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Temperature and Flow Conditions in a Reservoir with a Submerged Outlet Tunnel During the Winter Period

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The reservoir Sundsbarmvatn, in Southern Norway, is used for electricity production from November to May. Sundsbarmvatn has two main basins. Water from the upper basin, Mannerosfjorden, flows into the lower basin, Gullnesfjorden. The two basins are separated by a narrow sound with a sill. The regulation interval for Sundsbarmvatn is 612-574 m a.s.l., but the sill prevents Mannerosfjorden from being lowered below 580 m a.s.l. The water intake in Gullnesfjorden is 571 m a.s.l.

The water temperature conditions has been studied during two winters when the reservoir water was released. This study shows that a marked thermocline was gradually developed at the depth of withdrawal in Gullnesfjorden. In the epilimnion layer the temperature is gradually lowered through the winter, but in the hypolimnion layer the temperature seems to stay constant through the winter. In Mannerosfjorden, however, we find no clear thermocline at the end of the winter. The remaining water was relatively warm with temperatures mainly above 3 °C.

The sill between the two basins seems to have a strong influence on which depth the water is flowing out of Mannerosfjorden and hence on the temperature and circulation pattern in Gullnesfjorden. At the end of the winter season this flow is strengthening and initiates a homogeneous flow layer in Gullnesfjorden. This layer is dipping downwards towards the outlet tunnel. For this reason the temperature of the water leaving the power station is 0.4-1.2 °C colder than the hypolimnion temperature in the reservoir at the tunnel depth.

Introduction

Most studies of temperature conditions in Scandinavian lakes have been done in unregulated or only slightly regulated lakes in the summer period. In the winter period it is generally assumed that the temperature conditions in the lakes are more or less unchanged in the period from freeze-up until late spring when the solar radiaton starts penetrating the ice-cover. Some exceptions are found in lakes with a strong throughflow of cold water. In these lakes there will be a general downward movement of the termocline during the winter because the through-flowing water in the top layer erodes some of the water below the termocline. This is the case in several Norwegian fjord-lakes like Losna, Storsjøen and Sperillen, see e.g. Tesaker (1973). Another type of unregulated lakes where the winter temperature conditions may change during the frozen period, are the shallow lakes. In these lakes the heat flow from the bottom sediments can warm up the deepest water layer and induce some weak currents. This phenomenon is demonstrated e.g. in Lake Velen by Falkenmark (1973). In a regulated lake with a submerged outlet tunnel, the withdrawal of water from the deeper part of the lake will induce circulation of the reservoir water. This circulation may also alter the temperature distribution even when the lake is ice-covered. Very few field studies seem to have been published on the winter conditions in such reservoirs. In connection with the studies of water extraction from lakes that are intended to be used in heat pumps, Mäkitalo and Larsson (1983) did some theoretical studies on the temperature changes in ice-covered lakes. Rohman (1978) has also published some theoretical studies on the development of the temperature profiles in reservoirs during the winter season, mainly concentrating on the effects of the initial temperature profile and the diffusion in the water mass.

In this paper we will present results from a study that was done on temperature conditions in the Sundsbarmvatn Reservoir during the winter of 1985 by the Ice Section in the Norwegian Water Resources and Energy Administration.

Sundsbarmvatn Reservoir

The Sundsbarmvatn Reservoir is situated in Southern Norway, 130 km SW of Oslo. The lake was regulated in 1970 to serve as the winter supply of water to the Sundsbarm Power Station. Fig. 1 shows the outline of the reservoir when it is filled. (This water level is called HRV). The surface is then at 612 m a.s.l., the length of the lake is about 11 km and the width is 0.5-1.0 km. When the reservoir is at the lowest water level (called LRV) the surface elevation is 574 m a.s.l. Hence the regulation interval is 38 m and the volume of regulated water is $215 \times 10^6 m^3$. When the lake is at LRV the volume of water left in the lake is about $80 \times 10^6 m^3$. This means that out of the total water volume in the lake at HRV, 73 % may be released during the winter period. In most years the reservoir is nearly full in October-

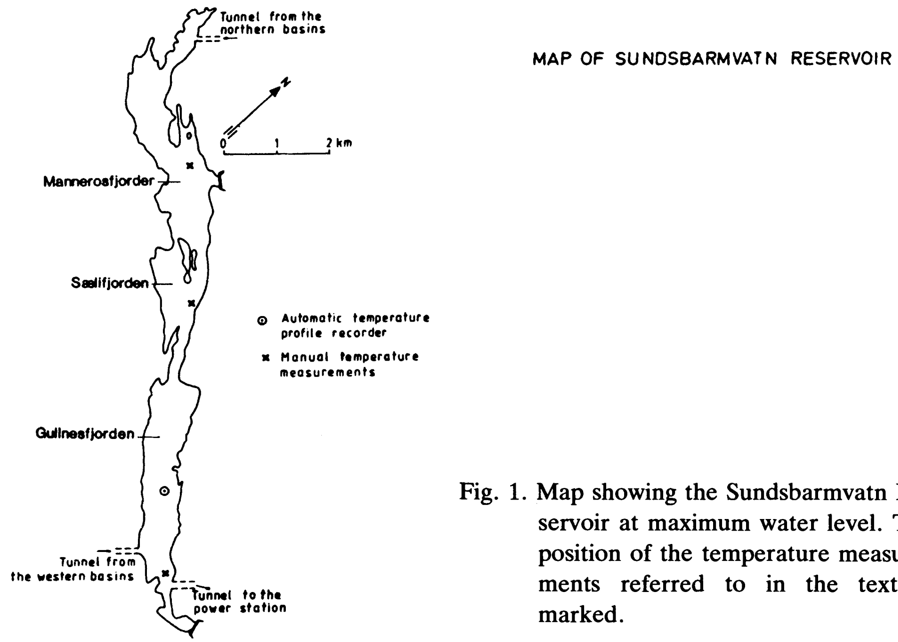

Fig. 1. Map showing the Sundsbarmvatn Reservoir at maximum water level. The position of the temperature measurements referred to in the text is marked.

November before the onset of the tapping season of the lake. The tapping is usually going on at a nearly constant speed until the end of April when the spring snow melt starts filling up the reservoir.

Most winters the minimum water level is at about 585 m a.s.l., so not all of the regulated water is used.

From Fig. 1 we see that the outlet tunnel is in the southern end of the reservoir. The tunnel opening is not horizontal but dips downwards at an angle of about 60°. The mean depth of the tunnel opening is at 571 m a.s.l. This means that the mean depth of withdrawal is 41 m below HRV and 3 m below LRV. At maximum capacity the power station consumes 26 m^3/s of water. The two diversion tunnels are supplying the reservoir with water from other basins. The tunnel in the northernmost end of the lake diverts water from about 170 km^2 drainage area and the tunnel from the western basins diverts water from about 185 km^2. In mid-winter these tunnels will supply about 2 m^3/s of water to the reservoir having a temperature only some tenth of a degree above the freezing point.

In Fig. 2 is shown a length profile of the reservoir, measured along the deepest parts of the lake. The reservoir can be split into two main basins, the northern one is called Mannerosfjorden and the southern one is called Gullnesfjorden. Mannerosfjorden has a rather uneven topography with a small but deep part going down to a maximum depth of 90 m at HRV. Gullnesfjorden has a more regular »bathtube«-shape and a maximum depth of 105 m at HRV. Between Mannerosfjorden and Gullnesfjorden there are several sills with smaller basins in between.

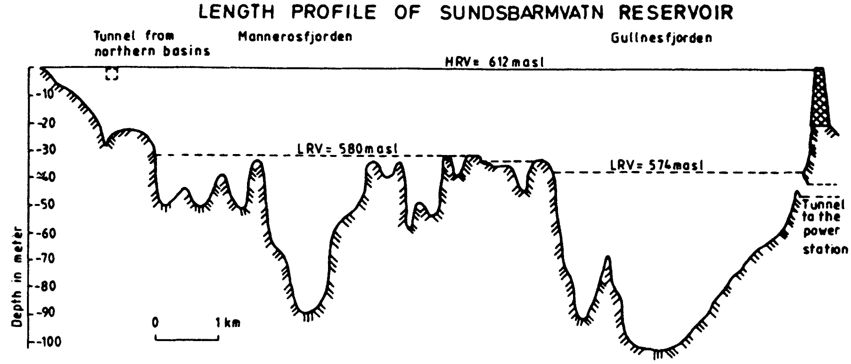

Fig. 2. Length profile of Sundsbarmvatn Reservoir along the deepest parts. The water level at the highest and lowest regulated water level (HRV and LRV) are marked.

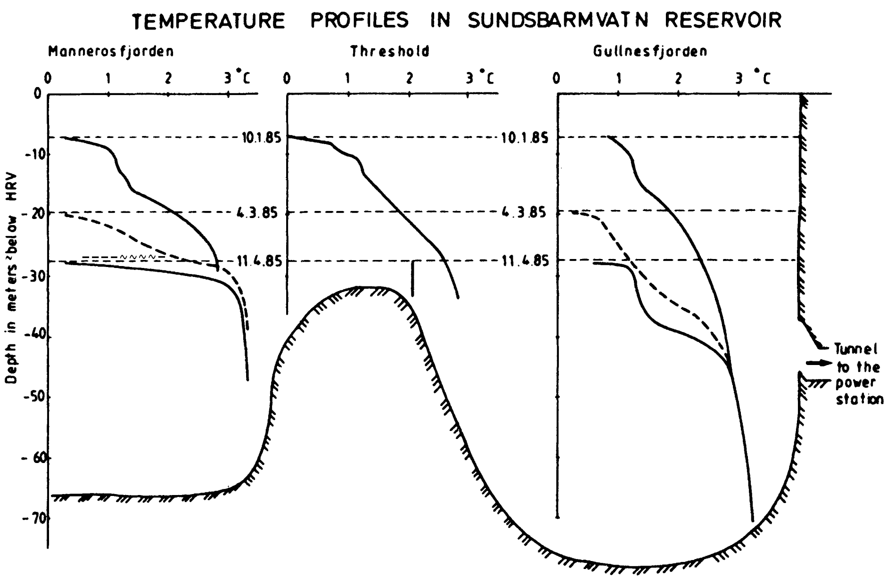

Fig. 3. The water level and the temperature profiles as measured on 10 January, 4 March and 11 April in Mannerosfjorden, at the threshold and in Gullnesfjorden. Compare with Figs. 1 and 2.

The threshold level is at 580 m a.s.l. This means that the water depth over the threshold is 32 m at HRV but near to nothing at LRV. At LRV the water is running as a river from Mannerosfjorden into Gullnesfjorden.

Some few years of observations seem to indicate that Mannerosfjorden usually freezes over in the middle of December and Gullnesfjorden freezes over a little later, probably 1-2 weeks. The break-up period is usually from the middle of May to the end of May. So the reservoir is normally ice-covered for 5 months.

Measurement Programme

The study was done to get some information on the temperature distribution in the reservoir. From this information we may be able to tell something about the water flow within the reservoir during the ice-covered period. Some measurements were available from the winter of 1982 and based on these data a special measurement programme was carried out in 1985. In Fig. 1 is marked the position of the temperature measurement points in the reservoir. An automatic temperature profile recorder was installed in Gullnesfjorden on 9 January, about 14 days after freeze-up had occurred. The temperature recorder is an Aanderaa TR-1 logger which records the temperature at 11 depths from just below the ice down to 50 m. At the threshold between Mannerosfjorden and Gullnesfjorden there were installed automatic recorders at three depths. In the outlet tunnel from Sundsbarm Power Station, the water temperature was also recorded automatically. Manual temperature profiles were measured several places on 10 January, 30 January, 4 March and finally on 11 April when the automatic recorders were removed.

The water level in the reservoir was recorded automatically at the power station. It was 604.9 m a.s.l. on 10 January and decreased gradually to 584.7 m a.s.l. on 11 April, so the water level was lowered 20 m during the period when the measurements were done.

Results

The temperature profiles in Mannerosfjorden, at the threshold and in Gullnesfjorden, are shown in Fig. 3 for the dates 10 January, 4 March and 11 April. We see that all the temperature profiles were very much the same on 10 January. The figure shows a general increase in temperature from the surface downward. On the 4 March the temperature profile in Mannerosfjorden indicated that there now is a much sharper increase in temperature with depth down to the threshold level. Unfortunately we have no temperature profile at the threshold on this date due to instrument problems. In Gullnesfjorden we can see that a weak termocline is starting to develop at the depth of about 35 m below HRV. On 11 April the increase in temperature is very sharp in Mannerosfjorden, from just under the ice-cover down to 5 m depth the temperature increases by 3 °C. Below the level of the threshold the temperature is very uniform and unchanged since 4 March. At the threshold the water depth was only 4-5 m and the channel was narrow. The temperature profile was uniform at 2.08 °C showing that the water flow now is so strong that the water is being well mixed before it enters Gullnesfjorden. In Gullnesfjorden the remaining water is divided into three layers. The upper 10 m have a rather uniform temperature about 1.5 °C, overlaying a thermocline layer of 10 m thickness where the temperature increases to 3 °C. Below this thermocline the temperature is only increasing slightly with depth and has not changed since 10 January. It is interesting to note that the depth of the outlet tunnel corresponds exactly to the depth in Gullnesfjorden below which there were no changes in the temperature profile.

The temperature at the outlet tunnel from the power station is shown in Fig. 4. There was a gradual decrease from 2.5 °C in mid-January to 1.4 °C in late March. It is interesting to compare this outlet temperature with the depth where we find the same temperature in the reservoir. This is done in Table 1 for every 10 days during the measurement period.

The results show that the temperature at the power station corresponds with the temperature in the reservoir at a depth of about 33 m below HRV. This is 8 m above the middle depth of the outlet tunnel. At the same depth as the outlet tunnel (41 m below HRV) the temperature in the reservoir was nearly constant at 2.75 °C, which is 0.4-1.2 °C warmer than the water coming through the power station.

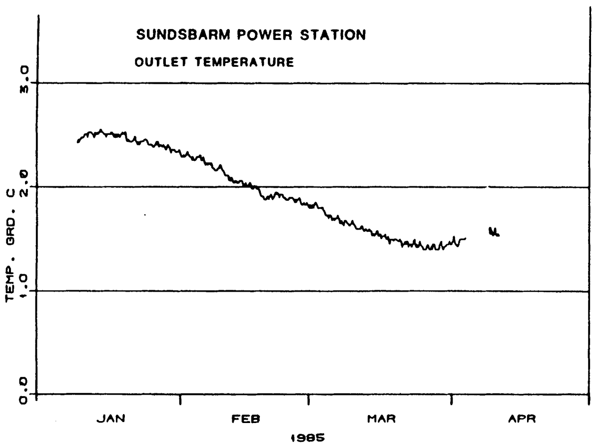

Fig. 4.
The temperature at the outlet tunnel from the Sundsbarm Power Station from 10 Jan.to 11 April 1985. The temperature is recorded every fourth hours.

Table 1

Date	Temperature out of the power station °C	Depth in Gullnesfjorden having the same temperature metres below HRV	Temperature in Gullnesfjorden at the intake depth °C
10 Jan.	2.47	31	2.82
1 Febr.	2.30	33	2.76
10 Febr.	2.14	31	2.75
20 Febr.	1.91	32.5	2.75
1 March	1.81	33	2.72
10 March	1.65	33	2.67
20 March	1.49	33.5	2.71
30 March	1.42	32	2.74
10 April	1.55	37	2.76

Discussion

It is quite evident that the sill between Mannerosfjorden and Gullnesfjorden does have a strong influence on the development of the temperature profiles both in Mannerosfjorden and in Gullnesfjorden. In Mannerosfjorden the sill prevents water from below the threshold level flowing into Gullnesfjorden. The result is that the remaining water in Mannerosfjorden is relatively warm at the end of the winter season. In Gullnesfjorden the inflowing water from Mannerosfjorden is mixed with colder surface water and seems to flow as a more or less distinct layer through Gullnesfjorden towards the outlet tunnel. Because the sill causes the water to mix in the top layer in Gullnesfjorden, this layer is dipping slightly downwards towards the tunnel entrance. The measurements done in 1985 were not comprehensive enough to allow a mapping of the flow pattern through the reservoir. However, at the position of the temperature recorder it seems likely that the mean depth of the flow layer was rather constant at 8 m above the middle depth of the tunnel entrance. From the recorder data in Fig. 5 we see that the temperature curves gradually turned more unstable during the period 1-10 April and the temperature in the upper 10 m-layer became more homogeneous. This corresponds to the temperature in the upper layer in Gullnesfjorden shown in Fig. 3. This homogeneous top layer therefore seems to have been developed from around 1 April onward as a result of the increasing flow velocity over the sill.

A simplified presentation of the two-dimensional flow pattern through the reservoir at the end of the winter season is shown in Fig. 6. In Mannerosfjorden there seems to be more or less unaffected water masses below the threshold level, and in Gullnesfjorden the water below the tunnel level seems to be unaffected. The usual idea of the withdrawal layer flowing into a submerged outlet tunnel, is like a

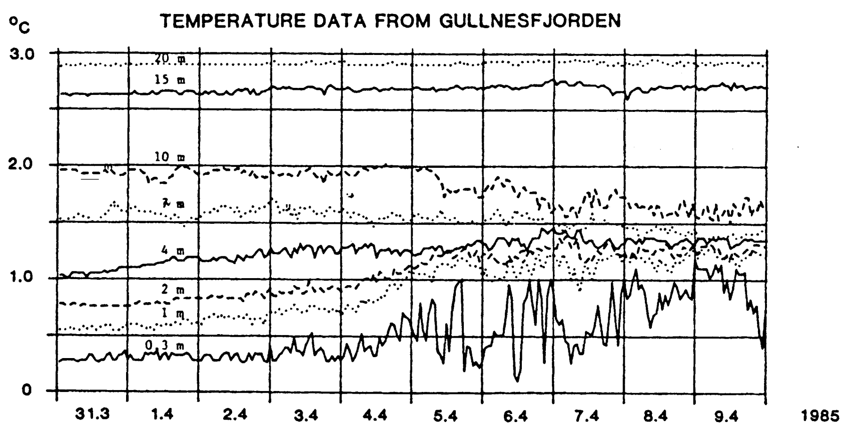

Fig. 5. Temperature curves from the upper 8 of the 11 depths recorded every hour in Gullnesfjorden. The curves show the temperature pattern at the end of the winter period. The depths are in metres below the ice.

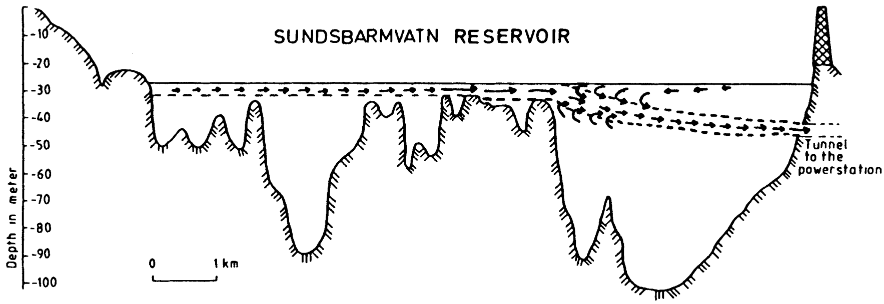

Fig. 6. The flow pattern in Sundsbarmvatn Reservoir at the end of the winter period as interpreted from the temperature measurements

bellshaped velocity distribution centered at the mean tunnel depth, see e.g. Brooks and Koh (1969). In Gullnesfjorden, however, the withdrawal layer must be dipping downwards towards the tunnel opening. In this way we can understand why the temperature of the water going through the power station is colder than the water at the intake depth in the reservoir, measured 2 km away from the intake tunnel.

Acknowledgement

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