The color of water

Climate induced water color increase in Nordic lakes and streams due to humus

Millions of people drink lake or stream water in the Nordic countries

Clean water, free from harmful organisms and chemical substances, is a necessity for human society. Compared to many other regions of the world, the raw water used for drinking water production is of good quality in the Nordic countries. Generally, groundwater maintains a better quality than surface waters. Nevertheless, millions of people in the Nordic countries use drinking water originating from lakes and streams. In Sweden for example, around 50% of the population use surface water, 25% use it after artificial infiltration, while only 25% get their drinking water from groundwater wells.

Humus causes problems for the drinking water production system

A main difference between groundwater and surface water is that the former generally contains very low concentrations of organic substances. Surface water on the contrary, exhibits large variations in organic matter content both in time and space. In non-polluted waters, most of the organic matter originates from the soils. These substances color the water yellow or brown. Studies in small alpine and boreal catchments in the Nordic region show that the annual humus leakage, measured as total organic carbon (TOC), varies between 10 and 200 kg C ha^{-1} y^{-1}. The colored organic matter is called *humus* or scientifically more correctly, *aquatic humic substances*, and it has always created problems in water treatment plants trying to produce drinking water of high quality. Humus reduction experiments took place already in 1908 at the Helsinki water treatment plant. Iron salt was added to the colored and turbid water from river Vantaa in order to precipitate the humus and clay particles. This process occurs in nature as well.

Humus is substrate (food) for bacteria and fungi. This can contribute to excess microorganism growth in the water distribution system, causing secondary problems such as diseases, taste and odor. Thus, the raw water has to be treated before it reaches a quality suitable for drinking and can be distributed to consumers. The EU drinking water directive (98/83/EC) has sharpened the enforcement of water quality norms, for example with regards to the humus content. Chemical treatment (iron, aluminum, polymers etc.), filtering and/or UV-radiation are used to reduce the humus concentration to acceptable levels. Chlorination can be used as a final treatment in order to keep the microorganism production in the distribution system at an acceptable level. Unfortunately, the remaining humus and added chlorine might react and create chlor-organic compounds with very unpleasant smell at extremely low concentrations.

What is humus?

Humic substances, humus, are the brown substances leached out of the soil by water. The yellow to brown color is caused by large and complex organic substances which are mainly derived from decomposing plants and animals. To some extent the color may also originate from secretions by microorganisms, plants and animals. Humus is an important factor for the transport and bioavailability of inorganic and organic nutrients. It affects the toxicity of heavy metals and organic pollutants in the environment, since it forms complexes with many toxic substances. Humus is also very important for surface water acidity due to its acid-base properties. Many surface waters are naturally acidic (pH<6) due to humic acids.

Enhanced water treatment problems during the 1990's

During the 1990's many Nordic water treatment plants experienced large production problems due to increased humus concentrations in their raw water. The costs for water treatment rose considerably, and still the quality of the drinking water deteriorated. Some municipalities even evaluated the possibilities for switching to other water supplies with better quality. Thus, it is of great interest for society to know whether the humus concentration will continue to rise, level out or return to more acceptable levels? To achieve this, important questions need to be answered, such as what effects could be expected due to a global climate change, resulting in warmer weather and higher precipitation in the Nordic countries? This project, funded by the Nordic Council of Ministers, the Swedish University of Agricultural Sciences (SLU), the Norwegian Institute for Water Research (NIVA), the Finnish Environment Institute (SYKE) and the University of Umeå, has had the aim of answering questions related to these issues. Some of the results are presented in this brochure.

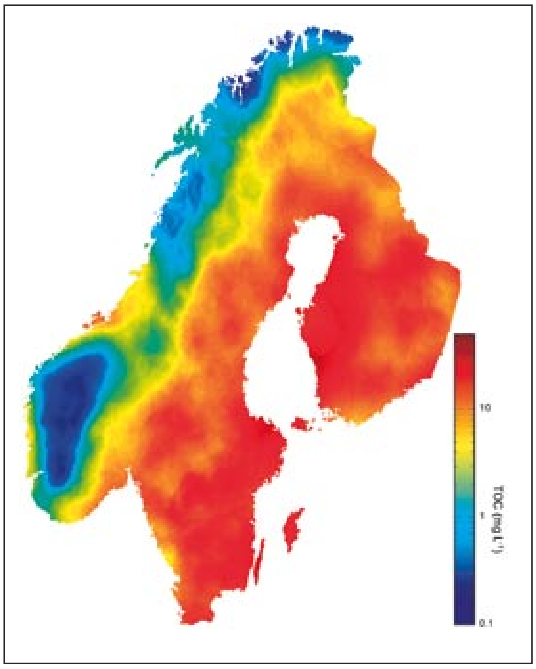


Figure 1. Map of humus concentrations, measured as TOC, in Fennoscandian lakes (n_{Tot}=4900 lakes), showing a strong west-east gradient from the clear lakes of western Norway to the humic lakes of Finland and eastern Sweden. The regional pattern is related to climate, soil depth and vegetation type.

Clear waters in Norway and colored waters in Sweden and Finland

In 1995, a Nordic survey of approximately 4 900 lakes was performed. The concentration of organic matter, measured as total organic carbon (TOC), in each lake was analysed. TOC gives a good estimate of the humus concentration in the water. Extremely low humus concentrations were found in the alpine regions of Norway (Figure 1). In these clear water lakes, having a TOC-concentration of less than 1 mg/l, the transparency might be well above 10 meters. The most colored waters were found in southeast Sweden and in Finland, with TOC-concentrations often above 20 mg/l. The transparency in those lakes rarely exceeds 1 m, and some of them have the color of coffee.

These humus gradients are mainly caused by different humus outputs from the soils due to differences in climate, soil and vegetation type, but they are also influenced by internal processes in the watercourses such as sedimentation, photo-oxidation, mineralization etc. High humus concentrations occur mainly in peat and forest covered areas with few lakes, i.e. areas with large soil pools of carbon and short water retention times. Low concentrations are found in regions with sparse vegetation, poorly developed organic soils and large lakes (small soil pools of carbon and long water retention times). The humus concentrations are usually higher in the headwaters compared to further downstream.

This knowledge is not new. Already in 1929, J.V. Eriksson stated that "*Anyone who just briefly has given our streams in forested areas some attention, most certainly has observed the following facts. The smallest streams are often dark brown, especially if they are discharging from mires. When they enter into a larger stream, you observe that the water is lighter in color. Even though most inlet streams to a lake have dark brown water, the outlet exhibits a less colored water, at least not dark brown, if the lake has a volume of any significance*".

Additionally, the concentrations of organic matter early in the last century (1916-1925) are very similar to those documented during the last decades (1965-2001) in some Swedish rivers in central and northern Sweden and in an inlet to Lake Vättern (River Domneån, Table 1). These data show that no dramatic changes have occurred during the last century with regards to the humus levels.

River	Time period	Mean value $KMnO_4$ (mg/l)	Standard deviation $KMnO_4$ (mg/l)	Number of observations
Domneån	1916-1925	61.3	16.2	51
	1966-2001	71.4	31.2	375
Klarälven	1916-1923	23.4	7.7	37
	1965-2000	28.4	9.2	426
Ljusnan	1916-1923	30.3	7.5	37
	1969-2001	36.0	13.8	356
Ljungan	1916-1923	23.6	4.3	36
	1969-2001	25.6	5.1	389
Indalsälven	1916-1923	19.9	2.4	35
	1969-2001	18.1	4.5	364
Skellefteälven	1916-1923	16.2	10.5	31
	1969-2001	17.3	8.3	382
Piteälven	1916-1923	13.2	4.6	34
	1967-2001	14.6	7.9	412
Abiskojokk	1919-1923	6.2	2.9	19
	1982-2000	5.2	5.1	226

Table 1. Humus concentrations measured as $KMnO_4$ consumption in some Swedish rivers during the early and late 20th century. The data from 1916-1925 were analysed by J.V. Eriksson, while the data from the later period are from SLU. The sampling points are situated close to each other, but are not identical in the two investigations.

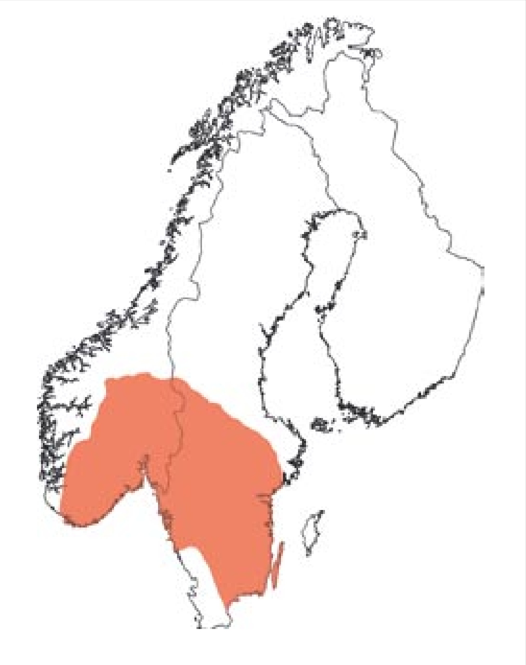


Figure 2. Regional humus trend pattern, measured as TOC, in Fennoscandian lakes. Lakes in the shaded area had a statistically significant increase in humus concentrations over the period 1990-1999. ($p < 0.05$, n_{Tot}=344 lakes, Mann-Kendall)

Increased humus concentrations in southern Scandinavia during the 1990's

Humus concentration changes during the 1990's were studied in 344 reference lakes in Norway, Sweden and Finland. The human impacts on the water quality in these lakes are restricted to atmospheric deposition and forestry. Statistically significant trends were mainly found in lakes in southeast Norway and southern Sweden (Figure 2). Similar humus trends have also been observed in watercourses in Scotland. These results confirm the observations of increased humus concentrations made at many water treatment plants.

Hydrologic characteristics influence the humus concentrations

The municipalities of Karlskrona, Falun and Stockholm have kindly put data to our disposal on the organic matter concentrations since the 1940's in River Lyckebyån, Lake Rogsjön and Görveln, respectively. Similar analytical methods, based on the permanganate ($KMnO_4$) consumption by oxidation of organic matter, have been used at the water treatment plants throughout the time period. The data show some examples of the long-term humus concentration variations in southern Sweden, corresponding to the region where increased humus concentrations were documented during the 1990's.

The three watercourses have more than 70% of their drainage areas covered by forests or peat. However, the hydrological characteristics are very different (Table 2). River Lyckebyån has a water retention time on the order of days and only 4% of the catchment area are lakes. The L. Görväln sub-basin is situated in the eastern part of Lake Mälaren, which is the third largest lake in Sweden. It has a water retention time of 0.6 years, (L. Mälaren = 2.8 years) and a lake area of 11% in the catchment. Lake Rogsjön has a long water retention time of 5.6 years and a large lake area of 14% in the drainage basin. Theoretically, it would take 5.6 years in L. Rogsjön to renew the water volume, while the water in R. Lyckebyån is renewed constantly.

Thus, R. Lyckebyån quickly responds to rain or snowmelt events and has a low potential for in-stream processes to reduce the humus concentrations. Lake Görväln and especially L. Rogsjön have a delayed response to weather variations and good potential for reductions of the humus content due to in-lake processes. These differences are mirrored in the humus concentrations expressed both as water color and $KMnO_4$ consumption (Table 2). As an average for the period 1940-2002, the water color in R. Lyckebyån was more than 4 times as high as in L. Görväln and more than 7 times as high as in L. Rogsjön.

Table 2. Drainage basin characteristics and average humus concentrations measured as water color and $KMnO_4$ consumption, during the period 1940 to 2000 in River Lyckebyån, Lake Rogsjön and Görveln.

Watercourse	Specific run-off $dm^3\ km^{-2}\ s^{-1}$	Water retention time, years	Catchment area km^2	Forest area	Lake area	Color mg Pt l^{-1}	$KMnO_4$ mg l^{-1}
Lyckebyån	7.6	<0.01	810	79%	4%	103	56
Görväln	7.2	0.6	22 603	70%	11%	23	24
Rogsjön	9.1	5.6	190	84%	14%	13	16

How do we measure humus?

The amount of organic matter in surface water can be measured in many different ways.
The list below gives some examples of different methods that are in use.

Name	Explanation	Contents
TOC (mg C/l)	Total organic carbon	All organic carbon in the sample.
DOC (mg C/l)	Dissolved organic carbon	All organic carbon which passes through a filter of a defined pore size.
BOD_7 (mg O_2/l)	Biochemical oxygen demand	The bacterial consumption of oxygen during 7 days. Less reproducible than COD.
COD_{Mn} (mg O_2/l)	Chemical oxygen demand	Chemical decomposition of organic carbon by $KMnO_4$. Chromate (COD_{Cr}) is used for industrial water.
$KMnO_4$ (mg/l)	Potassium permanganate consumption	Chemical decomposition of organic carbon by $KMnO_4$. $COD_{Mn} \approx KMnO_4/3{,}95 \approx$ DOC
Water color (mg Pt/l)	The water color is compared with the color of a standard	The water color in filtered water is compared with the color of a standard $PtCl_6^{-2}$-solution or disk. Humus, but also iron and manganese color the water. A subjective method!
Water absorbance	Absorbance measurement	The absorbance is measured on filtered water. Different wavelengths e.g. 254, 400, 420 or 436 nm are used. Better accuracy than water color.

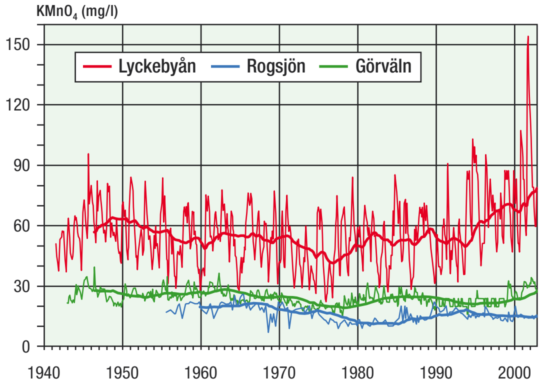


Figure 3a. The humus concentrations measured as $KMnO_4$ consumption, since the 1940's in river Lyckebyån (south Sweden), Lake Rogsjön (central Sweden) and Lake Görveln (east central Sweden). Thick lines are 60 month moving averages.

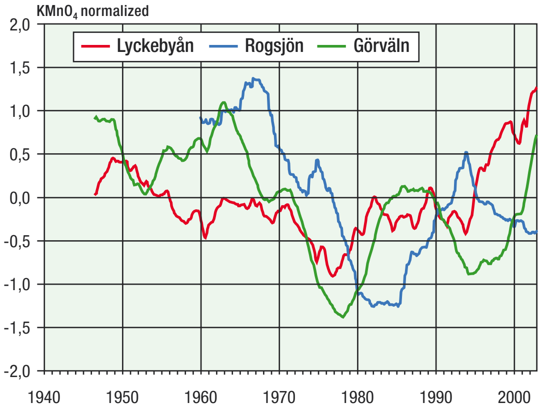


Figure 3b. Five years (60 month) moving averages of the normalized humus concentrations measured as $KMnO_4$ consumption, since the 1940's in river Lyckebyån, Lake Rogsjön and Lake Görveln.
Normalized value = (observed value – mean value) / standard deviation.

Long-term cyclic weather variations affect the humus concentration level

Each watercourse exhibits large humus concentration variations both seasonally and between years. The long-term variations are far from simple linear trends. Instead, the data indicate a more or less cyclic course of events (Figure 3a). In R. Lyckebyån, the humus concentrations increased in the beginning of the 1940's and were above average for some ten years around 1950, whereupon it decreased to a minimum in 1976. Thereafter, the humus concentrations slowly increased and reached the average level in 1993 before it reached the maximum value in 2002 (Figure 3b). The data from L. Rogsjön and L. Görväln also indicate cyclic trends, but the periodicity and amplitude varies. Looking at the periodicity, the humus cycles in L. Görväln seems to be almost in phase or slightly delayed (<2 years) with R. Lyckebyån, while the cycles in L. Rogsjön seems to be delayed by 4-7 years. These phase shifts indicate that the water retention time is an important factor influencing the timing of humus content peaks among different watercourses.

The humus concentration increased during the early 1940's in R. Lyckebyån (Figure 3). This coincided with a period of increased air temperature, increased precipitation and shorter periods of snow cover during wintertime. The decrease during the late 1960's and 1970's coincided with a period of increased air temperature, lower precipitation and shorter periods of snow cover (Figure 4). The humus concentration increase during the late 1970's and 1980's coincided with a period of lower air temperature, higher precipitation and longer periods of snow cover than normal. Higher air temperature and shorter periods of snow cover than normal characterized the 1990's. In the R. Lyckebyån region, where increased humus concentrations were documented, the precipitation was above normal. In the other two regions, the precipitation varied much more and was on average less than normal in the middle of the 1990's.

The large-scale cyclic patterns in the three watercourses show that climatic factors are fundamental for the humus dynamics. In R. Lyckebyån, there is a statistically significant positive relationships between the yearly average humus concentration and yearly precipitation. No such relation is found in L. Görväln and L. Rogsjön due to the longer water retention times and thereby delayed humus cycles. However, a positive relation between humus concentration and water discharge has been found in L. Rogsjön. Obviously, the amount of precipitation is very important for the humus leakage from soils, thereby influencing the humus levels in the watercourses. No relationships were found in the R. Lyckebyån between humus concentration and air temperature or the duration of snow cover.

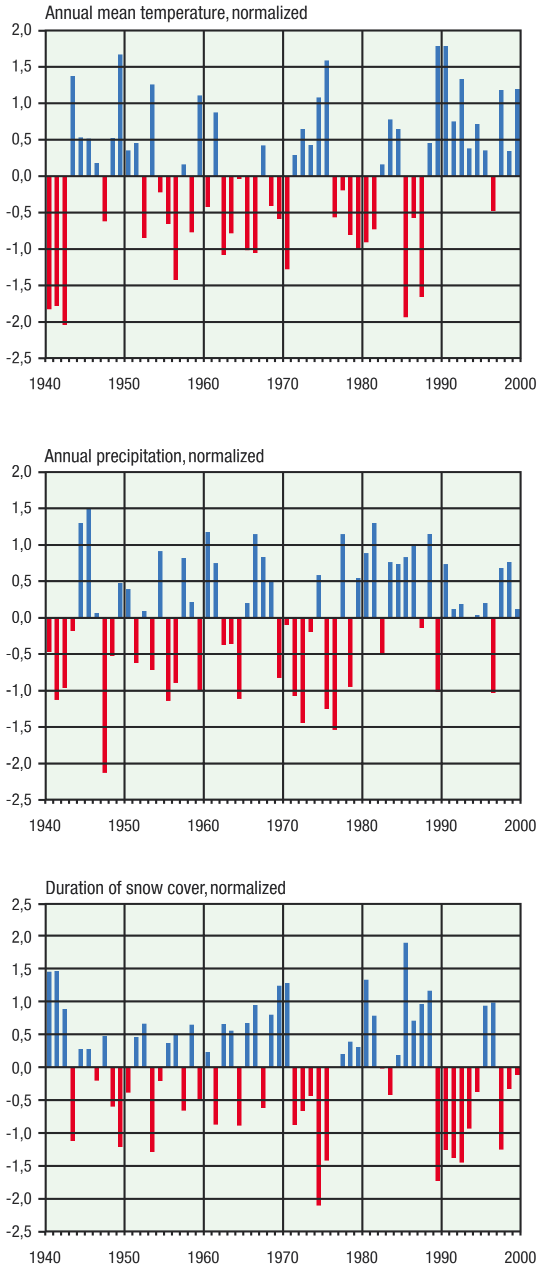


Figure 4. Average values of normalized annual air temperature, precipitation and duration of snow cover at the SMHI weather stations at Växjö (south Sweden), Falun (central Sweden) and Uppsala (east central Sweden). Normalized value = (observed value – mean value) / standard deviation.

Short-term weather variations cause humus concentration peaks in summer or winter

However, during the period 1940-2000 in R. Lyckebyån the maximum humus concentrations, measured as water color, occurred on 26 occasions during wintertime, December-March, and on 26 occasions during summertime, June-August. Based on the weather monitoring at Växjö, the winter humus peaks corresponded to years when the autumn and winter weather, September-March, on average were colder (<1°C), dryer (<25 mm) and had a shorter period of snow cover (<15 days) than normal. The summer humus concentration peaks corresponded to years when the same characteristics occurred in spring and summer, April-August. The humus peak values varied tremendously between years and ranged in wintertime from 81 to 178 mg Pt l^{-1} and in summertime from 81 to 224 mg Pt l^{-1}.

Between 1940 and 1965, winter humus peaks dominated (16 occasions) while summer peaks were rare (3 occasions). After 1966 this pattern changed and summer peaks dominated (23 occasions) and winter peaks became more rare (10 occasions). This shows that the autumn and winter have become warmer and wetter, while the spring and summer have become colder and dryer.

On a time scale of a decade or longer, high humus concentrations are induced by periods of more or less continuously increasing precipitation, while low concentrations are induced by longer periods of drought. Opposite to these long-term humus dynamics, the annual humus peaks in R. Lyckebyån are connected to cold and dry weather during the previous 5-7 months.

An interpretation of those two different patterns could be that long-term increases in precipitation, increase the groundwater level so that it comes in contact with surficial, organic rich soils over extensive areas. Most of the organic matter (more than 70%) is accumulated in the upper part of the mineral soil except for in bogs, mires and fens where it is mainly stored in the peat. The summer and winter humus peaks, however, are probably created when the groundwater temporarily levels off and the surface water runoff originates from peat land and permanent groundwater discharge areas, rich in organic matter. There are many studies from northern Sweden showing the importance of these riparian zones for the short-term humus dynamics in streams.

Riparian zones important for humus concentrations

Daily water discharge and biweekly humus concentrations in three small, forested catchments (0.2-0.4 km^2) during the period 1997 to 2001 are presented in Figure 5. The climate in Aneboda resembles that in R. Lyckebyån with the highest water discharge in autumn and winter. The climate in Kindla resembles that in L. Rogsjön, with run off events mainly in autumn and spring, but both summer and winter floods occur frequently. Gammtratten is situated in northern Sweden about 100 km west of Umeå. It has a typical northern climate with cold winters and intense flood episodes during snowmelt in spring and during rainstorms in summer.

At Aneboda, the seasonal humus dynamics are very similar to those in R. Lyckebyån with highest concentrations during low flow in summer. High water discharge in autumn and winter seems mainly to dilute the humus concentrations. At Kindla, the humus concentrations were low in late winter, increased steadily throughout the spring and summer and reached a maximum in early autumn. Humus peaks often occurred at snowmelt in spring and during other run off events. The dry summer 2001 was an exception with high humus peaks in summer similar to those at Aneboda. At Gammtratten, the lowest humus concentrations occurred at low run off in late winter, while high concentrations were documented during all water discharge events of any significance.

Besides climate, the area and localization of organic soils probably cause the differences in humus dynamics between the three catchments. At Aneboda, small differences in topography (30 m) and organic rich soils in extensive riparian zones in the lower parts characterize the catchment. The peat in these riparian zones is probably very important for the humus dynamics during low flow. During high flow events, dilution by groundwater from less organic rich soils in the upper part of the catchment, lateral flow on top of the peat and preferential flow (groundwater flow within "channels" in the peat) probably becomes important. At Kindla and Gammtratten, the topographic differences are 100 m and 135 m, respectively, and a thin border of peat locally covers the riparian zones. In the central part of the catchment at Kindla, a small mire is situated. This mire seems to be important during low flow, but during run off events the shallow groundwater is in contact with organic rich soils in the riparian zones in other parts of the catchment, causing humus concentration peaks. At Gammtratten, three small mires are located close to the water divide, but the organic soils in the riparian zones in other parts of the catchment seem to be more important for the humus dynamics during the frequently occurring flow events.

Large drainage basins are composed by a more or less endless number of small catchments like those in the examples above. The sub-basins are of different character and they are arranged in complicated mosaic patterns, sometimes including lakes. Thus, the humus concentrations in the outlet to large catchments give an average, integrated picture of the hydrology and the humus dynamics in all the tiny parts of the drainage basin.

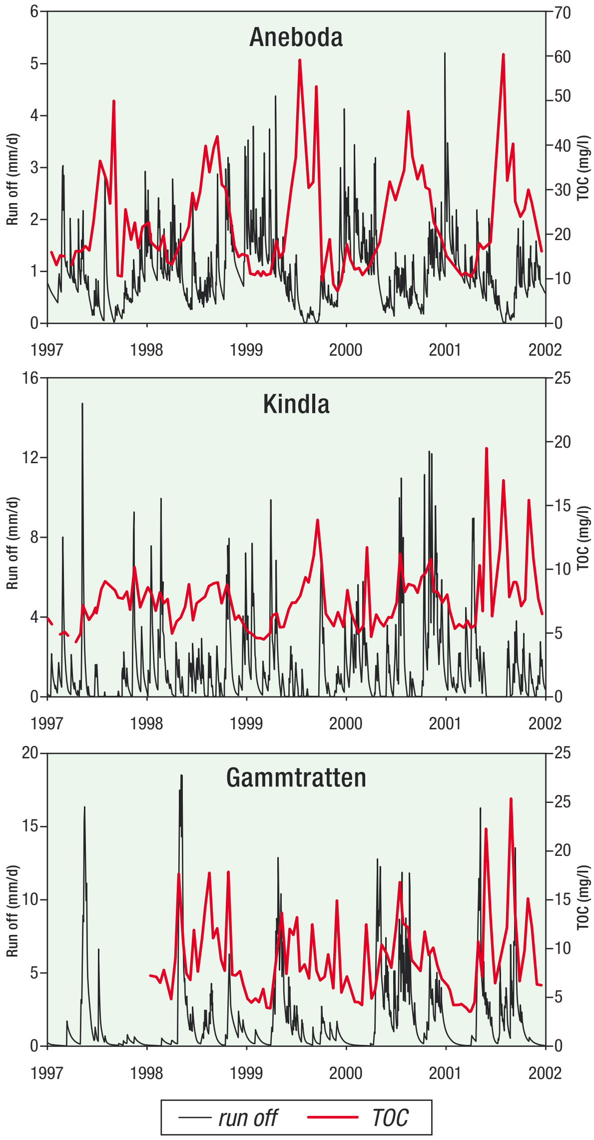
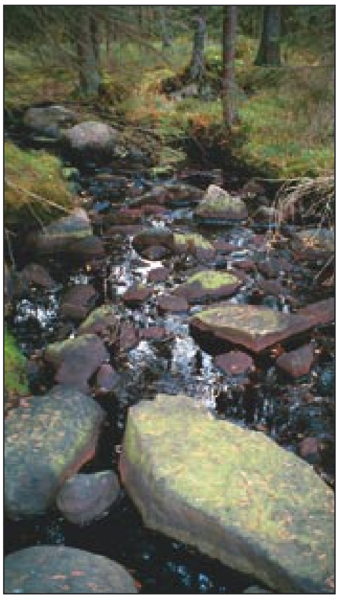
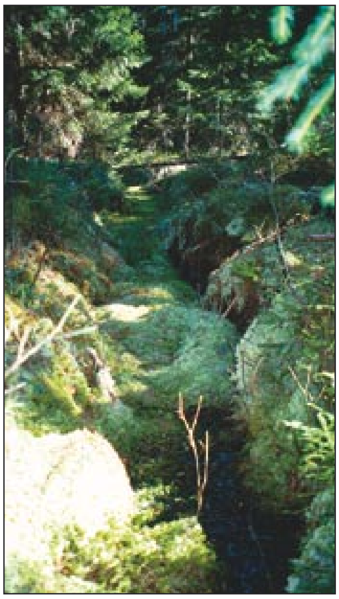
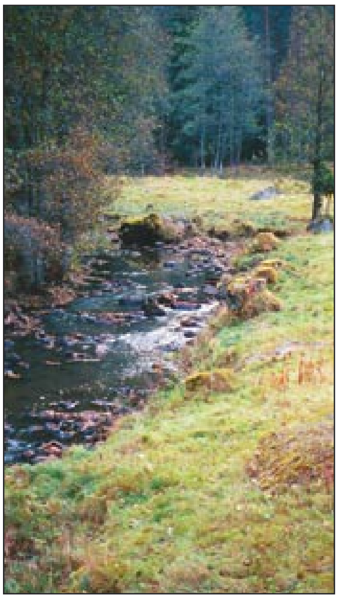
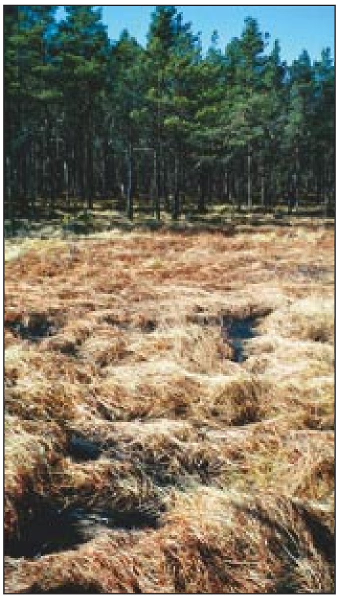


Figure 5. Daily run off and biweekly humus concentrations measured as TOC, over the period 1997-2001 at Aneboda (south Sweden), Kindla (central Sweden) and Gammtratten (north Sweden).









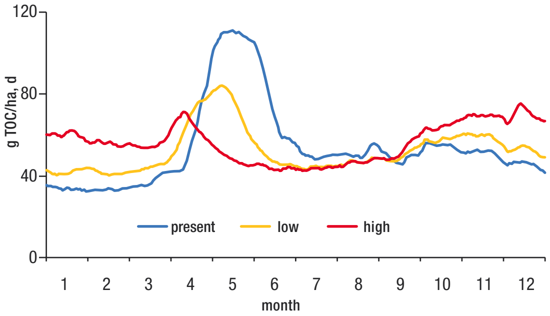


Figure 6. Predicted daily values of humus fluxes (TOC) at Hietapuro in southern Finland for present conditions (1990's) and for a low climate change scenario (1-3°C temperature increase, -1% to +15% precipitation increase) and a high climate change scenario (3-7°C temperature increase, -19% to +41% precipitation increase).

Will humus concentrations continue to rise in the future?

Since humus dynamics are intimately coupled to long-term and short-term weather variations, it is evident that humus concentrations will change over time. Looking at the long time series, the variations in humus concentrations exceed at least a factor of 3. If the amount of precipitation significantly decreases or increases during a decade we would expect the watercourses to become less or more colored by humus, respectively. Depending on the water retention times, they will respond rapidly or after some years. The humus concentrations in L. Rogsjön for instance, might increase in the coming years due the extremely high precipitation during 2000.

Since the scenarios regarding the weather in the future are very uncertain and differ widely, it is difficult to make reliable forecasts of the humus concentration trends. However, humus leakage simulations have been performed with a newly developed model on data from two small catchments in Finland. The climatic scenarios take into account possible temperature increases due to global warming, causing warmer and wetter winters and autumns and drier summers. The results indicate that the annual humus (TOC) fluxes could increase up to 26% in the worst case scenario, at a seasonal mean temperature increase of 3-7° C and a change in seasonal precipitation of -19% to +41% (Figure 6).

Implications for drinking water treatment

Large, long-term, climate induced humus concentration variations are a fact and should be expected in most lakes and streams. These variations should be taken into consideration at water treatment plants when planning for the future. By evaluating historical time series on water color and organic carbon concentrations in the raw water available to water treatment plants, it is possible to get a good estimate of the humus dynamics in the water supply. If high humus concentrations have occurred earlier you should expect them to appear again.

Global warming has also been accepted as a fact, but as yet we do not know the climatic effects in detail. However, most simulations indicate changed seasonal dynamics in addition to increased temperatures and greater precipitation. If those scenarios are relevant, the humus concentrations will be influenced. The Finnish model simulations indicate increased humus leakage. Additionally, it has been hypothesized that the increased forest production during the 20th century has increased the carbon pools in the soils, causing excess humus leakage to surface waters. Both of these issues need to be followed up and evaluated in the future.

Uncertainties like these make it very difficult to forecast future humus levels in Nordic lakes and rivers. One thing is for sure, however, and that is that the water color in forest waters will increase and decrease in cyclic patterns. A humble statement is that humus concentration variation in the future will be at least as large as in the past.

SLU

SYKE

NIVA

Nordic Council of Ministers

Information and contact persons: The project ”Climate induced variation of dissolved organic carbon in Nordic surface waters”, was financed by the Working Group on Environmental Monitoring and Data at the Nordic Council of Ministers (http://www.norden.org), the Department of Environmental Assessment, SLU (http://www.ma.slu.se), the Finnish Environment Institute (http://www.environment.fi/syke) and the Norwegian Institute for Water Research (http://www.niva.no). At the home pages you can obtain further information and get access to water chemistry data. Contact persons responsible for the content in this brochure are Stefan Löfgren (Sweden, project leader), Martin Forsius (Finland) and Tom Andersen (Norway). The photos in this brochure were taken by Stefan Löfgren.