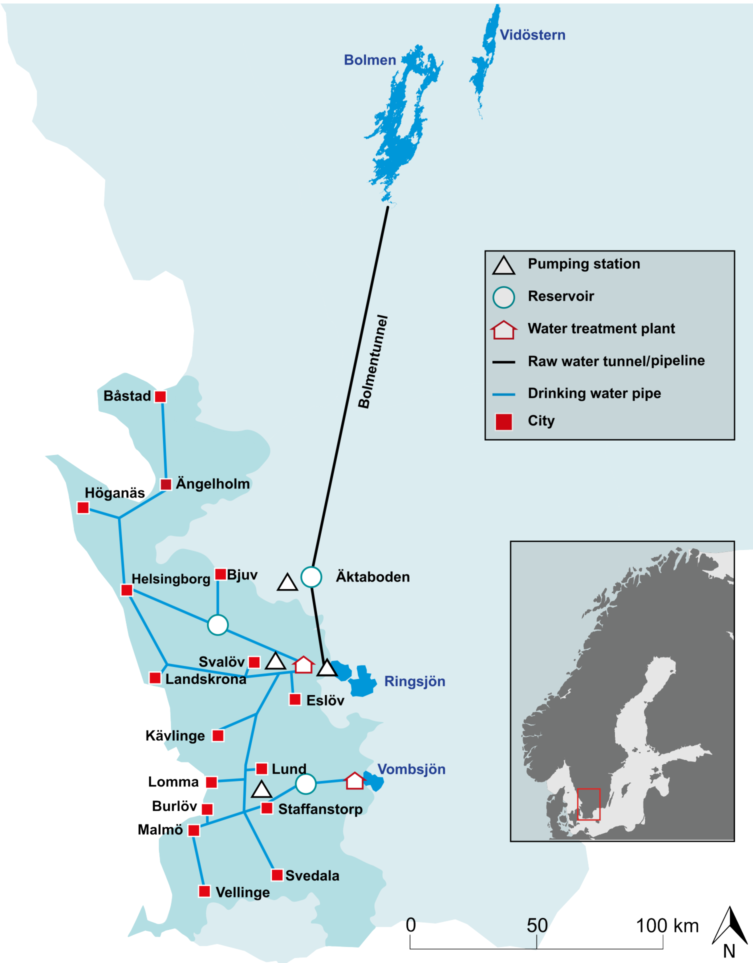

Figure 1: Sydvatten AB's distribution network including the two major source waters, Lake Bolmen and Lake Vomb, as well as the reserve source water Lake Ringsjön (adapted from Sydvatten AB (2018)). Figure not to scale.

Lake Bolmen, the study site in this thesis, is the main source water for Ringsjö WW. In order to meet the increasing demand due to steady population growth, Sydvatten AB is undertaking the effort to increase resilience in water supply by transferring Lake Bolmen water also to the Vomb WW to double the source water supply, which will make Lake Bolmen the primary source water for Ringsjö and Vomb WW. Thus, securing a healthy ecosystem that contributes to a secure, safe, and good quality source water is of highest priority.

Like many other lakes in the northern hemisphere, Lake Bolmen has experienced an increase in NOM during recent decades, resulting in increased treatment efforts needed to be undertaken by Sydvatten AB. In addition to these efforts, costs for chemicals, maintenance as well as carbon dioxide emissions have increased. The transport of chemicals needed to treat the source water makes up for close to 90 % of the total carbon dioxide emission of Sydvatten AB. This number could be reduced to almost half its size, if the amount of NOM in the source water could be lowered (Sydvatten AB 2021*a*).

Besides the mentioned challenges for drinking water production, increased level of NOM in the water and the connected browning pose other challenges for the affected ecosystem. Climate change has been determined as one of the main processes driving the increase of brownificaiton (De Wit et al. 2016, Blanchet et al. 2022). The connection between climate change and brownification lead among other things to an altered fish population, presumably connected to changes in the microbiology of the water, increased surface water temperatures, a lowered recreational value, and a less healthy ecosystem (Creed et al. 2018, Van Dorst 2020). Lower level of NOM in the source water would therefore also be favorable for the ecosystem and the recreational values of Lake Bolmen.

Even though, current knowledge regarding the increasing levels on NOM in surface waters is plenty, it is not sufficient to allow for strategies and measures to keep the levels acceptable for all parties of interest. Thus, extension of our knowledge on brownification is urgently needed, especially in quantifying cause-effect relationships. For the specific case of Lake Bolmen, it will contribute to the already undertaken effort of Sydvatten AB regarding the cooperation between municipalities, fishery associations (private and industrial), local authorities, such as landowners and the forest agency, as well as other stakeholders and decision makers to sustainably secure a safe and resilient source water as well as a healthy ecosystem. Additionally, it will enable other regions to adapt this knowledge to secure water resources for coming generations.

1.2 Objectives

The overarching aim of this thesis is to increase the knowledge and understanding of the process of brownification and the physical interactions with the environment it appears in. Specific objectives within this research work have been:

- develop an overall understanding of brownification with regard to the physical process (**Paper I** and **Paper III**)
- relate changes of brownification to seasonal variations and runoff events (**Paper I** and **II**) to improve the drinking water production (**Paper V**)
- analyze the distribution of brown water inside the lake and investigate transport and mixing (**Paper I** and **Paper IV**)
- suggest and analyze possible mitigation measures to remediate future increase of brownification (**Paper VI**).

In order to achieve the above-mentioned objectives, analysis and modeling at different spatial and temporal scales have been used considering the catchment of Lake Bolmen as well as the lake itself. Figure 2 visualizes the different aspects of this thesis.

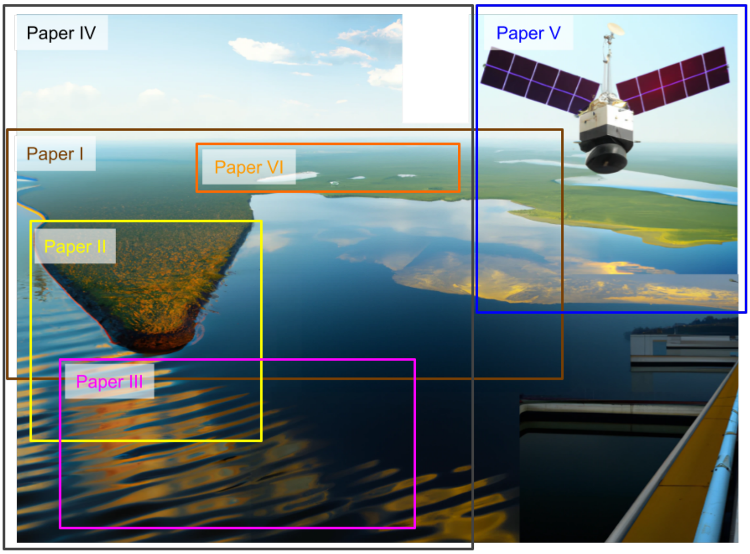

Figure 2: A graphical overview of the different aspects of this thesis related to a schematic picture of a lake and its catchment. The colored boxes represent the specific focus of each paper.

Paper I focuses mainly on long-term variations considering the entire catchment of Lake Bolmen, whereas **Paper II** targets short-term variations with a particular emphasis on a sub-basin of the lake located in the southern part. In **Paper III** the surface effects of waves and the possibility of material uptake from the lake bottom due to forces introduced by the waves are analyzed. **Paper IV** uses a box-model approach to simulate long-term variations of water color within Lake Bolmen. The possibility of using advances in remote sensing (RS) and artificial neural networks (ANNs) is investigated considering the forecast and prediction of water color in **Paper V**. **Paper VI** investigates the possibility of wetlands as mitigation measures against color and nutrients in the aquatic system.

2 Theoretical background

2.1 Brownification

Many lakes and streams, dominantly in the northern hemisphere, have increased in yellow-brown color, mainly as a results of increased levels of NOM. These terrestrial humic substances commonly leach from soils within the catchment and absorb light in the short wavelength, which makes them visible as yellow-brown to the human eye. NOM is a very complex mixture of organic matter (OM) with natural origin, varying chemical and physical properties originating from the decomposition of plants, animals, and organisms. Due to the varying properties of NOM, it can occur in particulate or dissolved form, where the part which is dissolved is called dissolved organic matter (DOM). Carbon is the key component of OM considered as the quantitative measurement. Hereby, total organic carbon (TOC) describes the total amount of carbon measurable, which is divided into particulate organic carbon (POC) and dissolved organic carbon (DOC). In the aquatic system DOC accounts for the greater part of NOM (Health Canada 2019). Figure 3 schematizes the fractionating of OM.

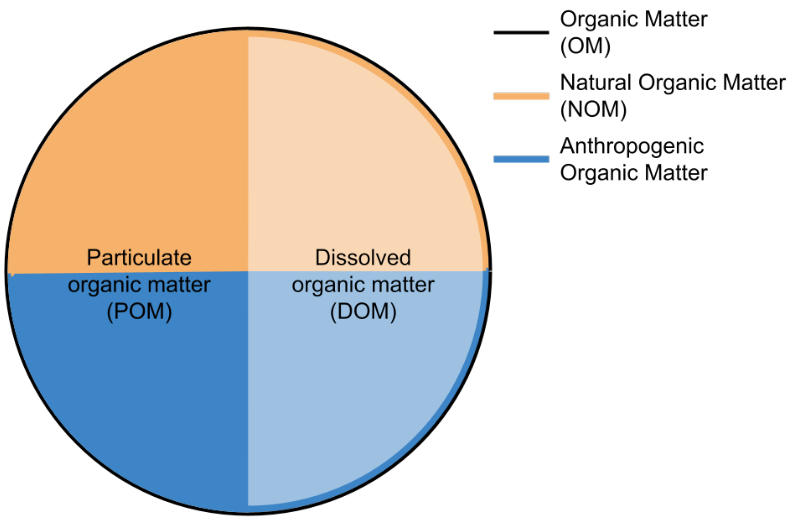

Figure 3: Schematization of OM fractionation where OM represent the entire circle and NOM and particulate organic matter (POM) are fractions of OM. The distribution is not to scale.

A rather minor part of DOM is produced internally in the water bodies through plankton and macrophytes (Löfgren et al. 2003, Graneli 2012). Additional to the rising levels of NOM, increases in iron, contribute to the higher color values (Ekström 2013, Björnerås et al. 2017). The process of increasing levels of NOM and iron in surface water is known as brownification (also called browning).

Levels of brownification are traditionally measured according to the APHA-Hazen scale in $mgPt/l$ (Hazen 1896). In recent years it has become more common to measure the level of color with the absorbance of light at different wavelengths. A wavelength of 254 nm has proven to be representative in applications considering water treatment (Köhler et al. 2016, Cascone et al. 2022) and wavelengths above 400 nm are commonly used when the combination of NOM and iron should be represented (Bennett & Drikas 1993, Löfgren et al. 2003, Köhler et al. 2013).

The magnitude of color varies seasonally, but also shows spatial variation. The complexity of the aquatic environment and interactions within the catchment of affected water bodies lead to a manifold of influencing factors and drivers. Climate variability and climate change and the effects of precipitation, temperature, and resulting runoff are the most influential driving forces, mainly determining long-term increases and seasonal variation (Pace & Cole 2002, Vogt et al. 2003, Graneli 2012, Kritzberg et al. 2020). The relationship between high values of color and increased precipitation, as well as the opposite, has been shown by De Wit et al. (2016) and Meyer-Jacob et al. (2019). The reduction of atmospheric acid deposition and its effects on changes of the soil pH, resulting in higher transportability for iron and NOM, are another discussed long-term driver (Monteith et al. 2007, Haaland et al. 2010, Ekström 2013, Björnerås et al. 2017). However, this theory has been weakened by the findings of Meyer-Jacob et al. (2019) and Kritzberg (2017), showing that increases in color actually surpasses the reduction of acid deposition in the atmosphere. Marked changes of land use in many catchments have resulted in an rapid increase of forested area, primarily industrial used coniferous forest. These changes affects the carbon budged within these catchments and are presumably related to increased OM loads and brown color in the surface waters of these catchments (Finstad et al. 2016, Temnerud et al. 2014, Škerlep et al. 2020, Blanchet et al. 2022). Other hypotheses include the consideration that the observed increases in NOM and brown-colored water may be explained not solely by increased forest biomass, but instead by the alterations made to enable forest plantation via ditching (Estlander et al. 2021). However, restored ditches have also been discussed as a useful measure counteracting the steady increase of NOM and color from an afforested catchment (Kritzberg et al. 2020).

Brownification poses challenges in different aspects for the ecosystem and for the usage of affected water bodies as source water for drinking water production.

One of the most obvious challenges is the impact on the recreational value of brownified water bodies caused by the common connection between dark water and insufficient water quality (Tuvendal & Elmqvist 2011, Keeler et al. 2015). Increased levels of brown color influence the attenuation of light and result in increased temperatures for the upper water layer. This does not only influence the bacterial activity, but can also result in drastic changes of the mixing regime, as well as the thermal stratification regime (Williamson et al. 2015, Creed et al. 2018). In addition, the decreases in solar radiation may increase the risk of waterborne pathogens caused by a decrease through ultraviolet (UV) inactivation (Blanchet et al. 2022). Changes in fish population, a decline of their nutritional value, and influence on the aquatic food web structures are other implications of brownification (Taipale et al. 2016, Van Dorst 2020). In general does the increase of OM affect the entire biodiversity of the ecosystem caused by a decrease of invertebrate populations and alternations of the composition of benthic macro invertebrate communities (Urrutia-Cordero et al. 2017, Brüsecke et al. 2022).

For the production of drinking water, increased levels of NOM result in higher treatment efforts leading to increased costs, waste, and CO_2 emissions. These efforts, among others, cause higher demands of flocculant, during chemical treatment, increased backwashing cycles of filters due to higher possibility of fouling and the possibility of toxic byproducts during disinfection (Eikebrokk et al. 2004, Lidén 2016, Keucken et al. 2017, Hägg et al. 2020, Anderson et al. 2023).

However, from different perspectives a specific amount of brownification and NOM in surface waters may be desirable, since lower amounts of DOC, one of the primary component of NOM, tend to increase biological activity. This leads to a more active and productive ecosystem. Yet, this level is relatively low and above a concentration of 5 mg/l the maximum is reached (Finstad et al. 2014, Wolf & Heuschele 2018). Hence, a balance between positive benefits and harmful challenges may be a desirable aim to strive for.

Paper I

focuses on the analysis of the long-term, seasonal, and spatial variability of browning in Lake Bolmen and its driving forces. This study has been initiated to relate process of brownification in Lake Bolmen to existing knowledge and point out location-specific characteristics.

2.2 Lake hydrology

The hydrologic cycle builds the foundation for hydrology and defines the mass balance, water movement, and storage of water on earth's surface (Evans III 2021). The hydrology of a lake involves the understanding of the quantitative balance of water including both the actual water body and its catchment. Thereby, it considers the influence of meteorological parameters, such as precipitation, temperature, and wind, as well as direct effects of these due to interactions within the catchment. Additionally, it also considers water quality parameters and relate them to the balance equation. The most basic equation for a single water quality parameter for a lake looks like the following (Bengtsson et al. 2012):

$$A(h)\frac{d}{dt} * hC = Q_{in} * C_{in} - Q_{out} * C \qquad (1)$$

where A describes the surface area of the lake, which may vary with the water level h. Together these variables define the actual lake water volume. Q is the flow, with different index for in- and outflow, transporting a specific concentration C of the quality parameter of interest. C without an index represents the average concentration within the lake. This formulation makes the assumption that evaporation and precipitation are negligible. They may almost balance each other in long-term considerations, often being less significant than the in- and outflow volumes. However, this is not always the case. Moreover, subsurface flows due to the groundwater and the saturated soil zone are not included.
In general, the balance equation stated above can be expanded and formulated as detailed as needed, based on the time scale selected, implying that the resolution of various processes will vary greatly. Thus, depending on the specific application the natural interactions may be rather complex.

Paper 1
takes a general approach in analyzing the hydrology of Lake Bolmen's catchment and relates its variability to changes in NOM and water color. A general water balance for Lake Bolmen is developed and related to the mass balance of NOM.

2.3 Lake hydrodynamics

Hydrodynamics of lakes focus on the physical properties of the movement of water within a lake. This includes various processes such as mixing, thermal stratification, circulations patterns, as well as wind-generated waves and associated currents. The physical water movement can be associated with chemical and physical water quality parameters, such as particle transport or temperature exchange that are influenced by the mixing conditions. In contrast to hydrology, hydrodynamics focuses not only on the mass balance, but also on the forces inducing water movement.
Even though the physical properties of a lake may the different than the one of the sea, lake hydrodynamics is closely related to the hydrodynamics of the sea. The specific properties for lakes have been described by Boyce (1974) as follows:

- Lakes are closed basins that hold mechanical energy within and dissipate it through heat.
- A lake water volume is considerable smaller than that of the sea and therefore not influenced by astronomical tides. However, for large lakes the water movement may be still be influenced by the Coriolis force.
- The principle source of mechanical energy to a lake is the wind, which is introduced through the water surface. The inflows and outflows of a lake are considered as

sources and sinks for energy.

The above-mentioned characterization was arrived at mainly considering the Great Lakes in the United States and is not applicable for all lakes. However, such simplifications build the foundation for most hydrodynamic calculations regarding lakes.
In brief, in contrast to lake hydrology, lake hydrodynamics additionally considers the momentum balance equation.

Wind-generated waves

Surface waves may not be the first driver one thinks of when considering forces in the water of a lake, but for larger lakes their influence may be of great significance. The forces created by waves can damage structures, affect the morphology as they transport sediment, and generate flows that influence transport and mixing of material. The basic theory for describing waves is often quite simple. However, superposition of many such simple waves are required to describe all the complexities found in nature. Figure 4 shows a two-dimensional profile of a wave with the three main properties wave height, water depth, and wave period, which are sufficient to completely specify a simple wave (Sorensen 1993).

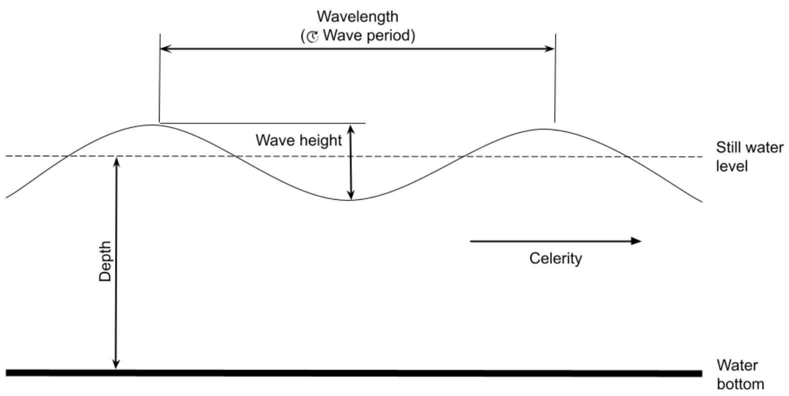

Figure 4: Two-dimensional profile of a wave and its main properties. The wave is traveling from left to right.

Wind is the most common mechanism for generating waves, especially in lakes. Other mechanisms may be vessels moving through the water or the gravitational force of the moon and sun for large water bodies like the sea, resulting in tides. Typically, the wave period

for wind-generated waves is in the range of 1 to 25 seconds, but in a lake it is normally in the range 1-5 seconds. The profile of the wave shown in Figure 4 is rather simple compared to the profile observed for wind-generated waves under natural conditions. However, the wave spectrum of wind-generated waves, determined by the distribution of wave energy over wave period and direction, can be described by multiple sinus waves with different amplitude, period, direction and phase, using Fourier analysis (Coastal Engineering Research Center 1984, Sorensen 1993).
Wind speed and duration, fetch length, and water depth are the basic determining factors for wind-generated waves. Other factors such as fetch width, lake bottom conditions, and the difference between water and air temperature may under certain conditions be important. Due to the topographical characteristics of lakes the generation of waves is commonly fetch-limited, resulting is smaller wave heights and shorter periods. The energy that is contained in waves, as displacement from the surface (potential energy) and their movement of water particles (kinetic energy), is dissipated through shear stresses at the air-water, water-water, and water-bottom surfaces. Thus, wind-generated waves play an important role considering the transport of material in the water column as well as through the interaction with the bottom sediments.

Material transport and bottom shear stress

With increasing wind velocity, the energy contained within the waves will increase as well through the oscillatory motion initiated by the waves. This rising energy results in higher shear stresses on the bottom, commonly denoted by τ_b, that can become large enough to initiate transport of the bottom material. The shear stress necessary to initiate transport of material is called the critical shear stress τ_{cr} (Komar & Miller 1973, Soulsby 1997, Wilcock 1993). The magnitude of τ_{cr} is primarily determined by the bed material and the presence of bed forms.
The oscillatory wave motion is circular in deep water, but gets elliptical in intermediate to shallow water. Close to the bottom this motion is reduced to a primarily horizontal oscillation with an orbital diameter d_0 described by:

$$d_0 = \frac{H}{sinh(2\pi h/L} \tag{2}$$

where, H is the wave height, h the water depth, and L the wavelength. The resulting velocity of this motion can be determined by:

$$U_w = \frac{\pi d_0}{T} \tag{3}$$

with T being the wave period (Komar & Miller 1973).
From the information presented, one can determine the shear stress at the bottom, which is described in further detail in section 4.5.

Paper III

analyses the wind-induced wave climate in Lake Bolmen and relates it to the shear stress at the lake bottom, which is compared with the critical shear stress for material mobilization. Already in Paper II it was hypothesized that wave currents may be strong enough to contribute to short-term peaks of water color (resuspension) and in Paper III this is analyzed in further detail.

3 Study site: Lake Bolmen

For this entire research, Sweden's twelfth largest lake, Lake Bolmen (Swedish Meteorological and Hydrological Institute 2008), was selected, since it is, together with lake Vomb, the main source water for Sydvatten AB (figure 1). Lake Bolmen is located in southern Sweden in the district of Småland.

3.1 The lake

Lake Bolmen is the larges lake in the Lagan River basin, has a surface area of 173 km^2, and is located at an elevation of approximately 141 m above sea level. The average water depth is 6.2 m with the largest depth being 38 m in the southern part of the lake (Romare & Cronberg 2004). Bolmsö island, located in the central part of the lake, has a size of 42 km^2 and separates Lake Bolmen into five parts having different hydrodynamic properties. Additionally, a sixth hydrodynamically different part of the lake (Kafjorden) is located at the southern-most end and is topographically separated through the Fettjesund sound (Figure 5a). The two northern parts of the lake are in comparison to the other parts relatively shallow. Average depth for the north-eastern sub-basin (I) is 2.5 m and for the north-western sub-basin (II) 3.3 m. In comparison, the average depths of the western (III) and southern (V) sub-basins are 7 m and 8 m, respectively. Interesting are the occasionally deep areas in the bathymetry, mainly located on the eastern side of the lake. Sub-basin VI is the smallest and shallowest of all of the sub-basins with an average depth of 1.9 m. A simplified bathymetric map of Lake Bolmen is shown in Figure 5b.

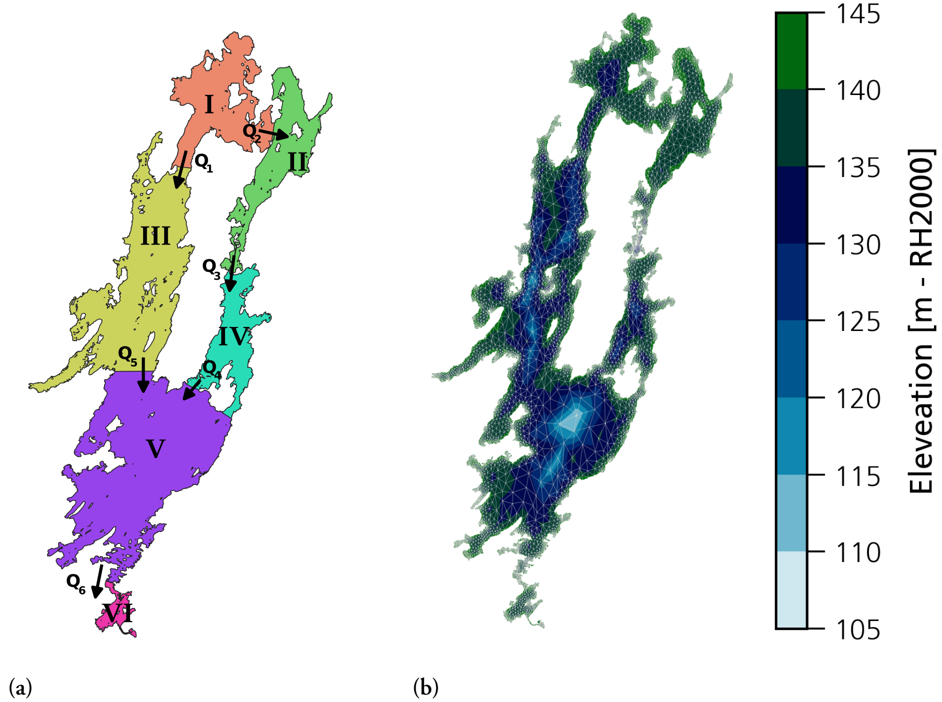

Figure 5: The six hydrodynamically different parts (sub-basins) of Lake Bolmen are shown in Figure (a) and a simplified bathymetry in the elevation system RH2000 in Figure (b)

Lake Bolmen is dimictic, oligotrophic, and holds good ecological and chemical status. However, the concentration of polybrominated diphenyl ethers (PBDE) and mercury are an exception (Vatteninformationssystem Sverige 2023). The first water quality measurements for the lake have been recorded in 1935. Since then, a continuous increase of organic matter and water color have been noticed. A special characteristic for this increase in color is that the northern part of the lake shows in general higher values than the southern part of the lake (Persson 2011). The same holds true for other chemical variables (Borgström 2020).

The relatively high amount of small islands scattered in the lake (Figure 6) results in complex hydrodynamic conditions and high biological diversity (Vatteninformationssystem Sverige 2023).

Figure 6: Areal picture of Lake Bolmen showing several smaller islands in the southern part of the lake (Source: Sydvatten AB (2023*b*)).

The three main tributaries Lillån, Storån, and Lidhultsån (locations shown in Figure 11) determine the main inflow to the lake and contribute about 71 % of the inflowing water. Additionally, there are many smaller tributaries like Dannäsån, Murån, Lillasjöbäcken, and Smedjebäcken, which may run dry during summer, but can significantly contribute to the carbon balance of the lake (Persson 2011). Lake Bolmen has a residence time of about 1.6 years and Klante et al. (2021) showed that about 80 % of the lake water are transported through the western part of the lake, which is also the side where the main tributaries enter. For a lake of this size and importance, monitoring of lake water quality, lake hydrology, and knowledge of hydrodynamic conditions are rather limited, which presented a challenge for the studies conducted in this thesis work.

Paper I and Paper II

analyzed the influence of internal lake flows as well as the contribution of smaller tributaries to the OM balance of the lake in detail. The main flow path within Lake Bolmen, including sub-basin retention times were investigated in Paper I. Paper II focused on short-term variability of OM and location specific influence, particularly in Kafjorden.

3.2 The catchment

The catchment of Lake Bolmen covers an area of 1650 km^2 and constitutes the largest sub-catchment in the Lagan river basin. The basin of Lake Bolmen has a north-south extension of about 100 km and is almost 25 km at its widest part in the east-west extension. It is situated within three counties, Halland, Kronoberg, and Jönköping (Vatteninformation-ssystem Sverige 2023).

Despite its size, the land use within the catchment is very homogeneous. Forest, mostly of coniferous type, is the dominant land use, followed by water surfaces, wetlands, and agriculture. Urban areas constitute less than 1 % of the land use within the catchment (Figure 7). This circumstance gives the catchment an almost pristine appearance. However, most of the forested area is used industrially.

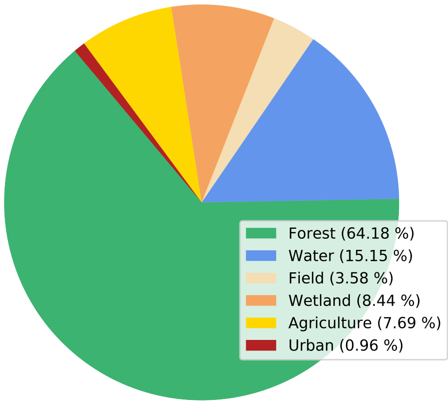

Figure 7: Distribution of land use within the catchment of Lake Bolmen.

The soils in the catchment mainly consist of till and peat with some glaciofluvial deposits, primarily located in the northern part. The largest peat land, Store Mosse, which is also the largest bog in southern Sweden, is located approximately 25 km north of Lake Bolmen. According to Peel et al. (2007), Bolmens catchment is located in the cold climate zone, without a dry season and warm summer, also called the hemiboreal climate. The annual average temperature is 3.5 °C and the annual precipitation 900 mm, considering the latest period 1991 to 2021 (Swedish Meteorological and Hydrological Institute 2023).

Paper VI

focuses on a specific mitigation measure in the form of wetlands and analyses their combined potential to reduce nutrients and water color. Even though the analyzed wetlands of the paper are not located within catchment of Lake Bolmen, the catchment properties are very similar to the one of Lake Bolmen.

3.3 The Bolmen Tunnel and drinking water system

The present source water supply for the western region of southernmost Sweden (Figure 1) is the result of a water supply plan devised during the 1960s. Since the water supply in southernmost Sweden was deemed not sufficient to cover the demand of the increasing population, a political decision was made to use Lake Bolmen in southern Sweden as the main source water for southernmost Sweden (Sydvatten AB 1971, 2020). The transport of water to the south has been realized through the construction of a approximately 80 km long tunnel, drilled through solid bedrock, known as the Bolmen Tunnel (Figure 8).

Figure 8: Photo of the Bolmen Tunnel from the inside taken during construction work (source: Sydvatten AB (2020))

Tunnel construction started in 1975 and the first water was transported through the tunnel in 1987. The tunnel has a length of 80 km and a cross sectional area of approximately 9 m^2. Except for some maintenance entrances, the tunnel is in major parts entirely filled with water. The bedrock comprising the tunnel surroundings is predominantly composed of gneiss, exhibiting diverse compositions and minor amounts of granite. Several sections of the rock show zones with fractures and crushed rock, and groundwater flow is occurring within the fractures (Stanfors 1987, Fetter 2014). The slope with a height difference of about 90 m makes it possible for the water to be transported by gravity and no pumping is necessary. Excess kinetic energy caused by gravity is dissipated in a reservoir at the tunnel outlet, from where the water from Lake Bolmen is transported to Ringsjö WW via a approximately 20 km long pipeline (Sydvatten AB 2020, Balkfors 2020). More details regarding the tunnel hydraulics are described in **Paper II**.

Ringsjö WW produces 1400 l/s water on average that is distributed to 12 municipalities in the western part of Skåne county. The treatment process consists of the combination chemical precipitation, biological treatment through a slow sandfilter, and disinfection with UV light and sodium hypochlorite (Sydvatten AB 2023*a*). **Paper II** describes the treatment process in further detail including a schematic visualization. The security of a safe water supply in the event of a blackout is guaranteed through redundant systems at all levels at Ringsjö WW.

Paper II
relates changes of organic matter content and brown color in the lake to water quality changes during the transport to the Ringsjö WW. In addition, implications on how drinking water treatment can be improved and how other treatment plants can benefit from this knowledge are given.

4 Methodology

This chapter will give an overview of the methodology used in the papers appended. More detailed information regarding the methodology can be found in respective paper.

4.1 Data collection and analysis

This study followed the overarching aim to increase the knowledge and understanding of the brownification process focusing on the physical interactions within the lake and its environment. Data of different typ and from a wide range of sources built the foundation that enabled this research. Almost all of the employed data have been gained from free and openly accessible sources. Thus, it is possible to modify, extend, and even improve the results of this research by compiling and collecting new, more comprehensive data, which opens for the possibility for future studies.

The most common base data for this thesis have been meteorological observations. Even though Bolmen is Sweden's twelfth largest lake (Swedish Meteorological and Hydrological Institute 2008) and its catchment area is relatively large, there are limited measurement data available. Meteorological data, which have been used to relate the changes in water quality to specific catchment conditions, such as changes in the climate, have been obtained from the Swedish Meteorological and Hydrological Institute (SMHI) [1]. However, the catchment of Lake Bolmen lacks an operational temperature measurement station and is has only two active stations to measure precipitation. The same applies to wind measurements as for temperature, so that data from stations in the vicinity of the catchment had to be used.

In addition to records of meteorological observations and georeferenced data, data regarding water quality and the wave climate have been employed, which will be explained in more detail in the sections 4.2 and 4.3, respectively.

Besides the mentioned base data a set of RS products were employed, which are described in detail in **Paper v**.

All data that were used in this thesis is georeferenced, meaning besides the measurement information they also contain information regarding the location of the measurements. The most common way to visualize georeferenced data is the use of maps. All map information, including data of land use have been obtained through the Lantmäteriet (Swedish Land Survey) open data portal [2].

Measurement equipment can generate unreliable readings due to several factors, leading to potential errors that may affect the analysis made and conclusions drawn. Thus, the implementation of data quality control and cleaning are necessary measures, which must be taken without introducing bias. Here, a combination of methods to remove faulty or

[1] https://www.smhi.se/data/meteorologi/ladda-ner-meteorologiska-observationer

[2] https://www.lantmateriet.se/oppnadata

outlier data (e.g., outside a specific standard deviation or percentile) was employed and the detailed procedures are specified in respective paper.
Typically, standard statistical analysis, yielding quantities such as mean, standard deviation, and percentiles were used initially to describe the data sets. Subsequently, more advanced statistical methods, including frequency, correlation, and regression analysis, as well as Fourier techniques, were employed and are further described in the papers.

4.2 Water quality measurements

Two main sources have been employed for water quality measurements. The continuous monitoring program of surface water quality in the Lagan River basin coordinated by Lagans water council (LWC) and measurements recorded within Sydvatten's self-monitoring program. LWC is a stakeholder interest group that was founded in 1995 and has the task of coordinating the different interests within the Lagan river catchment to achieve a good water quality, protect the catchments biodiversity, and ensure a even distribution of water quantity. Thus, one major task is the collection of water quality data at different locations within the entire catchment. Measurements from seven of these locations have been utilized (figure 9). It is important to mention that two of these seven stations are within Lake Bolmen and that they encompass two different measurement series each. One at the bottom of the lake and one at the surface, making it effectively nine measurement locations in total. Measurements in the tributaries are performed at a monthly frequency, but measurements inside the lake only once a year during summer.
Another set of water quality measurements have been provided through Sydvattens self-monitoring program, which is obligatory to ensure the production of water quality meeting governmental regulations. Moreover, the self-monitoring program is used to streamline water treatment and make it more efficient. The data used from the self-monitoring program mainly considered the source water quality at the outflow from Lake Bolmen, including data of the water quality after the lake water has passed through the tunnel. Data regarding the efficiency of different treatment steps in the WTP or information about the distributed water quality were beyond the scope of this thesis work. The measurement frequency of the data from Sydvatten is on an hourly basis. However, in the case of Piksborg (Figure 9) the records are providing only monthly values.
Common measured parameters used are among others pH, temperature, TOC, DOC, color in $mgPt/l$, and absorbance of light at specific wave length (mainly 254 nm and 420 nm). Additionally to the above mentioned measurements, monthly samples have been taken from April 2020 until September 2021 for the study performed in **Paper VI**. The collected samples were analyzed for total phosphorous (TP), total nitrogen (TN), TOC, and absorbance of light at a wavelength of 420 nm, which was taken as a proxy for water color. A detailed description of the used laboratory equipment and measurement procedure are described in **Paper VI**.

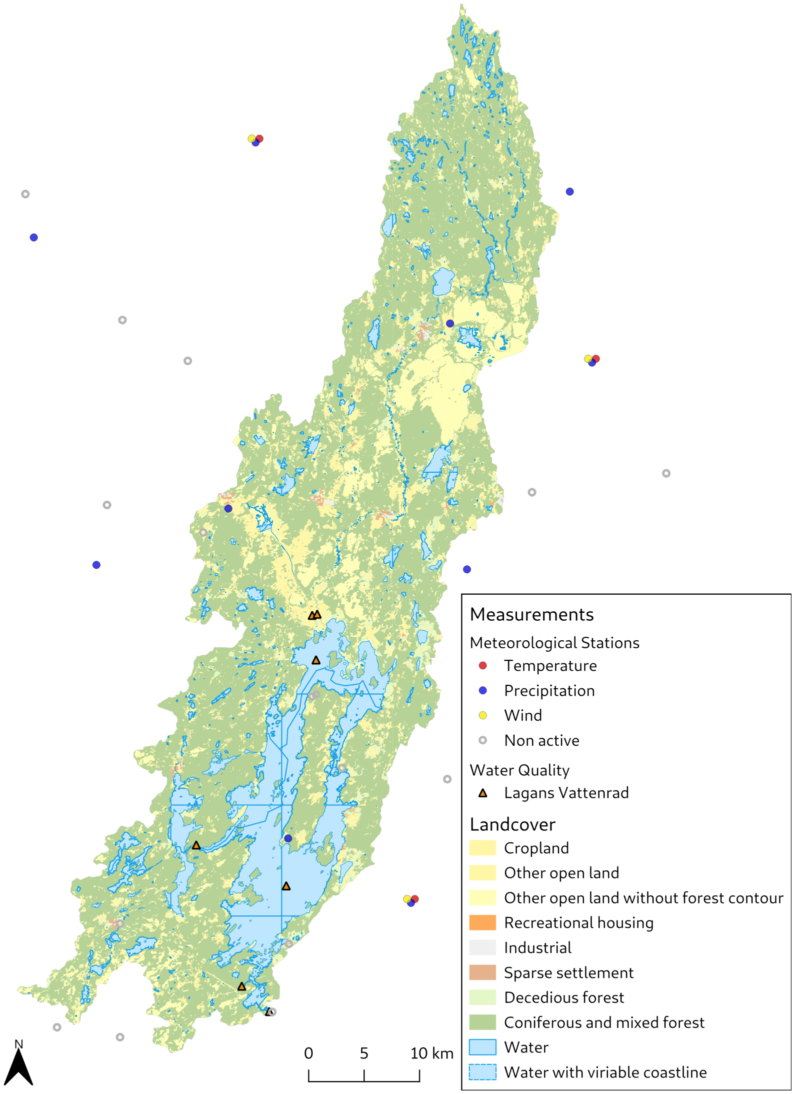

Figure 9: Locations of active meteorological stations and water quality sampling locations in the Lake Bolmen area.

Paper v

analyses the potential of using RS-based data in combination with ANNs to predict the level of water color (in this specific case absorbance of light at 254 nm wavelength (A254)), which can be helpful to streamline treatment processes and optimize the use of existing measurements, as well as plan for future ones.

4.3 Pressure gauge measurements

DOM is, as indicated by its naming, commonly suspended material within the water column and consists of a wide mix of natural substances. Due to the particle density and naturally occurring flocculation processes DOM tends to settle, if the hydrodynamic conditions allow for it. Thus, commonly the magnitude of measured color is higher at the bottom of a lake then on the surface (Hessen 1998, Temnerud et al. 2014). If no external forces strong enough would be introduced into the water column that could mobilize bed material, it would simply remain on the bottom of the lake, eventually being depleted through biological activity. However, this is commonly not the case in a lake as waves may introduce currents strong enough to resuspend this material before biological activity could break it down. This possibility of resuspension through wave currents has been shortly discussed in **Paper I** and **Paper II** and analyzed in further detail in **Paper III**. For this analysis it was necessary to collect information about the wave conditions at Lake Bolmen, which were not available prior to the measurements performed in connection with this thesis work.
As described earlier, Lake Bolmen is quite large and has a complex topography resulting in complex hydrodynamic conditions. Thus, it was necessary to collect information regarding the waves at several locations inside the lake. It was decided to collect measurements at three representative locations under consideration of the wind climate and prevailing fetch lengths, which mainly determines the wave conditions. The wave climate was measured at these locations during three separate occasions using a pressure sensor (RBR virtuoso[3]), which was always deployed with the same setup (Figure 10).

Figure 10: Pressure gauge as deployed in Lake Bolmen. The concrete block ensures a stable locations of the pressure gauge and keeps it above the lake bottom to prevent debris and fine sediment to block the pressure membrane.

The depth of deployment of the gauge was aimed at one meter. However, the water level regulation at the Lake Bolmen outlet due to the power station could not be considered. The elevation of the pressure gauge from the lake bottom was 0.24 m and the pressure was measured in a so called burst mode. In this mode, the pressure was recorded at hourly intervals for about 17 minutes at 16 Hz frequency. The first field campaign in 2021 took place during the 25th of March until the 30 April at the southern tip of Bolmsö Island. The second field campaign located just about 400 m south of the Bolmsö ferry line, was also meant to measure for a period of about one month. However, due to difficulties in the retrieval of the pressure gauge, this period lasted more than seven month and pressure data were recorded between 3rd of November 2021 until 9th of June 2022. In the final field campaign measurements were carried out inside the Kafjorden sub-basin of Lake Bolmen between 22nd of September and 20th of October 2022. The data recordings during the first and seconds field campaign have been used to calibrate and validate the wave model in **Paper III**, which was the foundation for analyzing the possibility of resuspension due to wave motion at the lake bottom.

4.4 Numerical modeling of waves with SWAN

Short-term peaks of DOM in surface waters are less well researched than the biological interactions in a long-term perspective. Moreover, such fluctuations at the short-term scale may be more related to the physics of the water body rather than its biological interactions. In **Paper I** and **Paper II** it has been hypothesized that wave-driven resuspension, induced through wind forces, may be the main driver of such short-term peaks. The above mentioned pressure gauge measurements have been conducted to achieve first insights into Lake Bolmen's wave climate and represent the first measurements of such kind for this specific region. Although these measurements offer insight into specific location characteristics, they do not provide the wave climate in other areas of Lake Bolmen. Therefore, the best approach to gain comprehensive knowledge and understanding of the entire wave climate of Lake Bolmen is the development of a wave model that can be calibrated and validated against these measurements. Such an approach has been taken in **Paper III** using the SWAN wave model. Results of this model do not only improve the knowledge regarding the Lake Bolmen wave climate, but also open up for the analysis of the earlier mentioned possibility of resuspension through the bottom shear stress from the waves.
SWAN, which stands for Simulating Waves Nearshore, is a third-generation model that was developed to calculate wave parameters in coastal zones, estuaries, and lakes. The spectral action balance equation is used to calculate wind-generated surface waves through the input of wind, current, and bathymetric data (Booij et al. 1996, Tolman & Chalikov 1996, The SWAN team 2022*a*). A simplified version of the spectral action balance equation is as follows:

$$\frac{\Delta F(f,\theta)}{\Delta t} = S_{tot} \tag{4}$$

$F(f,\theta)$ is describing the wave energy distribution over the wave frequency f and propagation direction θ. The sum of sources and sinks terms for all physical processes due to wind input, wave generation, wave dissipation, and non-linear wave-wave interactions is described through S_{tot} (Cavaleri et al. 2007, Tolman & Chalikov 1996, The SWAN team 2022*a*). Different formulations regarding the exponential wave growth, bottom friction, and white capping are implemented within SWAN and the user can select the most suitable ones. If no specific selection is made, SWAN sets default values for the calculation (The SWAN team 2022*b*).

A crucial part of the SWAN wave model is the mesh, which describes the spatial characteristics of the model domain including topographic and bathymetric properties. Lake Bolmen's shoreline is relatively complex and shallow areas are considered to be more affected by resuspension events than deeper, given the decrease in wave energy with depth. Therefore, it was decided to use an unstructured mesh, where the grid resolution was adjusted to the complexity of the shoreline and bathymetry as well as the areas of specific interest. Figure 5b shows the final mesh from the bathymetry applied, which has a resolution range from 50 m up to 3.5 km. Further details regarding the bathymetry and the mesh are provided in **Paper III**.

A non-stationary model has been established to simulate the waves using SWAN in second-generation propagation mode. For simplification and feasible computation time, all boundaries are considered as closed without any energy flux. The model period spans 26 years (1996-2021), which allows for sufficient temporal and spatial resolution regarding the predominant wave climate at Lake Bolmen. Results of the SWAN wave model have been employed to calculate the resulting shear stress at the lake bed, which is further discussed in the following section.

4.5 Shear stress calculations to evaluate the possibility of resuspension

Waves on the water surface cause water to move above the bed, inducing shear stresses. This motion is oscillatory and results in a thinner boundary layer when compared to a uni-directional flow. Also, the boundary layer growth is less due to the reversal in water motion, which causes higher shear stresses through larger velocity gradients. For specific wave conditions, a quasi-steady flow can develop at the bed with a constant maximum velocity resulting in a constant shear stress amplitude at the bed. The magnitude of the bottom shear stress is influenced by a manifold of factors such as wave height, wave period, water depth, and the characteristics of the bed material. Depending on the bed material, the shear stress at the bottom can be large enough to mobilize formerly settled material, commonly described as reuspension. The value that describes the shear stress necessary to initiate transport is called critical shear stress, donated as τ_{cr} (Komar & Miller 1973, Wilcock 1993, James et al. 2004). The hypothesis regarding wave-driven resuspension, implies that at occasions when wave currents result in shear stress above the critical value the waves contribute to short-term NOM-peaks.

The maximum shear stress induced by a wave at the bed (τ_b) is given by the following formula:

$$\tau_b = \frac{1}{2}\rho f_w U_w^2 \tag{5}$$

with ρ being the density of water, f_w the wave friction factor, and U_w the maximum horizontal wave velocity. U_w is described by the relationship between wave height, gravitational acceleration, water depth, and wavelength. The wave friction factor f_w is determined by the bed conditions, which commonly depend on the bed roughness characteristics and the Reynolds number. In general, however, the flow over the bed is rough turbulent, so the Reynolds number can be neglected and the bed conditions characterized by the roughness height described by a representative length k_s. Several formulations exist to derive the wave friction factor f_w from the representative roughness length k_s. The calculations performed in **Paper III** use the formulation by Swart (1974), which has proven to be applicable for a wide range of roughness conditions. A detailed description of this formulation can be found in the paper. Vegetation, sediment characteristics, and bed forms are important factors related to k_s, about which there are limited information in the case of Lake Bolmen. Therefore, typical values from other studies (Hawley & Lesht 1992, Pascolo et al. 2018) in this field were chosen to describe the finer sediments believed to contribute to the color of the water. The main configuration for the shear stress calculation was set to $k_s = 2.0\ mm$. In order to analyze the sensitivity in relation to k_s, given the limited information available, two other configurations with $k_s = 1.0\ mm$ and $k_s = 3.0\ mm$ have been employed in sensitivity tests.

Since the critical shear stress τ_{cr} is difficult to determine for a specific sediment at the bed and the available information about the bed conditions of Lake Bolmen are limited, a range of values from 0.05 to 1.0 N/m^2, with a step of 0.05 N/m^2 has been employed. The quantification of shear stress on resuspension has been based on a duration approach, assuming resuspension to occur when $\tau_b > \tau_{cr}$.

As discussed earlier, the resulting bottom shear stress τ_b depends on several factors including the water depth. Even though it is assumed that resuspension may be limited to shallower parts of the lake, an alteration of the water depth of d = 1.0, 1.5 and 2.0 m has been employed, in order to analyze the effects of water depth. Furthermore, the impact of ice cover, as well as the reduction in the duration of ice cover due to rising annual temperatures, has been considered since waves can only occur during the ice-free season. Therefore, the duration of ice cover considered in the model was changed from the typical December to March period under present climate conditions for Lake Bolmen to no ice cover at all.

4.6 Numerical box-model to simulate long-term variability

The quantitative analysis and reproduction of transport patterns of NOM within a water body, such as a lake, has at the time of writing this thesis not yet been done. Most commonly used are mass-balance models to quantify transports in the aquatic system (including both catchments and water bodies as specific units), however, a limitation of such models is that they treat the lake as a closed system and do not account for internal transport. Hydrodynamic factors, such as tributary inflows or internal currents, can cause variations that require information on tributary flows as well as material transport observations to be accurately quantified. For Lake Bolmen such information exists for the main tributaries through actual measurements and as model results from the S-HYPE model created by SMHI. Figure 11 shows these main tributaries mentioned. However, there are several other tributaries that may discharge water to Lake Bolmen that are not modeled by S-HYPE. Often they only contribute water during high-runoff seasons and are therefore not shown in the figure.

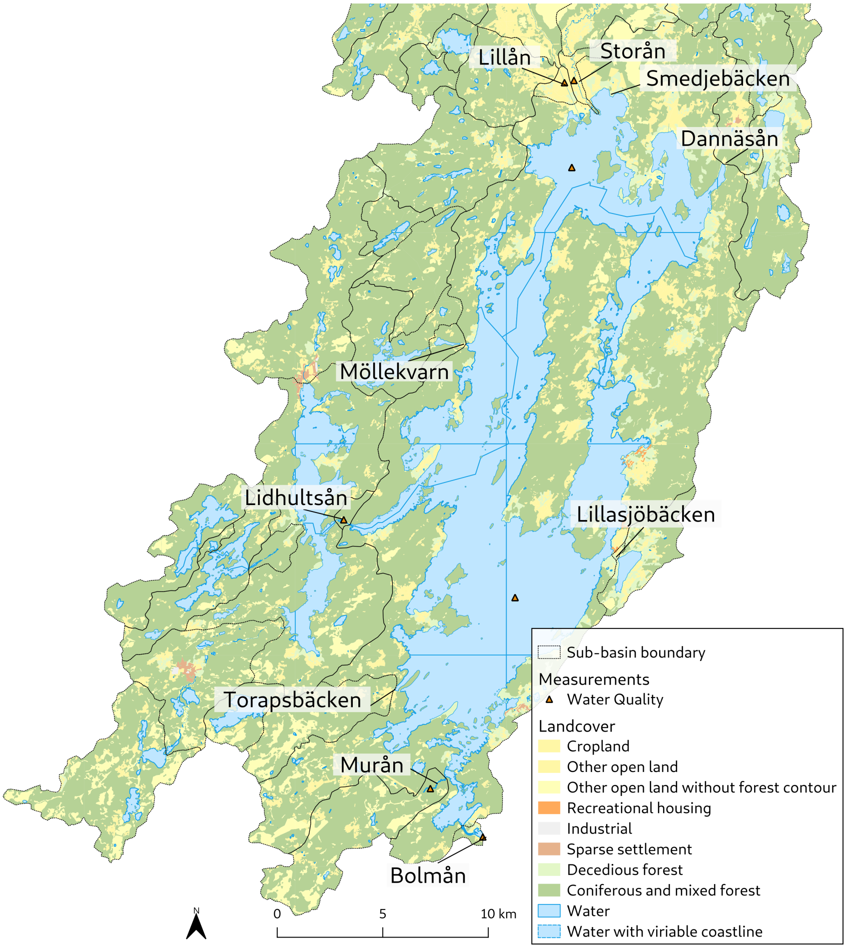

Figure 11: Larger and several smaller tributaries to Lake Bolmen as well as water quality sampling locations. The largest tributaries considering their average flow are Lillån, Storån and Lidhultsån.

The main aim of **Paper IV** was the creation of a more advanced, but still rather simple box model, that is able to reproduce the internal transport patterns of Lake Bolmen using information of the tributaries shown in Figure 11, including the observations of water quality in the lake. Therefore, the flow rates between the schematized different hydodynamics parts of Lake Bolmen, denoted as sub-basins (see figure 5a), were computed while considering the connections between these parts as bottlenecks constricting the flow. In contrast to Figure 5a, only five total sub-basins were considered (I - V), not including Kafjorden (VI). This has been done since the influence on the long-term transport patterns from Kafjorden are considered rather small due to its limited volume and short retention time, which has already been discussed in further detail in **Paper II**. Calibration and validation of the model was done using existing water level observations together with the measured outflows. Thus, the total outflow from the box-model considered in **Paper IV** represents the through-flow depicted with Q_6 in Figure 5a, including the flow through the hydropower station and the Bolmen tunnel reduced by the flow in the tributary Muràn.
The flows between the sub-basins through their constrictions were calculated based on the water balance equation for each sub-basin in combination with formulations of the energy equation for quasi-steady flow, assuming that the flow is driven by the water level difference between the sub-basins. In addition, a resistance coefficient following the formula by Dacry-Weisbach and the assumption that the cross sections can be described with a rectangular profile was introduced. The general formulation of the water balance equation for a typical sub-basin are as follows:

$$\frac{dh_i}{dt} = \frac{1}{A_i}(Q_{in} + Q_{np}) \tag{6}$$

$$Q_i = \sqrt{\frac{\Delta h_i}{\frac{1+fL_i/4H_i}{2gB_i^2H_i^2}}} \tag{7}$$

with h being the water level in a specific sub-basin, t the time, A the surface area of the sub-basin, Q_{in} the inflow to the sub-basin, which results from the sum of the in and outflows, including tributaries and possible upstream sub-basins, Q_{np} the influence of the difference between precipitation and evaporation. Q_i is the resulting outflow from the sub-basin i, where Δh_i is the water level difference between adjacent sub-basins. The geometry of a cross-sectional constriction is described by the length L_i, depth H_i and width B_i. The acceleration due to gravity is g.
Combined with the flow balance equations, a balance equation describing the color, or NOM content, in each sub-basin was formulated. Transport of NOM in and out from each sub-basin and considering the conservation formulation will change the color within each sub-basin. Therefore, the amount of NOM, and associated color, was treated as a concentration transported with the flow in and out of a particular sub-basin. Thus, it was assumed that NOM is directly related to the resulting color. Moreover, uniformity and

instant mixing within each sub-basin needed to be assumed, since available measurements were limited to only two locations within Lake Bolmen itself. Short-term variations are therefore not possible to resolve with the employed model, but seasonal, annual, and variations on the longer time scale may be reproduced. The general color balance equation for a typical sub-basin may be written as:

$$\frac{dc_i}{dt} = \frac{1}{V_i}(Q^i_{in}c^i_{in} - Q^i_{out}c_i) - c_i \sum_j k_j \tag{8}$$

with c_i being the concentration of sub-basin i, t the time, V_i the volume of the sub-basin, and c_{in} the concentration of the inflow. It is assumed that the material within each sub-basin is subject to decay caused by biological, physical, and chemical processors following a linear first-order reaction described by a coefficient k. The index j describes the different types of reactions present. Even though the formerly mentioned water balance equation employs the water levels as driving forces yielding the flows between the sub-basins, it is assumed that changes of the volumes are limited and can be neglected, which is assumed for equation 8.

With the above mentioned equations, it was possible to first calculate the in- and outflow of each sub-basin, and then couple the flow to the transported concentration. At start of the model steady state is assumed allowing the determination of the constriction flows with the water balance for each sub-basin. With the assumption that a water particle is either traveling along the western or the eastern side of the lake and loses the same energy during its passage, five unknowns with five equations needed to be solved. Hereby the inflow of the tributaries are given as well as the water level for sub-basin V. The friction coefficient K, appearing as the part of equation 7 represented by the term in the numerator, was adjusted through calibration using the measured water level in sub-basin V for validation.

Two main scenarios were studied to evaluate the usefulness of the box model. The first scenario focused on effects due to climate change, which have been proven to be related to increased color values as discussed in **Paper I**. Hereby, the flow from the tributaries as well as the color values entering the lake were modified with $\pm$ 40 %. Not implemented in the simulation were the effects on evaporation from temperature and decreasing ice cover, which was deemed small. The second scenario focused on the impact of possible mitigation measures within the catchment of the lake, such as wetlands. This kind of mitigation measures are further detailed in section 5.6 and **Paper VI**. Another investigated scenario were hydrodynamic changes within the lake itself, forcing the water along sub-basins I-II-IV to allow for longer retention times resulting in higher decay of color. However, this scenario is very unlikely to be realized as it will have severe effects on the lake ecology. It may also influence the productivity of the hydropower plant.

4.7 Forecasting and predicting levels of NOM with satellite data

Measuring the quality of surface waters is a time consuming and costly task. It may also involve considerable uncertainties, as measurement equipment may fail or create unreliable results. The advances in satellite technology and parameters measurable through them has increased rapidly during the last decades. Ever more capable computer systems, even on the personal level, make it possible to use these data and create models that may help to reduce the task of field measurements.

Paper v investigates the potential of forecasting and predicting the level of NOM in Lake Bolmen using data derived from satellite measurements. Here, forecasting is used in the sense of estimating the future magnitude of color, incorporating previous measurements into the independent variables, while prediction considers only the related variables without previous measurements. The ability of multiple linear regression (MLR) models were compared to more advanced ANN models. Satellite based data on precipitation[3], potential evapotranspiration (PET)[4], and enhanced vegetation index (EVI)[5] at sub-catchment level of Bolmen's catchment, as well as measurements of the A254 derived from Sydvattens self-monitoring program mentioned in section 4.2, have been used as input variables. In order to minimize the total amount of input variables, three new variables have been introduced aimed to represent spatial variability in the catchment. The so called CCOVs and ECOVs are based on the sub-catchment data on precipitation and the sub-catchment area which build two of the three variables. The third additional variable classifies the EVI based on the typical dominant values for specific land cover types. **Paper v** describes the setup of these three variables in further detail. It is important to notice that the actual sub-catchment data have only been used to calculate the catchment means, as well as the newly introduced variables, and have never been employed in the models itself. The maximum amount of input variables to the models is therefore 16.

In total 8 models (4 MLR and 4 ANN) have been employed using four different combinations of the mentioned input variables. Two of these groups were set up as 3-month forecasting and the other two as predictions models. The main difference between them is that the forecasting models accounted for former levels of the A254 withing their input variables and the predictions models are purely based on RS-based data. To account for the physical relationship between the input variables a range of specific lag times was introduced to each variable. This specific lag times were based on cross correlation with the A254 observations. A detailed description of the input variables can be found in **Paper v**.

[3]https://doi.org/10.5067/GPM/IMERGDL/DAY/06

[4]https://lpdaac.usgs.gov/products/mod16a2v006/

[5]https://lpdaac.usgs.gov/products/mod13q1v006/

5 Results and discussion

5.1 Variability of brownification

The variability in NOM concentration and its effects on the color of the water have already been shortly discussed in section 2.1 and the relationship to special features in the catchment area were emphasized.
The level of NOM and the yellowish-brown colored water in Lake Bolmen varies in time and space, occurring at different scales. These variations are driven by multiple factors, including changes within the catchment and internal processes within the water body itself (Björnerås et al. 2017, Kritzberg 2017). In **Paper I** the variation in NOM and color has been analyzed considering spatial, as well as seasonal and long-term aspects. **Paper II** on the other hand, focused mainly on variations on the time scale of weeks to hours. A spatial difference in the lake between north and south has been clearly shown, with commonly higher values of almost all water quality parameters in the northern part of Lake Bolmen. This circumstance has been related to the hydraulic characteristics of Lake Bolmen, which determine the mass transport in the lake. Reasons for the lower concentration of DOM and color magnitude in the southern part have been related to degradation through bacteria, as discussed by Tranvik (1998), and sedimentation as shown by Temnerud et al. (2014) and Svensson et al. (2015). The influence of solar degradation of DOM, as pointed out by Magyan & Dempsey (2021) has not been discussed in **Paper I**, but may also explain the lower values in the southern part. This as well as the composition of DOM should be analyzed further in future studies.
Seasonal variation of color and DOM in the lake were mainly driven by precipitation and resulting runoff changes within the year. It was shown that values of color usually peak during the late summer season, but no other significant seasonal pattern emerged from the analysis. Even though other seasonal peaks of color and NOM may be present, an analysis of them has not been possible because of the relatively low frequency (monthly records) of the underlying measurement data. Moreover, it could be shown that other water quality parameters follow a similar behavior as for example, pH and total phosphorous. A direct link between total phosphorous and increases in DOM cannot yet be explained. However, Huser et al. (2018) hypothesized that factors similar to browning are responsible for the fluctuations in phosphorus, including the long-term decline, which may be also true for Bolmen Lake (Borgström 2020). The seasonal variations in other water quality parameters are also discussed in **Paper I**. On the long-term scale the most noticeable increases besides water color discussed in **Paper I** are the increases in annual temperate and precipitation. Moreover, it has been shown that events with extraordinary high daily temperature as well as daily precipitation are on the rise. However, this has not yet shown any significant effects on the total discharge from Lake Bolmen (Figure 12). What could be shown is that the number of days with unusually high discharge values has increased with 50 % during

the last 70 years. This may be a result of increasing runoff due to higher annual precipitation and the fact that Lake Bolmen's water level has to be kept within a specific range (Forskningsstation Bolmen 2023).

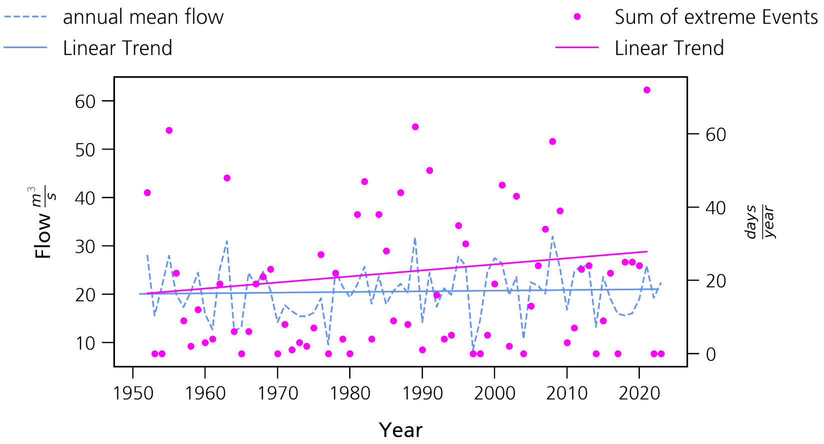

Figure 12: Annual average outflow and annual sum of extreme events (daily flow higher than 95 % of measurements) of Lake Bolmen measured at the hydropower plant in Skeen

Land use within Bolmen's basin is another factor that has changed significantly in the long-term perspective, showing increases in spruce afforestation, which have proven to be related to increases in browning (Škerlep et al. 2020). **Paper II** pointed out that the increased level of spruce cover alone may actually not be the single correlating factor to increases in DOC in the surface water, but also the underlying land use change due to draining of former wetlands through ditches is important. Also discussed was the correlation between increases in dead hard wood amounts and NOM. However, a decrease of water color after the storm Gudrun, which cleared large parts of forest in the catchment could not be explained satisfactory and further analysis is needed.

5.2 Flows in Lake Bolmen

Transport patterns within a lake on a short-term scale are mainly determined by external forces, such as the wind, and may relate to changes on the event scale. Long-term patterns, on the other hand, can usually be connected with large-scale currents and the movement of water through the lake. Such large-scale currents are the result of the relationship between the tributaries and outflow of the lake and therefore governed by the through-flow.
The long-term transport patterns have partly been analyzed in **Paper I**. Due to Lake Bolmen's complex shoreline configuration and bathymetry, a sub-basin division of the lake was introduced. Figure 1 shows this sub-basin configuration, with the difference that sub-basins V and VI have been considered as one sub-basin in the context of **Paper I**. The sub-basin VI shown in figure 1 was subsequently introduced as a separate entity in connection with the analysis and results obtained in **Paper II** because of its importance regarding water quality changes at short time scales at the intake to the Bolmen tunnel. The connections between the five sub-basins were considered as rectangular constrictions, comparable to open channels, with cross sections based on the geometry derived from bathymetric maps. Thus, equations based on open channel flow conditions have been used to estimate the flows between the basins. The frictional losses were determined according to the Darcy-Weisbach equation based on the constriction geometry, using a constant friction coefficient, and including some minor losses. Literature-based standard values were used for the coefficient in the Darcy-Weisbach equation and for the minor loss coefficients.
The gained information of the sub-basin flows have been used to calculate the respective time of water in each sub-basin. Given the results it can be shown that approximately 80 % of Lake Bolmen's water is transported along the western part of the lake under all inflow conditions. In addition, the retention times show that a particle moving along the eastern part of the lake would spend an additional time of about 5-8 months in the lake compared to the western side (7-14 month retention time), when the internal mixing of the lake is neglected. This indicates that long-term transport within Lake Bolmen is dominated by the western part of the lake.

5.3 SWAN wave model and bottom shear stress

The main objective of **Paper III** was to investigate the wave climate of Lake Bolmen with respect to hypothesized resuspension of formerly settled NOM. Furthermore, the effects of a decreased ice cover period, caused by rising annual temperatures, was investigated with implications for the general wave climate and induced bottom currents, affecting resuspension.

The results of the employed SWAN model, which computed the wave climate for Lake Bolmen for the 26 year period between 1996-2021, are the main input to the shear stress calculations, as described in section 4.5. Even though the pressure gauge measurements used to calibrate the SWAN model contain different uncertainties, such as the issue of resolving the actual wave period due to too large deployment depth, the results of the SWAN model are considered satisfactory. Analysis of the wave heights show reasonable agreement with the measurements (see Figure 13).

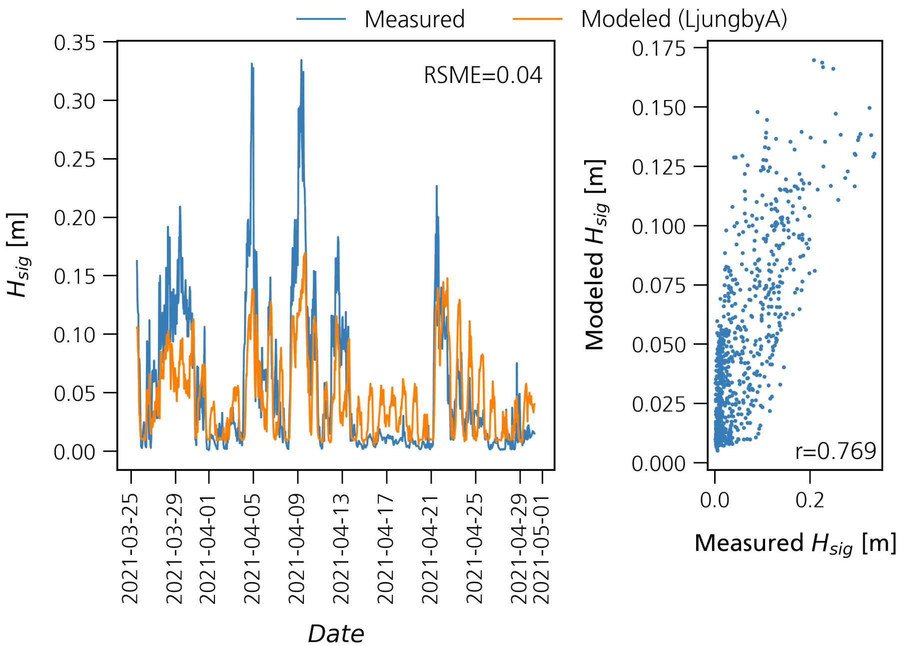

Figure 13: Comparision between measured and modeled wave heights for the location Bakarebo south of Bolmsö island.

However, in general the large wave heights are underestimated and the small wave heights slightly overestimated. This issue could not be resolved using different coefficient values for bottom friction, white capping, and breaking during calibration. As previously stated, the measured wave periods show less satisfactory result and were therefore not emphasized in the model calibration and validation. However, it is assumed that the wave period calculated by SWAN are representative, as it is a widely applied modeling software that has been shown to give satisfactory results in many other studies (e.g., Cavaleri et al. 2007, Moeini & Etemad-Shahidi 2009, Nicolodi et al. 2013, Seibt et al. 2013). Figure 14 shows the SWAN model results in terms of wave roses for different locations and a snapshot of an extreme event during the severe storm Gudrun in 2005 for reference.

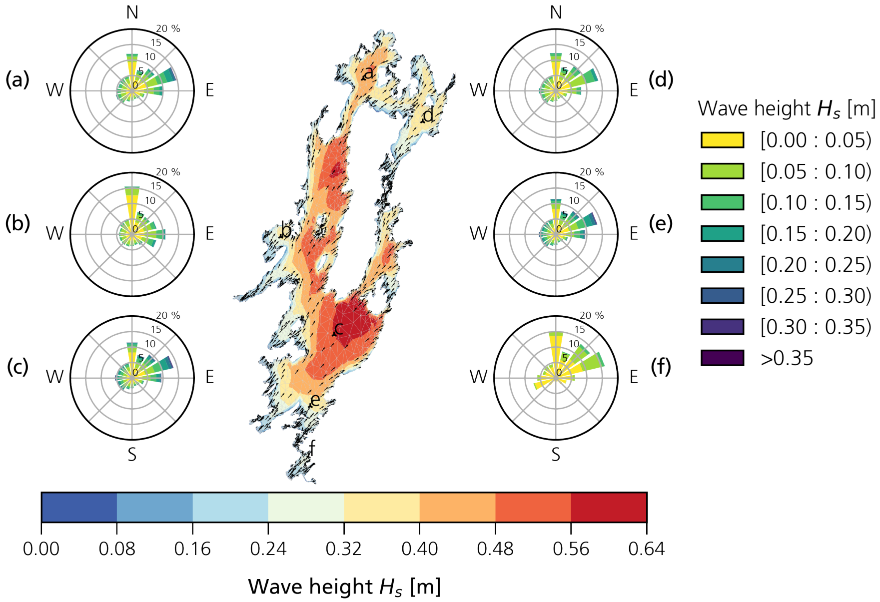

Figure 14: Result of the SWAN wave model. Circular plots show the wave roses for the locations denoted with letters (a) to (f) in the central figure. The contours in the central figure illustrate the wave conditions in Lake Bolmen during the storm Gudrun on the 9th of January at 3 o'clock.

During the modeling conducted in **Paper III** two different sources regarding wind data sets have been employed, producing slightly different results. One data set was based on local measurements from a meteorological station in close proximity to Lake Bolmen and the other one originated from the ERA5 model created by the European Center for Medium-Range Weather Forecasts (ECMWF). Even thought the wave model using the ERA5 data as wind input could achieve better agreement for large wave heights, the overestimation of small wave heights was much more pronounced. Thus, for calculation of the shear stress it was decided to use the model results using data from the meteorological station in close proximity.

Shear stresses and effects of ice cover changes

Section 4.5 discussed the theory around the critical shear stress τ_{cr} that is required to initiate material transport on the bed. **Paper III** aimed to analyze the possibility of resuspension by looking at the excess shear stress, which is the shear stress at the bed initiated by the wave motion over the critical shear stress. As discussed earlier, there are no measurements available regarding bed conditions, implying that it is difficult to estimate relevant τ_{cr} values for Lake Bolmen. Instead a range of values were implemented and the duration for which the bed shear stress exceeded a specific critical shear stress was determined.
Depth is one determining factor regarding the transfer of energy to the sediment layer at the bed, since the wave energy decreases with depth. The results show a relatively high sensitivity to water depth, where possible events of significant resuspension may only occur at shallow areas below 1.5 m. If the water depth is larger than 2 m, the annual hours of possible resuspension are small, since only major storms may initiate movement at the bed. Figure 15 shows the effect of water depth on the annual mean duration of exceedance for different critical shear stresses at the location M2 Sunnaryd on the western shore of Lake Bolmen.

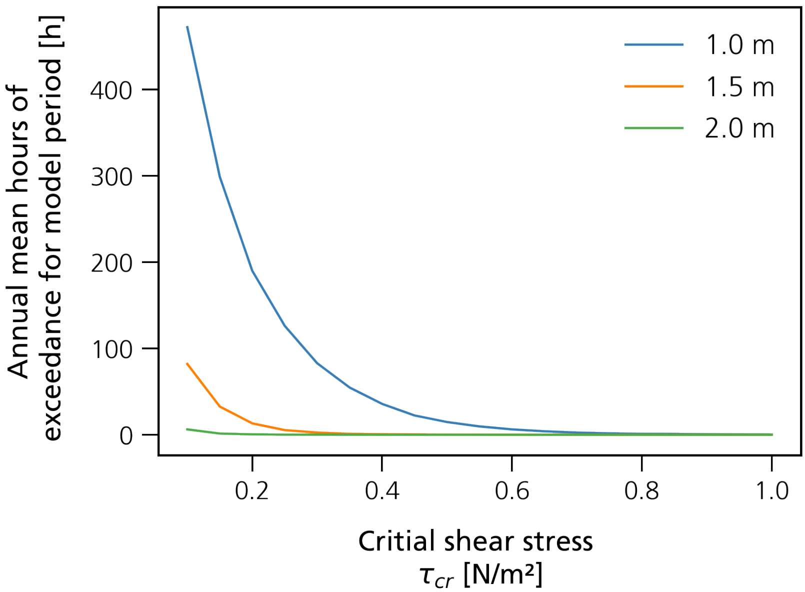

Figure 15: Annual mean duration of exceedance as a function of critical shear stress for different water depth. Calculated for the location M2 Sunnaryd on the western shore of Lake Bolmen.

The calculated exceedance duration also shows a marked sensitivity to the roughness of the bed material, since it affects the shear stress at bed induced by the waves. Figure 16 shows the calculation results varying the bottom roughness for a water depth of 1 m. The rougher the material on the bed is, the higher the possibility of resuspension. The results presented in **Paper III** also discuss how the bottom roughness, as well as the effects on the possibility of resuspension, may vary with location. At locations that are more exposed to southerly and south-westerly winds, resulting in a more energetic wave climate, the possibility of resuspension is much higher.

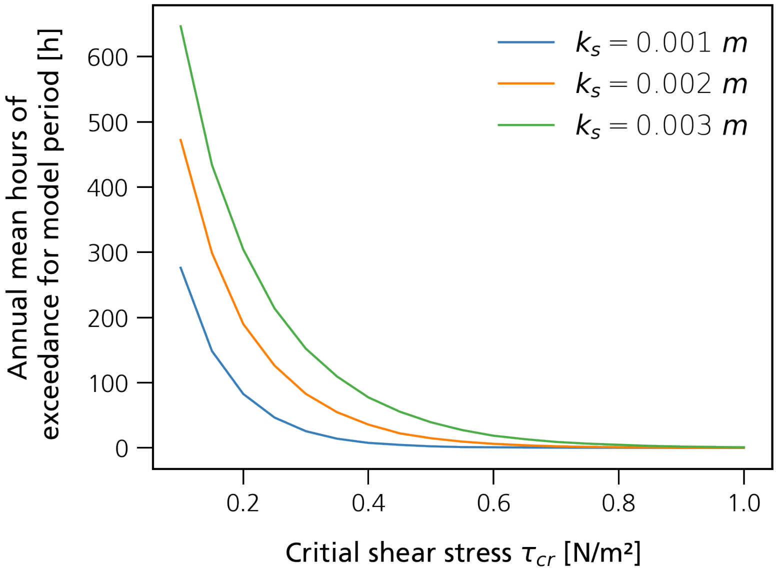

Figure 16: Annual mean duration of exceedance as a function of critical shear stress for different bed roughness. Calculated for the location M2 Sunnaryd on the western shore of Lake Bolmen.

The period Lake Bolmen is covered with ice shows a decreasing trend during the last decades (see Figure 17) as a response to increasing annual temperatures related to climate change. The typical period for ice cover on Lake Bolmen has been between December and March, which is also the period during which increased wind speeds occur with a higher frequency. Already in **Paper II** it was hypothesized that a decreasing period of ice cover may effect the possibility of resuspension of formerly settled material. The results presented in **Paper III** clearly showed that a decreasing ice cover will increase the possibility of resuspension (see figure 18).

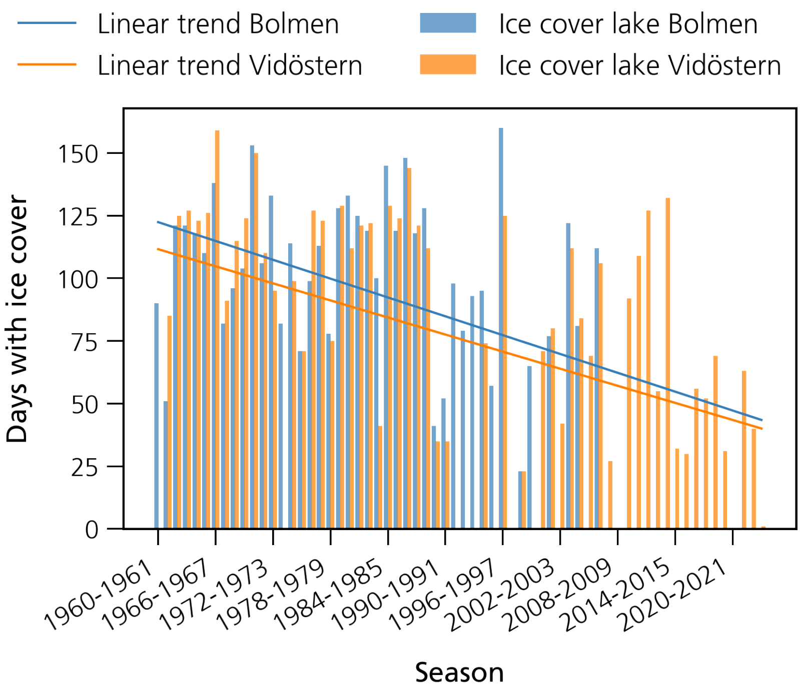

Figure 17: Seasonal accumulated days with ice cover for Lake Bolmen and Lake Vidöstern, which is a lake in close proximity to Lake Bolmen.

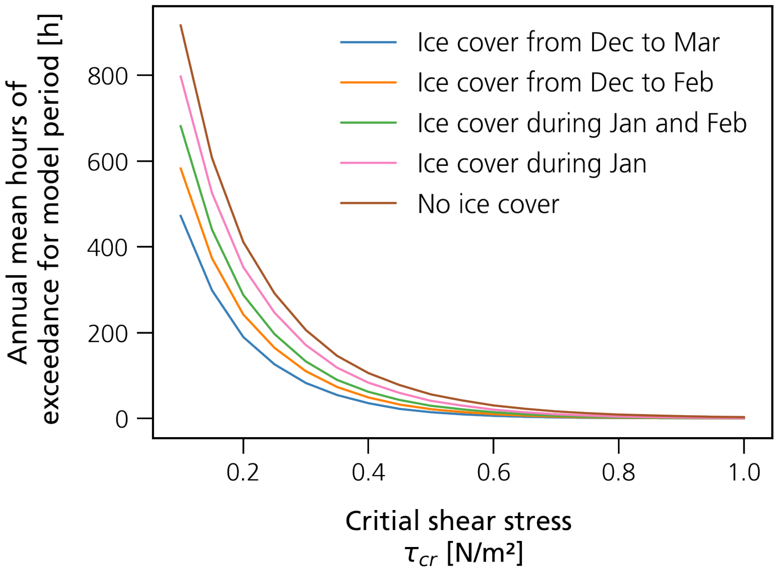

Figure 18: Effects of a decrease in the ice-cover period on Lake Bolmen on the exceedance duration regarding the possibility of resuspension for different critical shear stresses.

5.4 Hydrodynamic long-term box model

As described in section 4.6 different scenarios were applied in the box model to simulate the influence of climate change and various mitigation measures, focusing on their effects regarding the water color in the lake.
The first scenario simulated the influence of climate change, which is assumed to have large effects on the tributary flows. In order to cover a wide range of possible changes, the mean flows have been varied with ±40 %. Figure 19 shows the effect on the normalized mean concentration in two sub-basins (the most northern and southern ones), where a factor 1.0 presents the current state.

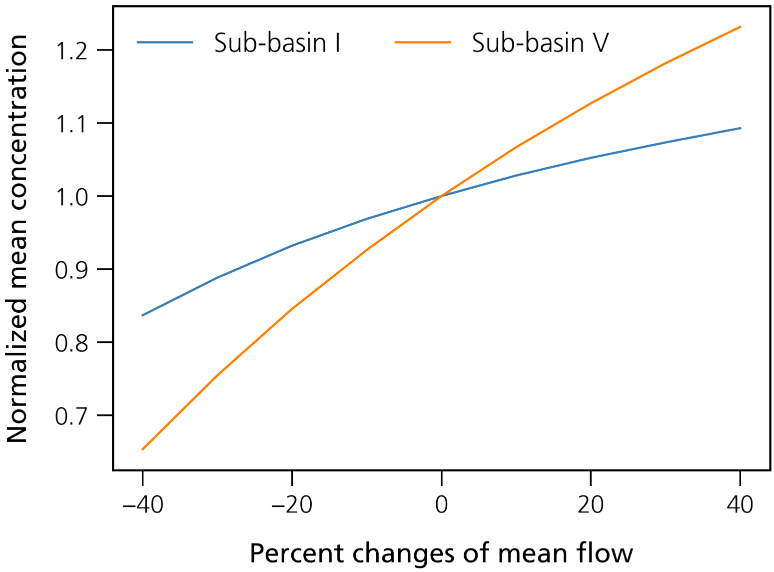

Figure 19: Normalized mean concentration representing water color in sub-basins I and V as a function of relative changes in all tributary inflows.

The results show that with an increased flow of 40 % the water color will increase with about 10 % and with a decreased flow of 40 % the water color may decrease with 15 % for the sub-basin I. For the larger sub-basin V these values are higher with an approximate increase of 20 % in water color and a decrease of up to 25 % for the same respective changes. Considering the current development of the climate, this would indicate that during the summer the water color within the lake may decrease compared to the current state. However, during the seasons with higher precipitation and resulting larger runoff, the color is likely to increase above the present value. Thus, seasonal variations are likely to increase in the future.
The second scenario focused on the possible introduction of mitigation measures inside

the catchment, affected the transported NOM and resulting water color in the tributaries. To simulate this condition the inflowing concentration to sub-basin I in the model from Storån and Lillån was changed with up to -50 % considering the current state. A decrease in water color entering into sub-basin I will reduce the resulting color in sub-basin V of up to 25 % (see Figure 20).

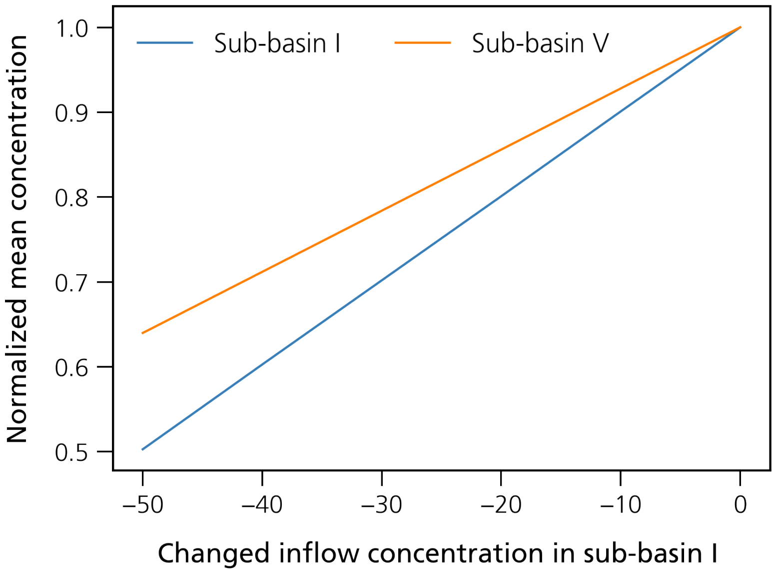

Figure 20: Normalized mean concentration representing water color in sub-basins I and V as a function of relative changes in color for the tributary inflows to sub-basin I (Storån and Lillån).

Finally, another mitigation measure was simulated, modifying the internal flow distribution in Lake Bolmen. In this case, the cross-sectional area of the constriction between sub-basins I and III was decreased to force the water to move a longer way along the eastern parts of Lake Bolmen, increasing the retention time. However, this scenario is not likely to be implemented considering costs and environmental impacts. Moreover, the effects were not very significant, where a decrease in the cross-sectional area with 75 % only yielded a reduction in the water color for sub-basin V of approximately 15 %.

5.5 Streamline water quality measurements with help of satellites

The main aim of **Paper v** was to evaluate the possibility of forecasting and predicting the level of NOM at the southern part of Lake Bolmen. As mentioned in section 4.7, forecasting is used in the sense of estimating the future magnitude of color, incorporating previous measurements into the known variables, whereas prediction considers only the related variables without using previous measurements.

In order to compare the model results to measured observations and relate them to each other, a set of statistical measures have been used, namely Pearson correlation coefficient (PCC), root-mean-square error (RMSE), and Nash–Sutcliffe model efficiency coefficient (NSE). Each of these measures provides specific information about the agreement between measured and modeled data. PCC and RMSE are more common in other applications, whereas NSE is typically used to assess hydrological model performance. Although the NSE is commonly used as a statistical goodness-of-fit measure in hydrology, its flexibility and applicability has been demonstrated in other fields (McCuen et al. 2006).

In general the employed ANN models always achieved higher values for the PCC than the MLR models, with the highest being 0.53 for the MLR prediction models and 0.63 for the ANN prediction models. The forecasting models achieved even higher results with 0.62 for MLR and 0.74 for ANN. The results are similar considering the values of RMSE. However, here the values for ANN are lower, where lower values are considered better when comparing results with the RMSE. The ANN models achieved better results regarding the NSE for all setups. Also in temporal evaluation, the ANN models could outperform the more common MLR models and achieve better agreement with the measurements (see Figure 21).

As discussed in section 4.7, each input variable was introduced to the model with a specific range of lag time based on cross correlation with the A254 measurements. This was done to account for the physical transport time within the catchment and lake system. The MLR models tend to select input variables with much higher lag times than the ANN models. Moreover, all MLR models setups, except the forecasting model purely based on former observations of A254, put a large weight on catchment averaged EVI data. The ANN models on the other hand, had the largest weight on input variables related to precipitation, which is considered as one of the main physical transporting mechanisms as it results in runoff. The connection between precipitation, runoff, and increased NOM content in the water has also been shown in **Paper i** and **Paper ii**. It is important to notice that due to the 8-day time-step employed during the model setup it has not been possible to resolve variations smaller than this time-step, even though observations of A254 are available at an hourly time-step.

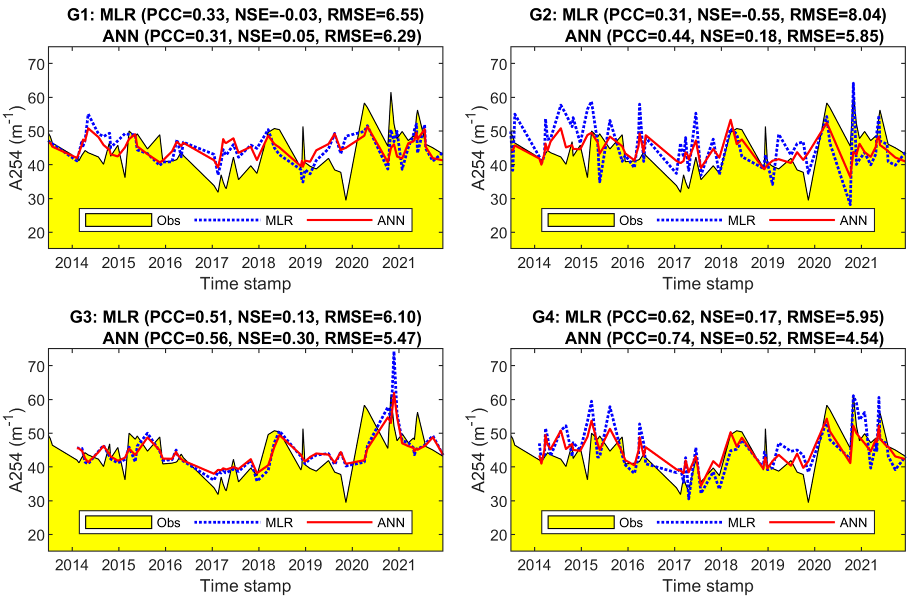

Figure 21: Time series comparison of one fold between the model results and observations for the eight different models employed.

Overall, the findings of **Paper v** demonstrate that, although the accuracy is lower than anticipated, it is still feasible to predict A254 and the associated color of a surface water body using RS-based data. The extra work required to build an ANN model may not be worthwhile the results when looking at a 3-month forecast, based only on prior A254 measurements, and the marginally poorer accuracy of the MLR model might be adequate instead. When RS-based data are included in the forecasting setup, the performance of the developed ANN model improves and its capacity to anticipate peak values increases noticeably. In-situ measurements will continue to be the best option until more accurate models are available, because none of the models presented can reach an accuracy that can be used to improve the drinking water treatment process in practice from the present perspective. Moreover, in-situ measurements of water quality are a necessity to further improve models such as the discussed ones and to ensure their accuracy. Thus, such models will most likely never replace in-situ measurements entirely, but may help to lower the measurement frequency. The presented model results of **Paper v**, which is one of the first approaches of this kind, are still useful to estimate long-term trends and can be employed to give a better picture of the near future, which will help to adjust large scale operations considering drinking water treatment. Additionally, future research can build on the gained knowledge and may include other RS-based parameters to present the physical connections even better.

5.6 Wetlands as multi-functional mitigation tools

Wetlands have the ability to retain, absorb, and transform nutrients and NOM through various biophysiochemical processes and act as a natural filter. Therefore, the construction of artificial wetlands is considered as a useful mitigation measure against future brownification. Moreover, their ecosystem is considered to increase the biodiversity locally (Hansson et al. 2005). However, wetlands are influenced by a manifold of external processes, which may determine these abilities. Thus, the evaluation of their performance as a multi-functional mitigation tool is not only important considering their preservation and restoration, but also in the construction of new wetlands. The main objective of **Paper VI** was to evaluate the multi-functional properties of wetlands and their applications as cost-effective tools to reduce nutrient and NOM loads to the receiving waters.

The sampling of water quality and the investigation of the nine wetlands in this study, all with different size, form, and catchment area, showed that not all wetlands are able to reduce nutrients, TOC, and water color to the same potential.

All wetlands showed a better ability to reduce TN than TP and water color, and did so most efficiently during the summer. The reduction of TP was commonly the highest during summer and fall, with significant variability between the wetlands. This may be explained by the size and the place of construction. The investigated wetlands are rather small (< 5 ha) and in close vicinity to, or constructed on, agricultural land that is prone to release legacy phosphorous from the soil when flooded (Kadlec 2016). The small size negatively affects the retention time of the wetlands, so that phosphorous does not have enough time to settle when moving through the wetlands (Johannesson et al. 2015, Ulén et al. 2019). Large seasonal variations have been observed considering the removal of TOC and water color, and the most efficient seasons were found to be summer and fall (see Figure 22).

The variability between the wetlands was even higher considering their ability to remove TOC and water color, which could be related to the catchment soils. Catchments with a high share of peat resulted in less efficient removal of TN, TOC, and water color. Peat is know for leaching carbon and contributing to the increase of NOM in surface waters, increasing the TOC concentration and resulting in a browner color (Nieminen et al. 2021). This leaching, however, could decrease with time and reach stable conditions when the wetlands get older (Lundin et al. 2017). The investigated wetlands were mostly younger than four years, which may not be sufficient to reach such stable conditions, which could explain the variability in space and occasionally occurring pulses of higher TOC and color concentrations.

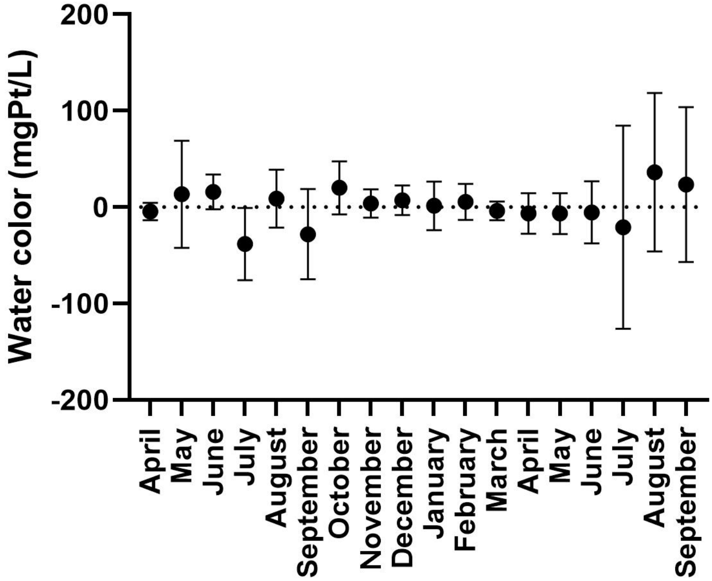

Figure 22: Annual variability in efficiency of removing water color within the sampled wetlands. The wetland constructed on peat land has been extracted from this analysis, since it gained less efficient results.

Another factor, which influenced the ability to take up nutrients, TOC, and water color, could be related to the land use in the catchment. Wetlands with catchments containing more than 25 % of agricultural lands showed a higher potential to remove TOC, and water color. On the other hand, wetlands located in a catchment with more than 25 % coniferous forest performed worse in reducing TN, TOC and water color. The characteristic of higher forest content in the catchment and increased brown water color has already been mentioned in **Paper I** and in other research (Finstad et al. 2016, Škerlep et al. 2020).
Paper I and **Paper II** showed that the increase of NOM in Lake Bolmen is related to runoff conditions, with higher runoff resulting in increased NOM loads and higher color values. This behavior could also be observed in the study performed in **Paper VI**, where catchments after high runoff events showed increased load of TN, TP, TOC, and water color. On the other hand, very low or no runoff resulted in a dry-up which decreased the potential to remove nutrients and NOM in the wetlands. Also, a release of phosphorus was observed after the re-wetting of dried-up wetlands.
The results of **Paper VI** show that wetlands may be useful as potential multi-functional mitigation tools, reducing both nutrients and NOM as well as brown color in the waters. However, several factors need to be considered when wetland, either restored or newly constructed, should be used to counteract future increases in NOM and reduce nutrient loads. Catchment conditions should be investigated prior to restoration or construction, preferably aiming at lower share of coniferous forest and possibly low amount of peat within

the catchment. Moreover, it is important to reconstruct or build new wetlands in a way that the hydrological design targets conditions where they never run dry and allow for a reasonably long retention time under both wet and dry circumstances.

6 Summary and Conclusion

Increasing the knowledge and understanding of the brownification process and the physical interactions within the catchment and lake environment was the overarching aim of this thesis work. The data collection, analysis, and contextualization provided the possibility to understand catchment-related processes in greater detail. Complementary hydro-physical modeling and calculations allowed for a better understanding regarding transport patterns and mechanisms connected to increased NOM loads in surface waters, using Lake Bolmen as the main study area. Moreover, the ability of alternative monitoring and modeling systems, using knowledge in connection with ANN modeling and RS-based data, as well as the capacity of natural mitigation measures, were investigated.

Paper I focused on analyzing water quality data related to catchment changes such as land use, precipitation, and runoff over a 31-year period. A water balance model, including the NOM transport, was developed. It has been shown that long-term variations and increases in NOM and related water color are mainly driven by climate change and precipitation patterns, which determine the runoff patterns. Increasing volume of spruce forest is another determining driver. However, land-use changes connected to the industrialization of forest may also be important. It was noticed that there is a correlation between the quantity of dead forest and color. The larger the amount of dead forest, the more intense the color becomes. However, the overall color decreased after the significant changes that occurred in the catchment caused by the storm Gudrun in 2005, as the trees that fell during the storm were quickly removed from the catchment.

The studies in **Paper II** took a more detailed approach and variations on the short-term scale, in days to weeks, have been analyzed. A strong focus was put on the connection between the sub-catchment of river Murån and the sub-basin downstream of the main lake, known as Kafjorden, as well as on the water quality changes at the inlet to the Bolmen Tunnel. In **Paper I**, it was previously noted that River Murån is a tributary with exceptionally high levels of NOM loads. It was shown that changes appearing in the sub-basin Kafjorden affect the water quality at the tunnel inlet on at time scale of days to weeks, whereas changes on the long-term scale shown in **Paper I** are related to Lake Bolmen and its catchment. Another focus was put on the connection between the inlet to the Bolmen tunnel and the water quality at the Ringsjö WW. Here, it was concluded that the tunnel affects the water quality at the WW with a time delay of about 7 days, but further investigations should be done considering sedimentation in, and groundwater intrusion to, the tunnel.

In **Paper III** the formerly hypothesized resuspension of sedimented NOM has been analyzed using a wave model and shear stress calculations at the bed. The wave model simulations were made using the widely acknowledged SWAN model, which was calibrated and validated based on pressure gauge observations collected during three field sampling periods. In addition, the effects of climate change and the effect of a decreasing ice cover period on Lake Bolmen were investigated. The results showed that resuspension is primarily an issue in shallower areas. It also increases with the roughness of the bed material. It was shown that increasing air temperatures, and the resulting shorter ice cover period, lead to more frequent resuspension events, which can result in more frequent short-term peaks of NOM and raise the water color to higher values at certain times of the year, especially during winter.

The main aim of **Paper IV** was the reconstruction and quantitative analysis of transport patterns of NOM and connected increased water color in Lake Bolmen. Therefore, a relatively simple box model was developed. Thus, the lake was separated into five different sub-basins, based on topographic and bathymetric characteristics. The hydraulic part of the model was calibrated and validated using water level observations. Measurements of the water color within the lake were used to calibrate and validate the predictions from the color concentration balance equations, including first-order reaction terms. Even though the employed input data were limited, the model was able to achieve satisfactory results considering long-term changes on the scale of seasons to decades. Two different scenarios, focusing on the possible effects of climate change and introducing mitigation measures, were applied in the model, providing insights to possible outcomes. A decrease of inflowing water, as a result of changes in precipitation patterns within the catchment, will result in lower color magnitudes within the lake, and vice versa. A 50 % lowering of the color level in the inflow to the most northern sub-basin of the lake (I), which has the tributaries with the highest color values, as a result of introduced mitigation measures within the basin, may lower the mean concentration with up to 35 % in the most southern sub-basin (V), compared to present-day conditions.

The aim of **Paper V** was to analyze the ability to simulate the level of NOM through a combination of RS-based data and advanced data transformation tools, here ANNs. The A254 was used as a proxy for NOM in this study. It was tested for both forecasting and prediction, where forecasting describes the simulation using former observations of A254, whereas prediction is only based on RS-derived independent data. Despite falling short of the expected level of accuracy, the outcomes of the study successfully demonstrated the potential of utilizing RS-based data to improve future water quality measurements and to help optimize treatment. As a pioneering method, the research was able to achieve satisfactory outcomes and identify valuable insights for future investigations in this field, such as the inclusion of RS-based data that are able to better describe runoff as well as other variables related to the process of NOM transport in the basin.

As one possible mitigation measure, wetlands have been investigated in **Paper VI** considering their ability to reduce nutrient and TOC loads. Their multifunctional potential, which includes land use that promotes biodiversity and improves surface water quality, has been shown. The wetlands studied showed a much higher efficiency to remove phosphorous, nitrogen and TOC during the warmer months of the year, implying that their importance as mitigation measures may increase with a changing climate with warmer temperatures during the winter. It was also demonstrated that locations with a high peat content and a dry out during the summer have a negative effect on the efficiency of wetlands, therefore special consideration must be given to their location and hydrology.

7 Limitations and future research

This thesis work focused on the complex aquatic ecosystem and its interaction with basin properties (i.e., catchment and lake), and as a necessity in describing the analyzed interactions, limitations had to be made.

First and foremost, simplifications of the basin complexity are required. It is not feasible to include all interacting processes from the largest to the smallest scale in a single study. Therefore, analysis of, for example, the microbiology or fungi interactions, has not been performed. Moreover, no detailed analysis has been carried out considering the pedology and geology of the basin. Even though it has partly been shown in **Paper VI** that specific soils are a determining factor, this analysis was not included. It is assumed that especially the interactions between the soil-fungi, the fungi-microbiology, and the microbiology-water phase are affecting and influencing the NOM characteristics, such as solubility, transport and composition. These effects may also change the microbiology composition entering the WW, which could influence the treatment from a physical, chemical, and biological perspective. Future research is needed to analyze this matter further and give better insights on interactions and governing processes.

Secondly, it was not possible to include all tributaries of Lake Bolmen into the hydrological and hydrodynamic analysis. Many of them are very small and only contribute on seasonal scale, some of them do not even have names. Tributary discharges used in, for example, the calculation done in **Paper IV**, were based on a large-scale hydrological model, which in itself contains uncertainties. Most of these uncertainties are the result of limits regarding measurements and background information. The interaction between groundwater and surface water has been neglected entirely, as sufficient measurements of the groundwater flow are not available in this region. This simplification may influence the obtained outcomes especially on the seasonal scale and the inclusion of this parameters could help to gain more satisfactory results. However, to be able to include all tributaries and the groundwater interactions, more measurements are needed on extensive spatial and temporal scales, although the feasibility to do this is questionable. During the time of writing this thesis, Sydvatten AB is making an effort to measure the flow in a number of tributaries on a more detailed basis, which will help to create a better balance model for Lake Bolmen. This knowledge will be included in a future version of the box model presented in **Paper IV**. Additionally, projects extending the knowledge regarding groundwater from a quantitative and qualitative perspective have started and will be conducted in the future.

The eastern part of Lake Bolmen, in particular the sub-basins II and IV as shown in Figure 5a, are less well researched and water quality measurements exist only to a very limited extent. The same applies to the change of water quality through the water column of Lake Bolmen, that is, the vertical variation from the surface to the bottom. In **Paper I** it is was briefly discussed that the water quality shows differences with depth in the lake, but no detailed analysis could be performed due to limited observations in time and space. Thus, calculations made in **Paper iv** assumed an instantaneous mixing within the water column and an even distribution in space for a particular sub-basin. To allow for more detailed analysis, especially the distribution of NOM within the water column more measurements are necessary. Such data would allow for more detailed models. Also in this particular case, Sydvatten AB has initiated measurements of the water quality through the water column within the sub-basins I to V of the lake. These observations will help to further develop the model described in **Paper iv** and most likely allow an extension to a more advanced 3-D model. Due to limited time resources, the currently existing measurements could not be included in this thesis work.

NOM is a complex mix of different organic substances and its composition can vary over time and is influenced by its environment. Different compositions have different effects on the microbiology as well as the drinking water treatment process (Slavik et al. 2021). However, this has not been considered within the thesis and the amount of NOM in the water body was commonly related to specific measurements of absorbance of light or similar, as a strong correlation has been shown to exist between them (e.g., Cascone et al. 2022). Even though this circumstance may involve some uncertainties considering the outcomes of all papers, influences are assumed to be minor at the scale analyzed.

In **Paper i** the influence of dead wood within the basin was shortly discussed and **Paper ii** mentioned the influence of ditches. Future research should further look into this connection and clarify how the contribution of NOM through ditches may be driven by groundwater interaction, as well as how the amount of dead wood within the basin may contribute. Such knowledge will also help to better investigate possible mitigation measures such as wetlands discussed in **Paper vi**, and allow for communication with and eduction of land owners in particular.

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