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Said Al-Kharusi, Enass

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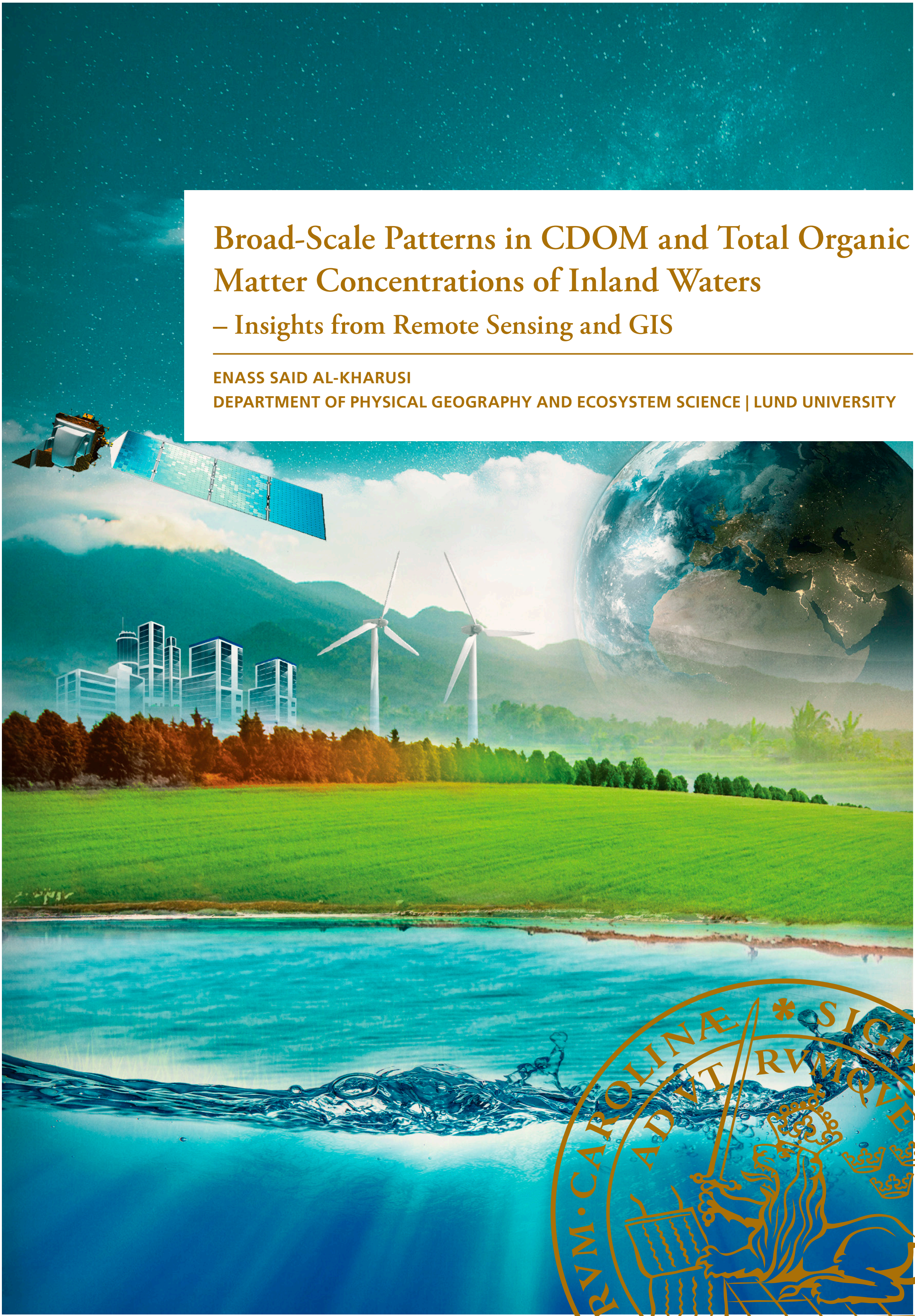
LUND UNIVERSITY

PO Box 117
221 00 Lund
+46 46-222 00 00



Broad-Scale Patterns in CDOM and Total Organic Matter Concentrations of Inland Waters

– Insights from Remote Sensing and GIS

ENASS SAID AL-KHARUSI
DEPARTMENT OF PHYSICAL GEOGRAPHY AND ECOSYSTEM SCIENCE | LUND UNIVERSITY

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Abstract
The rise in CDOM (coloured dissloved organic matter) is likely to be relatively more pronounced in remote northern regions. However, there is a lack of monitoring to confirm this. For this reason, there is a strong incentive to develop remote sensing-based methods to map CDOM in lakes across broader geographical scales and to include geograghic contex in such analysis. There is a lack of understanding of the mechanisms behind changes in water colour (i.e. CDOM) at large scales. The CDOM variations could be due to varying drivers, such as climate and landscape patterns or catchment features. This means that currently, we do not know the extent to which aquatic ecosystems need conservation efforts, such as management of the surrounding vegetation, to prevent CDOM leakage. Thus, there is need to better understand the drivers behind CDOM changes in inland waters.

Over the last few decades, remote sensing technologies and methods have developed dramatically for terrestrial ecosystems. Coupled with the broader availability of remote sensing data, free access to different data sources and the increased resolution of satellite platforms, remote sensing technology now has a significant impact on land monitoring. Due to the increasing demand for high-quality remote sensing data, the technology continues to improve, which makes remote sensing critical for reducing time and funding costs. Similar to these advances in terrestrial remote sensing, there is an increasing potential to provide information about inland waters by using remote sensing. For instance, recent advancements in designing remote sensors, such as the Landsat 8 operational land imager (OLI) and Sentinel-2 multispectral instrument (MSI), have solved past radiometric sensitivity issues and provide high spatial resolution. This thesis explored CDOM patterns on spatial and temporal scales. The overall aim was to investigate the capabilities of remote sensing (RS) and geographic information systems (GIS) to extend CDOM patterns from a regional to a broad scale. Different study sites in Europe, mainly Northern Scandinavia, including large numbers of lakes and rivers, were tested on different scales.

The results shows how climate changes (from wet to dry) can result in a combination of changes in hydrology, vegetation type and productivity, which can lead to intra-annual variations in the CDOM of recipient waters. It is also shown that drought can temporarily decrease values of CDOM in boreal lakes. In addition, it is demonstrated that combining remote sensing and GIS tools is an effective way to reveal the impact of different catchment parameters and morphometry on lake CDOM concentration. Moreover, the thesis shows that utlizing long-term remote sensing records of CDOM from the last few decades is a successful approach to fill the gaps of the missing lake data from in situ assessments. Finally, the results helped to explore links between water browning and the organic matter degradation rates in temperate European rivers at a continental scale. In conclusion, this thesis demonstrates the pogential use of remote sensing for mapping CDOM in a wide range of inland waters that are situated in complex, inaccessible regions that are not well-monitored.

Key words: Inlandwater ,Remote sensing, Sentinel-2 MSI, CDOM, GIS, climate change.

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Dedication

THIS THESIS IS DEDICATED TO MY WARM LAND
"SULTANATE OF OMAN"

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Acknowledgments

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" الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ "

Enass Said
Lund, Sweden, April 2021

بسم الله الرحمن الرحيم

الحمدلله رب العالمين على جزيل فضله وعطائه، الحمدلله الذي هداني السبيل، الحمدلله على توفقيه ورشاده بالإجتهاد في طلب العلم، الحمدلله الذي من علي بالصبر في تحصيل العلم من أهله.

"اللهم تقبل مني هذا الإجتهاد في طلبه ونتائج تحصيله خالصا لوجهك الكريم، وا كتب له القبول و النفع"

بادىء ذي بدء، أود أنا أعرب عن خالص وعميق شكري وتقديري لوالدي العزيزين لما قدماه لي طيلة حياتهما من بذل وعطاء، فلهم الفضل بعد رب العالمين لما أنا عليه اليوم.

أمي الحبيبة،،

لقد كان لكِ الأثر البالغ في نشأتي ورسم طموحي ومعالم مستقبلي الذي أنا أعيشه اليوم، بحرصك الدائم على متابعة مسيرتي التعليمية منذ الصغر أنا وأخوتي. كنتِ دائما تسقيني فضل العلم وكرمه وتنيري درب الطموح بقلبي دون أن تشعري، إلى أن بنيتَ في قلبي وروحي بيتا من الطموح يستحيل هدمه. لقد كتبت قصةً جميلةً عن إصرارك وأثرك البالغ علي وعلى إخوتي في الوصول إلى أسمى مراتب العلم، فعندما كنت في مقتبل المرحلة الإعداية، كنت أرسم معك أمنياتي لمستقبل باهر، وأنسج من وحي مخيلتي صورة لما أتطلع أن أكون عليه عندما أكبر. واليوم ها أنا أعود لتلك القصة التي كتبتها منذ سنوات وأنا أعانق ذلك الحلم التي ساندتيني في رسمه.

لقد كنتِ ومازلتِ- يا أمي- مثالاً لي للصبر والتضحية، وأحسبني أخذت منك هذه الخصال النبيلة دون أن أشعر، وقد أعانني الله أولاً ثم تلك الخصال على أن أتحمل سنوات الغربة الطوال وأن أقابل كل التحديات بمفردي وبقلب مطمئن. سأدعو لكِ بالخير ما حييت يا أمي في جهري وسري، في دعائي وصلواتي، وأدعو الله أن يجزيك خير الجزاء عني يا حبيبتي.

أبي الحبيب،،

أفخر دائماً بك وبإسمي المقرون بإسمك، وبصفاتك الطيبة التي أحملها. كنت ومازلت السند المتين لي بحياتي، وأود أن أنتهز الفرصة هنا لأعبر عن بالغ تقديري لما قدمته لي من دعم ورفقتك الطيبة إلى إسكتلندا لأنضم للفريق البحثي ببحر الشمال من جامعة أبردين. لقد كان لتلك الرحلة يا أبي صدىً ووقعاً جميلين في نفسي إلى يومنا هذا، رسما ملامح ما أنا عليه اليوم وزادا عندي شغف البحث والإطلاع عن كل ما هو جديد، وأن آخذ العلم من أهله، وأن أمد فضولي خارج الحدود الجغرافية التي نعيشها مهما كانت المشقة المترتبة على ذلك.

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والحمدلله الذي بنعمته تتم الصالحات،،،

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"رَبِّ أَوْزِعْنِي أَنْ أَشْكُرَ نِعْمَتَكَ الَّتِي أَنْعَمْتَ عَلَيَّ وَعَلَى وَالِدَيَّ وَأَنْ أَعْمَلَ صَالِحًا تَرْضَاهُ وَأَدْخِلْنِي بِرَحْمَتِكَ فِي عِبَادِكَ الصَّالِحِين"

سورة الأحقاف، آية ١٥

List of papers

I. Large-Scale Retrieval of Coloured Dissolved Organic Matter in Northern Lakes Using Sentinel-2 Data. **Enass Said. Al-Kharusi**, David E. Tenenbaum, Abdulhakim M. Abdi, Tiit Kutser, Jan Karlsson, Ann-Kristin Bergström and Martin Berggren. *“Remote Sensing* 12 (1): 157”. https://doi.org/10.3390/rs12010157.

II. Drought Offsets and Weakens the Controls on Colored Dissolved Organic Matter in Lakes-Insights from Remote Sensing Data. **Enass Said. Al-Kharusi**, Geert Hensgens, Abdulhakim M. Abdi, Tiit Kutser, Jan Karlsson, David E. Tenenbaum, Martin Berggren. *Submitted to “Remote Sensing of Environment, 2020”.*

III. Combined use of Records from Multiple Satellites to Reconstruct Long-Term Trends in Boreal Lakes Brownification. **Enass Said. Al-Kharusi**, Clemens Klante, Behshid Khodaei, Tiit Kutser, David E. Tenenbaum, Martin Berggren. *“Manuscript”*

IV. Decreasing Organic Carbon Bioreactivity in European Rivers. Martin Berggren, **Enass Said. Al-Kharusi**. *“Freshwater Biology* 65 (6): 1128–38”. https://doi.org/10.1111/fwb.13498.

Contributions

I. **ES.A** designed the workflow of the research together with the supervisors. **ES.A** performed the research, performed the data analysis, interpreted the results and led the writing with the co-authors.

II. **ES.A** designed the study together with the supervisors. **ES.A** performed the research. **ES.A** performed the data analysis with the co-authors and led the writing with the co-authors.

III. **ES.A** designed the study together with the supervisors. **ES.A** performed the research, performed the analysis with the co-authors, interpreted the results and led the writing with the co-authors.

IV. **ES.A** was involved with data analysis by performing of the GIS analyses and involved to interpret the data analysis related to GIS. **ES.A** edited and approved the manuscript.

List of Figures

Abbreviations

ALI	Advanced Land Imager
BoA	Bottom of Atmosphere
BOD$_5$	Biological Oxygen Demand
C:N	Carbon: Nitrogen
CDOM	Coloured Dissolved Organic Matters
CDOM$_{420}$	Coloured Dissolved Organic Matters (absorption at 420 nm)
CDOM$_{RS}$	Coloured Dissolved Organic Matters (measured from RS)
CLC	CORINE Land Cover
CH$_4$	Methane
Co$_2$	Carbon Dioxide
D8	Eight-Flow Direction Matrix
DEM	Digital Elevation Model
DOM	Dissolved Organic Matters
EEA	European Environmental Agency
ESA	European Space Agency
ETM+	Enhanced Thematic Mapper Plus
EU	European Union
GEE	Google Earth Engine
GHG	Green House Gasses
GIS	Geographic Information Systems
k	The First-Order Decay Coefficient
MK	Mann Kendall
MODIS	Moderate Resolution Imaging Spectroradiometer
MSI	Multispectral Instrument
NASA	National Aeronautics and Space Administration
NDVI	Normalise Difference Vegetation Index

NIR	Near Infrared
OLI	Operational Land Imager
PCDs	Physical Catchment Descriptors
PDI	Palmer Drought Index
RHESSys	Regional Hydro-Ecological Simulation System
RS	Remote Sensing
SeaWiFS	Sea-Viewing Wide Field-of-View Sensor
SMHI	Swedish Metrological and Hydrological Institute
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
TM	Thematic Mapper
TN	Total Nitrogen
ToA	Top of Atmosphere
TOC	Total Organic Carbon
TP	Total Phosphorus
TMI	Topographic Moisture Index
USGS	US Geological Survey
UAVs	Unmanned Aircraft Vehicle Systems
UV	Ultraviolet

1 Popular Summary in English

Inland waters are valuable to humankind due to the range of ecosystem services that they provide. Moreover, monitoring of inland water resources is vital to society. However, like many other ecosystems, inland waters have recently been exposed to multiple environmental pressures, such as organic and inorganic pollution. Moreover, as inland water resources are extremely sensitive to land use and climate change, it is a challenge to maintain high-quality water that is clean and free from chemical substances. The surface of water could face significant organic matter input, which usually originates from the soil. This organic matter stains the water yellow or brown, when the concentration of organic matter in the water increases.

There is high demand for surface water as a source of drinking water in the Scandinavian region. For example, Sweden and Norway get more than 50 per cent of their drinking water from lakes. The brownification in the water can contribute to several problems, such as disease, odour and bad-tasting drinking water, and it can threaten the sustainability of water resources. The Nordic region has experienced an increase in dissolved organic matter (DOM) in soil, which can travel from the land to lake water through surface runoff from rain or snowmelt water. Moreover, DOM strongly influence the ecosystem's function through many biogeochemical reactions, and increase the emission of greenhouse gases into the atmosphere.

Recently, attention has been devoted to water colour assessments in inland waters by estimating the coloured dissolved organic matter (CDOM), which is considered the main component that can contribute to water brownification. There is a strong link between terrestrial and aquatic ecosystems, as the flux of DOM can emerge from plants and soils and enter water through the process of leaching. There is an urgent need to monitor CDOM changes in inland water surfaces. Conventionally, field data (ground measurements) of CDOM in water have been limited to few measurements at a few places, whereas remote sensing can provide much more data about water colour on both regional and global scales.

This thesis explored CDOM patterns in space and time. The overall aim was to investigate the capabilities of remote sensing (RS) and geographic information systems (GIS) to extend CDOM patterns from a regional to a broad scale. Different study sites in Europe, mainly Northern Scandinavia, including large numbers of lakes and rivers, were tested on different scales. The first two chapters in this thesis focus on the large geographic area that includes many lakes in Sweden and Norway. It was found in the first chapter that data from the satellite Sentinel-2 MSI can be used for lake CDOM retrieval over a wide variety of lakes, and the best-performing algorithm was based on the green/red spectral ratio. Moreover, we found that land cover has a significant impact on CDOM in lakes. Therefore, in Chapter II, we were motivated to investigate the role of catchments and how they could contribute to the shifting CDOM in lakes. The results in Chapter II were obtained from RS and GIS, which provided insights into how CDOM variations during a dry and a wet year were driven by land cover, climate, and shape of the watershed. For the first time, we demonstrated the large-scale geographical CDOM variations in the landscape during drought, which has a strong impact on CDOM in lakes. Notably, droughts affected the large lakes by reduced inflowing water, and therefore, less CDOM was washed into the lakes. The study contributes to the understanding of the drivers controlling CDOM concentrations in inland waters on a regional large scale under severe climate conditions, such as drought.

In Chapter III**,** Lake Bolmen (Sweden's tenth largest lake) was chosen for the study because it is an important drinking water source and long-term monitoring data was available. On the regional scale, we explored satellite data sources, such as Landsat and Sentinel-2, and combined different sensors to enable more data from different time points. This is important in cloudy regions, such as Sweden. Furthermore, we used Lake Bolmen as a case study to demonstrate how a combination of data sources can be used to fill gaps in the current understanding of how CDOM has varied over the past decades. It can be concluded that using a combination of remote sensing records from Landsat and Sentinel-2 to reconstruct the long trend of CDOM in lake water is a promising approach.

The last chapter, Chapter IV, focused on the large patterns of temperate rivers on a continental scale. Although these rivers have experienced an increase in the total organic carbon (TOC) due to different scales of factors involving changes in land cover or land use, climate and soil acidity, the results show that the organic matter became more nitrogen poor. Additionally, the findings indicate that biological degradability of the organic material decreased by 50 percent between 1996 and 2012, which coincides with the ongoing water browning trend. However, the results also indicate that the reactivity has increased in river water with a low TOC, where internal processes in the water have a high relative influence on bulk TOC quality, whereas the reactivity is low near terrestrial hot spots for TOC export and during the years with high terrestrial TOC loading. Consequently, these results suggest that the impacts of browning on microbial water deoxygenation and greenhouse gas production are less severe than previously thought.

In conclusion, the combined findings of this thesis highlight the capabilities of remote sensing data integrated with GIS to extend the explanation of CDOM patterns to broad scale in space and time. The different methods and study sites used in this thesis will help to evaluate CDOM variations in response to future climate changes and land cover/use changes, including on a global scale. Knowledge of these space and time changes of CDOM patterns are needed to understand the nature of water browning, which has important consequences for carbon budgets and greenhouse gases in the ecosystem.

2 Preface and Specific Aims

A large majority of inland waters are not monitored regularly, and most of them have not been monitored at all, especially small lakes in inaccessible areas. Long-term water quality assessment information is necessary to enhance and restore lake ecosystems. Inland surface water quality has received significant attention globally because much of the world´s population depends on inland resources for potable water, recreation, tourism and sustenance. The remote sensing method, along with in situ water sampling and monitoring programmes for inland water recourses, could play an important role in securing future water resources. In addition, inland water plays an important role in both the global carbon cycle and oceans (see section 3.2.2 for references and further details). Therefore, there is a strong interest to extend the capabilities of remote sensing methods based on satellites' capacities.

Increasing concentrations of dissolved organic carbon (DOC) can result in surface water browning as frequently is reported for the boreal inland waters (Monteith *et al.*, 2007). The widespread phenomenon of water brownification can affect the value of the water, and, as consequences, this will enhance the risk and cost associated with water production (Matilainen *et al.*, 2010), increase the health risk by applying more treatment to the water (McDonald *et al.*, 2005), and the structure and function of the food webs (Creed *et al.*, 2018). Although several studies have developed methods to characterise the optical CDOM of inland waters (Kutser, Pierson, Kallio, *et al.*, 2005; Kutser *et al.*, 2015; Olmanson *et al.*, 2016; Toming *et al.*, 2016), monitoring CDOM 'brownification' on a large scale remains difficult. Additionally, using large-scale remote sensing data to monitor surface waters poses a challenge. On a small scale, the potential of reconstructing CDOM in inland waters, coupled with different drivers, such as land cover change and catchment morphometry, have not yet been fully explored. Combining the advantages that are offered by newer sensors can be promising to track water brownification. On a broader scale, the investigation of organic matter quantity in inland waters has not been investigated in depth.

Currently, water monitoring programmes across Europe are in place to monitor water quality parameters, such as water colour. Water colour is rapidly changing, and 'water browning' due to increased dissolved organic matter (DOM) concentrations is a persistent issue that has remained over decades (see section 3.3 for references and further details). The increasing DOM load from the terrestrial to the aquatic system could influence the internal processes of the aquatic ecosystem. Overall, browning could cause a shift from bioreactive algal DOM sources to terrestrial DOM, which is characterised by slower degradation.

The rise in CDOM is likely to be relatively more pronounced in remote northern regions; however, there is a lack of monitoring to confirm this. For this reason, there is a strong incentive to develop remote sensing-based methods to map CDOM in lakes across broader geographical scales. There is a lack of understanding of the functioning behind changes in water colour (i.e. CDOM) at large scales. They could be due to varying drivers, such as climate and landscape patterns or catchment features. This means that currently, we do not know the extent to which aquatic ecosystems need conservation efforts, such as reduced fishing pressures and management of the surrounding vegetation, to prevent CDOM leakage. Therefore, there is a need to better understand the process and drivers behind CDOM changes in inland waters. Such a contribution is necessary to increase our knowledge of CDOM shifts within inland waters. The research described in this thesis addresses the methodological and thematic objectives below.

2.1 Methodological Objectives:

I. Assess the potential of using high spatial and temporal resolution remote sensing to explore CDOM dissemination at a large scale (**Paper I**).

II. Explore the influence of data quality and different water body types in an optical analysis **(Paper I** and **Paper II)**.

III. Apply GIS techniques/approaches to create morphometry datasets of catchments and inland waters **(Paper II, Paper III** and **Paper IV**).

IV. Assess the potential for integrating different sensors at sufficient spatial and temporal resolutions for reconstructing and enhancing CDOM and water colour monitoring (**Paper III**).

2.2 Thematic Objectives:

I. Address CDOM variations both spatially and temporally in different types of inland waters at a large scale **(Paper I** and **Paper II**).

II. Address CDOM changes and determine the influence of different drivers on CDOM in both temperate and boreal environments over large geographic gradients **(Paper II** and **Paper IV)**.

III. Explore the patterns of organic matter in inland waters in both temporal and spatial scales, focusing on organic matter degradation rates in temperate European rivers **(Paper IV)**.

For further elaboration on the research papers that are included in this thesis, see Section 3.

3 Motivation, Background and Literature Review

3.1 Introduction

Inland surface waters represent major freshwater resources across the world. The importance of inland waters for humankind includes supplying water for drinking, fishing, energy, irrigation, etc. Additionally, they are places of recreation and economic activity that can easily affect the ecosystem´s environmental stability. The quality and colour of inland waters are driven by the different origins of substances and factors, such as nutrients, soil erosion, chemical substances and heavy metals, which are continuously added either naturally from the ecosystem or by human activities (Jaffé *et al.*, 2008; Kritzberg *et al.*, 2020). There is a strong link between water quality and colour, which is related to fundamental changes to the water properties (Kritzberg *et al.*, 2020). Although inland waters comprise a small fraction of the land surface, they are sites of intense biogeochemical activity (Cole *et al.*, 2007). For instance, lakes and rivers are an important source of atmospheric carbon dioxide and a significant component of continental carbon fate(Cole *et al.*, 2007; Tranvik *et al.*, 2009; Raymond *et al.*, 2013; Toming *et al.*, 2020).

Water colour has gradually changed in many inland waters across Europe and North America over the last few decades (Monteith *et al.*, 2007). Recent studies have shown that the change in water colour is one of the major widespread environmental changes that has occurred recently in inland waters (Jonsson *et al.*, 2001; Lapierre *et al.*, 2013; Soares *et al.*, 2019; Kritzberg *et al.*, 2020; Škerlep *et al.*, 2020). Sudden changes to the water colour are due to several factors or a combination of physical, chemical and biological factors in the terrestrial and aquatic systems (Meyer-Jacob *et al.*, 2019). Moreover, the potential drivers of water colour variability are the topography, land use and cover, acid deposition, weather patterns and climate change (Kritzberg *et al.*, 2020). There is a significant relationship with the land surrounding the water surface. which has a direct impact on changes to the water colour. For example, the dissolved decomposition products of DOM in the soil can be efficiently discharged into the surface water via hydrological channels and connections with the land (Tiwari *et al.*, 2017; Rizinjirabake *et al.*, 2018). Additionally, changes to the water colour could occur due to the accumulation of organic matter from the sediments (Bertrand *et al.*, 1993; Von Wachenfeldt *et al.*, 2008). In this respect, inland waters (e.g. lakes and rivers) have been considered a component of the earth's surface that intensely capture, process and transport organic matter from terrestrial soil (Laudon *et al.*, 2011; Soares *et al.*, 2019).

3.1.1 DOM

Conventionally, DOM is defined as any organic material that passes through a given filter (0.1 µm –0.7 µm) (Kalbitz *et al.*, 2000). In natural waters, DOM consists of a heterogeneous mixture of autochthonous (internal algal decomposition products) and allochthonous (terrestrial and anthropogenic inputs) material (Von Wachenfeldt *et al.*, 2008; Battin *et al.*, 2009; Li *et al.*, 2016). DOM significantly contributes to the water colour of inland waters that mainly get their brown pigments from surrounding terrestrial ecosystems (Berggren *et al.*, 2018). There is a strong connection between terrestrial and aquatic ecosystems, as the flux of DOM emerges from plants and soils, and it is a significant term in the terrestrial organic matter budget. Fundamentally, DOM strongly influences the ecosystem's function through many biogeochemical reactions, which could lead to the release of ecosystem labile compounds (e.g. hydrogen sulphide) and greenhouse gases (GHG) (e.g. CO_2) (Li *et al.*, 2016; Minor and Oyler, 2021).

3.1.2 The Connection between DOM and CDOM

Given the vital importance of organic matter in aquatic systems, it is highly advantageous to measure the concentrations of CDOM across large geographical areas over time (Brando and Dekker, 2003; Erin L. Hestir *et al.*, 2015; Li *et al.*, 2016, 2017). One characteristic property of CDOM is its ability to absorb light, which is conventionally measured in the laboratory as CDOM = $\ln(1/T_{440})$, where T_{440} is the share of photons that are transmitted through particle-free water per meter at a wavelength of 440 nm (Cuthbert *et al.*, 1992). Generally, CDOM absorbs both short-wavelength solar and ultraviolet (UV) radiation, the CDOM absorption decreases exponentially with increasing wavelength (Hojerslev, 1975). It is crucial to consider that CDOM absorbs most of the radiation in UV, especially in high latitude lakes, because the aquatic biota is protected from UV-B, which induces damage and affects the photochemical reaction. In most aquatic ecosystems, including fresh and coastal waters, quantifying CDOM is equivalent to knowing the absolute concentration of DOM in the water (Brezonik *et al.*, 2015; Harvey *et al.*, 2015), which represents most of the total organic content in the water. Although typically standardised at 440 nm, CDOM absorbs light in the whole ultraviolet spectrum plus visible light, with absorbance coefficients that decrease exponentially from 250 nm and show low values above 550 nm. It is important to highlight that DOM can be variable and controlled by different physical, chemical and biological processes, such as hydrology, photo-modifications and primary production.

Variability in the degree of pigmentation of different types of DOM means that the concentration of CDOM does not perfectly correlate with the DOM concentration in the water (Jaffé *et al.*, 2008).

3.2 Regulation and Functional Role of DOM and CDOM in Ecosystems

Recent studies have focused on DOM and CDOM to understand their dynamics, underlying processes and potential implications in ecosystems (Kalbitz *et al.*, 2000; Hestir *et al.*, 2015; Li *et al.*, 2016; Leinemann *et al.*, 2018; Gmach *et al.*, 2020; Minor *et al.*, 2021). DOM contributes to the mobile carbon pool, and it plays an important role in the global carbon cycle (Kalbitz *et al.*, 2000). As expected from organic matter degradation, CO_2 tends to increase in the surface water due to the increasing levels of CDOM. However, relationships between DOC to CO_2 vary (Lapierre *et al.*, 2013). The analysis of DOM samples' optical properties can be beneficial to assess water colour and understand the relationship between DOM-CDOM and CO_2 emissions into the atmosphere (Tranvik *et al.*, 2009).

The fates of DOM and CDOM depend on its interactions with mineral components and the mineralisation and immobilisation processes in the entire ecosystem. These processes are in turn dependent on ecosystem change that affect organic composition, e.g. change in land cover and climate (Kritzberg *et al.*, 2020). In this context, interest in studying the interactions between terrestrial-aquatic ecosystems has increased. The quantity and composition of DOM in inland waters may be influenced by land use and cover (Bodmer *et al.*, 2016). As a result of degradation, DOM becomes less humic and has a lower molecular weight when its ratio increases in croplands, wetlands and water. Thus, the effects of land use/cover change on DOM characteristics should have important implications for carbon cycling in inland water systems (Bodmer *et al.*, 2016; Soares *et al.*, 2019).

3.2.1 Reactivity of Organic Matter in Water

The potential of organic matter for degradation is called reactivity. Approximately 30% to 80% of terrestrial DOM is lost due to biological degradation in the water during (bio-reactivity) the transportation process from the catchment to the sea (Algesten *et al.*, 2004). The amount of allochthonous DOM material that is exported from the land to the lakes influences the ecosystem’s resilience, functions, metabolism and food web structure. DOM's relative contribution to the carbon pools in lakes varies depending on the heterogeneity in terrestrial loading and the landscape settings among lakes (Hope et al., 1994; Wilkinson *et al.* , 2013). High concentrations of reactive DOM in inland waters can lead to enhanced conversion of DOC to CO_2 in aquatic ecosystems, which can enhance higher concentrations and fluxes of CO_2 into the atmosphere (Sobek, G. Algesten, *et al.*, 2003Algesten *et al.*, 2004).

The differences in carbon composition between allochthonous and autochthonous material could impact the reactivity of DOM and thus aquatic system respiration. Karlsson *et al.* (2007) showed that different sources of DOM contribute to respiration in aquatic systems, and allochthonous DOM causes net heterotrophic conditions in unproductive lakes. Additionally, allochthonous DOM can significantly regulate the detrital food chains and control the water column's food web production (Berggren *et al.*, 2014).

Different factors can determine DOM reactivity in water, such as chemical and biological factors. There is a connection between the oxidation state and reactivity of aromatic compounds, where decay rate increase when oxidation rate is high (Mostovaya *et al.*, 2017). Besides biological reactivity, CDOM constituents can be highly reactive in sunlit water, which is called photo-reactivity. The photolysis increases the oxidation rate and biological CDOM decay (Berg *et al.*, 2019). Hence, by modifying the DOM, photo-reactivity not only leads to mineralization but is also is could positively affect the microbial DOM degradation rate (Scully *et al.*, 2003). Moreover, DOM bioreactivity vary between the seasons (Isles *et al.*, 2021) due light availability and nutrients, such as total nitrogen (TN) or total phosphorus (TP).

3.2.2 CDOM at the Global Scale of Carbon Cycle and GHG

The inland waters on the earth's surface play a major role in the global carbon (C) cycle (Holgerson *et al.*, 2016). Inland waters can influence the climate at the regional and global scales by exchanging heat and water with the atmosphere, which contributes to the release of GHG (Tranvik *et al.*, 2009). The consumption and production of GHG (e.g. carbon dioxide, methane and nitrous oxide) affect both the concentrations of GHG in the atmosphere and the atmosphere's heat budget (Bartosiewicz *et al.*, 2015). Despite the small sizes of inland waters (e.g. lakes and rivers), they are very active sites in a productive ecosystem (Tranvik *et al.*, 2009). The estimated fraction of CDOM in inland waters (lakes) has lower values (0.729 Pg) compared to the global carbon surface of the ocean (700 Pg), the carbon pool in vegetation (450 Pg–650 Pg) and carbon in soils (1500 Pg–2400 Pg) (Toming *et al.*, 2020). Several studies (Tranvik *et al.*, 2009; Bodmer *et al.*, 2016) have shown that lakes are an active site for the transportation, transformation and storage of significant amounts of carbon that originated in the terrestrial environment.

Methane (CH_4) and carbon dioxide (CO_2) are two GHG that are present in the atmosphere. They have been widely studied recently because of their significant impact on global warming (Wu *et al.*, 2012; Tang *et al.*, 2016). Carbon dioxide has a significant effect on the earth’s climate and is mostly responsible for the greenhouse effect. Methane is the second most important gas that contributes to atmospheric radiative forcing (Tang *et al.*, 2016). Furthermore, more inland waters were recently identified as prime sources of CH_4 and CO_2(Bodmer *et al.*, 2016; Tang *et al.*, 2016). Dissolved organic matter in water and the surrounding soils are direct sources and inputs of CO_2 into the atmosphere due to the extreme respiration of organic matter and high availability of nutrients (Bodmer *et al.*, 2016). The dissolution of organic matter into water results in CH_4 being produced through methanogenic processing. Additionally, CH_4 can be produced in the water through oxidative processing before reaching the atmosphere. An extreme amount of CH_4 can be emitted to the atmosphere by diffusion, effervescence and storage flux (Yang *et al.*, 2015).

Lakes in northern Europe and North America have the largest CDOM concentrations compared to the other continents(Freeman *et al.*, 2001; Skjelkvåle *et al.*, 2005; Monteith *et al.*, 2007b). Although lakes in Africa are very similar to lakes in Europe in terms of the high volume of water, the higher CDOM concentrations in European and North American lakes can be explained by meteorological and hydrological features and the lake morphometry in these regions (Tang *et al.*, 2016).

3.2.3 Seasonal Changes of CDOM and Climate Change

Numerous drivers have contributed to changes to the CDOM concentrations in inland waters. Many studies have shown the spatial and seasonal distributions of CDOM and addressed the factors that contribute to the increasing CDOM in lakes, estuaries and rivers (Haaland *et al.*, 2010; Toming *et al.*, 2020). The increasing temperature and precipitation in boreal landscapes has caused them to produce more terrestrial organic matter, which is then transferred from the soil to the aquatic ecosystem (Sobek *et al.*, 2003; Lapierre *et al.*, 2013; Klaus *et al.*, 2019). For instance, hydrological droughts can easily affect the water inflow and availability in the soil in severe climatic conditions (e.g. low precipitation and warmer temperatures) (Lake, 2003; Sobek *et al.*, 2003; Szkokan-Emilson *et al.*, 2017). Additionally, catchment and inland water morphometry can have a strong influence on CDOM in inland waters. (Lake, 2003; Sobek *et al.*, 2003; Szkokan-Emilson *et al.*, 2017) showed how the difference between catchments with respect to their morphometry (e.g. slope, size, area, elevation, etc.) contributes to the export of terrestrial DOM. The lake's position in the landscape has a strong influence on the CDOM concentration in lakes (Cardille *et al.*, 2007). Toming *et al.* (2020) emphasised the significant effect of weather and hydrological patterns on the lake water's CDOM concentration availability. Regarding the connection between lake water and terrestrial DOM, Crowther *et al.* (2016) found larger soil carbon sensitivity patterns for climate warming globally.

Precipitation affects CDOM concentration temporally and is strongly correlated with stream discharge. CDOM can decrease or be offset in the summer due to the reduced precipitation. Furthermore, drought can alter the hydrological network, which effects DOM transportation to the water surface (Toming *et al.*, 2009). (Toming *et al.*, 2009) showed how particular land cover types (e.g. forest, wetlands and vegetation) enhance the CDOM concentration in surface water, especially in headwaters, during spring flood events and in response to diverse chemical variables in the water. Additionally, there is a significant contribution to the catchment's physical characteristics and lake morphometry. Interestingly, CDOM concentrations have apparent differences that can be observed between large and small, high and low volume and deep and shallow lakes (Lake, 2003; Toming *et al.*, 2020).

3.3 Browning the Waters

The phenomenon of increasing CDOM and iron concentrations is called 'brownification' or 'browning water', and it has a direct impact on the structure and function of aquatic ecosystems (Lake, 2003; Toming *et al.*, 2020b). Browning water has been mainly attributed to the transportation of DOM from terrestrial to aquatic systems. Finstad et al. (2016) mentioned that climate, hydrology and land use are ambient drivers that contribute to brownification when combined with changes in sulphate deposition.

Since brownification has an important ecological impact, as it affects water quality/colour, it has become an environmental concern in many freshwater systems (Kankaala *et al.*, 2019). Moreover, the browning of water has implications for the ecosystem services that freshwater provides, as well as ecological consequences on the aquatic ecosystem, which affect the fish community and production (Kankaala *et al.*, 2019). Many studies have highlighted the implications of browning water (Karlsson *et al.*, 2015; Vasconcelos *et al.*, 2019). Moreover, a high concentration of DOM entering inland waters controls the light penetration in the water column. As a result of the decreased light penetration into the water, a remarkable shift of aquatic ecosystem thermal stability can occur by forming a shallower, warmer epilimnion and euphotic zone. Consequently, the DOM impacts primary production by binding the access of nutrients to the phytoplankton (Williamson *et al.*, 2015; Vasconcelos *et al.*, 2019; Senar, Creed and Trick, 2021).

3.3.1 CDOM in Boreal Regions

The ultimate source of CDOM in boreal lakes is terrestrial DOM. In this regard, there is a considerable variation in the export of DOM among catchments to surface inland waters (Laudon *et al.*, 2012). Boreal lakes play a vital role in the carbon cycle, as most of the source of the carbon area comes from the soil stock (Laudon *et al.*, 2012). Biogeochemical activities are considered key to the landscape, as they deliver organic matter from land to water through different mediums of environmental patterns (Sobek *et al.*, 2003; Laudon *et al.*, 2012). The boreal region's catchments are mainly covered with coniferous and mixed forest, which are largely associated with high terrestrial DOM in productive seasons (Laudon *et al.*, 2011). Additionally, there are wetlands in boreal areas, which may vary in abundance among catchments. The area that consists of wetlands has relatively large quantities of organic matter, which are usually well-drained (Mzobe *et al.*, 2018).

Lakes that are located in areas with a high percentage of wetlands and a low elevation have high concentrations of CDOM (Arvola *et al.,*2016; Mzobe *et al.*, 2020). In addition, lake size and drainage density can play an effective role in increasing the CDOM concentration in lakes (Mzobe *et al.*, 2020). However, the importance of drivers that shape the CDOM concentration in inland waters that shift between climate, landscape properties and hydrological activities is under serious consideration, as they actively contribute to the carbon budget globally. The seasonal cycle in boreal lakes has a characteristic cycle with increasing CDOM in spring after ice and snowmelt while decreasing in the summer and again becoming higher in autumn (Ågren *et al.*, 2008; Kothawala *et al.*, 2014). Advancements in remote sensing technology, GIS and modelling could support efforts to upscale our understanding of CDOM in inland waters at larger geographical scales; therefore, our knowledge of the interface between land and water will be improved.

3.3.2 CDOM in Temperate Rivers

DOM may reach surface waters directly by streams as a surface flow or through a subsurface interflow or groundwater inputs. Multiple processes can impact CDOM externally; as this has been addressed in previous sections, internal processes that impact CDOM are the focus of this subsection. Recently, European inland waters (e.g. temperate rivers) have experienced increasing amounts of DOM in their waters(Monteith *et al.*, 2007). However, the concentration of reactive CDOM can increase due to labile terrestrial DOM inputs (Lapierre *et al.*, 2013). The main consequence of increasing CDOM in surface waters is that it can affect food webs, especially phytoplankton. The phytoplankton production and biomass can be lower in browning water because of the limited light availability into the water surface layers (Deininger *et al.*, 2017). Additionally, any changes in land use can cause increasing nitrogen export, which could potentially affect phytoplankton's growth and activities(Kritzberg *et al.*, 2012). Large inputs of allochthonous DOM are considered to enhance phytoplankton productivity by changing the diatoms, cyanobacteria and mixotrophs, especially in the active pool of CDOM (Senar *et al.*, 2021). The photochemical condition helps to degrade CDOM in water by reacting with the sunlight, which could cause a decline in the oxygen availability in the water(Karlsson *et al.*, 2009; Creed *et al.*, 2018). The internal intrinsic processes that are relevant depend on the source or types of aromatic terrestrial DOM that get into the water (Karlsson *et al.*, 2009)

3.4 Remote Sensing of Water Quality

Assessing the water quality using remote sensing applications to measure CDOM in surface water has been of interest to the remote sensing community since the 1970s (Wrigley *et al.*, 1974). Optical remote sensing enables the reconstruction of water quality information for inland waters when a ground data assessment is lacking(Liu *et al.*, 2003; Olmanson *et al.*, 2011; Odermatt *et al.*, 2012; Cardille *et al.*, 2013). Remote sensing data has been successful for estimating water quality parameters, such as total suspended solids, turbidity, chlorophyll-a and CDOM (Kutser, Pierson, Kallio, *et al.*, 2005; Kutser *et al.*, 2016; Olmanson *et al.*, 2016; Liu *et al.*, 2017). The ocean satellites that have been developed for blue water marine remote sensing have coarse spatial resolutions, which makes them ineffective for remote sensing applications for inland water bodies, such as lakes, rivers and reservoirs (Erin Lee Hestir *et al.*, 2015). For example, sensors (e.g. SeaWIFS and MODIS) with large pixel sizes have failed to map small lakes because of the spatial and radiometric resolution issues (Erin Lee Hestir *et al.*, 2015). Land remote sensing satellites have shown progress in effectively measuring inland water quality (Wrigley and Horne, 1974; Kutser *et al.*, 2015; Gholizadeh *et al*., 2016). From a spatial resolution perspective, Landsat satellites (30 m) allow the measurement of small water bodies. Nowadays, high spatial resolution land satellites, such as Landsat 8 and Sentinel-2, have shown high potential for improving the measurement of water parameters.

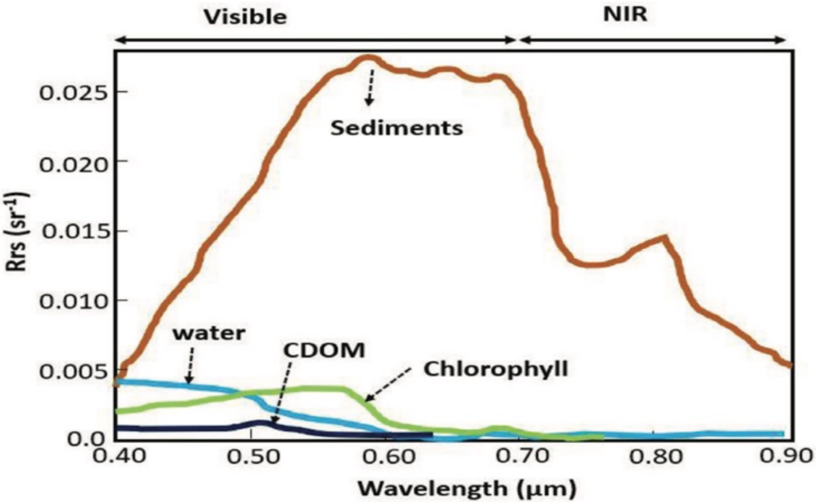

Figure 1 Reflectance spectra of different waters dominated by various optical properties (Source; Sherry PL, NASA).

3.4.1 CDOM and Spectral Response

CDOM, among other water quality parameters, is challenging to retrieve from spectral reflectance data using remote sensing. Several band ratio algorithms have been developed for measuring lake CDOM concentrations, and they are related to water colour and DOM concentrations (Topp *et al.*, 2020). Slonecker *et al.* (2015) and Toming *et al.* (2016) showed that the use of bio-optical modelling based on the green to red band ratio can be successfully used to map lake CDOM with a high spatial resolution. Most of the band ratios are based on the blue to green ratio, as water is usually highly responsive. In the blue area of the spectrum, CDOM absorption is high, whereas it is lower in the green (Kutser, 2012) (Figure 2). Moreover, different CDOM-retrieval algorithms have been developed that use green to red band ratios, which work very well over a wide variety of lakes in different parts of the world (Kutser *et al.*, 2005; Olmanson *et al.*, 2016; Slonecker *et al.*, 2015; Toming *et al.*, 2016. Kutser *et al.* (2005) explained the relationship between the green and red ratio calculated from advanced land imager (ALI) images and CDOM absorption measured from two lakes in southern Finland and southern Sweden, respectively. Toming *et al.* (2016) used the same relationship for Sentinel-2 images and was able to analyse CDOM absorption in nine lakes in Estonia. Furthermore, the users of the Landsat series mission found significant success in retrieving CDOM using the green and red band ratios (Kutser, 2012; Olmanson *et al.*, 2016).

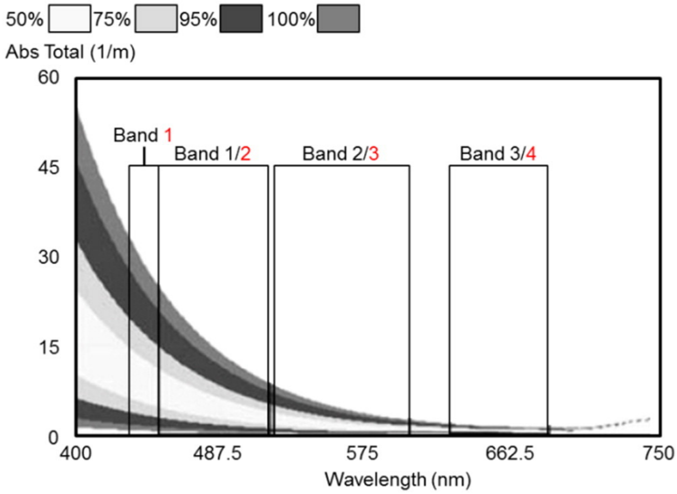

Figure 2 Reflectance spectra of CDOM in the electromagnetic spectrum and typical multispectral satellite sensors (Source;(Slonecker et al., 2015); after (Kutser et al., 2005))

3.4.2 Optical Sensors for Mapping CDOM

In this thesis, Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI and Sentinel-2 MSI were chosen to assess CDOM ‘water brownification’ because of their high spatial resolution performance that can detect CDOM in the water surface (Pahlevan *et al.,* 2018; Kutser, 2012).

3.4.2.1 Landsat

Over the past decade, there have been significant changes in the Landsat programme. After the changes that were made by NASA and the US Geological Survey (USGS) to the Landsat data policy, the Landsat archive became free and open to all users. Therefore, there are now long archive datasets of most Landsat satellites (Wulder *et al.*, 2019). The advancement of technology has helped to improve the Landsat mission to design sensors, such as the Thematic Mapper (TM) onboard Landsat 5, the Enhanced Thematic Mapper Plus (ETM+) onboard Landsat 7 and the most recent OLI onboard Landsat 8 (Figures 3 and 4). There are progressions for each of these sensors to detect or acquire CDOM from a broader range of multispectral bands due to increasing the spatial resolution to 30 m and shorter revisit times (16 days). The Landsat 5 TM archive has data available from 1984, followed by Landsat 7 ETM+ with data available from 1999. Notably, Landsat 6 failed to reach the earth’s orbit in 1993, which was a setback for the program. Landsat 8 OLI was placed into operational service in 2013. However, many studies have proven the capabilities of Landsats 5 TM and 7 ETM+ to map CDOM in lakes and seasonal CDOM (Wulder *et al.*, 2019). Recently, Landsat 8 has shown an improvement over these earlier satellites' capabilities to estimate CDOM. The high spectral resolution and radiometric sensitivity of Landsat 8 provide a more accurate detection and estimation of changes to water quality (Olmanson *et al.*, 2015; Alcântara *et al.*, 2016; Li *et al.*, 2018; Chen *et al.*, 2019).

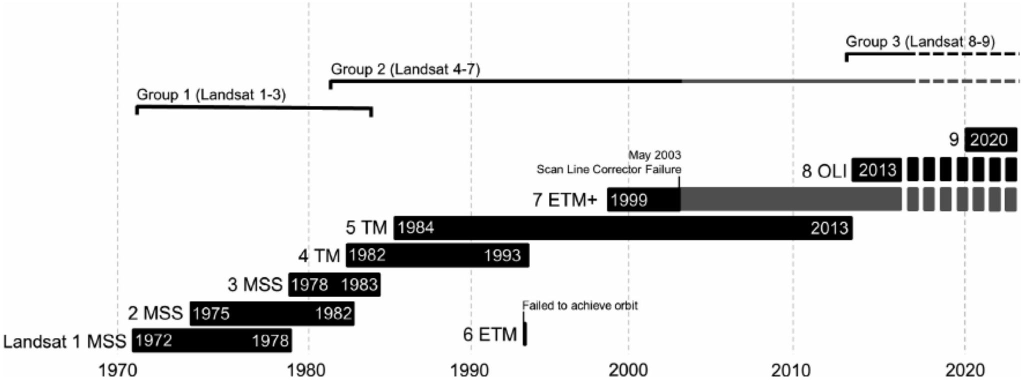

Figure 3 Timeline of Landsat sensors' launch dates and operation lifetime (Source; Young et al., 2017)

3.4.2.2 Sentinel-2

Sentinel-2, which was launched by the European Space Agency (ESA) in 2015, is a significant advancement for remote sensing applications of land monitoring over the Landsat programme mission for land monitoring. The Sentinel-2 constellation consists of two identical satellites (Sentinel-2A and Sentinel-2B) that operate together. The two-satellite constellation allows a five-day revisit time at the Equator and a two-to-three-day revisit time closer to the poles. The unique features of the Sentinel-2 are a wide swath width of 290 km, varying spatial resolution from 10 m to 60 m and 13 spectral bands. It provides a high radiometric and geometric image quality, offers global coverage of land surfaces, and has a high resolution than Landsat-8. Sentinel-2 imagery can provide information about the water properties, which are affected by the reflectance of light. The improvements of the spectral and temporal resolutions of Sentinel-2 (Drusch *et al.*, 2012) allow us to expect greater success in the mapping of CDOM in inland waters. Sentinel-2 could be a great optical tool to provide information on CDOM in inland waters and support for lake management (Olmanson *et al.*, 2015; Alcântara *et al.*, 2016; Li *et al.*, 2018; Chen *et al.*, 2019). The first test of Sentinel-2 was carried out by(Toming *et al.*, 2016) on nine lakes in Estonia, and they found that the green to red band ratio was adequately correlated with lake CDOM. Sentinel-2, with its 10 m spatial resolution, is well suited for capturing CDOM, even in small water bodies (Toming *et al.*, 2016) (Figure 4).

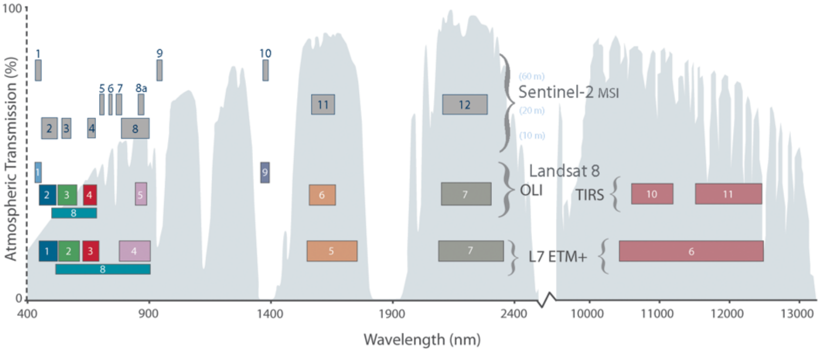

Figure 4 Spatial resolution of visible bands of Landsat and Sentinel-2 (Source; USGS)

3.4.3 Challenges of Optical Remote Sensing in the Boreal Lakes

Estimating CDOM from inland waters using optical remote sensing presents several challenges compared to ocean colour remote sensing (Baillarin *et al.*, 2012; ESA, 2015). Many challenges are associated with the estimation of optical properties when ratio type algorithms are developed for boreal inland waters (Kallio *et al.*, 2008; Kutser, 2012; Palmer *et al.*, 2015). One issue is that the water surface's optical properties can vary among different water bodies, which is inherent in the complexity of inland waters in their geographical, biological and chemical characteristics. As a result of the diversity of inland waters, the development of algorithms for inland waters is more complicated than for open ocean waters. The optical shapes of reflectance spectra for CDOM-rich waters can vary greatly, and it depends on what other material is on water and their contribution to the signal (Brezonik *et al.*, 2015).

Brezonik *et al.* (2005) found that CDOM was typically difficult to estimate over space and time when there was a high concentration of phytoplankton biomass in the aquatic ecosystem. Another complicated issue that is associated with optical remote sensing is atmospheric correction. The optical properties of inland waters can be sensitive to clouds, sun glints and other atmospheric particles (Palmer *et al.*, 2015), which can limit the choices of image availability in the study area.

3.5 GIS Applications for Inland Waters

Remote Sensing (RS) and GIS can significantly contribute to the assessment of water quality and recourses. Inlands waters are not distributed equally and can affect the water quality all over the world (Radwan *et al.*, 2017; Yang *et al.*, 2020). Allan *et al.* (1997) emphasised the importance of studying the landscape as an indicator of the level of organic matter movement to inland waters across large geographic gradients. Moreover, (Xu *et al.*, 2020) found that catchment characteristics and landscape patterns influenced water quality seasonally. GIS techniques can generate a set of physical catchment descriptors (PCDs) to characterise watersheds. Consequently, characterising the watershed's contributing area can improve the characterisation and understanding of the dissemination of CDOM in inland waters (e.g. lakes, streams and rivers). The tropical and boreal areas are productive areas because of the high percentage of forest cover that can contribute to shifting DOM from terrestrial to aquatic. Catchment features can correlate strongly with CDOM dissemination in inland waters, as presented by (Xu *et al.*, 2020)Several pertinent descriptors can describe the diverse terrain range of watersheds, such as elevation, slope, mean topographic moisture index (TMI), drainage density and percentage of land cover/use (Mzobe *et al.*, 2020). However, more geospatial analyses are needed in catchments to better define the conceptual framework of the controls of CDOM in inland waters under different mechanisms.

4 Introduction to the Research Papers

The extent and causes of increasing freshwater CDOM are still debated because the data that is required to assess CDOM in many areas is not available. The four papers that are part of this thesis provide insight into the understanding of how 'browning water' develops over time in a large geographical area. Coupling CDOM with drivers, such as climate, land use/cover and catchment morphology, will contribute greatly to conceptualising water brownification. The first paper is based on Sentinel-2's data that is used to map CDOM in lakes across landscape gradients that are distributed in five regions in Sweden. The second paper deals with a specific driver, such as climate, land cover or catchment morphology, that can enhance CDOM in boreal lakes using an integration of GIS and remote sensing datasets. In Paper III, the Landsat series of satellites and Sentinel-2 are used to reconstruct CDOM over the past three decades, using Lake Bolmen as a case study site. In the fourth paper, datasets of river organic matter and its bio-reactivity across continental Europe are evaluated in 25 countries from different perspectives, considering the catchment types and river morphometry features.

4.1 **Paper I**: 'Large-Scale Retrieval of Coloured Dissolved Organic Matter in Northern Lakes Using Sentinel-2 Data'

4.1.1 Relevance to the Thesis' Objectives

The first paper contributes to both the methodological and thematic objectives of the thesis. From **a methodological perspective**, the utility of Sentinel-2 is examined to assess the potential of using high spatial and temporal resolution imagery to explore the CDOM distribution at a large scale (**Objective 1**). The accuracy of the Sentinel-2 products was also tested from non-atmospherically corrected and atmospherically corrected data by evaluating the CDOM values to assess any residuals errors among a variety of water body types (**Objective 2**). From a **thematic perspective**, we explored different types of lakes according to their geographical settings and sizes to address CDOM variations both spatially and temporally at a large scale (**Objective 1**).

We chose a wide range of inland waters (lakes) in northern and southern Sweden. Choosing the initial study area was important for both methodological and thematic objectives for several reasons. First, the study sites of the lakes have sampling records for absorbance values of CDOM during the summer of 2016, which will help us to validate the CDOM that was recorded optically using an in situ record of the study area. Second, the study area's regions comprise diverse land covers that range from different types of forest (e.g. coniferous and broadleaf) to shrubs and wetlands. This allowed us to test the methodology over large spatial and temporal scales and across a range of landcovers.

4.1.2 Paper Overview

This paper tested the suitability of the recently launched Sentinel-2 multispectral imager (MSI) to monitor CDOM in various types of northern lakes. Although previous studies(Toming *et al.*, 2016; Liu *et al.*, 2017) have investigated the Sentinel-2 retrieval algorithm for CDOM at the local level, we are the first to test this method's broad utility in a cross-regional study covering a large geographical extent. Ground measurements of $CDOM_{420}$ (CDOM absorption at a 420 nm wavelength) were performed in 46 lakes in five districts (Västerbotten W, Jämtland, Värmland, Västerbotten E and Norrbotten) across Sweden. The relationships were evaluated between $CDOM_{420}$ and band ratios derived from Sentinel-2A level 1C products and level 2A atmospherically corrected images. Although the band ratios B2/B3 (460 nm/560 nm) and B3/B5 (560 nm/705 nm) showed poor relationships with $CDOM_{420}$, in levels 1C and 2A data, there was a significant power relationship between the atmospherically corrected B3/B4 ratio and $CDOM_{420}$ ($R^2 = 0.28$, $n = 46$). This relationship was further improved ($R^2 = 0.65$, $n = 41$) by removing the observations that were affected by clouds.

The development of the method used in this paper has great potential for the monitoring of many lakes at the landscape scale. This will help to identify the regions that are the most sensitive to water brownification or changes to the water colour and could potentially need adaptive management concerning land use and natural resource monitoring. In conclusion, the method developed in this paper makes good use of the high resolution of Sentinel-2. It can decrease the time and effort required to monitor CDOM compared to the traditional methods of water sampling, which leaves more time and resources for the effective management of water resources.

4.2 **Paper II**: 'Drought Offsets and Weakens the Controls on Coloured Dissolved Organic Matter in Lakes - Insights from Remote Sensing Data'

4.2.1 Relevance to the Thesis' Objectives

In the second paper, we used remote sensing data (Sentinel-2) to acquire CDOM values and integrate them with a wide range of datasets related to catchment and lake morphology using GIS tools. From **a methodological perspective**, we used GIS techniques/applications to create morphometry datasets of catchments and inland waters (**Objective 3**). We addressed the CDOM changes and determined the influence of different drivers on CDOM in boreal lakes over a large geographic area (**Objective 2**). Approximately 255 boreal lakes were tested. The impact of land cover, the Palmer drought index (PDI) and climate data on lake CDOM in different seasons were analysed.

4.2.2 Paper Overview

In this paper, we assembled data on climate, catchment, land cover and morphology variables to test hypothesised broad-scale shifts in the regulation of lake CDOM between a wet (normal) year (2016) and an extremely dry year (2018). The study covers 255 remotely sensed boreal lakes that are distributed across various environmental and geographic gradients in Sweden and Norway. We showed how drought strongly decreased lake CDOM during the dry year. For this year, a significant correlation was found between the PDI and lake CDOM, especially in large lakes, which had a presumed high degree of catchment uncoupling due to drought. However, all three types of explanatory variables – climate, land cover and morphology – had a more substantial impact on lake CDOM in the wet year. Therefore, drought systematically weakened the regulation of CDOM and created lower values of CDOM. Our results show that drought has a direct effect on lake CDOM and acts indirectly by changing the spatial regulation of CDOM in boreal lakes. The results suggest that continued increases in extreme climate episodes will cause strong increases in the temporal variability of CDOM in lakes, potentially leading to lower ecosystem stability. Our study's findings contribute to the understanding of the consequences of the changes on the ecology and biogeochemistry of lakes.

4.3 **Paper III**: ‘Combined use of Records from Multiple Satellites to Reconstruct Long-Term Trends in Boreal Lakes Brownification’

4.3.1 Relevance to the Thesis’ Objectives

The third paper tested the potential of reconstructing the $\mathrm{CDOM_{RS}}$ concentration over the last decades using remote sensing imagery and evaluated how different catchments impact the lake CDOM. In addition, we evaluated $\mathrm{CDOM_{RS}}$ at temporal and spatial scales. Although the Landsats’ sensors were not designed for inland water, they showed potential for measuring inland waters properties, such as $\mathrm{CDOM_{RS}}$ concentration. Landsat 5 (TM) has been available since 1984, Landsat 7 (ETM+) started operating in 1999 and Landsat 8 (OLI) has been available since 2013. The results of **Paper I** showed a relatively good potential for mapping inland $\mathrm{CDOM_{RS}}$ concentrations using Landsat and Sentinel-2. Combined time series of lake CDOM were created from data from the Landsat and Sentinel-2 for further analysis, as combining the images enables us to achieve a higher revisit time (**Objective 4**).

4.3.2 Paper Overview

In this paper, we explored how satellite data sources affect the agreement between remotely sensed $\mathrm{CDOM_{RS}}$ and measured the colour (Pt L^{-1}) on the Platinum-Cobalt scale. We used Lake Bolmen (Sweden’s tenth largest lake) as a case study site to demonstrate how a combination of data sources can fill the gaps in the current understanding of how $\mathrm{CDOM_{RS}}$ has varied spatiotemporally over the past decades. Lake Bolmen was chosen for the study because it has several nearby sampling stations with long-term sampling records for the water colour, which show considerable spatial variability in the degree of browning. The water brownification information acquired from satellite data by assessing $\mathrm{CDOM_{RS}}$ over long periods can help us to gain more knowledge about the Bolmen catchment and fill the gap of missing in situ measurements of water colour.

We found that Kendall’s rank correlation coefficient for agreement with the measured colour was around 0.3 in most cases. However, we concluded that using a combination of remote sensing records from Landsat and Sentinel-2 to reconstruct long trends of $\mathrm{CDOM_{RS}}$ in lake water is a promising approach. This study's findings support the work towards understanding lake $\mathrm{CDOM_{RS}}$ variations globally, as at present, the availability of long-term lake monitoring data is only available for limited countries and regions. Satellite remote sensing will help to fill the data gaps for the regions where no in situ data exists.

4.4 **Paper IV**: “Decreasing Organic Carbon Bioreactivity in European Rivers’

4.4.1 Relevance to the Thesis’ Objectives

In the fourth paper, we used organic matter data at the continental scale of Europe from the monitoring programmes of 24 countries using Waterbase, which is Europe's most extensive water quality database compilation. It is available online from the following link: https://www.eea.europa.eu/data-and-maps/data/waterbase-water-quality-2. From the **thematic perspective**, we explored the patterns of organic matter in inland waters in both temporal and spatial scales, focusing on organic matter degradation rates in temperate European rivers (**Objective 3**). We used GIS to create datasets of catchment landcover and river size. The site characteristics of 3,486 EU monitoring rivers were included in the study. We evaluated the most abundant land use in a 1 km radius around each site (agricultural fields, urban/constructed areas or the residual ‘natural’ areas) and river size on a scale from one to ten.

4.4.2 Paper Overview

This paper focuses on European rivers that have experienced an increased loading of total organic carbon (TOC) from terrestrial sources due to land use change, climate and soil acidity. The results showed that the first-order decay coefficient k (share of the carbon lost per day) decreased by two orders of magnitude as a power function of increasing TOC. This relationship could be partly explained by the carbon quality, as the C:N ratio of the organic matter was the lowest in rivers with high reactivity and low TOC and vice versa. Furthermore, the results showed that TOC increased by 18% from 1996 to 2012, whereas k decreased by as much as 50%. Consequently, the biological oxygen demand in the water decreased over time, despite the water browning trend (increased TOC). Together, these results suggest that reactivity is low near terrestrial hot spots for TOC export and during years with high terrestrial TOC loading. However, it increases in rivers with low TOC concentrations where internal processes in the water have a high relative influence on bulk TOC quality. Therefore, the browning of European freshwaters is linked to strong decreases in TOC reactivity on a continental scale, which suggests that the impacts of browning on microbial water deoxygenation and greenhouse gas production are less severe than previously thought.

5 Materials and Methods

5.1 Study Area

The selected study areas vary in the four papers in the thesis. In **Paper I**, 46 lakes were selected in five different districts in Sweden during the summer of 2016 to investigate CDOM in a large variety of lakes. These are as follows: the *Norrbotten* subarctic unproductive landscape, which mainly comprises birch forests, shrublands and bare rocks; *Västerbotten E*, which is characterised by a boreal continuous spruce forest and peat wetlands; and *Västerbotten W* and *Jämtland* districts. All lakes were sampled more than once. The time difference between the satellite image acquisition and the corresponding in situ data collection ranged between one week and ten weeks. We decided to use the data from field campaigns with dates that were close to Sentinel-2A overpasses.

In **Paper II**, 255 boreal lakes in Sweden and Norway were selected to evaluate lake CDOM across broad environmental gradients. Forty-four lakes were located in Nord-Trøndelag in Norway, which has variable land cover with mixed forest, natural grassland, wetlands, moors and heathland. The remaining 211 lakes were located in Sweden along a latitudinal gradient, from an unproductive subarctic landscape in the far north (which mainly comprised birch forest, shrublands and bare rocks) to a relatively productive boreal forest in the south.

In **Paper III,** Lake Bolmen was selected as a study area to reconstruct long-term $CDOM_{RS}$ values using satellite data. Lake Bolmen consists of the following four basins: northern, southern, eastern and western sub-lakes. This is because the island of Bolmsö is located in the middle. The northern part of Lake Bolmen is shallow with an approximate maximum depth of 13 meters. The southern part of Lake Bolmen is deeper compared to the northern part, with a maximum depth of 37 meters. Generally, the land in the Lake Bolmen watershed mainly consists of forests, marshes, wetlands and agriculture land (Persson, 2011). Water sampling from Lake Bolmen started in 1966. Since 1984, the Sydvatten agency has regularly sampled the water colour (mg*Pt/l), total organic carbon (TOC) (mg/l) and turbidity (FNU) at seven sites of Lake Bolmen.

In the **Paper IV**, the study area was extended to the continental level by including 3486 river sites in 24 countries in Europe. This study area has data records from 1973 to 2017. However, the river sites' catchment areas are distributed in different land covers, such as agricultural fields, forests, urban/constructed areas and natural areas.

5.2 Methods of In Situ Measurements of DOM

Water samples for this study were collected by Umeå University (Ecology and Environmental Science Department) from 46 lakes in **Paper I**. The samples were made by pooling water from multiple depths (ca. four to five evenly distributed depths) within the mixed layer above the thermocline at the deepest point of each lake. The water samples were kept cool until their arrival at the laboratory, where the samples were filtered (GF/F = 0.7 µm) and analysed for absorbance using a Jasco V-560 UV/vis spectrophotometer (Easton, MD, USA). The filtered samples were refrigerated for up to one week before absorbance analyses were carried out. The measured absorbance values were converted to $a(420)_{\mathrm{CDOM}}$ in Napierian units (based on a natural logarithm) using the equation $a(420)_{\mathrm{CDOM}} = 2.303D/r$, where D is the measured absorbance and r is the cell path length (in m) (Persson, 2011).

In **Paper III**, in situ samples were collected from Lake Bolmen. The parameter that was used in this study was water colour (mg*Pt/l). Since 1984, samples have been regularly collected by the Sydvatten agency in seven sites of Lake Bolmen. The frequency of the data collection varies depending on the monitoring station. The estimation of the water colour values was made using spectrophotometric measurements in a 5 cm cuvette, according to the international standards (Cuthbert *et al.*, 1992). The measurements were carried out at 420 nm, which is traditionally used in Sweden (https://www.slu.se/en/).

In **Paper IV**, the river data records were extracted for both biological oxygen demand (BOD_5) and TOC measurements and were based on at least three replicate measurements during the year. The BOD_5 was measured as the loss of dissolved oxygen (mg/L) due to organic matter degradation by the ambient microbial community under suppressed nitrification, and the BOD measurements were taken from the five-day 20°C dark incubations (BOD_5). The Waterbase data selection included 7,577 values of total phosphorus (TP), 6,439 of total nitrogen (TN) and 3,850 chlorophyll-a values. In 2,821 cases (26%), we were able to calculate the C:N ratio of the organic matter by dividing the TOC by either the reported total organic nitrogen (when available) or the difference between the TN and the reported total inorganic nitrogen. The BOD was measured using Winkler titration or electronic/optical sensors in a variable number of replicate and blank samples of certain volumes.

In **Paper I,** the remote sensing analysis included the following processes: image download, pre-processing and atmospheric correction. Sentinel-2A level-1 (L1C)

MSI data was downloaded from the Scientific Data Hub (https://scihub.copernicus.eu), which has been developed by ESA. Sentinel-2A images have been available since June 2015. Images were downloaded for dates between June and October 2016. The level-1C product is composed of 100 km^2 tiles that are projected to cartographic coordinates. Per-pixel radiometric measurements were provided in the top of atmosphere (TOA) reflectance with all parameters to transform them into radiances. Level-1C products were resampled with a constant ground sampling distance (GSD) of 10 m, 20 m and 60 m, depending on the native resolution of the different spectral bands. The images from WGS84 UTM zone 33 with 10 m and 20 m resolutions (WGS-84 datum) were used. Sentinel-2 Toolbox (S2TBX) version 2.2.4 in the Sentinel Application Platform (SNAP) version 2.2.3 on Windows 10 (64 bit) was used to process the images. Then, 3x3 cloud-free pixels were extracted from each sampling point situated in the middle of the lake, and the mean values of the pixel windows were used for further analyses. To get the level-2A (L2A) bottom of atmosphere (BoA) reflectance, the Sen2cor atmospheric correction was applied. Some of the images that were used in the study were contaminated with haze and clouds. Therefore, nearby less-affected lake areas near the sampling station were selected manually if the clouds or cloud shadows were above the sampling point.

In **Paper II,** Sentinel-2 data was used to assess lake CDOM for 255 studied lakes using the methodology described in **Paper I**. Briefly, Sentinel-2 satellite observations between June and August of 2016 and 2018 were downloaded from the Copernicus Scientific Data Hub (https://scihub.copernicus.eu). The effects of the atmosphere, cirrus clouds and terrain were removed from the 2016 data using the Sen2Cor module. The 2018 imagery was already available in level 2A (i.e. atmospherically corrected by ESA using Sen2cor). In addition, we used a digital elevation model (DEM) from the Shuttle Radar Topography Mission (SRTM) at a 30-meter spatial resolution (downloaded from https://earthexplorer.usgs.gov) to delineate watersheds.

In **Paper III**, satellite data was imported and processed using the Google Earth Engine (GEE) platform. A series of data from different Landsat satellites was available in the following GEE Landsat (ToA) Tier 1 collections: Landsat 5 ETM, Landsat 7 ETM+ and Landsat 8 OLI. We used Tier 1 data, including Level-1 Precision and Terrain (L1TP) corrected data, that had well-characterised radiometry and were inter-calibrated across the different Landsat instruments. It had the highest available data quality and was considered suitable for the time series analysis. The ToA data was used in previous studies (Kutser, 2012). Kallio et al. demonstrated that atmospheric correction adds uncertainty when the older (4, 5, 7) Landsats are used in lake CDOM mapping. We imported data from the seven study sites in Lake Bolmen in decimal geographic coordinates using GEE clouds. The cloudy pixels were filtered out by applying a mask function for each satellite dataset, and all edge pixels were removed from the site's boundary.

5.3 Data Compilation and GIS Applications

Several sets of data were used from online sources, such as land cover and climate data. The land cover data that was used in **Papers I** and **III** was obtained using the 2000, 2006, 2012 and 2018 CORINE Land Cover (CLC) datasets provided by the Copernicus Land Monitoring Service (https://land.copernicus.eu/pan-european/corine-land-cover). These land dataset covers are inventories of 44 classes and are presented as a cartographic product for most areas of Europe at a scale of 1:100,000. The climate data used in **Paper II** (average air temperature [°C] and precipitation [mm] was downloaded from ERA5-Land (https://doi.org/10.24381/cds.68d2bb30) for June to August of 2016 and 2018. We downloaded the PDI from the Climatic Research Unit (CRU) (https://crudata.uea.ac.uk/cru/data/drought/) for June to August of 2016 and 2018. In **Paper III**, we used the average annual air temperature (°C) and precipitation (mm) from the Swedish Metrological and Hydrological Institute (SMHI; https://www.smhi.se/q/Lund/2693678)from 1984 to 2020. In **Paper II**, the PDI was downloaded from June to August for 2016 and 2018 from the Climatic Research Unit (CRU) (https://crudata.uea.ac.uk/cru/data/drought/). In **Paper IV**, we used data from the online EU monitoring database, which is called Waterbase and maintained by EEA version 2018_1). The annually aggregated version of the database (T_WISE4_AggregatedData: 3.2 million records) was downloaded, which contained the annual mean parameter values from the site monitoring records. The selection resulted in 11,060 records from 1973 to 2017 and provided the annual means of 133,833 individual samples in 3,486 river sites from 24 countries.

GIS techniques were used in different processes in the thesis. In **Paper II**, we used a raster DEM to define the watersheds and drainage networks through an eight-flow direction matrix (D8) analysis. We followed the sequence of analysis steps provided by ArcGIS 10.3.1. Each step involved one of the following neighbourhood analysis operations: fill sinks, slope, aspect, flow direction, flow accumulation, stream link and stream order. These were based on which of the watershed delineations was performed. A set of PCDs for the upstream contribution areas for all watershed and water body (lakes) locations were produced through a diverse set of spatial analyses, which were initially developed by Peters et al. (2007) (Figure 2). The normalised difference vegetation index (NDVI) data (Bianchi *et al.*, 2020) was used to evaluate the landscape vegetation patterns. The NDVI is based on the contrast between absorption in the red band by chlorophyll pigments and reflectance in the near infrared (NIR) band caused by internal scattering within vegetation leaves. The NDVI index was calculated using the ArcGIS 10.3.1 platform using Sentinel-2 data for the summers of 2016 and 2018. In **Paper IV**, the approximation of the total upstream catchment area for each river site coordinate was calculated using ArcGIS 10.5.1 from the EEA database Ecrins Version 1, Jun 2012.

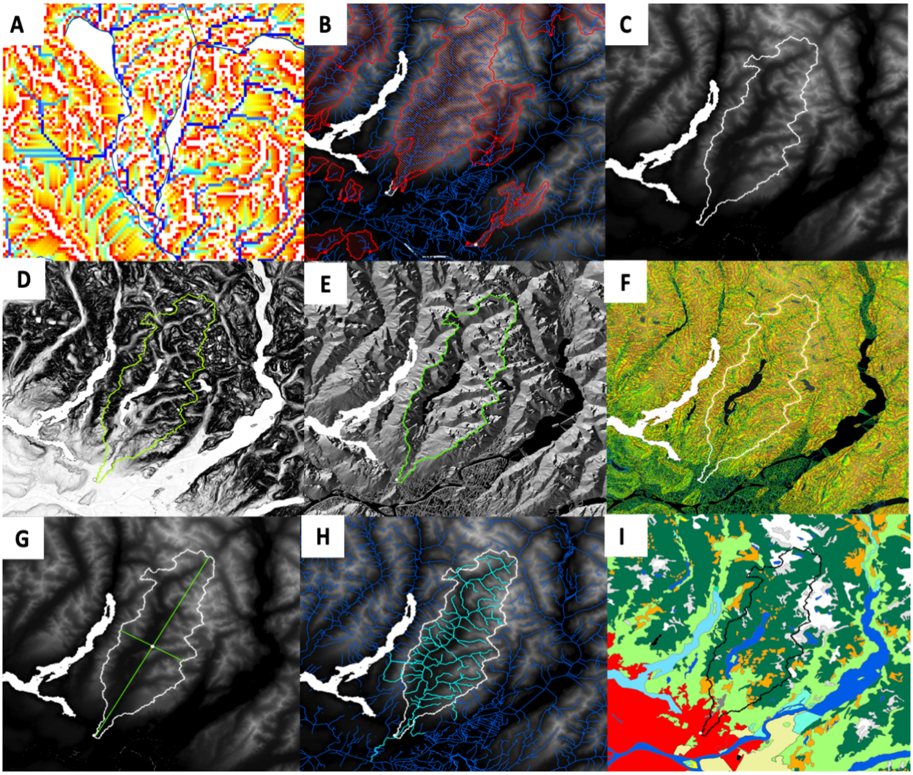

Figure 5 A set of PCDs for the upstream contributing areas: (A, B) Finding sampling locations of watersheds on derived drainage networks; (C) Finding elevation values using standard GIS operations to calculate the statistics; (D) Finding slope values using standard GIS operations to calculate the statistics; **(E)** Finding aspects that are decomposed into (north-south) and (east-west) components to be averaged via a circular statistic; **(F)** Finding the topographic witness index (TWI); **(G)** Calculating the basin perimeter and area from standard operations, finding length and width using outlet and centroid; **(H)** Finding the length of all stream segments within the catchment (removing portions of polylines that cross the boundary) and dividing it by the catchment area to produce a density metric; **(I)** Finding the percentage of disturbed land use per catchment by reclassifying the land cover attributes to reflect whether or not they are included in a particular catchment using tabulate areas of classes within the catchment and calculating the percentage. (Source; Peters et al.,2007)

6 Implications of Results, Syntheses, and Perspectives

This section of the thesis highlights the main implications of the results and summarises the main reflections of the study's perspectives.

6.1 CDOM Variations in Boreal Lakes with Optical Remote Sensing

Monitoring CDOM variations has been a topic of interest in aquatic field. This thesis shows that these studies can benefit from advancements in optical remote sensing that enable lake CDOM to be mapped. The rapid progression of remote sensing instruments allows us to map CDOM in lakes and rivers through better spatial, temporal and radiometric resolutions. Furthermore, the remote sensing image archives are becoming decades long. This allows us to reconstruct CDOM variability for large geographic areas over several decades. We assessed the impact of different drivers, such as topography (catchment characteristics), climate and land cover, on lake CDOM content using land and aquatic remote sensing products (**Figure 6**).

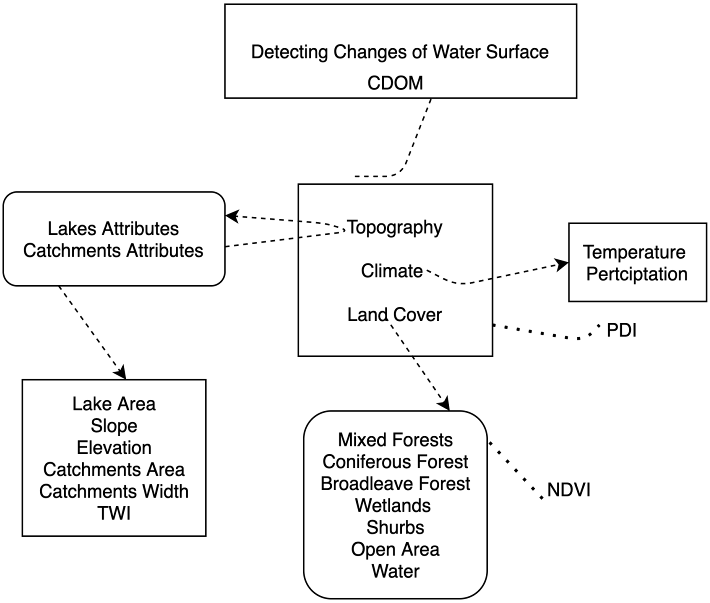

Figure 6 The main drivers affecting the CDOM concentrations in inland waters

6.1.1 Retrieving CDOM at a Large-Scale and Dealing with Atmospheric Artefacts

This thesis demonstrated the efficacy of different band ratios that were produced from Sentinel-2 data to retrieve CDOM concentrations. The relatively high spatial resolution of Sentinel-2 allows us to map CDOM in small bodies of water. In **Paper I**, we evaluated different CDOM retrieval algorithms using Sentinel-2A MSI data for Swedish lakes. The combined catchment area of the lakes was approximately 800 km^2, and it was distributed across large parts of Sweden. We were able to rate the performance of Sen2Cor by comparing the ToA and BoA reflectance spectra (Figure 7).

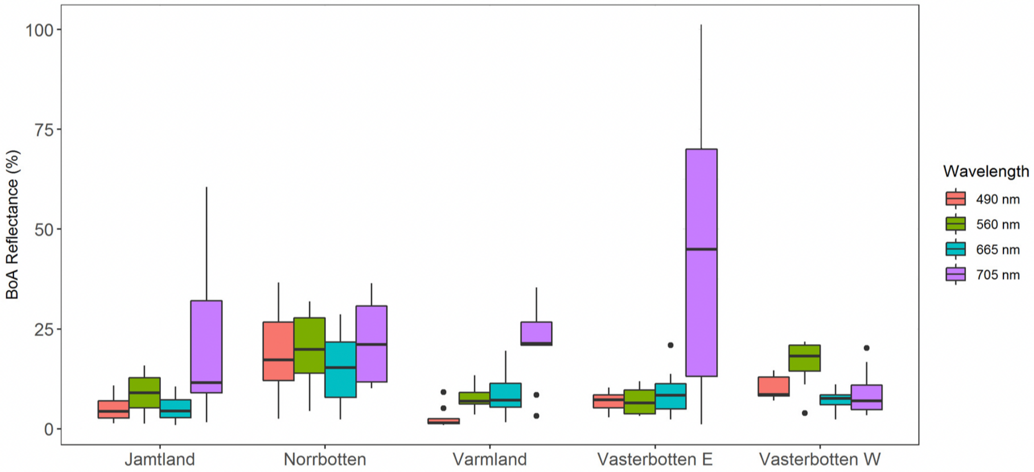

Figure 7 Reflectance spectra of 46 lakes in the five Swedish regions in this study. The reflectance values are BoA reflectance after atmospheric correction (Source; Paper I;(Al-Kharusi et al., 2020))

On a larger scale, when combining multiple images, we found that CDOM retrieval was more successful when atmospheric correction was applied to the imagery. However, Toming *et al.* (2016) found that for Sentinel-2A, CDOM retrieval on the small scale (using a single image) performed better when non-atmospherically corrected imagery was used. We found that atmospheric correction must be applied to avoid unwanted illumination effects that may be larger than the variability in water parameters. The green/red band ratios explained a relatively high proportion of the variance in CDOM ($R^2 = 0.65$) after the removal of outliers that were strongly affected by atmospheric conditions, such as haze and thin cirrus clouds. These outliers were not detected during the initial screening process, in which we removed the lakes that were completely covered by clouds because they contained cirrus clouds and haze that were harder to detect with the naked eye. Therefore, they were removed in the secondary, more detailed inspection.

As the main aim of **Paper I** was to test the efficiency of the MSI sensor for mapping CDOM concentrations at large scales, rather than developing a new algorithm, we applied the final model of the green/red band ratios. We evaluated the added value of using Sen2Cor by comparing the in situ and modelled CDOM before and after atmospheric correction using the green/red band ratios. CDOM has similar patterns and ranges across the study regions for the modelled and in situ measurements (Figure 8). Based on this analysis, we found that atmospheric correction generally worked well, and the algorithm performance was evaluated using a repeated *k*-fold cross-validation to obtain more reasonable estimates of model coefficients. The findings of **Paper I** demonstrate the effectiveness of Sentinel-2 data in retrieving lake CDOM over a wide range of waters that are situated in complex environments. It is especially useful in the case of inaccessible regions that are not well monitored. In **Paper II**, we extended the CDOM retrieval to about 255 boreal lakes that were located in Sweden and Norway.

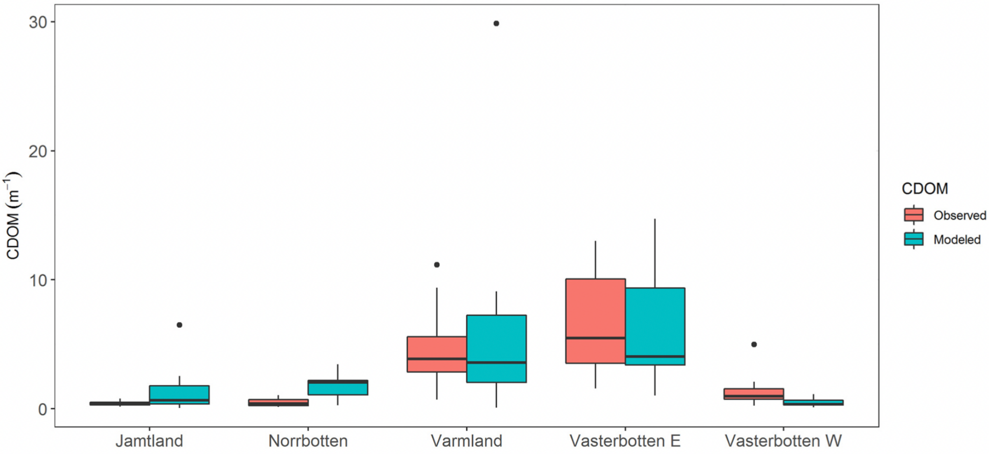

Figure 8 CDOM absorption coefficient at 420 nm, calculated from Sentinel-2A data and water samples, based on the results from 41 Swedish lakes (Source; Paper I;(Al-Kharusi et al., 2020).

6.1.2 Spatial and Temporal Variability of CDOM

The results of **Papers I** and **II** showed that CDOM concentrations vary in a wide range of complex freshwater systems. This is probably caused by highly variable catchment characteristics (e.g. vegetation type, density or land cover variety). Previous studies found that surrounding sources of carbon (e.g. vegetation and soils) enhance the CDOM values in lake water (Boyle *et al.*, 2009; Williams *et al.*, 2010; Li *et al.*, 2018). Our study area consisted of a mixture of wetlands that were significantly represented in the total catchment area and other areas that were dominated by a mixture of broadleaf and coniferous forests, which could further explain the high values of CDOM in those regions (Boyle *et al.*, 2009; Williams *et al.*, 2010; Li *et al.*, 2018). On the other hand, some parts of the study area had a low percentage of forest and were mostly covered by herbaceous cover, which could be the reason for the low CDOM levels that were found in this region and the more transparent water compared to other regions.

Moreover, several areas that were covered in this thesis had a large proportion of mixed forest and herbaceous cover, which could explain why CDOM at the edges of the lakes in this region had higher values than those found at lake centres. Overall, the lakes in the areas that were surrounded by different types of mixed, broadleaf and coniferous forests and wetlands had the highest levels of CDOM compared to the lakes that were surrounded by herbaceous vegetation or heathlands. A potential problem with our analysis in **Paper I** is that there was a mismatch of up to approximately ten weeks between the field sampling date and the date of acquisition of a cloud-free image that was suitable for the analysis. However, (Maie *et al.*, 2006) suggested that such a time difference would not significantly affect the relationship between the measured and remotely sensed CDOM if there were no phytoplankton blooms or massive influxes of water (due to the heavy rain) into the lake. In our case, the timing was adequate, which was justified by the fact that our model was able to explain 65% of the variability in CDOM, which is relatively high compared to other studies (Kutser *et al.*, 2016; Toming *et al.*, 2016) that used Sentinel-2 data. This can be explained by the stability of weather between the in situ sampling, image acquisition and type of lake. Moreover, in boreal headwater lakes, the CDOM only varies marginally during the summer (Kutser *et al.*, 2016; Toming *et al.*, 2016).

6.1.3 Regulations of CDOM by Ecosystem and Climate Drivers

One of the key objectives of this thesis was to explore the influence of different drivers on the CDOM concentration in boreal areas across large gradients and geographic scales with varying climate statuses. In **Paper II,** we discussed the effects that climate, land cover and catchment morphology have on the patterns of lake CDOM during both dry and wet conditions and their implications in the context of climate change (Figure 9). Although we hypothesised shifts in the importance of different types of regulations of CDOM depending on the drought intensity, the results showed that all studied variable categories – climate, land cover and morphology – had a stronger impact on CDOM in the wet year vs. the dry year.

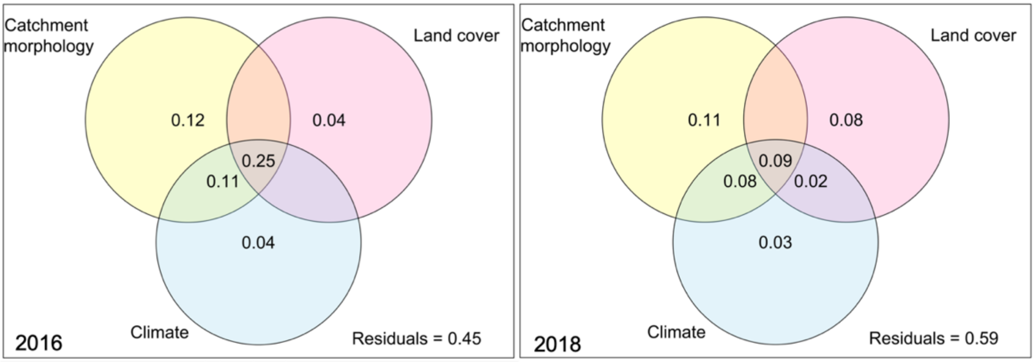

Figure 9 Variance partitioning of CDOM for the categories' catchment morphology (16 variables), land cover (11 variables) and climate (three variables) in 2016 and 2018. The total adjusted was R2 = 0.56 and 0.41 in 2016 and 2018, respectively. The partitioning of the adjusted R^2 is shown in the graph. Insignificant values are not shown (Source;Paper II)

The variance partitioning results did not support the hypothesised shift from land cover control during wet conditions to climate control during drought. Instead, the variance that was explained by all variable categories, except land cover, decreased from the wet year to the dry year. One reason for this could be that the catchment influence on lake CDOM is more strongly expressed during wet conditions, when the lakes are more hydrologically connected to their surroundings. Furthermore, the results agree with the past findings of temperature-driven increases in the production of soil carbon and transfer of carbon to boreal lakes (Berggren *et al.*, 2018). Since the temperature-dependent microbial degradation does not usually remove a larger fraction of the DOM during its transit through boreal lakes, climatic effects of the internal turnover of CDOM in the lakes may not have been of major importance. This may vary with water residence times (Jonsson *et al.*, 2001; Berggren *et al.*, 2018).

The results of **Paper II** stress the importance of wet conditions for the controls of climate, land cover and morphometry on lake CDOM. Although the total land cover influence on CDOM decreased as expected from the wet year to the dry year, the variance partitioning unexpectedly showed that land cover explained slightly more unique CDOM variability during dry conditions because a high accumulation of the soil's organic carbon occurs in wetlands' catchments. These have large water reserves and can export even greater DOM concentrations during base flow (Jonsson *et al.*, 2001; Berggren *et al.*, 2018). Under the morphology driver, the lake area has a negative impact on CDOM variations. As a result of the data analysis **in Paper II**, there was a negative correlation between CDOM and lake area in the dry year of 2018. However, no such direct relationship was found in the wet year of 2016. The role of the lake area as a regulator of CDOM, where the biggest lakes have the highest offset in CDOM and lower concentrations during drought, is a key result that supports the stipulated importance of hydrological connectivity.

Overall, the results of **Paper II** highlighted that CDOM variations during drought are relatively difficult to predict, which implies that drought not only offsets CDOM toward lower values but also weakens its regulation with a wide range of factors (Figure 10). This finding agrees with previous results that point to disrupted linkages between lake waters and catchments during periods of drought (Laudon *et al.*, 2012).

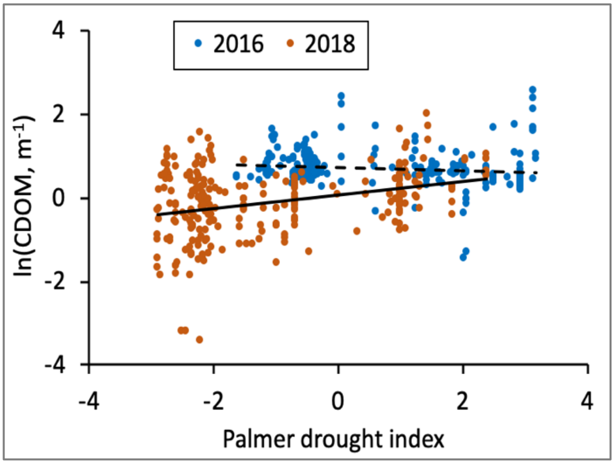

Figure 10 Relationship between ln-transformed CDOM (m-1) and PDI (y = 0.1677x + 0.0652; R2 = 0.11; p < 0.0001) for all regions in the dry summer season of 2018. In the wet year of 2016, there was no significant relationship (Source;Paper II).

This suggests that variations in the PDI do not affect CDOM; rather, it is the anomaly in the PDI during an unusually dry period that affects CDOM. During the dry year of 2018, the degree of drought (more negative PDI) caused decreased lake CDOM, whereas no significant direct impact on PDI was observed during the wet year of 2016. Drought is known to affect the hydrological connectivity between catchments and recipient freshwaters as a result of a sequential decline in precipitation, soil moisture, groundwater levels, runoff and streamflow (Szkokan-Emilson *et al.*, 2017). Water and DOM normally move laterally from upstream to downstream, whereas the streams are connected hydrologically with the riparian zone and vertically with the hyporheic zone and groundwater (Lake, 2003). In this way, water bodies can be disconnected from their surroundings with reduced water flow, which has several consequences for the water quality and habitats (Lake, 2003). Additionally, during drought, a larger part of the hydrological input to lakes may be in the form of deeper groundwater, which is known to dilute DOM (Lake, 2003; Vazquez *et al.*, 2011; Szkokan-Emilson *et al.*, 2017).

6.1.4 Thresholding in CDOM in Changing Climate

Paper II of this study shows how a warmer climate can affect lake CDOM concentrations during a wet year, whereas increased drought can temporarily decrease values as upland carbon sources are temporarily disconnected from the hydrological system (Tiwari *et al.*, 2017). Drought has a major impact on terrestrial microbial activities, with wide-ranging impacts on carbon and nutrient cycling and plant production (Szkokan-Emilson *et al.*, 2017). Low soil moisture can stress microorganisms, restrict key enzymes involved in soil organic matter processing and leach DOM and nutrients from litter (Xiao *et al.*, 2018), thus decreasing the potential for the export of constituents (including CDOM) from soils to streams. However, drought may not only limit the hydrological delivery of DOM and CDOM to lakes; it can also decrease the production and mobilisation of DOM in the catchment, which helps to explain why the lake CDOM was significantly lower during the year of the drought, particularly in the most severely impacted areas. The results suggest that when a wet period follows a dry period, CDOM can quickly increase and could become even higher than it was before the dry period (Toberman *et al.*, 2008; Wu *et al.*, 2018). Therefore, climate changes can result in changes to the hydrology, vegetation type and productivity, which leads to greater intra-annual variations in the CDOM of recipient waters.

6.1.5 Reconstructed and Integrated CDOM Using Landsat and Sentinel-2

An overarching objective of this thesis was to take advantage of remote sensing sensors (satellites) to fill the gaps of missing data of CDOM over the last decades. We tested whether a combination of different satellite records could be used to accurately detect whether brownification had occurred over the last few decades. The main findings of **Paper III** show that remote sensing allows the CDOM patterns and trends across the study area of Lake Bolmen to be reconstructed. (Tank *et al.*, 2018)) showed that using the TOA radiance rather than the BoA reflectance worked better for low sensitivity sensors, such as Landsats 4–7. However, our results show that atmospherically corrected imagery provides better results when more sensitive sensors, such as Landsat-8 and Sentinel-2, are used.

The Mann-Kendall (MK) trend analysis was applied to test the $\mathrm{CDOM_{RS}}$ trend in **Paper III**. The results showed statistically significant increasing trends in almost all stations in Lake Bolmen. Additionally, in most cases, Kendall's rank correlation coefficient for agreement with the measured colour was around 0.3. The results demonstrated that using a combination of remote sensing records from Landsat and Sentinel-2 to reconstruct a long trend of CDOM in Lake Bolmen is a promising approach.

6.2 Water Brownification in Temperate Rivers

6.2.1 Organic Matter on a Continental Scale

Moving from a regional to a continental scale provides another perspective in addressing the water variations of CDOM. European rivers experience increased loading of TOC from terrestrial sources due to factors involving changes to the land use, climate and soil acidity (Skjelkvåle *et al.*, 2005; Monteith *et al.*, 2007; Hruška *et al.*, 2009)**.** Although the rivers studied in Paper IV are distributed over millions of square kilometres, they are not necessarily representative of rivers in other regions with fundamentally different climates and vegetation. In contrast, the results agree with a large-scale survey of approximately 400 unproductive rivers and lakes in boreal Québec, where the DOC was equally bio reactive, regardless of how brown, organic and carbon-rich the water was (Lapierre *et al.*, 2013). In boreal regions (addressed in **Papers I** and **II**), the TOC is overwhelmingly influenced by the export from the natural terrestrial landscape (Algesten *et al.*, 2004). Additionally, because the ecosystems are unproductive, it only takes a small amount of terrestrial carbon to dominate the bulk pool of organic matter (Algesten *et al.*, 2004). Moreover, the impact of urban and agricultural areas on organic carbon reactivity is small in northern boreal and subarctic rivers (Soares *et al.*, 2019). Therefore, the impact of terrestrial plant sources dominate the TOC in many freshwaters (Soares *et al.*, 2019). However, when coloured DOC appears in low concentrations relative to chlorophyll-a, the relative importance of the internal loading of organic matter from algal sources increases (Bade *et al.*, 2007). Therefore, the observed high reactivity of TOC at low concentrations could be due to relatively large contributions of reactive and nitrogen rich algal organic matter.

In Paper IV, we studied river width and upstream areas from the catchment morphology to test any significant relationships or influences from catchment characteristics on water parameters. The results showed that the median river had a width of slightly above 10 m and a catchment area of approximately 600 km^2 (Figure 4A). Apparent outliers in the relationship between the river catchment area and width typically occurred when the sampling point was near a small river that discharged into a larger river. The river width or catchment area did not significantly correlate with k (the first-order decay coefficient) or any of the water chemistry variables, except for chlorophyll-a. The site's mean chlorophyll-a increased more than 10-fold along a power function of increasing catchment size (Figure 4B; $R^2 = 0.12$), from values of around 2 µg L^{-1} in the smallest catchment to values of around 20 µg L^{-1} in the largest catchments.

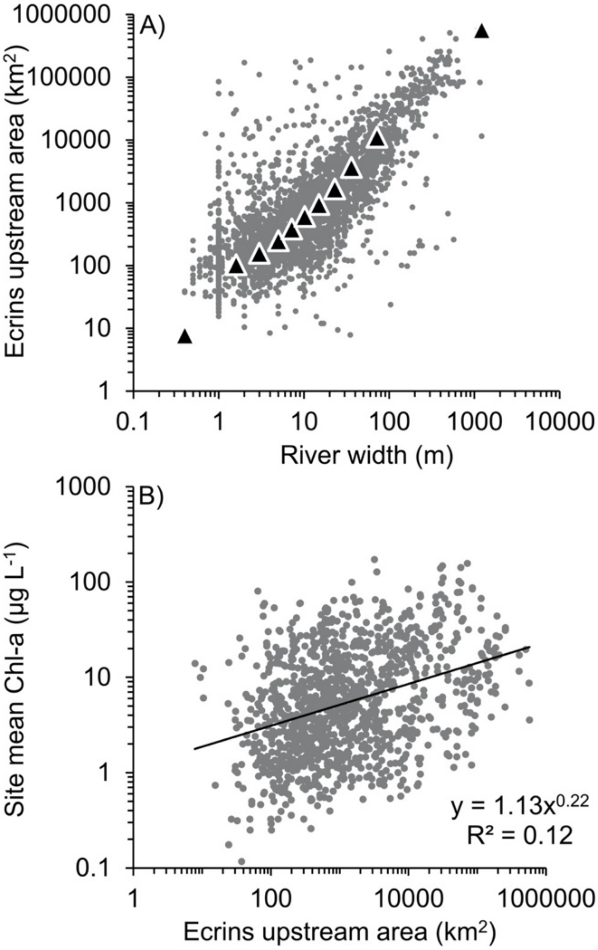

Figure 11 a) Upstream catchment area according to the Ecrins database of the 3,205 study sites with known coordinates plotted against the river width (filled circles). The triangles show every tenth percentile of the respective distributions. b) The power relationship between the site's mean chlorophyll-a and Ecrins upstream catchment area (n = 1163). Note the logarithmic axes. (Source;Paper IV; (Berggren and Al-Kharusi, 2020)

6.2.2 Changes in the Bioreactivity of Organic Matter in Rivers

Previous continental-scale analyses of the EU monitoring database have shown that the total and inorganic nitrogen and phosphorus in rivers have either stayed at the same levels or decreased over the last couple of decades (EEA, 2015). Combining the findings of **Paper IV** with the general increases in coloured terrestrially-derived organic carbon in European freshwaters (Bade *et al.*, 2007) could show that the source of the TOC has gradually shifted from internal nutrient-boosted production by algae to external loading from the terrestrial environment, which suggests a major and systematic shift in the source and quality of the TOC. Moreover, improved wastewater treatment and mitigation measures to reduce organic matter leaching from agricultural fields (EEA, 2015; Skjelkvåle *et al.*, 2005) could have further contributed to the decreasing concentrations of reactive TOC. The k (the first-order decay coefficient) decreased by two orders of magnitude as a power function of increasing TOC. This relationship could be partly explained by the carbon quality, as the C:N ratio of the organic matter was the lowest in rivers that had high reactivity and low TOC rivers, and vice versa. A trend analysis showed that TOC increased by 18% from 1996 to 2012, whereas k decreased by as much as 50%. Consequently, the biological oxygen demand in the water decreased over time, despite the water 'browning' trend. The results of **Paper IV** suggest that the reactivity is low near terrestrial hot spots for TOC export and during years with high terrestrial TOC loading. However, it increases in rivers with low TOC concentrations where internal processes in the water have a high relative influence on the bulk TOC quality. Therefore, the browning of European freshwaters is linked to strong decreases in TOC reactivity on a continental scale, which suggests that the impacts of browning on water deoxygenation and greenhouse gas production may be less severe than previously thought.

7 Conclusion and Final Remarks

In this thesis, we used CDOM as a measure of water brownification. The results of this thesis show that lake CDOM can be mapped from space over a wide variety of lakes. This allows us to improve our knowledge about inland waters and discover how they are linked to their catchments. The results that were obtained for a wide range of lakes in different landscape settings demonstrate the broadly applicable green/red spectral ratio-based algorithms in the retrieval of $CDOM_{420}$ from Sentinel-2 data (**Papers I** and **II**). Additionally, the results show that there is a high potential to integrate different sensors (Landsat 5,7 and 8 and Sentinel-2) and improve the capability to reveal CDOM changes and potential trends over the past four decades (**Paper III**).

It was demonstrated that combining remote sensing and GIS tools is an effective way to reveal the impact of different catchment parameters on lake CDOM concentration (**Paper II**). Furthermore, in **Paper IV,** GIS helped to estimate the upstream area to investigate the quality of organic matter for each river on a continental scale.

The main results of the thesis can be summarised as follows:

Paper I demonstrate the effective use of Sentinel-2 MSI for mapping a wide range of inland waters that are situated in complex and inaccessible regions that are not well-monitored. The finding of this study could be used to map the regions that are the most sensitive to water brownification, and therefore, potentially in need of adapted management regarding land use and fishing practices on a landscape scale.

Paper II shows how climate changes (from wet to dry) can result in a combination of changes in hydrology, vegetation type and productivity, which can lead to intra-annual variations in the CDOM of recipient waters. The increased drought can temporarily decrease values of CDOM in boreal lakes, as upland carbon sources are temporarily disconnected from the hydrological system. When a wet period follows a dry period, CDOM could quickly increase and become higher than it was before the dry period. The projected future climate, with more extreme alternations between dry and wet periods, will likely cause increasing variability in CDOM, which in turn, may result in major and nonlinear changes in important lake ecosystem functions, such as gross primary production and fish biomass. Considering that some lakes are the main sources of potable water for nearby residents, this might lead to greater costs for drinking water treatment, since large variations in CDOM imply a need to implement different treatment protocols to improve the water quality.

Paper III suggests that retrieving long-term records of $\mathrm{CDOM_{RS}}$ optically from the last few decades is a successful approach to fill the gaps of the missing $\mathrm{CDOM_{RS}}$ lake data from in situ assessments. New satellites, such as Landsat-8 (OLI) and Sentinel-2 (MSI), provide more accurate temporal estimates (increase the number of revisits) of lake $\mathrm{CDOM_{RS}}$. However, they have short data records. Combining the results of earlier satellites, such as Landsat 5 TM, Landsat 7 ETM+ and Landsat 8 OLI, with Sentinel-2 MSI allows us to create an almost four-decade long data series and provides us with information about the changes that occur in Lake Bolmen over wide geographic areas. This is especially important because in situ data series from lakes are extremely rare for long records.

Paper IV demonstrates that the first-order decay constant in 3,486 European rivers is negatively correlated with TOC concentrations and the C:N ratio of the organic matter. Additionally, the reactivity has decreased by half during the years 1996–2012, which correlates with the ongoing water browning trend. The outcome of the study points to an unexplored potential benefit of monitoring the data to address patterns and trends in organic matter reactivity on the continental scale.

8 Outlook and Future Work

8.1 Personal Reflection

The findings of this thesis leave several questions unanswered, which has inspired me to think critically about possible future research regarding water brownification. It is important to determine and control non-point factors/sources of organic matter as part of an efficient strategy for watershed management to minimise the load of organic matter on surface waters. To predict the spatial patterns of brownification in varied surface waters, a distributed modelling approach is required. More applied research needs to be done in this context to address the common problems of water brownification connected to the water flow into the terrestrial area using a variety of hydrogeological modelling approaches.

Nonetheless, to support the achievement of the Sustainable Development Goal (SDG6): Water and Sanitation for all by 2030, we need to utilise advanced models to understand how extreme climate conditions, such as drought, can be related to unstable changes in inland water functions, services, and biodiversity loss.

8.2 Research Needs

First, to obtain realistic future projections about the interface between terrestrial and aquatic ecosystems with respect to CDOM, we need to conduct further research on CDOM quantities in inland waters to gain a better understanding of northern boreal catchments. Focusing on how streamflow regimes of similar catchments diverge and observing how hydrological behaviour is linked to landscape features under certain present and changing climate conditions are vital. Insights from hydro ecological models can provide a framework to conceptualise and investigate the relationships between climate, landscape and water resources in more detail. In this regard, we can run hydro ecological modelling, such as the Regional Hydro-Ecological Simulation System (RHESSys) and the Soil and Water Assessment Tool (SWAT). RHESSys is a distributed physical-based model that requires a large data input to provide useful results, and it is unusual in its ability to model catchment water, carbon, nitrogen and energy in a distributed fashion. The structure of both RHESSys and SWAT consists of a GIS drive approach, which is capable of organising the spatial information describing a catchment to allow insights into how key processes function on a spatial basis. In both cases, spatial data is required to instantiate the landscape object hierarchy and construct a spatially distributed object representation of the catchment. The spatial heterogeneity of the watershed can be considered when using the SWAT model with an appropriate soil profile. Additionally, the runoff of the surface is routed with the hydrological network channels to the main basin, which will help to predict the source of water brownification in large measurements.

Second, there is still a need to improve the methods to achieve a more accurate retrieval of water quality parameters. The recently launched satellites (Sentinel-2 and Landsat-8) have high spatial resolutions that were not offered by previous satellites. When combined (two Sentinel-2 and one Landsat-8), they provide a relatively high revisit time. However, they were not designed for aquatic remote sensing. Therefore, the development of methods (atmospheric correction and the retrieval of water constituents) to utilise these sensors in aquatic research and monitoring is still in early stages. The use of optical remote sensing (that can provide us with information on water properties) is limited to cloud-free days. Therefore, in my opinion, there is a crucial need to fill data gaps by utilising unmanned airborne vehicles (UAVs) and automated in-water automatic measuring stations and combining them with models and satellite data to monitor the sensitive areas of inland and coastal waters.

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Insights from Remote Sensing and GIS

From pixel to the observation of changes in surface water - This thesis raises the stakes of the capabilities of remote sensing data integrated with GIS applications to extend the explanation of change in colour patterns of inland surface waters to a broad scale and in response to climate changes, surface runoff and land cover/use changes. Knowledge of these space and time changes are needed to understand the nature of surface water changing (e.g., water browning), that has important consequences for carbon budgets and greenhouse gases in the ecosystems.

”Land, water and the sky are interconnected in an entrenched way that any changes in one will impact the others, hence affect our lives. It is a necessity that we further understand and study these interconnections, by maximizing our use of Remote Sensing technologies, that have become our observing eye on Planet Earth.” **Enass Said**

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