sweden water research

SYDVATTEN

LUND UNIVERSITY

Lake Bolmen

Past, present and future

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Sammanfattning

Globalt har mänskliga aktiviteter påverkat sjöar negativt genom försämring av sjöars vattenkvalité, där dricksvatten har identifierats som en viktig resurs som hotas av framtida effekter av klimatförändringar och andra storskaliga globala hot. Bolmen är en sjö av stort intresse och värde på grund av de ekosystemtjänster som sjön tillhandahåller, exempelvis vatten till dricksvatten till sju kommuner i Skåne. Flera vattenkvalitéparametrar har blivit identifierade och analyserade utifrån tre fokuspunkter som består av tre storskaliga globala hot, brunifiering, eutrofiering (övergödning) och klimatförändring. Parametrarna som analyseras är siktdjup, vattenfärg, turbiditet, totalt kväve, total fosfor, total organiskt kol, syre, alkalinitet, konduktivitet, pH, klorofyll *a* och vattentemperatur.

Klimatförändring, brunifiering och eutrofiering är hot som påverkar resursanvändning, biodiversitet och ekosystemfunktioner. Ökande vattenfärg är en generell trend i många vatten i boreala, tempererade regioner, något som kan påverka akvatiska ekosystem och ekosystemtjänster negativt. Eutrofiering leder till en ökad näringsinput i akvatiska system som leder till en intensifiering av biologisk aktivitet i det akvatiska systemet, vilket i sin tur kan leda till signifikanta förändringar i komposition och struktur i akvatiska ekosystem samt påverkar alg tillväxt. Klimatförändring har en negativ påverkan på våra akvatiska ekosystem och vattenkemi. Vattenresurser påverkas redan av klimatförändring, brunifiering och eutrofiering, något som hotar framtida produktion av dricksvatten och dricksvattentäkter.

Syftet med den här rapporten är att visa nuvarande status och trender i vattenkemi för sjön Bolmen, genom att sammanställa övervakningsdata från 1966 till 2018. På grund av stor variation i vattenkemi mellan den södra och norra bassängen i sjön Bolmen så behandlas de separat.

Den norra delen är brunare och mer eutrof än den södra delen av sjön Bolmen, med högre värden av klorofyll *a*, konduktivitet, vattenfärg och total fosfor och lägre värden för siktdjup. Huvudinflödet till sjön Bolmen, Storån, flödar in i den norra delen av sjön. Storåns vatten påverkas av jordbruksmark, skogsmark och kärr- och myrmark innan Storåns vatten kommer in i Bolmen, vilket kan vara en av anledningarna till högre färgvärden och näringsämnen i den norra delen av sjön då Storåns vatten är brunt och näringsrikt.

Dricksvattenproduktionen hotas av brunifiering och eutrofiering av sjön Bolmen, vilket kan påverka sjöns framtida lämplighet som dricksvattentäkt. Klorofyll *a* har visat en ökande trend i Bolmen, med relativt höga värden i den norra delen, men total biomassa av cyanobakterier (blågrönalger) har inte varit särskilt hög. Det sker ingen ökning av totalt kväve eller totalt fosfor, vilket leder till att klorofyll *a* troligtvis kommer sjunka inom en snar framtid. Vattenfärg har sjunkit under de senaste 10 åren och med en sjunkande trend så verkar inte brunifiering av Bolmens vatten vara något omedelbart hot. Sjön Bolmens framtid som dricksvattentäkt ser därmed lovande ut.

Trots att det inte verkar finnas något omedelbart hot, sett till vattenkvalitén i Bolmen, så är det ändå av stor vikt att vara uppmärksam på förändringar i sjön eftersom eventuella ökningar i alg-tillväxt och vattenfärg utgör ett hot mot användningen av råvatten som dricksvatten. **Därav är det av stor vikt, och en stark rekommendation, att fortsätta övervaka parametrarna vattenfärg, klorofyll a, cyanobakterier, kväve och fosfor för att få en tidig varning om de positiva trenderna skulle avstanna eller på annat sätt förändras.**

Introduction

Human activities, for example urban settlement, forestry, recreation and agriculture, have affected lakes negatively worldwide by deteriorating the lake water quality. Attention worldwide is now focused on the sustainability of lake environments and diverse approaches to lake restoration are being made to improve water quality (Bakker et al. 2016; Stroom & Kardinaal, 2016; Desta et al. 2017; Gal & Zohary, 2017; Janssen, 2019).

Several recent investigations, conducted by the Swedish government, have identified drinking water as an important resource that is at risk from future effects of climate change (SOU, 2015; SOU, 2016). Surface water is an important resource in Sweden, producing approximately 50% of all drinking water, whereas the other 50% is divided equally between natural and artificial ground water (Boholm & Prutzer, 2017). Natural ground water comes from natural ground water reservoirs, whereas artificial ground water is produced by infiltration of surface water through a land gravel layer. Drinking water and wastewater are generally transported through communal infrastructure, except in less populated areas. Were communal infrastructure is not available, private facilities for drinking water and waste water are needed. More than a million permanent residents and approximately equally as many part-time residents have private facilities is Sweden. However, most citizens in Sweden live in urban and peri-urban surroundings thus have access to communal infrastructure and water provided by their municipality (Boholm & Prutzer, 2017).

Lake Bolmen is a lake of considerable interest and value due to the ecosystem services it provides, for example it acts as a drinking water reservoir and sustain commercial fishing and recreation. Seven municipalities in Scania are dependent on water from Lake Bolmen. Water from Lake Bolmen has been used since 1987 when the Bolmen Water Tunnel (Bolmentunneln) was constructed and taken into service. Water is transported from Lake Bolmen, through the Bolmen Water Tunnel to be discharged at the waterworks Ringsjöverket in Scania where water is treated to become drinking water (Persson, 2011). When the raw water from Lake Bolmen has been treated, it provides the municipalities Eslöv, Helsingborg, Höganäs, Kävlinge, Landskrona, Lomma, Lund and Svalöv, as well as small parts of Malmö and Staffanstorp municipalities with drinking water (Vatteninformationssystemet Sverige VISS, 2019). In regard to Scania’s long-term water supply, raw water from Lake Bolmen is essential.

Focus points and parameters

For this report three threats to the drinking water quality of Lake Bolmen are in focus, including *brownification*, *eutrophication* and *climate change*.

To cover the effects of the three threats mentioned above, several variables have been selected for deeper analysis, including Secchi depth, water color, turbidity, total nitrogen, total phosphorus, total organic carbon (TOC), oxygen, alkalinity, conductivity, pH, chlorophyll a, cyanobacteria and temperature (Table 1). For detailed information about chosen parameters, see Appendix 1 *Parameters of interest.*

Table 1 Parameters of interest seen to the three focus points brownification, eutrophication and climate change.

Parameters of interest seen to		
Brownification	**Eutrophication**	**Climate change**
Water color	Conductivity	Water temperature
TOC (total organic carbon)	Total phosphorus	Oxygen (surface and bottom)
Turbidity	Total nitrogen	
Secchi depth	Chlorophyll a & Cyanobacteria	
pH	Turbidity	
Alkalinity	Secchi depth	
	Oxygen (surface and bottom)	

Brownification

Many lakes and running waters in the Northern hemisphere have problems with drastically increasing water color (Monteith et al. 2007; Haaland et al. 2010) which has been linked with the gradual, long-term increased concentrations of dissolved organic carbon (DOM) in freshwater systems (Clark et al. 2010). Several drivers behind this phenomenon have been attributed to increasing temperatures, reduced acid deposition, changes in land-use and hydrological factors (Hongve et al. 2004; Monteith et al. 2007; Ekström et al. 2011; Ekström et al. 2016; Lenard & Ejankowski, 2017; Kritzberg, 2017, Kritzberg et al. 2019).

Increasing water color is a general trend in many freshwaters (Figure 1) in boreal, temperate regions, sometimes referred to as brownification (Pound et al. 2013). This process of increased water color has ecological as well as societal consequences which might affect the structure and function of aquatic ecosystems (Chow et al. 2007). Increased water color can, for example, affect the recreational value of the lake, reduce the light entering the water, affect the fish community and the potential to use the lake as a drinking water reservoir. Hence, TOC, color and Secchi depth are important parameters to monitor.

Figure 1 Brown looking water in the south part of Lake Bolmen. Photo: Odensjö, Anna Borgström

Eutrophication

For decades, water quality of freshwater lakes have been deteriorating due to anthropogenic activities leading to negative impact on both biodiversity and the use of lakes as a water resource (Søndergaard and Jeppesen 2007). The main problem facing many surface waters is cultural eutrophication. Eutrophication, due to nutrient enrichment, causes an intensification of biological activity in the system which can lead to significant changes in the composition and structure of aquatic ecosystems and to algal blooms. Eutrophication usually results in a shift in the algal community and an increase in the occurrence and concentration of nuisance algal blooms. When it comes to eutrophic freshwater lakes, harmful cyanobacteria are usually dominating which is an increasing problem that affects ecosystem, recreation as well as human and animal health (Kosten et al. 2012).

Symptoms of eutrophication in freshwaters may also be intensified by climate change, and nutrient control will have to be intensified to improve water quality (Trolle et al. 2011). Changes in rainfall patterns, temperature, intensified storms and melting glaciers are all caused by climate change and it will increase the nutrient loading to waters globally (Jeppesen et al. 2011). Nutrient inputs, often phosphorus and nitrogen, will have to be reduced in order to reduce the effect of eutrophication. Thus, total phosphorus, total nitrogen, conductivity, alkalinity, chlorophyll a, cyanobacteria, oxygen and temperature are of importance to monitor in lakes and will therefore be addressed as diagnostic variables for eutrophication in this report.

Climate change

There are several anthropogenic impacts that affect climate change which in turn can affect the water quality of lakes. The climate has been proven to have a direct influence on temperature distributions, nutrient loadings, phytoplankton abundance and the water chemistry of lakes (Mooij et al. 2005; Jeppesen et al. 2009).

Water resources are already today affected by climate change, endangering future supplies of drinking water and future climate warming are estimated to exacerbate the effects (SOU, 2015). There are several different types of risks that are related to climate change, including threats to ecosystem services, such as using a lake as a drinking water reservoir and for recreation, but also to animal and human health. Extreme weather events, sea-level rise and environmental degradation all pose a risk to human health (Boholm & Prutzer, 2017), where the continuing provisioning of clean drinking water creates a worldwide problem (Wheeler and von Braun, 2013). According to The Intergovernmental Panel on Climate Change (IPCC), increased heavy rainfall, increasing temperatures (Figure 2), drought and more frequent natural hazards will affect both the availability and quality of drinking water. Water quality will most likely decrease with rising water temperatures due to increased thermal stability and altered mixing patterns in lakes, consequently reducing oxygen concentrations and increasing the release of phosphorus from the sediments to the water (Bates et al. 2008). These changes may exacerbate water pollution (including sediment,

Figure 2 Lake Bolmen in mid-February 2020. There is generally ice on the lake during February, which was not the case in February 2020. Photo: Western part of Lake Bolmen, Anna Borgström

nutrients, pesticides, salt, pathogens and dissolved organic carbon) and thermal pollution with risks of negative effects on the reliability and operating costs of water systems, ecosystems and human health (Bates et al. 2008). These changes may promote the growth of microbes, such as bacteria and algae in the water, thus increasing the risk of outbreaks of waterborne diseases and algal blooms (Hall et al. 2002; Kumagai et al. 2003; McMichael et al. 2006; Delpla et al. 2009).

Synergies between focus points

Brownification, eutrophication and climate change are large-scale environmental changes that can interact, which in turn can lead to synergistic effects, hence the interaction between large-scale environmental changes can produce a combined effect which might be greater than their separate effects. Kosten et al (2012) show that nutrients and climate can act synergistically to benefit cyanobacterial dominance among phytoplankton. Both eutrophication and brownification affect water transparency (Figure 3), however, together eutrophication and browning will reduce water transparency more than they would separately (Kritzberg et al. 2019). Cyanobacteria might not be stimulated by increased brownification alone (Hansson et al. 2013), but there are studies suggesting that climate change acting together with browning can benefit certain toxic-producing cyanobacteria (Ekvall et al. 2013). The cyanobacteria *Microcystis botrys* reacted synergistically to a rise in temperature and increased browning with both increased biomass and increased microcystin concentration (Ekvall et al. 2013). Microcystins, released by certain cyanobacteria, are harmful to aquatic organisms and terrestrial organisms including humans. Increased concentrations of microcystins and cyanobacteria can have negative consequences for certain ecosystem services, such as using a lake as a drinking water supply (Ekvall et al. 2013).

Figure 3 Brown water and algae affect water transparency. Browning can act together with climate change and benefit certain cyanobacteria; hence it is good to be aware of possible synergies between different threats. Photo: Lake Bolmen in February 2020, Anna Borgström

Globally, water bodies are facing several severe challenges, many of them acting in concert or even showing synergies. Brownification, eutrophication and climate change are all factors that affect water resources globally and have consequences for the treatment, production, economy and distribution of drinking water.

Aim

The aim of this report is to show the present status, as well as trends in water chemistry of Lake Bolmen, by compiling monitoring data from 1966 to 2018, with focus on water chemistry parameters that are connected to the three focus points brownification, eutrophication and climate change. The continuous measuring of water chemistry has created an important database which enables analysis of trends and changes in water quality in Lake Bolmen, although no synthesis of the data has previously been performed.

Lake Bolmen is essential to Scania's long-term water supply and of importance for commercial fishing and recreation, hence a synthesis of the trends and changes in water quality is of considerable interest. Due to the possibility to analyse trends and changes in water quality over a long timeline, it can enable the detection of early warnings and challenges in water quality which might lead to an increased demand and adaptation for effective methods for production of drinking water.

Material and Method

Water chemistry has been measured in Lake Bolmen since, at least, 1966 and is still ongoing, with only a few gaps in the monitoring. The focus of this report is on brownification, eutrophication and climate change where parameters of interest are Secchi depth, total nitrogen, total phosphorus, conductivity, alkalinity, pH, water temperature, water color, turbidity, oxygen (surface and bottom), chlorophyll a and TOC. For all parameters, except chlorophyll a and TOC, there are data from 1966 until 2018. For chlorophyll a there are measurements from 1974 until 2018 and for TOC the measurements are from 1987 until 2018. Measurements of cyanobacteria, conducted during the years 2004 until 2018 by Medins Havs och Vattenkonsulter AB for Lagans Vattenråd, are also used in the report since cyanobacterial blooms can be a considerable problem in lakes during the summer period.

Data handling and irregularities

Since samples have been taken in both the northern and southern part of Lake Bolmen, and the water chemistry differs considerably between the sites, results for both Bolmen North and South will be analysed separately. The northern and southern parts of the lake are also very different with respect to depth and shape and they are also separated by an island. All those factors resulted in the decision that the parts will be analysed separately and compared.

Data was gathered from Lake Bolmen, including both the southern and northern parts, several times per year by Limnologiska institutionen, Lunds Universitet, assigned by Sydvatten AB, at a depth of 0,2 meters, between 1966 and 1998 and once per year by Medins Havs och Vattenkonsulter AB assigned by Lagans Vattenråd, at a depth of 0,5 meters, between 1982 and 2018. Oxygen at the bottom of the north and south part of Lake Bolmen were measured at 10 and 25 meters, respectively. However, since Lagans Vattenråd only sampled once per year (August or September), only water chemistry sampled during late summer are used in this report, thereby allowing for long-term comparisons of summer conditions. Thus, only data sampled from 1st of July to 30th of September are used and in case there was more than one sampling during this period a mean value has been used for that year.

In long-term data sets, performed by different consultants, it is common with irregularities in sampling method and intensity; so also regarding the data base for Lake Bolmen. Hence, for the variable Secchi depth there are a few cases where a lot of values are missing for the period July to September. In those cases, if available, values from October have been used and if so this has been specified in the figure legend. For Bolmen North, October values for

Secchi depth has been used during the years 1970 – 1972 and 1974 – 1979 and for Bolmen South, October values for Secchi depth has been used for the years 1970 – 1971, 1974 – 1979. Also, for the variable Secchi depth it is unclear whether or not a water telescope was used for the measuring during the period 1966 to 1990. However, from 1991 values from Lagans Vattenråd are used which were measured with the help of a water telescope.

For the parameter pH, there is one value for Bolmen South from July in 1935 measured by Limnologiska institutionen, Lunds Universitet. This value is included in the report. There are, however, no data available between 1936 and 1965.

Other, occasional, missing values are specified in the figure legend for respective parameter. For example, TOC has only been measured by Lagans Vattenråd between 1987 and 2018, with a few years where data is missing. For missing values of parameters, see Appendix 2.

Description of sample site - Lake Bolmen

Lake Bolmen is situated in southwestern Sweden (latitude: 56.8373° N; longitude: 13.6738° E) in three counties, Kronoberg, Jönköping and Halland (Figure 4) and it is the tenth largest lake in Sweden, with an area of 184 km^2 (Romare & Cronberg, 2004). Bolmen basin has an area of 1640 km^2 and is the largest sub-basin of the River Lagan watershed, which has an entire area of 6454 km^2 (Persson, 2011).

Figure 4 A satellite photo of Lake Bolmen, with surrounding villages and the bigger city Ljungby, on the east side of Lake Bolmen. Source: Google Maps

Lake Bolmen is approximately 30 km from north to south and approximately 10 km wide from east to west. The lake is divided into the northern, southern, eastern and western sub-lake, due to a large island in the middle. The north and south part of Lake Bolmen are very different with respect to depth and shape. The largest part of the lake is covered by the southern sub-lake, with a maximum depth of 37 meters (Romare & Cronberg, 2004) and an average depth of 8 meters whilst the northern sub-lake is shallower with a maximum depth of only 13 meters and an average depth of 5-6 meters. During summer the southern part of Lake Bolmen is usually stratified with a thermocline between 10-20 meters (Romare & Cronberg, 2004; Persson, 2011).

The main inflow to Lake Bolmen is the river Storån, which drains approximately 30% of the drainage area of 667 km^2. Storån drainage basin consists of mainly forest (58%) and marshland (28%), with little agricultural land (10%) in the lower part of the drainage basin, and 4 % lakes. The inflow of Storån is in the north part of Lake Bolmen. The water from Storån is humic and relatively poor in nutrients (Romare & Cronberg, 2004). In the south part of Lake Bolmen is an inflow from River Murån, which drains a smaller area, 21 km^2, in the south of Lake Bolmen. Forest (60%) and marshland (32%) dominates the drainage basin of River Murån, with only a small part consisting of agricultural land (7%). Äspenäs bog is drained to one of Muråns tributaries and it has been used for peat mining since the end of the 1980s. In the water of River Murån the amount of organic substances is high due to high levels of humic substances, which may, in turn, also contribute to the relatively high amounts of phosphorus and nitrogen, as well as the low pH. Lake Bolmen is drained through Bolmsån River.

Land-use Bolmen area

Hummocky moraine dominates the Bolmen area (Andersson, 1998) and the land in the total Lake Bolmen basin consists of approximately 64% forest, 15% lakes and streams, 8% marshes and wetlands, 8% agricultural land, 4% heath acide and remaining land. Only 0,7% comprises urban area and 0,25% impervious surface (SMHI modelldata, 2019).

Results

Secchi depth

Secchi depth has been decreasing in both basins since mid-1960, however the decrease is more pronounced in the southern part of Lake Bolmen. In the north part the Secchi depth is varying, although a slight decrease can be seen. During 2017 and 2018, Secchi depth has increased in both parts of the lake (Figure 5). There is a clear difference between the two parts of Lake Bolmen, with higher values in the south part. Secchi depth has been, and still is higher in Bolmen South with values generally above 3 meters. At Bolmen North Secchi depth rarely has been, and still rarely rises, above 3 meters. Hence, sunlight can reach deeper in the water column in Bolmen South.

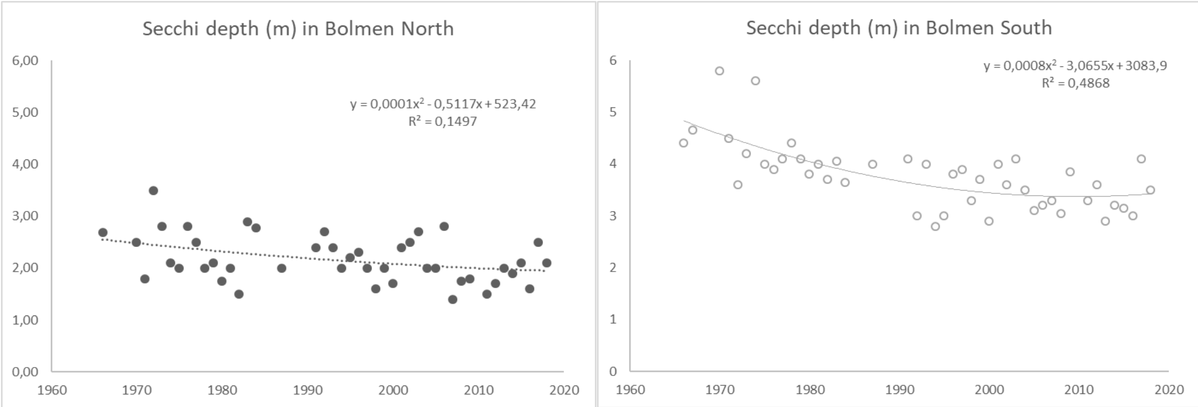


Figure 5 Secchi depth in the North (left) and South part (right) of Lake Bolmen, with a clear difference in Secchi depth between the two parts. Secchi depth is higher at Bolmen South. For both parts of the lake, Secchi depth has been decreasing although during 2017 and 2018 Secchi depth increased for both parts of the lake. Years with October values used for Secchi depth for Bolmen North is 1970 – 1972 and 1974 – 1979 whilst years for Bolmen South is 1970 – 1971, 1974 – 1979. There is also an uncertainty in whether or not a water telescope has been used to measure Secchi depth during the period 1966 – 1990. However, from 1991 and onward values measured with the help of a water telescope are used.

Chlorophyll a

Although the levels of algal chlorophyll a were similar between the two basins in the 1970s, the levels are nowadays about twice as high in the northern, compared to the southern part of the lake (Figure 6). Chlorophyll a has been increasing in Bolmen South since beginning of 1980s (Figure 6, right). The values have varied a lot during the years, with both dips and peaks. The highest values of chlorophyll a, in Bolmen South, are found during the end of 1990 and beginning of 2000, with values above 10 µg/l. However, there is an increasing trend for chlorophyll a in Bolmen South. Values are also increasing in Bolmen North, since the beginning of 1990s (Figure 6, left). The highest values are found between 2010 and 2015 with values above 15 µg/l. Chlorophyll a is increasing in Bolmen North, whilst it fluctuates a lot in Bolmen South. However, since 2008 chlorophyll a has shown an increasing trend in Bolmen South, except in 2018.

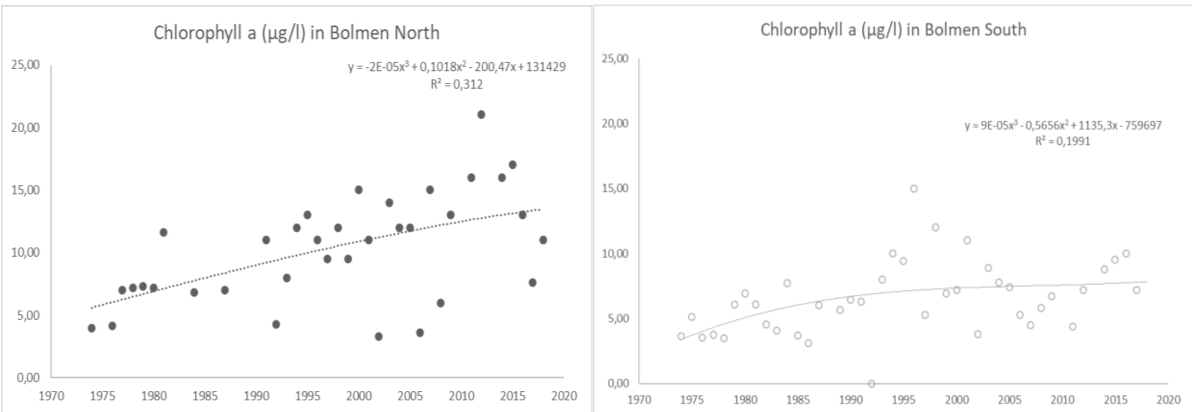


Figure 6 There are higher values of chlorophyll a measured in Bolmen North (left) than in Bolmen South (right). In Bolmen South the chlorophyll a has varied a lot between different years whereas in Bolmen North the variation has been less pronounced, instead chlorophyll a often has shown high levels in Bolmen North. During the last three years, chlorophyll a has decreased in Bolmen North.

The proportion of cyanobacteria has been fluctuating a lot between the years for both the south and north basins of Lake Bolmen (Figure 7), with no trend showing. However, there are usually higher values of cyanobacteria in the southern part of Lake Bolmen. The proportion of cyanobacteria rarely rises above 10 % in Bolmen North, whereas the proportion of cyanobacteria often passes 10 % in the southern part, with values occasionally rising above 25 %.

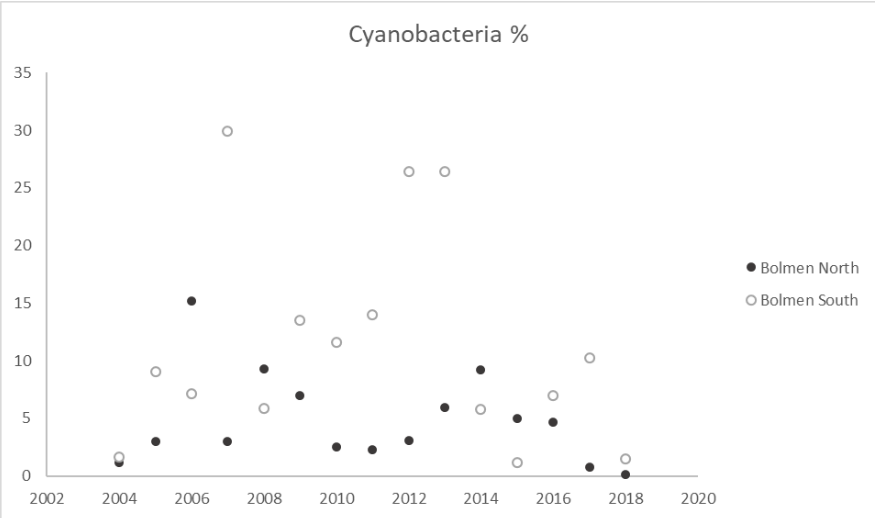


Figure 7 The proportion of cyanobacteria (in percent), measured between 2004 and 2018, in the north and south part of Lake Bolmen. There is a higher proportion of cyanobacteria growth in the south part of Lake Bolmen, however, there is no trend for Bolmen North or Bolmen South instead cyanobacteria is fluctuating between the years with no alarmingly high proportion.

Temperature

The temperature is fluctuating but overall there is an increasing trend for water temperature in Lake Bolmen, for both the north and south part at least from the mid-1990s (Figure 8). The increase in temperature in Bolmen South and North are similar with approximately the same temperatures. However, the water temperature is varying more at Bolmen North, with temperatures reaching below 14°C and above 24°C. According to the long-term data Bolmen South does not have temperatures reaching below 14°C or above 24°C.

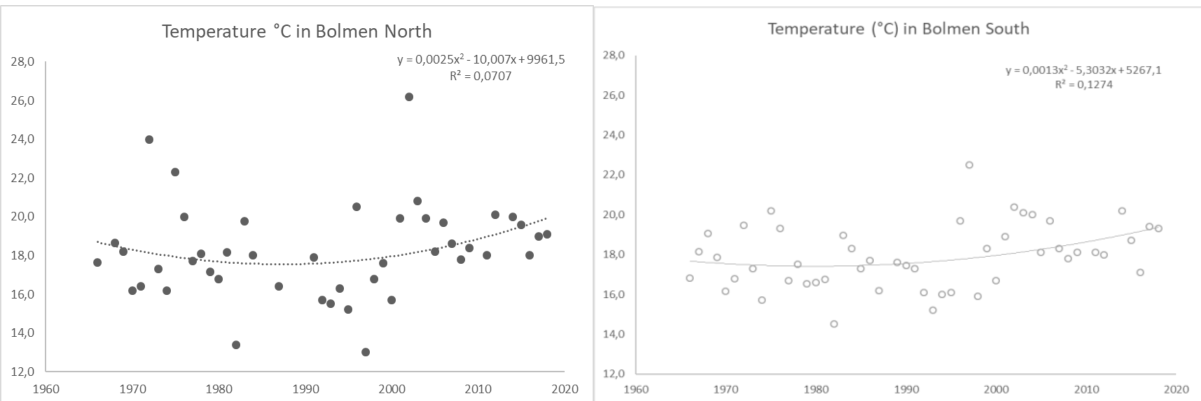


Figure 8 Temperature in the water for Bolmen North (left) and Bolmen South (right). Between the two parts of the lake there is not a lot of variability in the water temperature, however there are more scattered values for Bolmen North with temperatures reaching below 14°C and above 24°C. Water temperature is showing an increasing trend for both parts of Lake Bolmen.

pH

The pH measured in Bolmen South varies a lot, however, it shows a clear increase from the mid-1960 to end of 2010 (Figure 9, right). For Bolmen South there is a measured value of pH 6,8 in 1935, i.e. before any major anthropogenic influences. At Bolmen North, pH is also showing an increasing trend between mid-1960 to the end of 2010 (Figure 9, left). However, pH does not vary as much in Bolmen North as in Bolmen South. For Bolmen South pH values under 6,6 have been measured during the long-term sampling, whilst in Bolmen North for the same time period, no values under 6,6 in pH were measured. The increase in pH is also more drastic in Bolmen South.

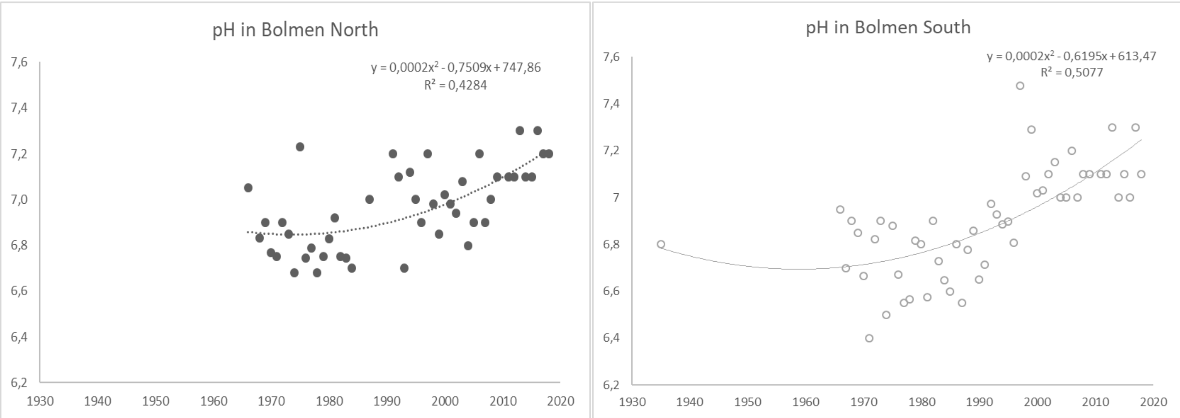


Figure 9 pH in Bolmen North (left) and Bolmen South (right). pH has been increasing in both Bolmen South and Bolmen North since end of 1970s and pH still shows an increasing trend in both parts of Lake Bolmen. In the south part of Lake Bolmen there is a single pH value of 6,8 from 1935, which is included in the figure.

Alkalinity

Alkalinity has been increasing in Bolmen North although the increasing trend has been levelling off since about 2010 (Figure 10, left). Alkalinity has been increasing since mid-1960 in Bolmen South and the increasing trend is, in contrast to the northern basin, still continuing (Figure 10, right). Overall, alkalinity is higher in Bolmen North than at Bolmen South and for both parts of the lake a peak can be seen between the years 1995 and 2005.

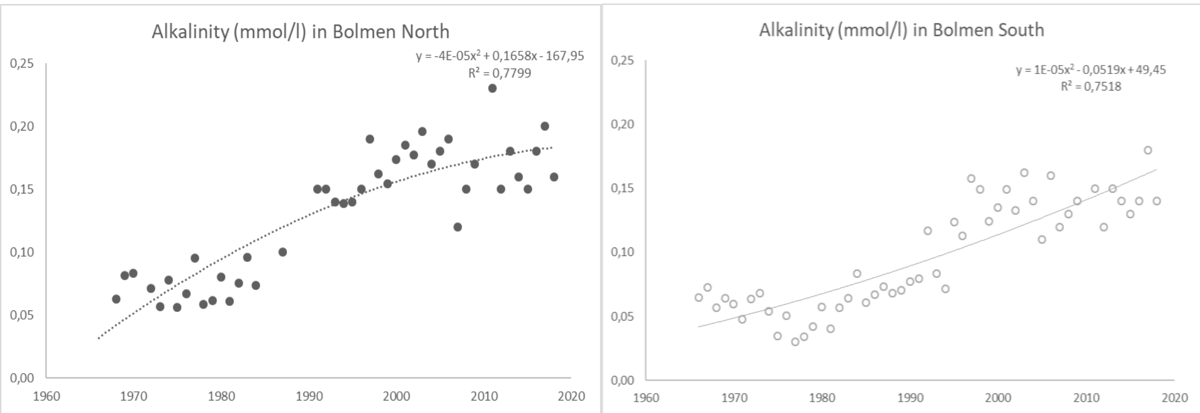
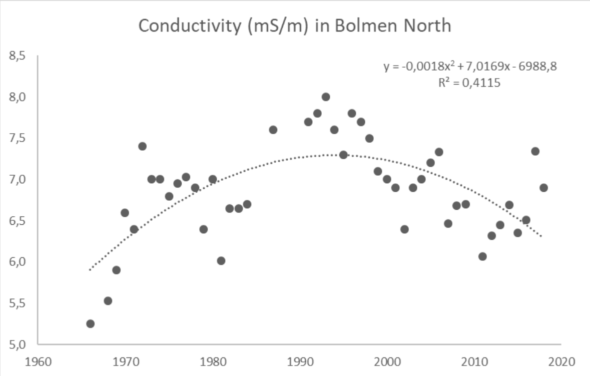


Figure 10 Alkalinity has increased since the end of 1970 in both Bolmen North (left) and Bolmen South (right). Alkalinity have higher values in Bolmen North. The trendline shows an increasing trend for alkalinity.

Conductivity

Conductivity is fluctuating considerably in both parts of Lake Bolmen (Figure 11), with a high peak in conductivity between 1990 to 2000. There has been a decreasing trend for conductivity in both Bolmen South and Bolmen North since the 1990s, although since 2010 the conductivity has again started to increase in both parts of Lake Bolmen. Conductivity is generally higher in Bolmen North, which means there are more dissolved salts in Bolmen North than in Bolmen South.



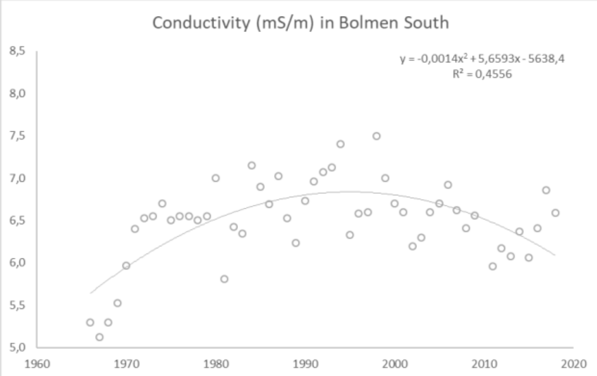
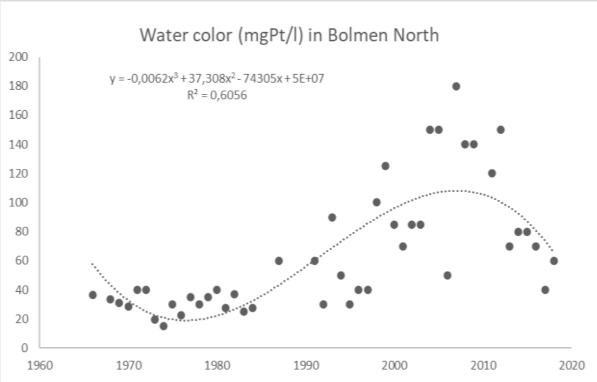


Figure 11 Conductivity is increasing for both the north (left) and south part (right) of Lake Bolmen. In both Bolmen South and Bolmen North, there is a peak in conductivity levels between the years 1990 and 2000. The conductivity levels are generally higher and varies more in Bolmen North.

Water color

The parameter water color was stable between 20 to 40 mgPt/l in Bolmen North and somewhat lower in the southern basin from mid-1960 until mid-1980 (Figure 12). Thereafter, water color has been increasing drastically with the highest values measured between 2004 and 2012. In Bolmen South, water color had a stable value at approximately 20 mgPt/l from mid-1960 until mid-1980. However, since mid-1980 color has been increasing in Bolmen South, with the highest values between 2007 and 2012. In Bolmen North there are higher water color values than in Bolmen South with values reaching 140 – 180 mgPt/l for the time period 2004 until 2012, whereas the water color values in Bolmen South during the same time period were 60 to 100 mgPt/l. However, it should be noted that from 2013 the water color values in both Bolmen South and North have been decreasing. The trend for Lake Bolmen shows an increase in water color for both the north and south basin. During the last 10 years the trend shows a decrease in the southern and northern basin.



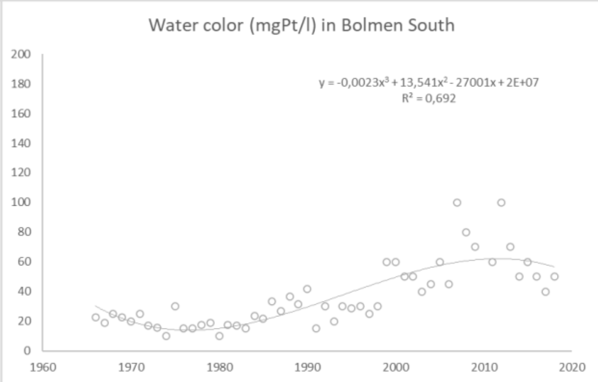
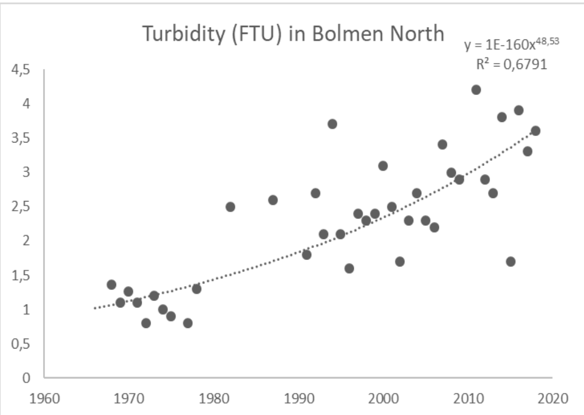


Figure 12 Water color levels have increased in Lake Bolmen, for both the north (left) and south part (right). For the last 10 years, water color is decreasing in both parts of Lake Bolmen. Water color shows an increasing trend that decreases during the last 10 years. Water color levels are lower in Bolmen South, with no value above 100 mgPt/l whilst in Bolmen North a lot of values are above 100 mgPt/l from end of 1990 and onwards with values reaching as high as 180 mgPt/l.

Turbidity

Turbidity shows an increasing trend for both basins (Figure 13). However, in Bolmen North turbidity is increasing more drastically and is significantly higher, generally showing values above 1,5 FTU after 1990. In Bolmen South, measured values for turbidity often stays below 1,5 FTU and the trend is less steep.



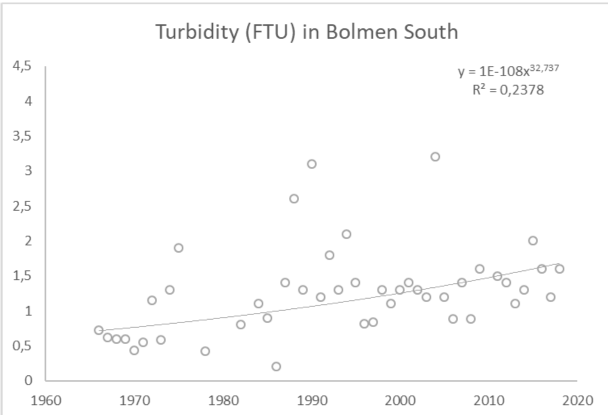


Figure 13 Turbidity is increasing both in Bolmen North (left) and Bolmen South (right) and it is also showing an increasing trend, although much steeper in Bolmen North compared to Bolmen South. Bolmen North has higher turbidity, often reaching above 1,5 FTU, than Bolmen South.

Oxygen

Oxygen, in the surface layer, is slowly decreasing in both basins of Lake Bolmen (Figure 14), but is at similar levels for both basins. There are a few peaks in oxygen levels in both basins, with the largest peak at the end of the 1970s and beginning of 1980s, although oxygen levels fluctuate considerably among years.

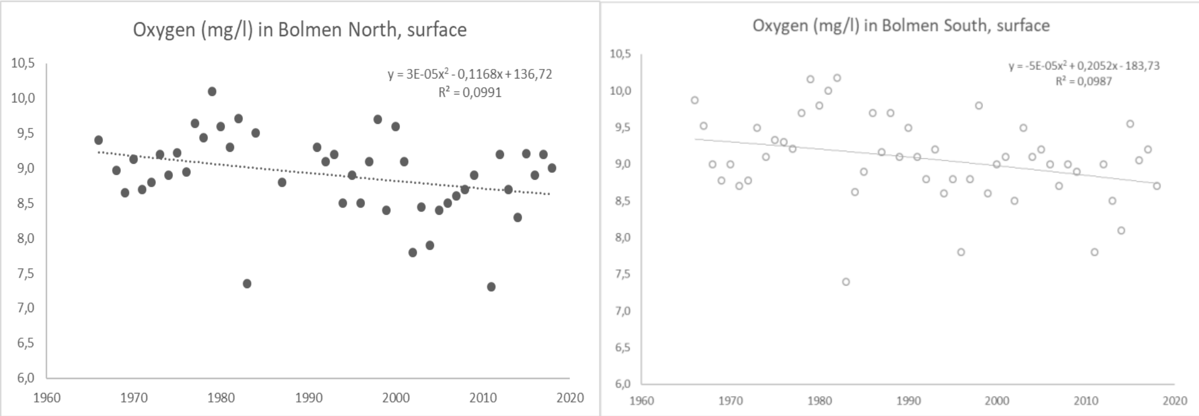


Figure 14 Oxygen levels for the surface water in Lake Bolmen, showing both the northern (left) and southern part (right). In both parts of the lake, the oxygen is at a similar level, rarely going below 8,5 mg/l or above 10 mg/l. There is a larger peak in oxygen levels during end of 1970s and beginning of 1980s in both basins of Lake Bolmen.

Oxygen at the bottom of Lake Bolmen has shown a decreasing trend in both the northern and southern basin (Figure 15) that has levelled off since 2000. The decreasing trend has been steeper in Bolmen South. During mid-1990 the oxygen levels in Bolmen South decreased for a few years before they increased again. However, from mid-1960 to mid-1980 the oxygen levels were between 5,5 and 9 mg/l whilst from 2000 and onwards the oxygen levels were often between 4 and 6 mg/l. Oxygen levels dropped during a few occasions in Bolmen North, especially between 1995 and 2005. Oxygen levels in Bolmen North was generally between 7 and 10 mg/l. Overall, oxygen levels were higher at the bottom of Bolmen North than at the bottom of Bolmen South.

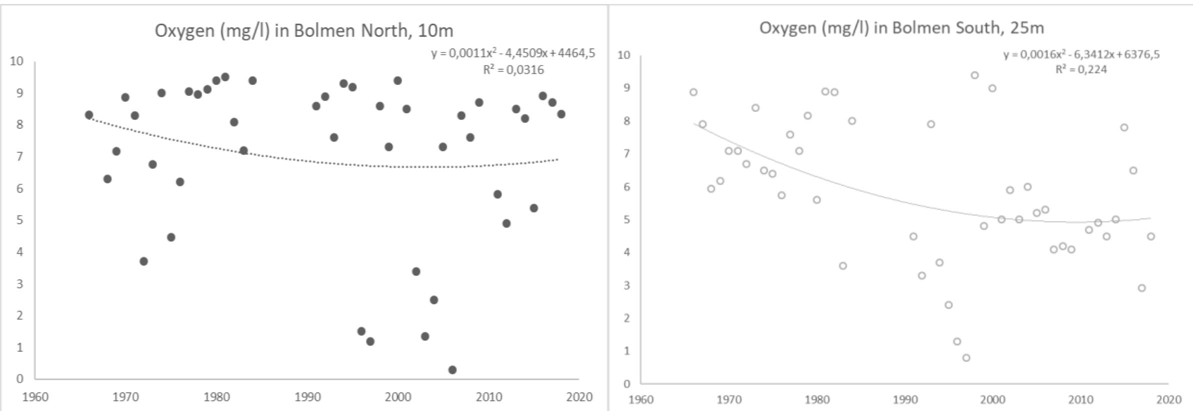


Figure 15 Oxygen levels at the bottom for Bolmen North (left) and Bolmen South (right). Oxygen is measured at 25 meters depth at Bolmen South and 10 meters depth and Bolmen North. Oxygen levels are lower and varies more at Bolmen South than at Bolmen North. Oxygen shows a decreasing trend for both parts of Lake Bolmen, although oxygen at Bolmen South is decreasing more drastically than at Bolmen North. From 1990, Bolmen South often have oxygen levels under 6 mg/l whilst Bolmen North often have oxygen levels above 7 mg/l for the same time period.

Total phosphorus

Total phosphorus increased until approximately 1980s in the southern part of Lake Bolmen, but has since then shown a decreasing trend (Figure 16, right). However, total phosphorus increased in the north part of Lake Bolmen until 2000 when it started to decrease (Figure 16, left), although the variance among years is considerable. Values of total phosphorus have generally been higher in the northern, than in the southern basin.

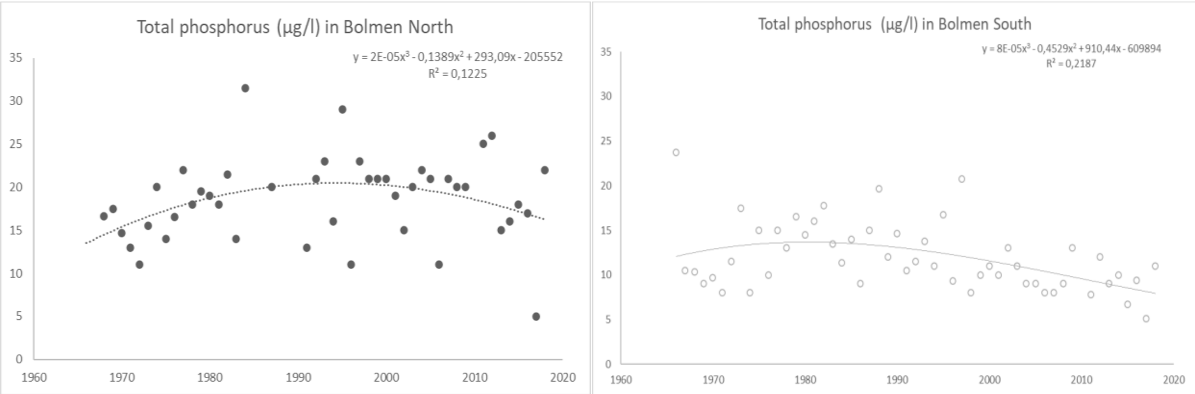


Figure 16 Total phosphorus shows a decreasing trend in Bolmen South (right). In Bolmen North (left) there is an increasing trend until approximately the year 2000 when the trend starts to show a decrease in total phosphorus. Values for total phosphorus are generally higher in Bolmen North, with values often above 15 µg/l, than in Bolmen South, with values rarely above 15 µg/l.

Total nitrogen

Total nitrogen has been relatively constant in both the northern and southern basin of Lake Bolmen, with values between 400 and 600 µg/l (Figure 17). However, between approximately 1995 and 2005 there was a peak with increased values for total nitrogen in both basins, with the largest peak in the northern basin. During this period total nitrogen reached above 600 µg/l. In Bolmen North, total nitrogen often reached closer to 800 µg/l during this time period. Total nitrogen is varying in ernboth the south and northern basin of Lake Bolmen and the trends are fluctuating with slight increases varied with slight decreases. Overall, total nitrogen is relatively constant.

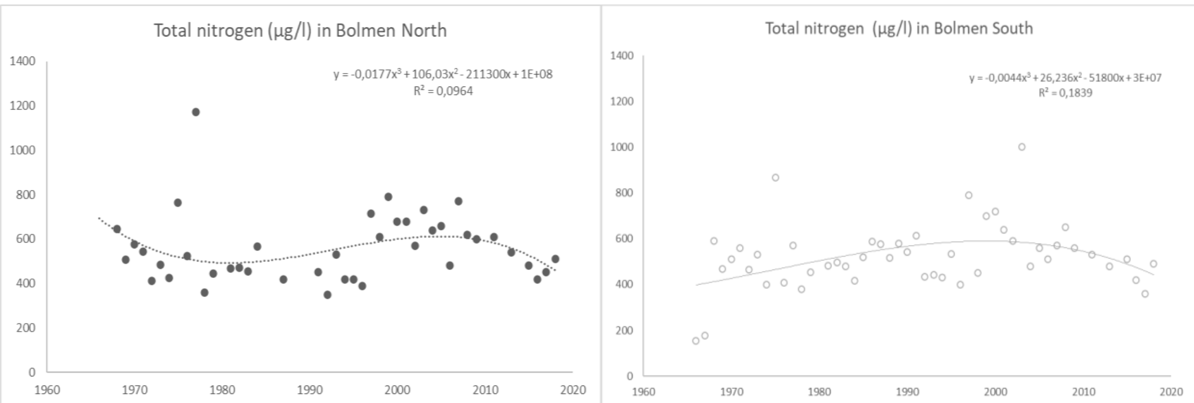


Figure 17 Total nitrogen shows a fluctuating trend in the north part of Lake Bolmen (left) whilst the trend shows a slight increase until approximately 2000 when the trend shows a slight ongoing decrease in the south part of Lake Bolmen (right). Total nitrogen is relatively constant with values commonly between 400 and 600 µg/l in both Bolmen South and North, however between the mid-1990 and mid-2000 there is a peak in increasing nitrogen with values reaching above 600 µg/l in both parts of Lake Bolmen, with some values reaching closer to 800 µg/l in Bolmen North.

Total organic carbon

Total organic carbon (TOC) has generally been higher in Bolmen North, with values often above 12, compared to Bolmen South, with values rarely above 12 (Figure 18). TOC is fluctuating between the years in the north part of Lake Bolmen, but there has been an increasing trend between 1995 until 2010. After that the TOC became lower again (Figure 18). In Bolmen South TOC increased somewhat between 1995 until 2010, but thereafter the values have been relatively stable. In Bolmen North, values for TOC varies more than in Bolmen South. Between 2003 and 2012, there was a peak of TOC in Bolmen North. During this period, TOC values were above 16 in Bolmen North. From 2013 TOC values decreased and are now below 12 in Bolmen North. Between 2007 and 2012 there was a peak in Bolmen South, with measured values of TOC above 10.

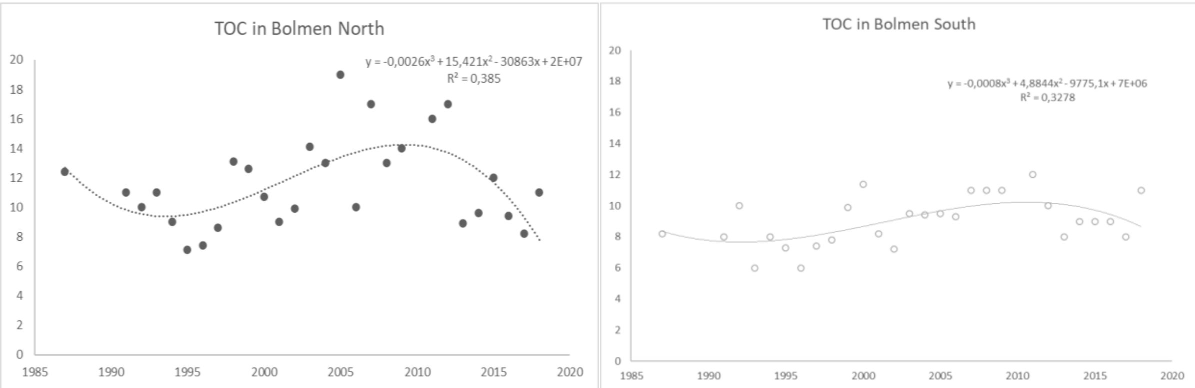


Figure 18 Total organic carbon (TOC) is showing an increasing trend between 1995 until 2010, whereas after the trend is showing a decrease in TOC in both the northern and southern basin of Lake Bolmen. In Bolmen South (right), TOC values are under 12 whilst at Bolmen North (left), values for TOC often are above 12. In Bolmen North, values for TOC varies more than in Bolmen South. There was a peak of TOC in Bolmen North between 2005 and 2012, with TOC values above 16. From 2013 and onwards TOC values are below 12 in Bolmen North.

Discussion

Most parameters show similar patterns in the north compared to south basins but there are differences in trends for several variables between the two basins in Lake Bolmen (Figure 19). The increasing parameters for the north basin of the lake are chlorophyll a, temperature, pH, conductivity, alkalinity, turbidity (Figure 6; 8; 9; 10; 11; 13) whilst decreasing parameters are Secchi depth, color, oxygen (surface), oxygen (bottom), total phosphorus and TOC (Figure 5; 12; 14; 15; 16; 18), whereas total nitrogen (Figure 17) are relatively stable for Bolmen North. For Bolmen South the increasing parameters are chlorophyll a, water temperature, pH, alkalinity, turbidity and TOC (Figure 6; 8; 9; 10; 13; 18) whilst the decreasing parameters are Secchi depth, conductivity, color, oxygen (surface), oxygen (bottom) and total phosphorus (Figure 5; 11; 12;14; 15; 16). The parameter that is relatively constant is total nitrogen (Figure 17).

Focus points	Parameters of interest	Trend Bolmen North	Trend Bolmen South
Brownification	Secchi depth	↘	↘
	pH	↗	↗
	Alkalinity	↗	↗
	Colour	↷	↷
	Turbidity	↗	↗
	TOC (Total organic carbon)	↷	↗
Eutrophication	Secchi depth	↘	↘
	Chlorophyll a	↗	↗
	Conductivity	↷	↷
	Turbidity	↗	↗
	Oxygen (surface)	↘	↘
	Oxygen (bottom)	↘	↘
	Total phosphorus	↷	↘
	Total nitrogen	→	→
Climate change	Temperature	↗	↗
	Oxygen (surface)	↘	↘
	Oxygen (bottom)	↘	↘

Figure 19 An overarching figure on the trends of the different parameters. The arrows show the trendline for the specified parameter divided into the three focus points chosen for the report, that is brownification, eutrophication and climate change. The directions of the arrows are based on the trend that the parameters are currently indicating.

Although Bolmen South and Bolmen North are one lake, there is a difference in water chemistry. The parameters chlorophyll a, alkalinity, conductivity, color, turbidity and total phosphorus (see Figure 6, 10, 11, 12, 13 &16) are lower at Bolmen South compared to Bolmen North whilst the parameter Secchi depth (Figure 5) is higher at Bolmen South. The parameters water temperature, pH, oxygen in both surface and bottom layer, total nitrogen and TOC (see Figure 8, 9, 14, 15, 17 & 18) are approximately the same values for the south and north basin of Lake Bolmen. The increase of pH could be due to liming to some extent of inflowing rivers to Lake Bolmen (Romare & Cronberg, 2004).

The south basin of Lake Bolmen is deeper, with clearer water, compared to the shallower north basin of the lake. The lower values for chlorophyll a, alkalinity, conductivity, color, total phosphorus and TOC and higher value for Secchi depth at Bolmen South might indicate that there is an ongoing purification and dilution of the water when it travels from the north basin to the south basin of Lake Bolmen, since the volume of Bolmen South is larger. Due to the larger area of water exposed to the sun in the south part of Lake Bolmen, photo-oxidation could also be an important part seen to the lower values of color and TOC. Solar radiation, primarily UV-B, degrade humic substances making it more accessible for bacteria which can decrease the color of the water (Granéli et al., 1996).

Brownification

Brownification is an ongoing global problem for aquatic ecosystems, ecosystem services, ecosystem function and water quality. In this report the parameters *Secchi depth*, *pH*, *alkalinity*, *color*, *turbidity* and *TOC* are of interest regarding the focus point brownification (see Appendix 1). In Lake Bolmen there has been a considerable browning of the water with a significant increase in water color, starting during the mid-1980s (see Figure 12). During mid-1980s there was also a drastic increase in turbidity (Figure 13), pH (Figure 9) and alkalinity (Figure 10) for both basins in Lake Bolmen. Secchi depth (Figure 5) is also decreasing over the years, however, Secchi depth has not changed as drastically as the parameters turbidity, pH, alkalinity and color. Since the time-series for TOC (Figure 18) is starting 1987 there is no measurements to show if TOC would have increased together with the above-mentioned parameters. Although, during the drastic increase in color between 2004 and 2012 there was a drastic increase in TOC for the same time-interval in Lake Bolmen. However, from 2012, there has been a drastic decrease in water color in Lake Bolmen. During the same time-period there was a decrease in TOC and a slight increase in Secchi depth. In January 2005, the cyclone Gudrun hit Sweden which caused significant financial damage to the forest industry and millions of cubic metres of trees were blown down in southern Sweden. The cyclone might be one factor behind the increased water color values in Lake Bolmen. Although Bolmen North had increasing water color values already during 2004, the trees that fell during the cyclone could still be affecting the water color for several years after the storm hit southern Sweden. For Bolmen South, water color increased during 2007 which may also be partly due to the cyclone Gudrun. Afforestation, especially through "sprucification", i.e. that large areas have been planted with spruce, might play an important role in explaining browning in southern Sweden, however, with afforestation there might be a lag of several decades on water color (Kritzberg, 2017; Škerlep et al. 2020).

There are three drivers that have been proposed as contributors to the global problem of browning, climate change, acid deposition and land use (Kritzberg et al. 2019). The increase in water color in Lake Bolmen coincides with a decrease in sulfur deposition to lakes and streams (Skjelkvåle et al. 2005), which can cause browning of waters. A reduction in sulfur deposition leads to an increase in the pH of the soil which increases the charge and the solubility of organic matter, thus the transport from the terrestrial to the aquatic system is facilitated (Monteith et al. 2007; Ekström et al. 2011). This pH increase is also seen in the water of Lake Bolmen from about 1980 and onwards. Hence reversed acidification may be one mechanism behind the increasing color values and ongoing brownification of Lake Bolmen. If acid deposition is the major driver of brownification, then increased browning of our waters might be a return to a more "natural state" (Monteith et al. 2007). However, a study by Kritzberg (2017) shows that increasing water color due to decreasing S deposition was not corroborated by some historical records. Hence other drivers likely have a role in increasing browning than only recovery from acidification.

Increases in DOC and iron (Fe) concentrations can lead to increased browning in freshwaters in temperate boreal regions, especially in freshwaters where coniferous forests dominate (Björnerås et al. 2017). The proportion of wetland and coniferous forest in the catchment are positively related to DOC and Fe concentrations (Mattsson et al. 2009). This might be another reason to previously increased color values in Lake Bolmen. Hummocky moraine dominates this area (Andersson, 1998) and land cover around Lake Bolmen Basin consists of approximately 64% forest with 8% marshes and wetlands (SMHI modelldata, 2019). Land use and land cover change might be of greater importance to browning of waters than previously thought (Kritzberg, 2017; Meyer-Jacob et al. 2019; Škerlep et al. 2020).

Eutrophication

The second focus point is eutrophication. *Eutrophication* is a global problem affecting aquatic ecosystems and changing water quality. Lake Bolmen is not classified as a eutrophic lake, however, there can still be an ongoing eutrophication process in the lake. The parameters regarding eutrophication in this report are *Secchi depth, chlorophyll a, cyanobacteria, conductivity, turbidity, oxygen* (surface and bottom), *phosphorus* and *nitrogen* (see Appendix 1). Since 1990 algal chlorophyll a (Figure 6) has increased significantly in Lake Bolmen in the north part. An increase in algal growth can affect the light penetration in the water column, thereby affecting both turbidity and Secchi depth. Turbidity (Figure 13) has increased and Secchi depth (Figure 5) has decreased in accordance with the increasing chlorophyll a. With enough algae growth, oxygen might decrease, especially in the bottom of a lake where dead organisms are degraded by oxygen demanding bacteria. Oxygen in surface water of Lake Bolmen is decreasing (see Figure 14) and for Bolmen South there is a decreasing trend for oxygen at the bottom water (see Figure 15) whilst oxygen at the bottom water in Bolmen North is fluctuating a lot with several measurements with low oxygen levels. A decrease in oxygen could affect the internal load of phosphorus in Lake Bolmen, if it were to become anoxic, since anoxia can lead to increased release of phosphorus from the sediment to the water column hence increasing available phosphorus to algae in the water column (Parsons et al. 2017; Ostrofsky & Marbach, 2019). During the end of 1990 phosphorus levels in Lake Bolmen increased drastically until mid-2000, when the levels started to decrease. However, the deposition of phosphorus in Lake Bolmen has been steady on approximately 50 %, indicating a good retention capacity in the lake (Romare & Cronberg, 2004).

The levels of nitrate and organic nitrogen in Lake Bolmen have been increasing. The increased plankton quantity is seen by increased values of chlorophyll a in the north basin of Lake Bolmen. During 2006 the total algal biomass and amount of cyanobacteria were relatively high, which had also been seen during 1993 and 1995 (Romare & Cronberg, 2004). The biomass of phytoplankton is moderate in the south part of Lake Bolmen whilst phytoplankton biomass is very high in the north part of Lake Bolmen. However, the status of the phytoplankton assessment of the south and north part of Lake Bolmen were classified as good status and moderate status respectively (Medins Havs och Vattenkonsulter, 2019). In Lake Bolmen the biomass has been dominated by diatoms and small unicellular algae, which could indicate eutrophication, however for now it is the indifferent species of diatoms that dominates (Romare & Cronberg, 2004; Medins Havs och Vattenkonsulter AB, 2019). Worth to mention is that there have been measurable levels of *Gonyostomum semen* in Lake Bolmen every year since 2002 and during 2004 the levels of *Gonyostomum semen* was high (Romare & Cronberg, 2004). There have been higher levels of algae growing in Bolmen North than in Bolmen South (Figure 6), whilst the levels of cyanobacterial growth have had a higher proportional percentage in Bolmen South (Figure 7). The proportional percentage of cyanobacteria is not yet alarmingly high for Lake Bolmen (Medins Havs och Vattenkonsulter AB, 2019). Although the amount of cyanobacteria is currently not alarming, they should be monitored since some of them are toxic and may severely reduce the quality of the lake as a drinking water reservoir and also for recreation.

It can be said that a mild eutrophication process is ongoing in Lake Bolmen, especially in the north basin of the lake. As stated previously, the river Storån might bring in nutrients to the north basin of the lake. However, there are smaller rivers entering Lake Bolmen which might also affect the water of Lake Bolmen. The river Unnenån which flows to Lake Unnen and then later enters Lake Bolmen in the west, had according to Romare & Cronberg (2004), an ongoing mild eutrophication problem about 15 years ago. The increased eutrophication may partly be a result of airborne pollutants, primarily nitrogen, together with increased input of organic and inorganic compounds, like phosphorus, from waters that flow into Lake Bolmen (Romare & Cronberg, 2004). The water from Lake Unnen flows to the western part of Lake Bolmen and might add nutrients to Lake Bolmen. The ongoing eutrophication process of Lake Bolmen is probably mainly caused by the catchment areas of both the river Storån and the river Unnenån.

Climate change

Climate change, the third focus point, is a global problem with rising temperatures, shifting weather patterns and rising sea levels. The parameters regarding this focus point are *water temperature* and *oxygen* in both surface and bottom water (see Appendix 1). Water temperature is fluctuating in Lake Bolmen over the years; however, it does show an increasing trend (Figure 8). Colder water can hold more oxygen than warmer water, hence warmer water temperature can affect dissolved oxygen in the lake water negatively and in Lake Bolmen there is a decrease in oxygen in the surface layer (Figure 14). Oxygen at the bottom layer in Lake Bolmen is decreasing in the south basin whilst it is stable in the north basin, although there are measurements were oxygen level are low in both basins. The south basin is deeper than the north basin, often with a stratification during the summer months (Romare & Cronberg, 2004; Persson, 2011).

Several research studies suggest that climate change strongly affect water resources by affecting chemical, physical and biological processes through the influence on lake stratification, hydrology, and light availability (Magnuson et al. 1997; Schindler, 1997; Bates et al. 2008). Nutrient availability, nutrient recycling and concentrations of deep-water oxygen and dissolved organic carbon are also affected by climate change (Magnuson et al. 1997; Schindler 1997). Moreover, increased temperatures could increase algal growth in the water surface layer, which will increase the oxygen in the surface water due to photosynthesis during the day. However, respiration performed during the night by algae use up oxygen from the water column and increased algal growth will lead to increased amounts of algae sinking to the bottom of the lake, which, in turn, will increase decomposition by bacteria, a process that consume large amounts of oxygen in the bottom water layer. Hence, this process will promote oxygen deficiency in the bottom water of the lake. The stratification that often occur during summer, in turn, can prevent surface water from mixing with the bottom water which can lead to oxygen-free bottom water and nutrient deficient surface water, since there is no mixing between the bottom and surface water.

Altered vegetation cover, enhanced terrestrial productivity and effects on the water level on production and transport of terrestrial DOC, are processes that are associated to climate change which, in turn, can increase browning (de With et al. 2016). Climate change has led to increased temperatures and changed weather patterns which can increase browning through increased precipitation. DOC export to surface waters, and thereby increased browning of the water, is promoted by precipitation by increased water runoff through soils. However, precipitation can also raise the water level and thus increase connectivity between organic soils and surface waters which in turn may also increase browning of our freshwaters (Laudon et al. 2011). Hence, browning might increase during periods with high precipitation. Increased terrestrial organic carbon production, decomposition, and export to surface waters have been related to longer growing seasons as a result to the increasing temperatures which may also increase browning. Hence, it is of great importance to remember that although brownification, eutrophication and climate change are separate focus points in this report, these large-scale global stressors may sometimes act in concert.

Conclusion

The north basin of Lake Bolmen is both browner and more eutrophic than the south basin of the lake. There are higher values of chlorophyll a, conductivity, color and total phosphorus and a lower value for Secchi depth at Bolmen North. The main inflow, Storån, to Lake Bolmen is in the north basin, which might be the reason to higher values of certain parameters at Bolmen North. Storån drainage basin consists of 58 % forest, 28 % marshland, 10 % agricultural land and 4 % lake area (Romare & Cronberg, 2004) which all affect the water from Storån before it enters Lake Bolmen. The inflowing water from Storån is humic (Romare & Cronberg, 2004) which might be the cause to the increased color values in Lake Bolmen, and the reason why the color values are higher at Bolmen North. The higher color values of Bolmen North can also be due to higher levels of chlorophyll a and TOC. There is some agricultural land draining to Storån, which leak nutrients and could be a reason for the higher values of chlorophyll a, conductivity and total phosphorus. Bolmen South covers a larger area than Bolmen North, which leads to that a larger area is exposed to sunlight where photo-oxidation of organic matter can take place, which in turn can explain why Bolmen South is less brown. However, photo-oxidation break down large carbon compounds making the carbon more accessible for bacteria. The decomposition of carbon by bacteria is a process that use oxygen, hence, in a lake with high concentrations of DOC, oxygen might be depleted due to bacterial decomposition of carbon compounds (Lindell et al. 2000).

Since 1991, organic substances have been increasing in Lake Bolmen, which is correlated with increased water color values. According to Romare and Cronberg (2004), it is difficult to determine whether the increase is due to increased leaching of humic substances from forests or organic materials produced on land or in water. However, in Lake Bolmen the previous increase in water color and nitrogen levels are most obvious during April and May (Romare & Cronberg, 2004), whereas during August and September no increase could be recorded. This may indicate that changes in water color and nitrogen in Lake Bolmen is temperature dependent. Since 2008 analysis show that the trend regarding water color is decreasing with more significant decrease since 2012. This might indicate a slow-down of the brownification process (Clemens Klante, et al 2020, pers. comm).

Evaluation and predictions for the use of Lake Bolmen as a drinking water reservoir

Brownification of Lake Bolmen poses a challenge for the drinking water production, which gave rise to questions of Lake Bolmens future use as a drinking water reservoir. However, browning of Lake Bolmen has decreased the last 10 years and with a currently decreasing trend of water color in Lake Bolmen it does not seem like browning poses an immediate threat to Lake Bolmen. Chlorophyll a shows an increasing trend in Lake Bolmen, with relatively high values in the north basin, although total biomass of cyanobacteria has not been particularly high in Lake Bolmen, except for a few years in the south basin. With no increase in total nitrogen or total phosphorus, chlorophyll a will likely level off in the near future instead of increasing. The future use for Lake Bolmen as a drinking water reservoir therefore looks promising.

Hence, according to the long-term data of Lake Bolmen’s water quality there does not seem to be any immediate threats to the lake as a water reservoir. However, since both algal growth and browning poses a threat to the use of raw water as drinking water as well as ecosystem services, ecosystem function and recreation, **it is of utmost importance, and a strong recommendation, to continue to monitor the parameters water color, chlorophyll a, cyanobacteria, total nitrogen and total phosphorus to get an early warning for a potential change in trends.**

However, if the equally high water color found in the north part of Lake Bolmen would also be found in the south, the drinking water production would have to adapt to this new condition of water quality. Little is also known about if there is a synergistic relationship between brownification and climate change which may promote higher algae growth and certain toxic-producing cyanobacteria. Increased concentrations of humic substances, microcystins, algae and cyanobacteria can have negative consequences for the usage of lakes as a drinking water supply. In turn, this might lead to an increased demand for effective methods for production of good quality drinking water and might lead to major changes in the treatment process of the water and in turn risk affecting the environment.

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Appendix

Appendix 1

Parameters of interest
Why these parameters have been decided upon is described here.

Measurements of a lakes **Secchi depth** shows the transparency of the lake water. Transparency shows how deep sunlight can penetrate through the water. The abundance of particles and dissolved organic material in the water determine the water transparency. The light cannot penetrate deep into the water column if the water contains a lot of particles. Sunlight is important for the growth of plants and algae; thus, water transparency can give indications about the trophic state of a lake. Water transparency is measured with the help of a Secchi disk that is lowered into the water column. With high water transparency the Secchi depth is high, whilst with low water transparency the Secchi depth is low.

Chlorophyll *a* is measured in lakes to determine how much algae is in the lake. In a moderate amount, algae are important in lakes since it adds oxygen to the water column due to photosynthesis. However, too much algae in a lake can produce a foul odour, be unpleasant to swim in and create oxygen-free lake bottoms since the decomposition process of dead algae use up oxygen. The lake's water quality and trophic state can be indicated by measuring chlorophyll a. The concentrations of algae vary over the year and the growth of algae depends on several factors. These factors include, but are not limited to, water temperature, water transparency, predation and nutrient availability. Increasing algae concentration results in decreasing water transparency.

pH is a common measurement conducted in lakes. It is a measure of the hydrogen ion (H^+) concentration of the water and is shown on a scale of 1.0 to 14.0. The higher the value the more alkaline the water is whilst the lower pH is the more acidic the water is. When pH is 7.0 the water is neutral. Above pH 7.0 the lake water is alkaline whilst below pH 7.0 the water is acidic. In a lake, both chemical and biological processes are affected by pH and different aquatic organisms have different ranges of pH within which they thrive. Toxic elements and compounds, for example heavy metals, can become mobile and be taken up by aquatic plants and animals at a low pH. Changes in pH can be caused by, for example, atmospheric deposition, wastewater discharges and erosion of surrounding rock. The pH scale is logarithmic, thus a drop in pH by 1.0 unit is a 10-fold increase in acidity.

Alkalinity is a measure of a water's buffering capacity, thus its ability to neutralize acids. Alkaline compounds in the water remove H^+ ions, by combining with the H^+ ion to create new compounds, and lower the acidity of the water, hence increases the pH. Due to the water's buffering capacity, the pH can withstand some acid entering the waters. Hence, measuring alkalinity is important to determine lakes ability to neutralize acidic pollution. The alkalinity in the lake usually comes from the rocks and land surrounding the lake. Precipitation also is of importance, since it falls in the surrounding area of the lake and most of the water entering the lake comes from runoff over the landscape.

Conductivity is a measure of conducted electricity in water, due to dissolved salts. Conductivity is a measure of how easily electricity is flowing through the water, which gives an indirect estimate of how many salts that are dissolved in the water. The conductivity of a lake depends on what types of rock and soil are around the waterbodies, water temperature and the amount of water inflow from streams and precipitation. Conductivity increases with increasing water temperature, easily eroded rocks and soil and with little water inflow and precipitation. Hence, conductivity decreases with decreasing water temperature, increasing water inflow and precipitation and rocks that are hard to erode. Water pollution is also a common reason for increasing conductivity. Conductivity can be seen as an indirect measure of a water's saltiness, which can affect aquatic organism negatively. Aquatic organisms are adapted for a certain salinity range in the waters they live in. If the salinity changes the aquatic organisms might end up outside of the range of salinity that they have adapted to live in, which might affect them negatively.

Temperature has a major influence on the biological activity of aquatic organisms, with higher water temperature the greater the biological activity. Most aquatic organisms have preferred temperature ranges where they thrive. Water chemistry is also affected by temperature, for example temperature directly affects the lake waters capacity to hold oxygen. Temperature changes in lakes occur both due to seasonal changes but also due to daily variations between day and night. Deeper lakes can also become separated by different layers due to differences in temperature, thermal stratification occurs.

Color of the water is caused by dissolved compounds in water, both natural and anthropogenic. Surface water, commonly used for drinking water, can exhibit large variations in content of organic matter. Most of the organic matter, called humus, originates from soils in non-polluted waters and color the water brown or yellow. Aquatic humic substances have created problems in water treatment plants for a long time. Since humus is substrate for bacteria and fungi it can create problems with excess microorganism growth in the water distribution system and cause secondary problems such as taste, odour, and disease. Hence, treatment of the raw water before it reaches drinking water quality is necessary.

The cloudiness of a lake can be measured by **turbidity** where things that will make the lake water cloudy will increase turbidity. Lake water can become cloudy by for example silt, algae, mud, runoff or chemicals. Turbidity can, however, vary throughout the seasons. High turbidity in lakes can be problematic since it can have negative effects on the lake's overall health. During summer, floating algae can cause high turbidity and with high enough abundance of algae it can block out sun needed for other plants to grow in the water. High turbidity can also be problematic for fish who use their vision to hunt for prey.

Measuring **oxygen** in a lake means measuring dissolved oxygen in the lake water. There are two main sources of oxygen in a lake, either through plant and algae photosynthesis or diffusion to the lake surface water from the atmosphere. Oxygen is a necessity for most living organisms. Most aquatic organisms breathe the oxygen dissolved in the water. Temperature of the lake water plays an important role in determining the amount of oxygen dissolved in the lake, were temperature is directly related to the amount of dissolved oxygen. Oxygen is more soluble in cold water than in warm water. Overall lake health can be indicated by the amount of dissolved oxygen in the water. Two processes use up the oxygen in the lake water, respiration and decomposition. If a lot of oxygen is reduced, aquatic organisms become stressed and in those cases oxygen becomes absent all oxygen-breathing aquatic organisms must move to an oxygenated zone or die. During summer, deeper lakes can become stratified which can cause the lake bottom to become anoxic, especially if there is a lot of decomposition on the bottom of the lake. When the lake is stratified there is no replenishing of oxygen at the lake bottom, since it is cut off from the surface water. However, oxygen gets replenished at the bottom of the lake during spring and fall due to lake mixing.

Total phosphorus is another important measurement in lakes. Phosphorus is important as a nutrient for plant and algae growth, however, in most lakes phosphorus is a limiting nutrient. Thus, phosphorus has a direct effect on plant and algae growth in lakes. Total phosphorus is a good measurement to get a good indication on lakes water quality and trophic state, since it measures both phosphate available to plants and algae and phosphorus suspended in lake water. Phosphorus originates from several sources. Major sources for phosphorus in lakes include human and animal wastes, runoff from farmland, fertilized lawns, soil erosion and septic systems. Another way for phosphorus to enter lakes is from the bottom sediment of a lake. When a lake bottom is anoxic, the sediment releases phosphorus to the water column which will fuel algae growth when the lake water is mixing again. If inputs of phosphor entering a lake are decreased or eliminated, water quality can improve due to less plants and algae growth.

Another nutrient that is important for plant and algae growth is **nitrogen**. However, an overabundance of nutrients in lake water can cause a number of ecological and health effects. Nitrite, nitrate and ammonium are three forms of nitrogen that is needed for plant and algae growth. All three forms of nitrogen are measured whilst measuring total nitrogen. Nitrogen is fairly common in the environment, but it is also introduced to water through sewage and fertilizers. Heavy rain can cause runoff containing plenty of nutrients which enters nearby streams and lakes. Nitrogen can also enter lake water from the atmosphere. Different forms of nitrogen can also be formed in water bodies through oxidation of other forms of nitrogen and organic nitrogen compounds. Excess nitrogen in lakes can cause overgrowth of aquatic plants and algae. With too much nitrogen, the excessive growth of algae and plants can clog water intakes, block light from deeper waters and use up dissolved oxygen in the water during decomposition. With enough excess nutrients, eutrophication of the lake can occur.

The total amount of carbon in organic compounds in an aqueous system is measured as **total organic carbon (TOC)**. TOC is an important parameter when it comes to monitoring overall levels of organic compounds present in an aquatic system. TOC is an important sum parameter in the assessment of the organic pollution of water.

Appendix 2

In this table it is visible which years that are lacking measurements during the period 1st of July until 30th of September. Missing years are shown for each parameter and for the north and south basin of Lake Bolmen.

Years lacking measurements												
Bolmen North basin												
Secchi depth	Chloro-phyll	Tempera-ture	pH	Alka-linity	Conduc-tivity	Color	Turbi-dity	Oxygen surface	Oxygen bottom	Tot P	Tot N	TOC
1967	1975	1967	1967	1966	1967	1967	1966	1967	1967	1966	1966	1988
1968	1982	1985	1985	1967	1985	1985	1967	1985	1985	1967	1967	1989
1969	1983	1986	1986	1971	1986	1986	1976	1986	1986	1985	1980	1990
1985	1985	1988	1988	1985	1988	1988	1979	1988	1987	1986	1985	2010
1986	1986	1989	1989	1986	1989	1989	1980	1989	1988	1988	1986	
1988	1988	1990	1990	1988	1990	1990	1981	1990	1989	1989	1988	
1989	1990	2010	2010	1989	2010	2010	1983	2010	1990	1990	1989	
1990	2010	2013		1990			1984		2010	2010	1990	
2010	2013			2010			1985				2010	
							1986				2012	
							1988				2014	
							1989					
							1990					
							2010					
Bolmen South basin												
Secchi depth	Chloro-phyll	Tempera-ture	pH	Alka-linity	Conduc-tivity	Color	Turbi-dity	Oxygen surface	Oxygen bottom	Tot P	Tot N	TOC
1968	1988	1988	2010	2010	2010	2010	1976	2010	1985	2010	1980	1988
1969	2010	2010					1977		1986		2010	1989
1985	2013	2013					1979		1987		2012	1990
1986	2018						1980		1988		2014	2010
1988							1981		1989			
1989							1983		1990			
1990							2010		2010			
2010												

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