On natural organic matter and lake hydrology in Lake Bolmen

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Abstract: The importance of understanding lake hydrology also in the case of drinking water treatment is reviewed and some examples of how Sydvatten uses different methods for improving the knowledge of the important raw water resource Lake Bolmen are presented in this paper. New investigations will be undertaken in lake hydrology monitoring and modelling. Remote sensing for raw water quality mapping will be initiated and advanced technologies for treating raw water rich in natural organic matter will be tested.

Introduction
Lake hydrology and lake water quality is of great importance for stakeholders using the lake in different aspects. Professor Lars Bengtsson has studied lake hydrology for many years and contributed significantly to the understanding of this subject. In fact his first scientific papers and his thesis dealt with lake hydrology and lake circulations, not least advanced mathematical modelling of the circulation processes (Bengtsson, 1973a, Bengtsson, 1973b and Bengtsson, 1973c). He has continued to inspire researchers with investigations of thermal regimes of lakes, the effect of ice coverage on lakes, further studies of circulation processes, paleolimnological investigations of lake water quality and change processes, remote sensing in lake quality monitoring and recently the hydrological properties of shallow lakes. This has been of great importance for the development of better understanding of lake hydrology and lake dynamics.

One aspect of physical limnology and water quality, particularly important for a drinking water producer, is the presence of natural organic matter (NOM) in surface water. NOM is present in all natural waters. NOM is sometimes colour-free but more often visible through the browning effect it has on water. In drinking water treatment, NOM is often the chemical
challenge for preparation, traditionally removed through treatment with flocculation, coagulation and sedimentation/filtration. It is also a hygienic concern. In the Swedish Climate and Vulnerability investigation (SOU 2007:60) was stressed that the increased burden of natural organic matter in surface waters increased the risk of hygiene problems due to contamination from bacteria, viruses and parasites.

NOM in water is present in different size fractions from smaller molecular size (200–400 g/mole) up to large molecules (10,000 g/mole or larger). In Sweden, NOM-rich waters are common especially in the southern and central part and less common in northern part of the country. Swedish drinking water is mainly produced from surface water supplies – more than half of the supply comes directly from surface waters and another quarter comes from infiltrated surface water through artificial groundwater recharge. In particular the larger water utilities have extensive treatment of surface water sources. A total of at least 6 million people in Sweden receive their drinking water directly or indirectly from NOM-rich surface raw water.

Organic matter in surface waters

The state of knowledge about the dynamics of NOM in nature is limited, or maybe better, the complexity of NOM in nature is large. In many waters of Sweden already exists a trend towards browning or colour increase, even visible in the abstracted groundwater produced through artificial recharge. Water colour affects the water chemistry. The water colour in recent years has become browner and has since the 1970s more than doubled in many waters (see Figure 1). The colour also varies with season; different lakes displaying different patterns. In the longer term there are several results suggesting that the colour in Swedish surface waters have increased dramatically, and that the waters not in a long time have been so coloured as currently.

Yet paleolimnological studies indicate that the present conditions not are unique. High colour/humic content has been present before, as evidenced by measurements of organic carbon in lake sediments. The paleolimnological investigations suggest that surface water from the 1800s and earlier had more colour and contained high concentrations of organic matter than even at present.

The concentration of NOM in water varies depending on the land use of the catchment, size and type of the water body, climate and hydrology of the area. Although patterns are complex, some general rules can still be
identified. The type of land surrounding the water body affects the NOM-content. For example, the average NOM concentration in sea water is below 0.5 mg/l and in swamps it can be higher than 60 mg/l. The lakes of the boreal region usually contain the highest NOM concentration among fresh water sources. The boreal zone lakes receive the highest mass of NOM from the allochton, terrestrial, sources while autochthon production is modest. The hydrology of the catchment, especially the runoff, plays thus a major role on the leaching of organic material from the terrestrial source to the lakes. The decomposition rate of organic material on the top layer of the soil by microorganisms is controlled by temperature. An increase in temperature increases the decomposition rate of soil organic matter. The production of NOM in the soil layer is mainly controlled by microbial activity, while the transport of NOM from the soil layer mainly is controlled by the hydrological processes. NOM has generally high resistance to further microbial degradation. NOM can adsorb heavy metals and other organic compounds, which can cause elevated concentration of metals in the natural water system. For accurately predetermine the required water treatment extent and method, better understandings of NOM dynamics in surface water industry should be provided.

Organic matter in water supply

For drinking water producers elevated levels of organic matter in drinking water is thus of a concern. The present water treatment scheme is often insufficient for reducing organic material in drinking water. Elevated
NOM-concentrations in treated water can cause nuances such as tarnish of the water and smell and taste disorders. But further on, organic matter can serve as substrates for microbial regrowth and enhance biofilm growth in the water mains, which can lead to hygiene problems. Other hygienic problems are that the most common disinfection method, to use chlorination, causes formation of trihalomethane (THM) and other disinfection byproducts, which in some cases are suspected to give rise to carcinogens in drinking water. The higher the content of organic matter in water is, the greater the risk for THM-formation. NOM also reduces the efficiency of disinfection when oxidizing agents, such as the chlorine or ozone, are used. Chlorine can seldom be used for disinfection of water with NOM concentrations greater than about 3 mg/L due to large immediate consumption of chlorine for oxidizing NOM to THM. For effective disinfection of bacteria and viruses the chlorine present in free form (chlorine, hypochlorite or chlorine dioxide) should be into contact long enough with the microorganisms. In the case of elevated NOM content in water, free chlorine decomposes rapidly (10–15 minutes) to organic chloramines with very low disinfection efficacy. Is ammonia present in the water, chloramines are formed with slightly higher disinfecting effect, but still very low. To keep the chlorine in the free form, so-called breakpoint chlorination is required, using high chlorine doses (> 2 mg/L). According to Swedish Drinking water regulations, no more than 1 mg/L chlorine must be added to the drinking water to reduce formation of THM. Thus, break-point chlorination is illegal in Sweden and this is not an option. Other measures are needed.

Many water utilities use activated carbon filtration to protect against odour interfering substances formed by algae. NOM at concentrations above approximately 2 mg/L decreases further sharply the adsorption capacity of activated carbon. The carbon is saturated with NOM after 1–2 months of operation. Freshly activated carbon can effectively remove many interfering chemical species, such as low levels of petroleum products (emissions associated with boating accidents, extreme weather, etc.) pollution associated with sewage and stormwater discharges, pesticide residuals etc. With high NOM in the water, the activated carbon is rapidly saturated and its ability to sorb pollutants, including petroleum products, to levels below odour threshold ceases. NOM is of concern for the water industry.
Sydvatten – South Sweden water supply

The Drinking water utility Sydvatten produces drinking water from two main water sources, Lake Vombsjön in Skåne and Lake Bolmen in Småland. Representatives from five main cities of Western Scania formed a municipal committee in 1961 which made a common joint response to build and manage a tunnel from Lake Bolmen to lead lake water to the waterworks Ringsjöverket in Stehag, where good drinking water could be produced. In 1966 Aktiebolaget Sydvatten was formed, which gradually transferred to a regional water supply company for western part of Skåne. In 1976, seven new municipalities became members and owners of Sydvatten and during the 21st Century also Bjuv, Vellinge and Skurup has joined. The Bolmen tunnel was taken in operation in 1987. In total, Sydvatten invested in modernised and improved water treatment plants and distribution systems during 1983–2000 for more than 1 000 Million SEK. Together with the investment in the Bolmen tunnel itself, the total gross assets in the company are about 2 000 Million SEK (Persson and Johansson, 2010).

The Lake Bolmen

Raw water from Lake Bolmen is now a central part of Scania’s long-term water supply. Lake Bolmen is the largest lake in southern Sweden, and the tenth largest lake in Sweden with the area of 184 km². The entire Bolmen basin, with the area of 1640 km², is the largest sub-basin of the River Lagan watershed, which in total covers about 6454 km². The lake is elongated in a north–south direction, about 30 km and in east west direction about 10 km wide with a beautiful island Bolmsö located in the middle of the lake. It is situated in southwestern Sweden within three counties, Kronoberg, Jönköping and Halland. In the total Lake Bolmen basin, about 48% of the land comprises forest, 22% marsh, 20 % lakes and about 9% is cultivated land. The three major tributaries of the lake are Storån River, Lillån River and Lake Unnen. In addition there are a number of other small streams such as: Dannäsån, Mjösjöbäcken, Harasjöbäcken and Murån. Lake Bolmen is drained through the River Bolmsån, where a hydropower plant is placed. The plant is located in Skeen. In Skeen, water is also led to the Bolmen-tunnel and finally discharged to the waterworks Ringsjöverket in Scania where the water is treated to drinking water quality.

The presence of a large island in the middle of the lake divides the lake into northern, southern, eastern and western sub-lake. The southern part
covers the largest portion of the lake area with the maximum depth of 37 m and average depth of 8 m. The maximum depth of the northern part is only 13 m and the average depth is 5–6 m. From Storån and Lillån Rivers, the northern part receives about half of the total inflow of the lake. The southern part is usually stratified in summer with a thermocline between 10–20 meters depth. The NOM concentration or water colour in the Lake Bolmen watershed is measured at the entrance of the lake from the streams Storån, Lillån, Murån and Unnen. The retention time of the lake is about 2.8 year.

Since the late 1990s, the colour in the raw water from Lake Bolmen has increased steadily as has the amount of organic matter (see Figure 2 and Table 1). This trend is negative for the lake’s water quality and ecology. Brown water reduces light inflow and affects the balance in different biota, particularly reduces the population of salmon, trout and pike. The formation and transport of NOM in Lake Bolmen watershed is complex and affected by many parameters including temperature and runoff. Storån River contributes the largest fraction of both water and NOM substance to Lake Bolmen. Due to the existence of strong positive correlation between the colour value of Storån River and Lillån River and their colour contribution is very big, about 87% in 2007, any change of colour value of Storån could affect the water colour of the lake. Both the intra-annual and interannual variation of water colour of Storån River seems to be very large. The summer and autumn season are dominated by peak value of colour intensity, while the spring and winter are dominated by the minimum value. There is also a positive and significant statistical correlation between mean

![Buffering capacity in Lake Bolmen](image)

Figure 2. The observed buffering capacity in the lake Bolmen from 1982 and onwards.
annual discharge and colour value. During summer and autumn season the influence of discharge is high relative to spring and winter seasons, in terms of contribution to NOM, measured as the water colour. In Sweden, climate change is predicted to have increased runoff (Andréasson et al., 2007). Due to the existence of positive correlation between discharge and water colour value it can be concluded that the climate change will increase the water colour of Lake Bolmen, particularly in Storån River.

From a technical point of view, Sydvatten needs to use larger amounts of chemicals in the treatment of NOM-richer raw water to drinking water, which in addition to an increased environmental load also gives rise to an increased amount of waterworks sludge and rising treatment costs.

Table 1. Yearly average, maximum and minimum values of water colour from 1987–2007 in Storån River, the largest tributary to Lake Bolmen; the yearly standard deviation and the factor (used to compare the difference between yearly peak and minimum value).

<table>
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<th>Maximum</th>
<th>Minimum</th>
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Lake hydrology research is important for the water supply

NOM variation need to be better understood. Sydvatten have therefore chosen to alert regulators of the lake on the change, and initiated a knowledge survey of the lake’s water quality changes in collaboration with Lund University. Lake hydrology, draining, temperature and precipitation affect the NOM-content and the colour of water. In particular, the tributaries to the lake have presented a sharp increase in NOM and colour during the last fifteen years (see Figure 3). Statistical correlations between colour and precipitation, however, showed only a weak positive correlation.

The solubility of NOM increases with increasing soil water pH. Acid rain has immobilized organic matter in the soil layer. Since 1980, acid rain intensity has been reduced, sulphate deposition decreased, pH increased in soil water and buffering capacity in Lake Bolmen increased (see Figure 2).

Land use also affects NOM in water. The Bolmen area has probably the highest percentage of drained forest on peat in Sweden. The quantities of materials that were previously bound to soil discharged through the tributaries to Lake Bolmen. The annual precipitation has also increased slightly in western Småland during the last twenty years. An important factor affecting NOM formation and degradation is the length of the growing sea-

Figure 3. Changes in colour (above) and concentration of organic carbon (below) in southern (▾) and northern (◮) part of Lake Bolmen (Data from SRK databases).
With climate change, it will gradually increase in Sweden and according to SMHI forecasts has grown by about 90 days in central Sweden at the end of this century. Longer growing season increases the production of forest biomass and hence NOM. Yet warmer climate also affects degradation pathways. Likely the wood production will be more deciduous forest-based, which in turn affects the type of NOM added to the surface waters.

Remote sensing
Together with other water providers and active researchers and in close cooperation with researchers of the division of Water Resources Engineering, Sydvatten has initiated a more comprehensive study program that should lead to better understanding of the water quality development in the area and possibly to identify measures against further browning of lake
Bolmen waters. One part of the studies will be to use remote sensing from the satellite MERIS. The water quality information is derived from MERIS fr-data with a spatial resolution of 300 meters and spectral characteristics that are specially adapted to water applications (see Figure 5). MERIS covers the Bolmen area approximately 4–5 days per week, but the number of available images is limited by clouds. In practice, one can expect between 20–30 useful images per summer season (April–September). Earlier work on the great lakes Vänern, Vättern and Mälaren have shown that the satellite based water quality measurements are highly correlated to field measurements, yet sometimes a bit off in absolute values. New algorithms are under development and initial evaluations have shown good results regarding the absolute levels.

MERIS fr-data will be processed and analysed for Bolmen including correction for land-water interaction, atmospheric correction, geometric correction and application of water quality algorithms to the data. Bolmen is one of Sweden’s larger lakes but small compared to Lakes Vänern, Vättern and Mälaren, which have been in focus for water quality remote sensing earlier. 300 m resolution should however be enough for Bolmen. It
should be possible to extract useful data for further analysis. The corrected and extracted data will be analysed for trends, differences and changes in the spatial domain and with respect to concentration levels. The satellite based measurements will also be compared to field based measurements for evaluation and for investigating the possibility to derive accurate absolute level for the concentration of chlorophyll (Figure 6), suspended matter (Figure 7) and humus (Figure 8) in Bolmen. 12 locations in and close to Bolmen are regularly sampled and that data will be used in the analysis. Temperature, colour, TOC, nutrients, minerals, turbidity, chlorophyll, pH, conductivity, alkalinity, Secchi depth, oxygen content and oxygen saturation are regularly monitored for these locations. The work will start in 2012 and be conducted by Sydvatten AB, Brockmann Geomatics Sweden AB, Jönköping, Halland and Kronoberg County Boards with support from the Swedish Space Agency. Of particular interest for Sydvatten is to investigate whether satellite based water quality information can be used also to support the decision making for the operators at the waterworks Ringsjöverket.
Enhanced water treatment technologies

Another crucial knowledge arena to study is treatment methods for removing any NOM present in water. Optimization of the present coagulation and filtration treatment process at Ringsjöverket may be done and further NOM removed. NOM can also be removed with the help of advanced oxidizing technology (AOT) such as ozone or hydrogen peroxide, or through membrane treatment.

Membrane structure, applied pre-treatment, water quality parameters such as organic, inorganic and biological content, choice of coagulant, dosing system and operating conditions as flux, trans-membrane pressure (TMP), flushing and washing intervals are central parameters for the performance of the membrane plant. Generally, experiments in lab-scale are not sufficient to understand the final production of a membrane plant; at least pilot-plant scale studies should be conducted to clarify the relationship between raw water properties and membrane performance. Therefore, Sydvatten has been involved in pilot plant studies with ultrafiltration membranes at Kvarnagården waterworks in Varberg since 2010. The project manager is Alexander Keucken at VIVAB. The studies use an independent microfilter and existing sand filters as pretreatment step and a fully automatic pilot plant equipped with various UF modules. The pilot plant has a maximum capacity of 6.5 m$^3$/h and allows for three different operating modes (dead-end, continuously and proportionally concentrate outlet with and without fast forward). Important performance parameters such as net and gross flux, permeability, TMP and water exchange is calculated continuously through data from pressure, temperature and flow measurements. Furthermore, the membrane functions in different modes of operation as well as maintenance measures are studied in detail. In parallel to the practical experiments is a follow-up of surface water quality through real-time measurement with a focus on the weather – and seasonal variations of organic fractions. The pilot plant has been operated during the tuning period without pre-treatment with 70 l/m2h (gross flux) and reasonable efforts by means of automated back washings and cleanings (Cleaning In Place, CIP). Raw water has been characterized with respect to organic matter (TOC and its fractions, SUVA) and source. The results tentatively show that it was a very good effect on the reduction of colour with UF already at a relatively low dosage, about one gram of aluminium per cubic meter of raw water. These studies will be executed also for the waterworks Ringsjöverket in the coming year.
The importance of thorough lake hydrology studies is probably obvious for the reader now. Valuable theories and methodologies as investigated and presented by professor Lars Bengtsson will continue to be used by modern lake hydrologists. So will the spirit of knowledge seeking glow also for new generations of water researchers. Only so can the supply of wholesome and clean drinking water continue.

Acknowledgements

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