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# MODELLING AND HYDRAULIC MANAGEMENT OF A BOREAL RESERVOIR SYSTEM FOR MITIGATING NUISANCE AGENTS IN A PUBLIC WATER SUPPLY – AKERSHUS, NORWAY

*by TORULV TJOMSLAND and OLAV M. SKULBERG*
*Norwegian Institute for Water Research, NIVA, NO-0349 Oslo, Norway*
*e-mail: torulv.tjomsland@niva.no*

## Abstract

The numerical model CE-QUAL-W2 was used for exploring hydraulic measures to minimize the water quality problems experienced by the water works at Aurevatn reservoir, Baerum municipality, serving sixty thousand inhabitants with potable water. The dystrophic nature of the reservoir water is reflected by high values for colour and total organic carbon. The composition of phytoplankton is made up of cyanobacteria, chlorophytes and chrysophytes in moderate concentrations. Problematic contamination of the raw water originates from the development of cyanobacteria. Primary concern has *Anabaena lemmermannii*, producing extracellular substances including geosmin and microcystin. A controlled suppression of the noxious organisms is pursued, and this initiated the requirement for the studies here reported. A number of simulations were tried. The results were interpretable in terms of interacting influences between hydraulic management and microalgal development. An adoptable operating strategy for the system of reservoirs was devised. The implications for an expedient water management are stated. The most important efforts were to use bottom water intake from the upstream reservoirs, and to keep high water level both in Lake Aurevatn and the upstream reservoirs. Effort to remove algal rich surface layer by increased flow over the dam might lead to negative results.

*Key words* – Cyanobacteria, CE-QUAL-W2, hydraulic management, microalgae, public water supply, water quality, water quality model, water work

## Introduction

The Aurevatn reservoir supports Baerum municipality (Akershus, Norway) with natural clean water used as raw water for the public water works serving ca. 60,000 inhabitants. The catchment area is a forest-covered hilly landscape (ca 300–600 m above sea level) with some areas of bogs and other wetlands. The drainage basin is forming the river system Trehoerningsvassdraget, including the lakes Trehoerningen, Byvatn, Smaavatn and Aurevatn, and with a regulated contribution of water from the L. Heggelivatn. The chemical water quality is characterized by low concentrations of suspended matter, relatively high values for colour and total organic carbon (humic water), and low content of minerals according to the type of bedrock. The dystrophic nature of the pelagic water is reflected in the species composition of the phytoplankton, dominated by cyanobacteria, chlorophytes and chrysophytes in moderate development.

Episodic problems have been experienced with off-flavours in the water supply. The consumer complaints relate to the presence of earthy-musty taste of the drinking water. Geosmin produced by cyanobacteria is the cause of these events. Growth of microbes both in the pelagic and in benthic communities is involved in the flavour contamination of the raw water. Of primary concern is the cyanobacteria *Anabaena lemmermannii*, with a planktic population including toxigenic strains liable to pollute the water with microcystin (Tjomsland & Skulberg 2005).

The local authoritative for the water works intend to manage the reservoirs being able to deliver abundant high-quality water for consumers. A controlled suppression of the noxious planktic cyanobacteria is pursued. The objective of the studies here reported was to define hydraulic measures to minimize the water quality problems and discomfort related to the microbiological agents in the drinking water. The solution searched for was based on using a water quality model (Strafaci 2003). This account describes the adaptation and application of the numerical model CE-QUAL-W2 (Cole & Wells 2002).

## Material and methods

### Site description

The four lakes in the catchment (Figure 1) belong to the boreal dimictic type, being circulating freely twice a year. They are directly stratified in summer and inversely stratified during winter.

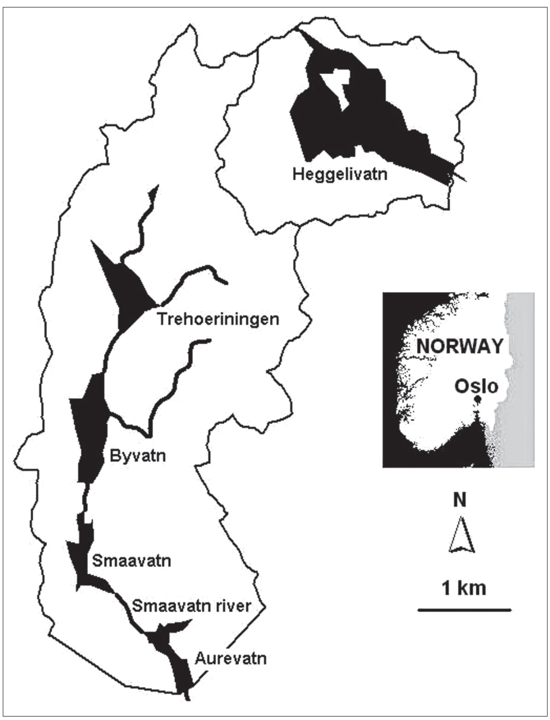


Figure 1. *The Aurevatn reservoir is localized 13 km NW of Oslo.*

Lake Aurevatn is the last in the chain of reservoirs that supply the raw water to the water works belonging to Baerum municipality. The installation was brought into service in the 1960-ties. The reservoir has a maximum storage volume of 1.98 million $m^3$. The surface area is 0.22 $km^2$. The raw water intake is placed 14 m below the highest regulated water level. It is situated close to the dam in the southern end of the lake. The mean water flow is 0.5 $m^3/s$.

There are three other reservoirs in the system, respectively L. Smaavatn, L. Byvatn and L. Trehoerningen. Lake Trehoerningen has in addition regulated tunnel transference with water from a lake in the neighborhood catchment – Lake Heggelivatn. The region is mainly covered by coniferous forest, and there is neglectable pollution from human activities. Information about the main reservoirs with respect to their hydrological, chemical and biological characteristics is summarized in Table 1. The general conditions met with emphasize high content of total organic carbon (> 4.8 TOC, mg C/l), moderate biomass of microalgae (<2.5 µg chlorophyll a) and low concentrations of total phosphorus (in the interval 3–6 µg P/l). In accordance with the nature of the lake water in the reservoirs, typical indicator species of microalgae – proliferating in dystrophic localities – are prevalent (Table 1).

### Field sampling and analysis

Sampling took place at monthly intervals May–October 2004 at the deepest point of the Aurevatn reservoir. Water samples for biological and chemical analysis were taken from regular intervals within the water column with a modified Ruttner sampler. Vertical distribution of water temperature was measured simultaneously, together with conductivity and oxygen concentration. Intact, and formalin-conserved (5 %) samples were collected for microscopical analyses. The material was transported immediately to the laboratory for further processing.

Identification of microalgae was made by optical microscopy on living and formalin conserved material. The classification and taxonomy follow conventional handbooks (Ettl et al. 2001). The collected water samples were analyzed for chlorophyll *a* content and chemical composition using laboratory methods according to Norwegian standard (NIVA 2004).

During 2004 the water level in the reservoir, the temperature and colour of the raw water intake were measured automatically. From May to October a temperature logger was placed in the inflowing river, and a meteorological station for registration of wind, air temperature, humidity and irradiance were operated on the dam by the outlet of L. Aurevatn. For the rest of the year,

Table 1. *Reservoir characteristics and the nature of the lake water (Skulberg 2004).*

| | | Trehoerningen | Byvatn | Smaavatn | Aurevatn |
|---|---|---|---|---|---|
| Hydrological particulars | | | | | |
| Surface area, | $km^2$ | 0.31 | 0.48 | 0.18 | 0.22 |
| Volume, | mill.$m^3$ | 0.99 | 4.40 | 0.50 | 1.98 |
| Regulated depth, | m | 4.5 | 17 | 7 | 14 |
| Residence time, | days (24 hours) | 24 | 105 | 12 | 47 |
| Chemical properties | | | | | |
| Acidity, | pH | 6.7–6.8 | 6.6–6.7 | 6.5–6.7 | 6.5–6.6 |
| Conductivity, | µS/cm (20°C) | 2.1–2.7 | 2.1–2.5 | 2.0–2.8 | 2.1–2.7 |
| Colour (filtered water), | mg Pt/l | 26–38 | 28–37 | 26–36 | 26–35 |
| Total phosphorus, | µg P/l | 4–4 | 3–4 | 4–5 | 4–6 |
| Total nitrogen, | µg N/l | 263–272 | 250–318 | 235–324 | 235–324 |
| Total organic carbon (TOC), | mg C/l | 4.6–5.8 | 4.8–5.5 | 4.8–5.5 | 4.8–5.3 |
| Representative microalgae | | | | | |
| *Anabaena lemmermannii* | | + | + | + | + |
| *Chroococcus limneticus* | | + | ÷ | + | + |
| *Botryococcus braunii* | | + | + | ÷ | + |
| *Gemellicystis neglecta* | | ÷ | + | + | + |
| *Dinobryon borgei* | | + | + | + | + |
| *Mallomonas caudata* | | + | + | + | + |
| *Tabellaria flocculosa* | | + | + | + | + |
| *Cryptomonas marsonii* | | + | + | + | + |
| *Ceratium hirundinella* | | + | + | ÷ | + |

\+ regularly present, observation period 2002–2004
÷ not occuring in the samples analyzed

meteorological data were obtained from the routine registrations made in Oslo by the Norwegian Meteorological Institute.

### The water quality model

The numerical model CE-QUAL-W2 calculates current, temperature, ice cover, oxygen, pH, particles, water chemistry, bacteria, organic matter, sediments-water reactions, algae etc (Cole & Wells 2002). The input is climatic conditions, quantity and quality of water in the inlets, and water flow in the outlets. The model is two-dimensional (length-depth), which means it is well suited for rivers and narrow lakes with similar conditions on both sides in the length direction. The model handles also pipe lines and dams with various outlet systems.

## Results and discussion

### Hydrographic parameters

The field data describing the water quality in the Smaavatn River (inflow to the Aurvatn Reservoir) and the Aurevatn reservoir are summarized in Table 2. The river water was mainly of the same chemical composition as the reservoir water, constituting the raw water supply of the water works. The observed data from 2004 were used for the calibration of the model, and for modifying the model to expressing the internal circumstances for essential processes in the Aurevatn reservoir.

### Application of the CE-QUAL-W2 model

Simulated temperatures showed good accordance with the measurements through the year, both for the raw water intake (Figure 2), and in the profile of the water column in the middle of the Aurevatn reservoir (Figure 3). The deviations were seldom greater than 1°C. This indicates that the model handles the hydrodynamics in the reservoir in a reasonable way. However, there was a systematic difference. The simulated temperatures increased too early in the spring. That was caused by a too early simulated break up of the ice cover. The reason is probably that the model does not consider the isolating effect of snow lying above the winter ice.

Two life-form types of phytoplankton – belonging to cyanophytes and chrysophytes – were used in the model as a consortium. The results of the modeling presented

Table 2. *Concentration ranges of total phosphorus, total nitrogen, total organic carbon and chlorophyll a in Smaavatn river and Aurevatn reservoir (Skulberg 2004, Tjomsland og Skulberg 2005).*

| | | Smaavatn River | Aurevatn Reservoir |
|---|---|---|---|
| May | | | |
| Total phosphorus | µg P/l | 4.0 | 3.0–6.0 |
| Total nitrogen | µg N/l | 285 | 285–300 |
| TOC | mg C/l | 6.1 | 6.2–6.3 |
| Chlorofyll *a* | µg/l | 1.40 | 0.3–2.5 |
| June | | | |
| Total phosphorus | µg P/l | 3.0 | 3.0–5.0 |
| Total nitrogen | µg N/l | 240 | 230–290 |
| TOC | mg C/l | 5.9 | 5.7–6.0 |
| Chlorofyll *a* | µg/l | 1.8 | 0.7–2.1 |
| July | | | |
| Total phosphorus | µg P/l | 4.0 | 4.0–4.1 |
| Total nitrogen | µg N/l | 225 | 250–530 |
| TOC | mg C/l | 6.2 | 6.0–6.1 |
| Chlorofyll *a* | µg/l | 1.8 | 0.3–1.3 |
| August | | | |
| Total phosphorus | µg P/l | 3.0 | 3.0–5.0 |
| Total nitrogen | µg N/l | 260 | 220–305 |
| TOC | mg C/l | 6.2 | 6.1–6.2 |
| Chlorofyll *a* | µg/l | 1.6 | 0.6–1.7 |
| September | | | |
| Total phosphorus | µg P/l | 3.0 | 3.0–5.0 |
| Total nitrogen | µg N/l | 245 | 245–250 |
| TOC | mg C/l | 6.5 | 5.8–6.2 |
| Chlorofyll *a* | µg/l | 1.8 | 0.6–1.4 |
| October | | | |
| Total phosphorus | µg P/l | 4.0 | 4.0–5.0 |
| Total nitrogen | µg N/l | 255 | 260–300 |
| TOC | mg C/l | – | – |
| Chlorofyll *a* | µg/l | 1.0 | 0.5–1.0 |

are based on the amounts in one sum of the microalgae when developing. The simulated total content of planktic algae expressed as chlorophyll *a* showed a reasonable good accordance with the field observations (Figure 4). Like other models, CE-QUAL-W2 is grounded on the belief that it is possible to make realistic estimates provided that sufficient information about the controlling factors in the reservoirs is furnished. The microalgal growth factors involved are first of all temperature, light and plant nutrients (phosphorus is limiting).

The first task of modeling was to assemble a reasonable base simulation of the structural behaviour of the reservoir and its content of phytoplankton.

The highest population densities of microalgae usually develop in the upper layer, 0–4 m deep, of the water column. We wanted to examine what would happen if this top layer could be drawn off from the reservoir by an extra discharge. A simulation was run with the assumption that an increase in outflow water from the reservoir was accomplished in the period June–September amounting to a magnitude of 0.5 and 1.0 $m^3/s$ respectively. This increased discharge should be emptied over the dam. The water level in the reservoir was held constant, equaling its highest regulated state. The simulated results showed that such an increased inflow to the reservoir involved that the content of microalgae become greater in the relevant water layer (Figure 5). Therefore, the needed improvement for the quality of the raw water would not be gained. The extra discharge, equivalent to 1 $m^3/s$ during 2.5 days, corresponds to the volume of water present in the upper-most meter of the reservoir. The model run implied that this water mass mainly was drawn from the upper three meter of the water column. The surface layer of the reservoir therefore should effec-

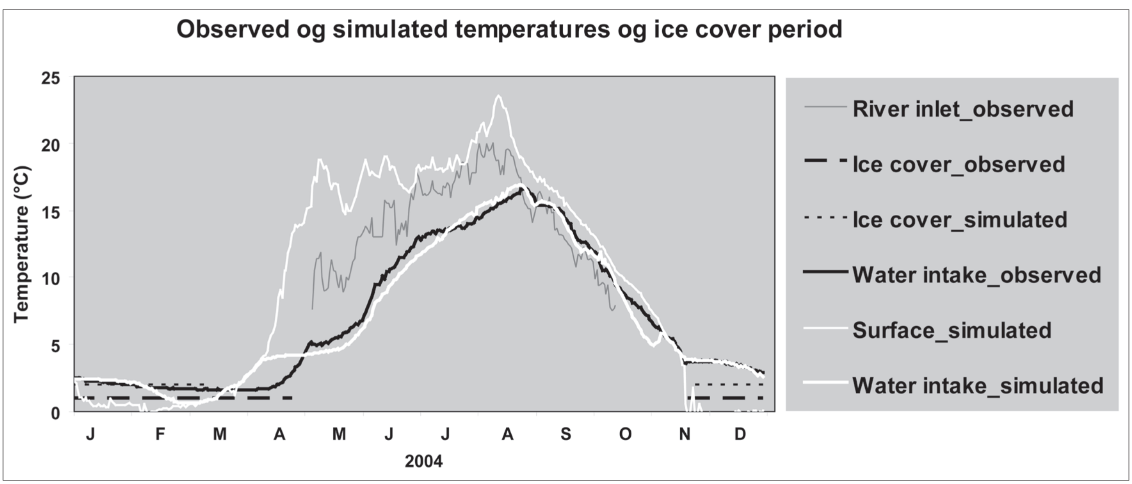


Figure 2. *Simulated temperature in the raw water intake was in good approximation to the measured values.*

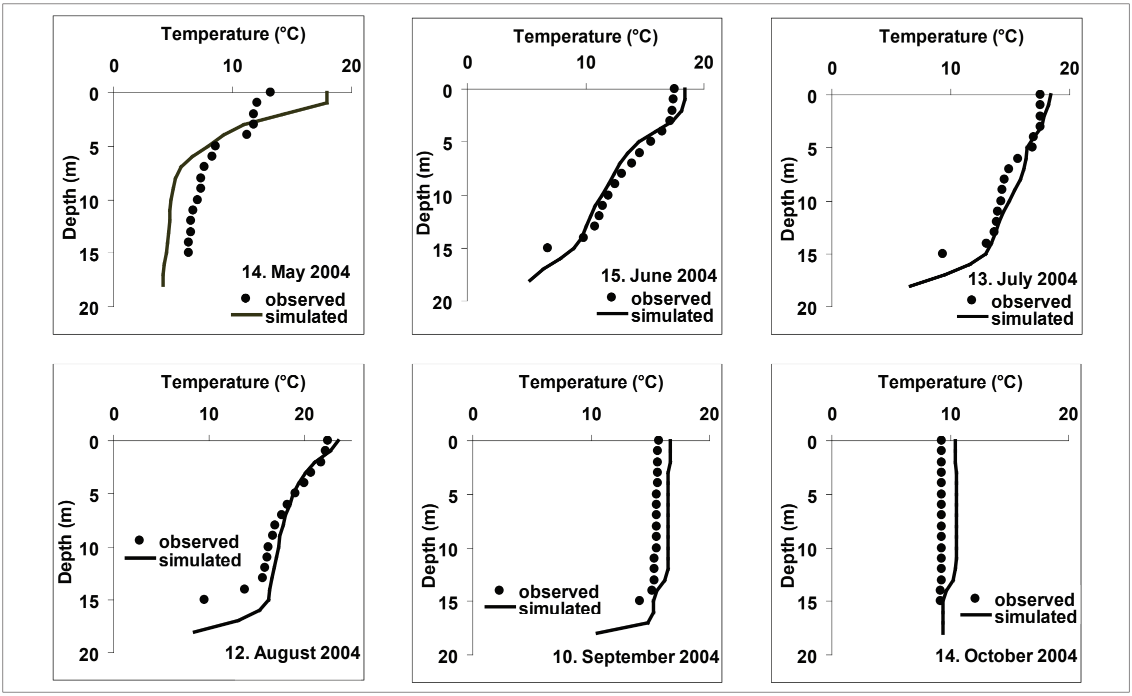


Figure 3. *Simulated temperature in the water-column profile of the Aurevatn reservoir showed good accordance with real conditions.*

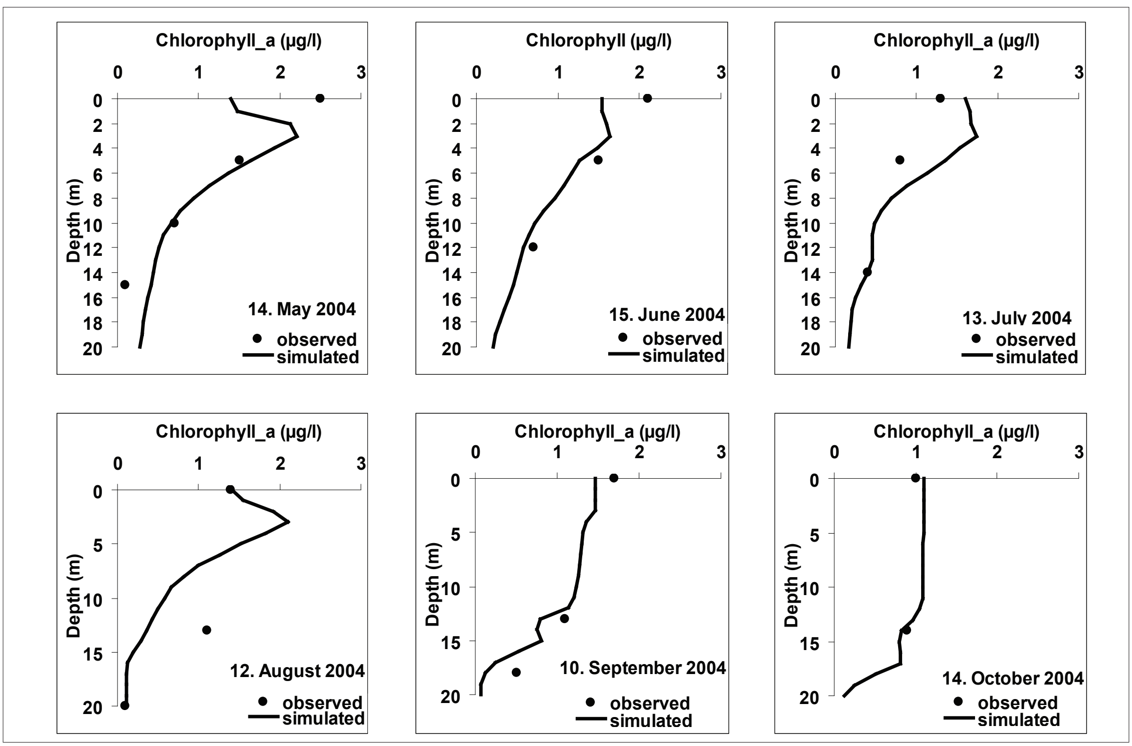


Figure 4. *Simulated total content of microalgae measured as chlorophyll a was satisfactory consistent with the observed field data.*

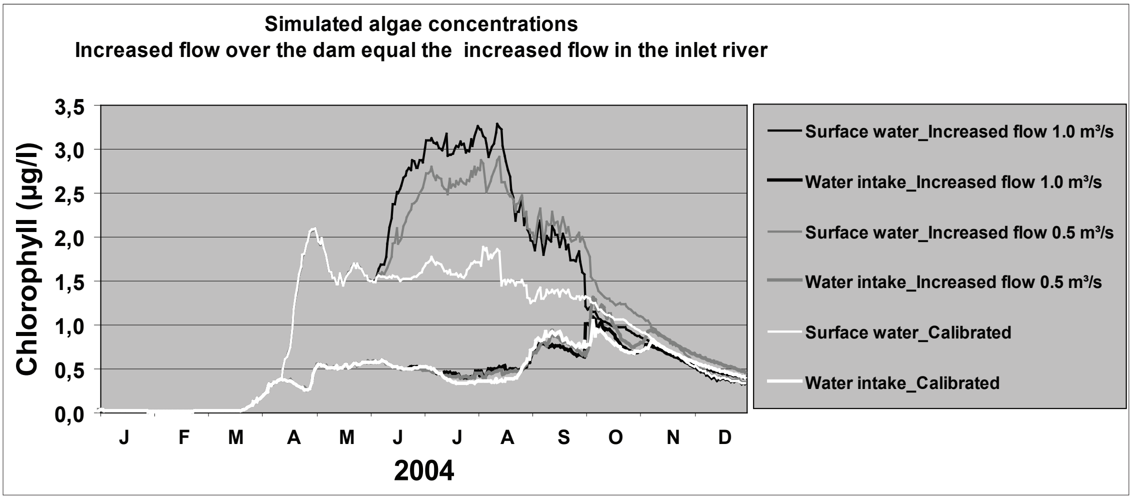


Figure 5. *An increased discharge emptied over the dam equivalent to the volume of water in the upper-most meter of the Aurevatn reservoir involved a stimulation of growth of microalgae. An improvement for the quality of the raw water would not be obtained by this hydraulic operation.*

tively have been renewed. We interpreted the problem with the increased content of microalgae in the raw water being caused by a more vigorous growth of microalgae, exceeding their reduction via the out transport from the reservoir. The renewed surface water in the reservoir carried very likely extra inoculums with microalgae, and would moreover receive an addition of plant nutrients from deeper water layers.

An alternative procedure for a removal of surface water over the dam can consist of reducing the water volume in the reservoir. A model run was made with this presumption. The inflowing water to the reservoir was kept unchanged. An extra discharge over the dam equivalent to 1 $m^3$/s was sustained for 2.5 days and 10 days. This led to shrinking water levels in the reservoir, corresponding to 1.5 m and 6 m respectively. This was managed by directing 2/3 of the volumes of water over the dam, and the rest through the raw water intake. With these assumptions the simulated content of microalgae increased both in the surface layer of the reservoirs and in the raw water (Figure 6). Comparable with the scenario above, the surface water would be reinforced with nutrient rich water from underneath, giving better growth conditions for microalgae. The reduced difference in height between the surface layer and the level of the raw water intake will favor mixing processes, and bring about increased supply of microalgae. This is a reasonable result according to the field observations during 2004. The concentration of the microalgae was evidently higher at 8 m depth in the reservoir, compared with the situation at 14 m depth (Figure 4).

These two model based scenarios being at hand imply that it will be important to operate the reservoir with a high water stage through the summer period. A lowering of only 1 m may lead to significant increase in the content of undesirable microalgae in the raw water.

The purpose of making the next scenarios was to find possible strategies to operate the upstream reservoirs suitably to minimize the algal content in the water intake. First we wanted to examine to what extent the microalgae in the outflowing water from the nearest upstream reservoir L. Smaavatn influenced the quality of the intakewater. To look for this effect a simulation was run where the assumptions included no algal growth in the Aurevatn reservoir, and all environmental conditions else were as calibrated values for 2004 (Figure 7, curves marked: _No algal growth). The concentrations of microalgae in the raw water then become somewhat smaller, but were still of the same magnitude. This finding indicated that the transport of microalgae by the inflowing river also was important for the algal content in the water intake. However, the amount of microalgae in the surface layer of the Aurevatn reservoir appeared to diminish. From this follows that the content during 2004 (calibrated values) mainly was a result of algal growth in the surface layer. According to the calibrated results the relevant inflowing water was colder than the surface water during the summer (Figure 2). Consequently the inflowing upstream water primarily moved through the reservoir underneath the surface layer and giving its biological effects in the intakewater.

In order to find out the effects when water from the

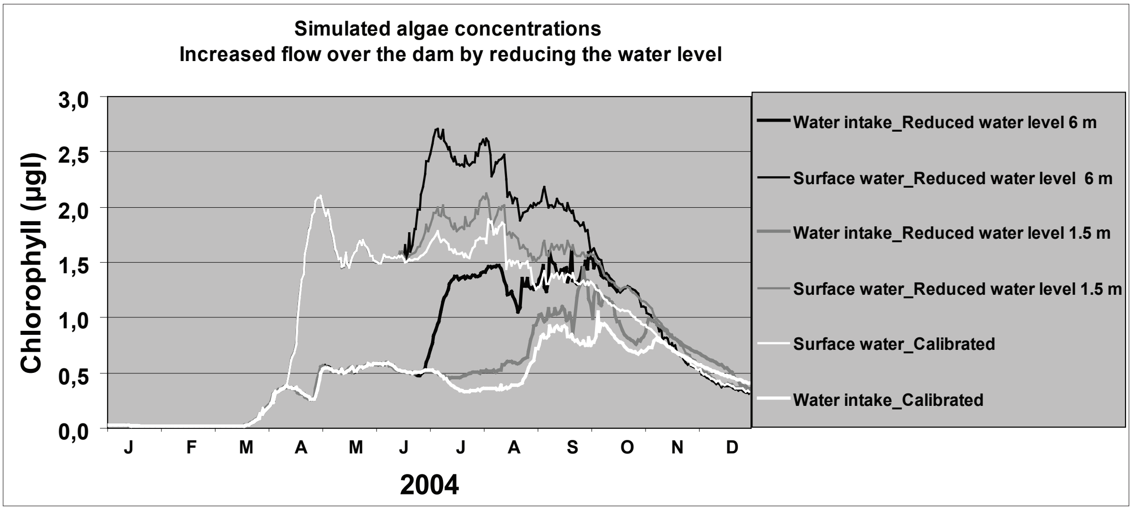


Figure 6. *An alternative procedure for a removal of surface water from the Aurevatn reservoir was examined based on reducing the water volume (explanation, see text). The results obtained in the simulation implied increased content of microalgae both in the surface water and in the raw water.*

inflowing river was mixed with the surface layer in the Aurevatn reservoir, the temperature in the raw water intake was given similar values as in the surface layer, and the simulation run again. The effect was considerably higher concentrations of microalgae in the surface layer of the reservoir (Figure 7). This scenario represents dam overflow from the upstream reservoirs, and consequently did not seem to improve the water quality in the water intake.

Questions to be examined were the possibility of using various outlet depths in the upstream reservoirs (L. Smaavatn and L. Byvatn). Especially the effects of release of bottom water were of interest. The attention was directed on consequences of the temperature and the content of microalgae in the inflowing river to the Aurevatn reservoir. If the water was released over the dams of the two upstream reservoirs, the temperature would become higher than the observed summer values

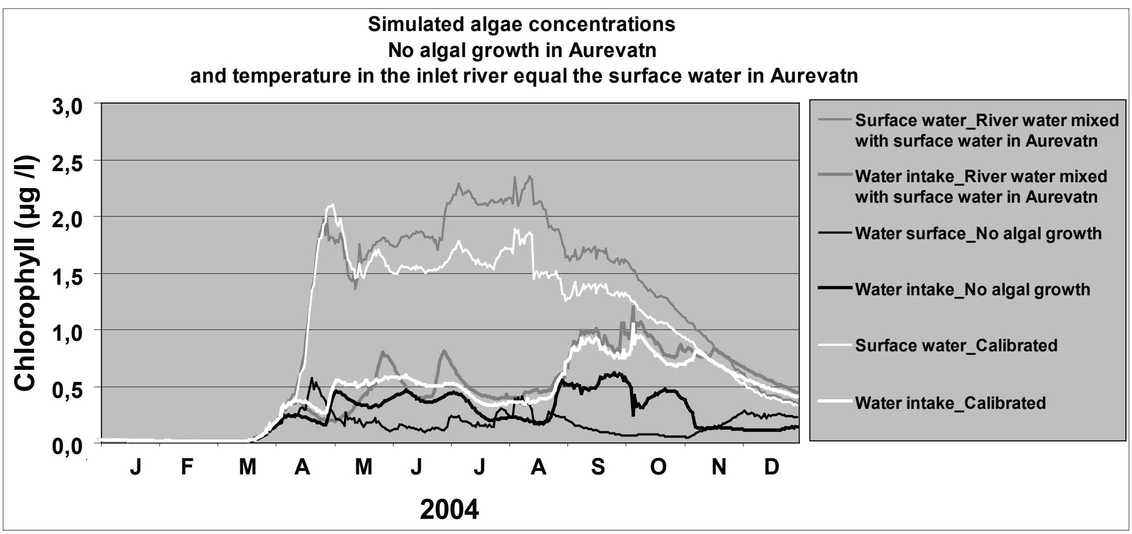


Figure 7. *The transport of microalgae with the inflowing river from L. Smaavatn influenced considerably the quality of raw water (explanation, see text). Use of dam overflow (surface discharges) from the upstream reservoirs did not improve the water quality in the water intake.*

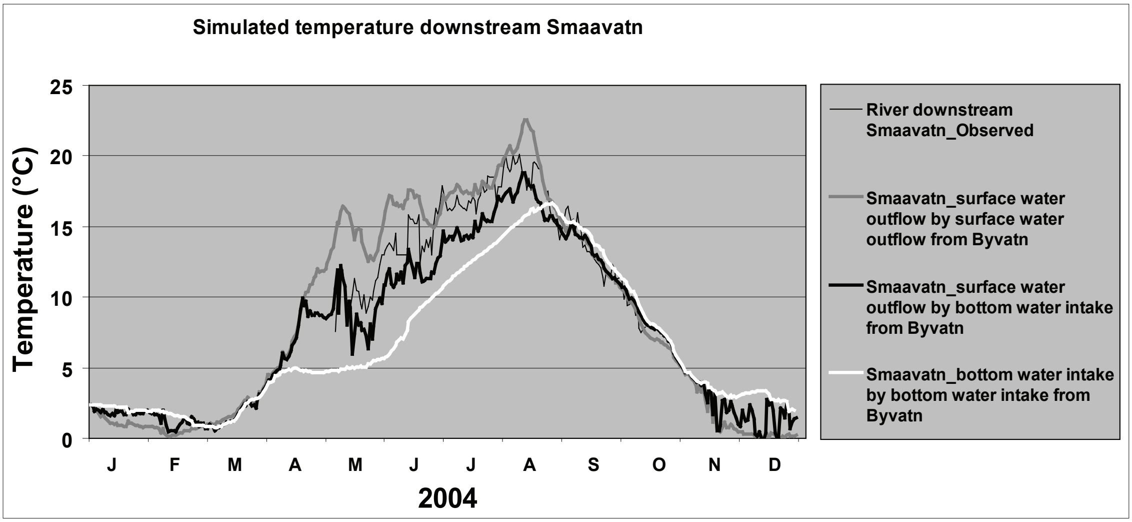


Figure 8. *Operating bottom water discharges from the upstream reservoirs (L. Byvatn and L. Smaavatn) will result in low water temperature in the inflowing river to the Aurevatn reservoir.*

2004 in the inflowing river (Figure 8). The coldest water during the summer would be reached if the bottom outlets at 17 m depth (L. Byvatn) and 7 m depth (L. Smaavatn) were used in combination. This operation would simultaneously result in smaller concentration of microalgae in the inflowing river to Aurevatn reservoir (Figure 9). The field observation 2004 supported that the simulated results were reasonable. In the Aurevatn reservoir the operation would result in lower concentrations of microalgae in the raw water to the water work (Figure 10). The content of microalgaes in the surface layer most of the summer would be considerably lower than the calibrated values. In case of reduced water level in the Aurevatn reservoir, the negative effects on the quality of the intakewater would be smaller.

## Conclusions and remarks

Having set up the numerical model CE-QUAL-W2, we explored ways that might reconcile the achievement of a modest growth of microalgae with the requirements of

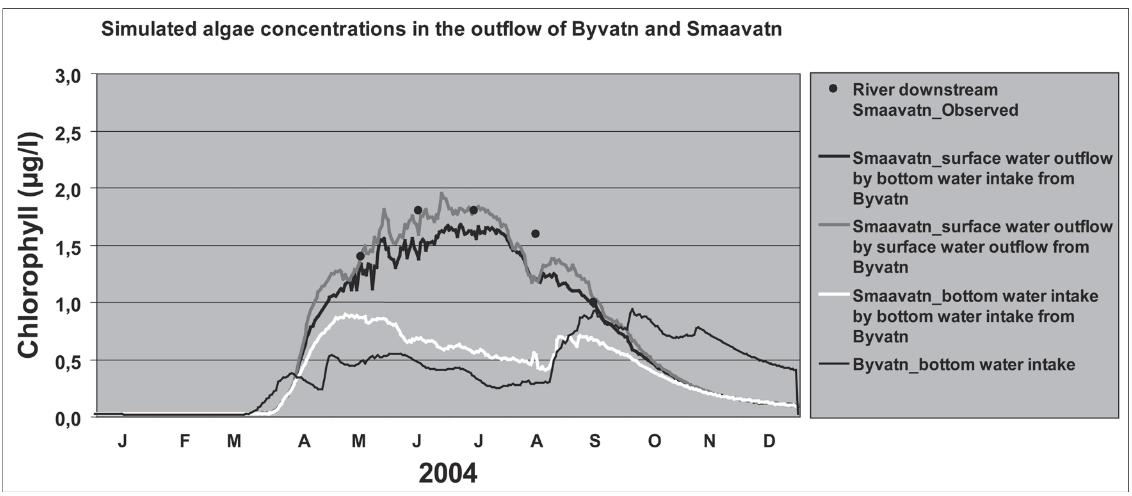


Figure 9. *To obtain low concentrations of microalgae in the inflowing river to the Aurevatn reservoir, bottom water discharges from both of the upstream reservoirs (L. Byvatn and L. Smaavatn) should be operated.*

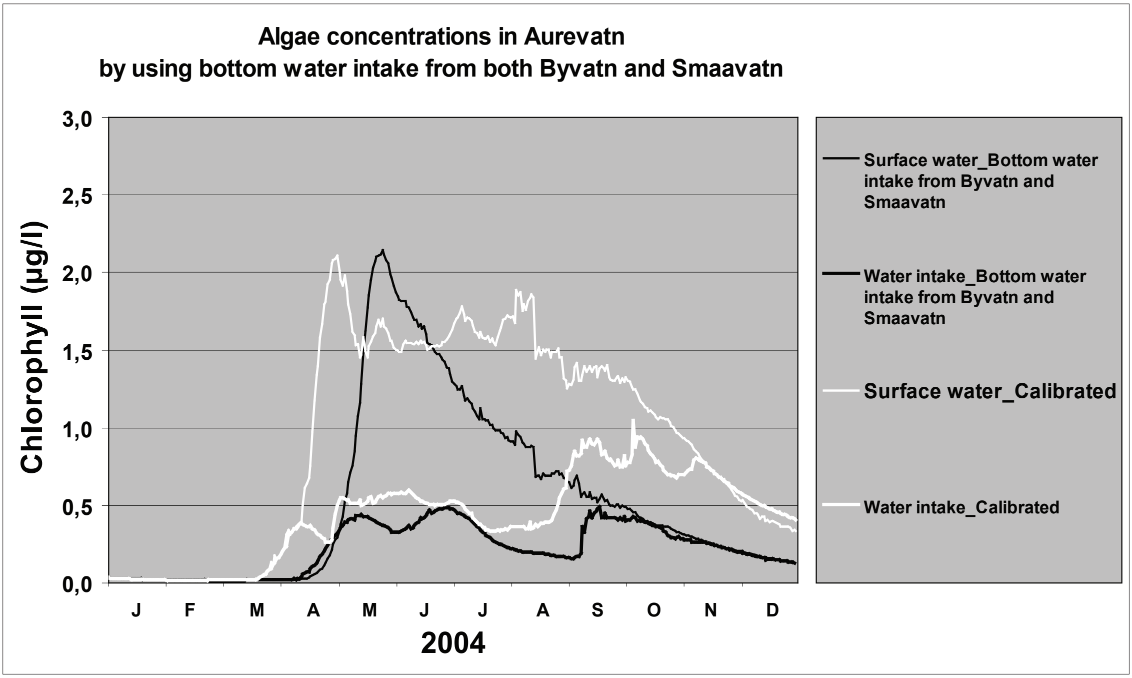


Figure 10. *The hydraulic management of the reservoir system including combined bottom water discharges from L. Byvatn and L. Smaavatn will result in lower concentrations of microalgae in the raw water intake to the water works.*

regular use of the Aurevatn reservoir. A number of simulations were tried, in which exchange volumes, increase in outflow water, adding water from upstream reservoirs and using various outlet depths in the reservoirs were considered. The results were interpretable in terms of the interacting influences between hydraulic management and microalgal development. An adoptable operating strategy for the reservoir system was devised that would result in lower concentrations of relevant noxious planktic organisms in the raw water.

Implications for an expedient hydraulic management of the reservoir system include:

- Use of bottom water discharge from the upstream reservoirs (Especially L. Byvatn and L. Smaavatn).
- Keeping continuously the water level at highest regulated stage in the Aurevatn reservoir and in the three other reservoirs.
- Increased flow over the dam in the Aurevatn reservoir – intended to remove the microalgal rich layer of surface water – may cause unwanted raw water quality effects for the water work.

We should like as a final point to mention the potential important effects on phytoplankton development by both short-term and long-term variations in the climatic conditions. Those charged with the management of lakes need onwards to pay more attention to water quality problems that are not only driven by changes in the catchment, but are influenced by differences in the weather operating on a global scale (George 2002).

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