R-04-30

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November 2004

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Keywords: Lake hydrology, Coupmodel, Uppland, *Chara* lakes, Young lakes, Small catchment.

Foreword

This report is based on a Master of Science Thesis by /Widén, 2001/, which contained analysis of measurement data collected during the summer of 2000, as well as some computer simulations of water flows. Here, the analysis has been extended to include data collected during the autumn of 2000, together with improved simulations. Some measurements that were mainly analysed within the Master's Project are included in the Appendix.

Abstract

The groundwater flow to two small Swedish lakes in northern Uppland, Lake Eckarfjärden and Lake Hällefjärd, was investigated during the summer and autumn of the year 2000.

Lake Eckarfjärden, 2 km south of Forsmark, is situated in an area that will constitute the uppermost part of the catchment over SFR-1 (a disposal for low and intermediate level radioactive waste in the bedrock) when it rises over the sea level. Lake Eckarfjärden was known to have an outflow stream and now also a small inflow stream was found. By performing water flow measurements in the inflow and outflow stream, as well as measurements of lake evaporation related parameters, it should be possible to find the residual amount of inflowing groundwater, assuming a minor groundwater outflow.

Lake Hällefjärd is situated on the Hållnäs peninsula and is, on the other hand, a seepage lake. It is to a large extent surrounded by peatland (fen) and lacks visible connections to both inflow and outflow streams. The one-dimensional physical Coupmodel was run with a quasi-two-dimensional approach to simulate the possible groundwater inflow from the catchment to Lake Hällefjärd. Continuous recording of the lake water level as well as six groundwater levels and the precipitation provided the main input data to the model and data for comparison with model output.

It was concluded that a major fraction of water flow from the catchment passed by the sides of Lake Hällefjärd, and did not enter the lake. No direct response on the lake water level due to localised inflow from groundwater was observed. The level of the lake only responded to the precipitation falling on the lake and to lake evaporation, and no rise in the lake level due to groundwater inflow could be seen. The simulated inflow pattern that best corresponded to the measured lake level variation in Lake Hällefjärd represented a substantially delayed groundwater inflow originated from a small but stable hydraulic gradient.

Sammanfattning

Grundvattenflödet till två små sjöar i norra Uppland, Eckarfjärden och Hällefjärd, undersöktes under sommaren och hösten år 2000.

Eckarfjärden, 2 km söder om Forsmark, ligger i ett område som kommer att utgöra den översta delen av avrinningsområdet över SFR-1 (lager för låg- och medelaktivt radioaktivt avfall i berggrunden) när det stiger över havsytan. Det är känt att Eckarfjärden har en bäck som utflöde och nu hittades även ett litet inflödande dike. Genom att göra vattenflödesmätningar i det inflödande och det utflödande vattendraget, samt mätingar av parameterar relaterade till sjöavdunstningen, skulle det vara möjligt att få fram den återstående mängden inflödande grundvatten, om man antar ett minimalt grundvattenutflöde.

Hällefjärd ligger på Hållnäs-halvön och är, till skillnad från Eckarfjärden, en ”sippringssjö” (seepage lake). Hällefjärd omges till stor del av myrmark och saknar synliga förbindelser till både inflödande och utflödande vattendrag. Den endimensionella fysikaliska Coupmodellen kördes med ett kvasi-tvådimensionellt angreppssätt för att simulera möjligt grundvatteninflöde från avrinningsområdet till Hällefjärd. Kontinuerliga mätningar av sjönivån samt sex grundvattennivåer och nederbörden utgjorde huvudsakliga data för att testa modelen.

Slutsatsen blev att större delen av vattnet från avrinningsområdet inte flödade in i sjön utan passerade på sidorna av Hällefjärd. Ingen direkt respons i sjönivån orsakad av preferentiellt grundvatteninflöde observerades. Sjönivån reagerade bara på regnet som föll på sjön och på avdunstningen och ingen ökning i sjönivån från grundvatteninflöde kunde ses. Det simulerade inflödesmönstret som bäst motsvarade den uppmätta sjönivåvariationen i Hällefjärd representerade ett avsevärt dämpat och tidsförskjutet grundvatteninflöde som kom ifrån en liten men stabil hydraulisk gradient.

Contents

1 Introduction

Tracking of waterborne nutrients and pollutants entering lakes requires knowledge about the water balance of the lake and the water pathways to, from and around the lake. Three possible pathways are overland flow, stream flow and groundwater flow. For Nordic conditions, overland flow is normally a small fraction and the most important question has been to understand the partitioning between shallow and deeper groundwater, with different transit times. Studies of runoff generation and flow paths in forested till have e.g. been performed by /Espeby, 1990/ and /Rodhe, 1989/ but the problem of finding methods to properly estimate water flow paths and quantities has still not been fully solved.

Of the components in a lake's water balance, the groundwater inflow and outflow, as well as the evaporation, are the most difficult to quantify. A specific question, related to the planned deep repository for nuclear waste, is the possible amount of (possibly contaminated) deep bedrock groundwater entering a lake. As a leakage from the waste containers might occur during a long time interval, the temporal development (ontogeny) of the lakes to mires and raised bogs and the water flow paths involved are worth studying. A specific question is how, and to what extent, water exchanges occur between lakes and surrounding wetlands. Only few studies on the general hydrologic connection between lakes and surrounding wetlands could be found in the literature. Hydrologic investigations of Nordic lakes are also seldom made, and especially not studies on seepage lakes, i.e. lakes that lack stream inflow, outflow or both and thus are dominated by groundwater flow. /Norrström and Jacks, 1996/ used seepage metres, a chemical tracer, lake bottom piezometers and water chemical analyses to quantify inflow to a lake through bottom sediments and macropores as well as seepage outflow from a Norwegian lake, which to a large extent was surrounded by peatlands. They found that flow in macropores dominated during high-flow events, while seepage remained almost constant. The chemistry of the macropore water changed between wet and dry periods, suggesting that during wet periods the water source is shallow soil water and during dry periods the source is deeper groundwater. The peat water seemed to be immobile with a long turnover time, and the water flowed through the macropores instead. /Vanek, 1991/ has studied the groundwater phosphorous transport to a Swedish seepage lake and has identified a groundwater inflow and outflow side. The inflow side had a positive hydraulic gradient towards the lake, and the nearshore water had higher electrical conductivity than the outflow side. /Eser and Rosen, 1999/ investigated a large wetland adjacent to a lake in New Zealand. They found that the main groundwater gradient was towards the lake but only the wetland piezometer closest to the lake showed groundwater levels clearly related to the lake level. Further from the lake, factors such as precipitation influenced the other piezometers more than the lake level did. Other studies of the interaction between lakes and surrounding wetlands have been performed in areas where stream water dominates the water flow in the wetlands /Branfireun and Roulet, 1998; Mitsch and Reeder, 1992/, or where the water level on the wetland is periodically above the peat surface and continuous with the lake water /Price, 1994a/.

Some modelling has been done of the water flows in wetlands adjacent to open water. /Bradley, 1996/ modelled the three-dimensional transient watertable variations in a British floodplain wetland using MODFLOW and compared it with measured values. Hydraulic conductivities, especially the vertical, were found to be very important – measured values varied over a wide range and the vertical stratigraphy had to be carefully implemented in the model representation of the site. The estimation of the evapotranspiration was also found to be a large possible source of error. Bradley assumed that the model predictions would have been even better if the unsaturated water flux had been included. /Dall'O et al.

2001/ developed a multi-box water level and lateral exchange model, FEUWAnet, to simulate water flows in wetlands adjacent to lakes and streams. The model showed good agreement with measured water levels when applied to an alder (*Alnus*) wetland adjacent to a lake in northern Germany. The problem of how to correctly measure groundwater levels in a wetland to get reliable calibration data was discussed.

The purpose of this report is to present detailed data on groundwater fluctuations around a lake and to demonstrate how such data can be used to quantify the exchange rate between the lake and its surroundings. The question raised is whether it is possible that the lake lacks inflow and is only slowly drained when an excess of water occurs.

1.1 Northern Uppland

The coastal lakes in the Forsmark area, Uppsala county, represent three types of lake ecosystems, which also have different hydrology; oligotrophic hardwater lakes, brownwater lakes and deep eutrophic lakes /Brunberg and Blomqvist, 2000/. Most of the oligotrophic hardwater lakes, which also are called *Chara* lakes from the predominance of *Chara* on the lake bottoms, are seepage lakes and they are to a large extent surrounded by mires. The brownwater lakes, on the other hand, are dominated by stream water though-flow and the water flow is thus easier to quantify. One of the brownwater lakes is Finnsjön, where extensive investigations have been made by SKB. These investigations were however concentrated on the deep groundwater and not on the shallow water flow to the lake /Carlsson and Gidlund, 1983/. /Nilsson, 2001/ has made a preliminary carbon budget for two *Chara* lakes, Lake Hällefjärd and Lake Eckarfjärden, and she emphasises the importance of finding the water flow rates and paths though the mire and the lake bottom. This report aims to find out more about the water turnover rate of these two lakes (Figure 1-1).

The emphasis in the measurements and the simulations has been put on Lake Hällefjärd, because it lacks stream inflow and outflow and also because of its larger ratio of surrounding fens. Lake Hällefjärd is also easier to cover with measurements because of the smaller size of the lake and the catchment. The catchment of Lake Eckarfjärden will constitute the uppermost part of the catchment over SFR-1 (a disposal for low and intermediate level radioactive waste in the bedrock) when it rises over sea level by around the year 3500 AD /Brydsten, 1999/. Thus measurements made at Lake Eckarfjärden are presented to contribute to the picture of this very specific area.

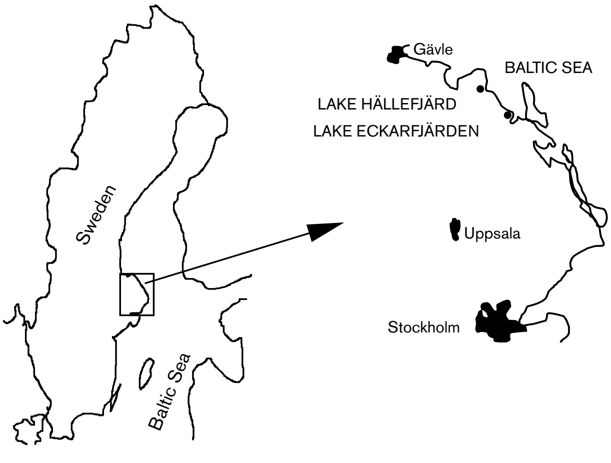

Figure 1-1. *Map showing the general location of the lakes.*

2 Site description

2.1 Lake Hällefjärd

Lake Hällefjärd (60°30' N, 17°57' E) is situated in central Sweden, about 130 km north of Stockholm (Figure 2-1) and only 2 km from the Baltic Sea. It was developed around 1370 due to land uprise /Brydsten, pers comm, 2000/. This seepage lake is situated in the middle of the small catchment (0.50 km^2), which was identified by /Halvarsson, 2001/ (Figure 2-1). The lake area is 0.025 km^2, and thus covers 5% of the catchment. On most sides the lake is surrounded by peatland, which makes up 13% of the catchment area. The remaining 82% is coniferous forest on till. There are no settlements within the catchment, and according to the Swedish well archive /SGU, 2000/ no pumping wells are situated in the catchment. Lake Hällefjärd does not have any visible inlet or outlet and is thus classified as a seepage lake. The outflow from the catchment is presumed to be an open drain installed in the southern part of the peatland. Despite the drain, the lake level is regarded as not having been lowered /Haglund, 1972/. In the north, the water divide is along a gravelled road, and north of the road the peatland continues. The water divide is probably not fixed, but it is assumed that the hydraulic connection between the two sides of the road is of minor importance.

The bedrock consists of metamorphic volcanic rocks (leptite and older granitoids), which belong to the Swedish primary rock /Söderholm et al. 1983/. The catchment is dominated by sandy till, with some precambrian outcrops that are found on the south-western and eastern borders of the catchment /Persson, 1986/. The till is partly boulder-rich, especially in the western part. The till is very calcareous and not from the same origin as the acidic bedrock. No clay has been found in the catchment. As already noted, peat soils are also abundant around the lake. The maximum peat depth found by steel rod sounding and GPR (Ground Penetrating Radar, Appendix 1) was 3.6 m, at a point northeast of the lake. The maximum depth to the bedrock of the investigated spots and transects was about 6.5 to 7 m. The lake is topographically formed from a small depression in the bedrock. The fen surrounding the lake is also found within this depression. The fen consists of hummocks and hollows, and the hollows close to the lake in particular often hold surface water. At some parts along the lake shore, as well as adjacent to two ponds on the fen south of the lake, the fen is floating.

The forest is dominated by Norway spruce (*Picea abies*), with e.g. bilberry (*Vaccinium myrtillus*) on the floor /Halvarsson, 2001/. In the eastern part of the catchment, the forest has been logged, and has not yet been planted again. The brown mosses and *Sphagnum* peatland is dominated by common reed (*Phragmites australis*) /Haglund, 1972/. Some Scots pine (*Pinus sylvestris*) as well as some birch (*Betula*) also grow there. The calcareous environment favours e.g. rare orchids and the peatland is thus classified as extremely-rich fen /Halvarsson, 2001/. The fen and the lake also host the rare merefrog (*Rana lessonae*) and medicinal leech (*Hirudo medicinalis*). Because of the high abundance of rare species, the fen is classified as a Nature Protection Area. Further description of the catchment, especially its botany, is given by /Halvarsson, 2001/ and /Haglund, 1972/ among others.

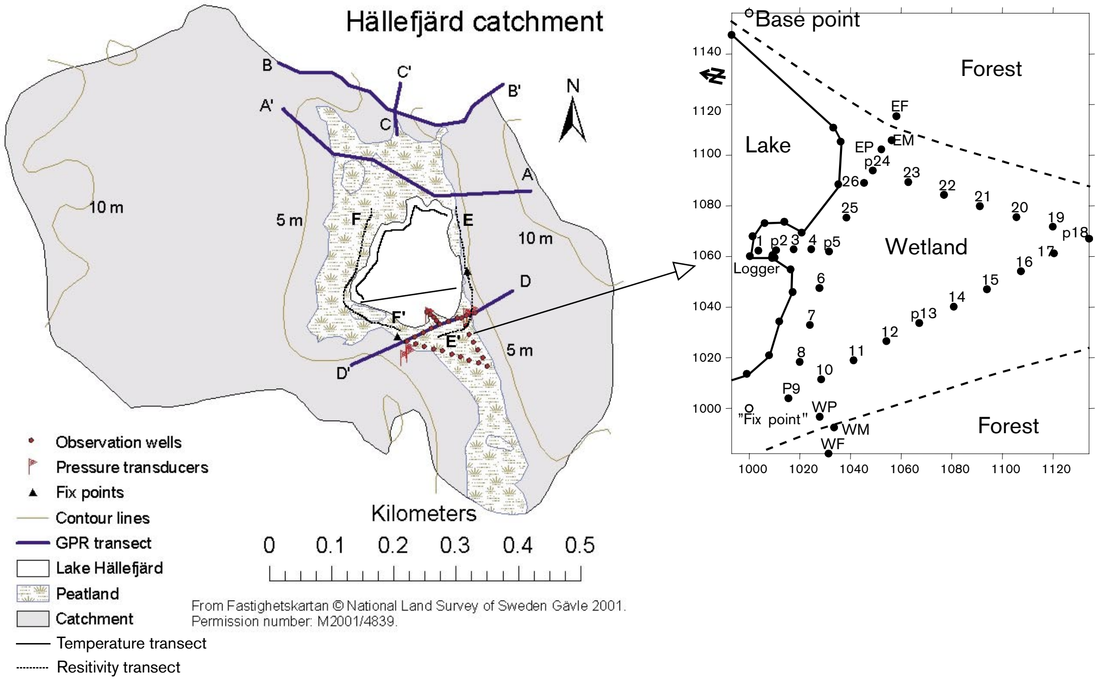

Figure 2-1. *Map showing the catchment of Lake Hällefjärd and specific details of it's experiment area.*

Left: *Lake Hällefjärd and the surrounding catchment. Note that the lake is situated in the middle. The lake area, the peatland area, and the elevation contour lines are taken from the 1:10,000 map © Lantmäteriverket (National Land Survey). The catchment area is taken from /Halvarsson, 2001/. Detailed surveying gave the relative position of the groundwater tubes (observation wells = manual groundwater tubes, pressure transducers = continuous groundwater tubes), which were added manually to this map. The range of the GPR (Ground Penetrating Radar), the resistivity transect and the bottom temperature transect was drawn by freehand on the map. The first installed data logger with e.g. the lake level and precipitation recording is placed on the point of land on the southern shore.*

Right: *Groundwater tubes in the peatland south of Lake Hällefjärd. The points labelled with a digit have tubes for manual measurements, the points labelled p+digit have both groundwater tubes and piezometers for manual measurements, the points labelled with characters are continuous groundwater tubes. EP is situated on the same point as 27 and EF is situated on the same spot as 28. The continuous lake level tube is situated a few metres from p2, towards the shore. The surveyed lake level points are also marked. The dashed lines which mark the border between the peatland and the forest, as well as the North arrow were arbitrarily drawn. The length unit is metre.*

The lake itself is very shallow with a mean depth of 0.9 m, a maximum depth of 1.5 m and a volume of 0.022 Mm^3 /Brunberg and Blomqvist, 1999/. *Chara* grows on a large proportion of the lake bottom. The bottom sediment is very soft with a low mineral content, and is defined as algal gyttja /Halvarsson, 2001/. Close to the eastern shore the sediment is somewhat firmer. The maximum thickness of the sediment is 0.85 m /Brunberg, pers comm, 2001/. The lake is classified as an oligotrophic hardwater lake, a *Chara* lake /Brunberg and Blomqvist, 1999/. The ecosystem of the lake is regarded as relatively undisturbed from anthropogenic impact /Halvarsson, 2001/. Further descriptions of the limnological aspects of the lake are given by /Halvarsson, 2001; Brunberg and Blomqvist, 1999 and 2000/ and /Brunberg et al. 2002/.

Mean precipitation over the area is 650–700 mm/year, including correction for losses in the measurements, and the discharge is about 200 mm/year, which gives an actual evaporation of 450 mm/year /Söderholm et al. 1983/. Based on this discharge, the total volume of the lake and three theoretical areas of inflow to the lake, turnover times will vary from 80 days to 94 days to 4.4 years. The shortest time is obtained when the total catchment area is accounted for, the second shortest when 15% of the area is assumed to be on the outflow side and the longest time when only the lake area is accounted for.

2.2 Lake Eckarfjärden

Lake Eckarfjärden (60°20’ N, 18°12’ E) is situated in central Sweden, about 110 km north of Stockholm (Figure 2-1) and 2 km from Forsmark. The lake has been (geologically) recently formed due to land uprise from the Baltic, which is only 2.5 km away. The catchment of the lake is given in /Brunberg and Blomqvist, 1998/. The 1.51 km^2 large catchment is 73% covered by forest, 7% by peatland, 5% by farmland and the lake constitutes 15% (0.23 km^2) of the catchment area /Brunberg and Blomqvist, 1998/. The lake has both a small stream inflow and a slightly larger outflow and is thus classified as a drainage lake. At a visit to the lake on May 19, 2000, the stream inflow was roughly estimated to be around 2 l/s. The outlet has been drained, which lowered the lake by 0.3 m /Brunberg and Blomqvist, 1999/. There are no settlements within the catchment, and according to the Swedish well archive /SGU, 2000/ no pumping wells are situated in the catchment.

The bedrock consists of metamorphic volcanic rocks (leptite and older granitoids), which belong to the Swedish primary rock /Söderholm et al. 1983/. The catchment is dominated by sandy till, with some precambrian outcrops /Persson C, 1985/. The till is very calcareous and not from the same origin as the acidic bedrock. Some glacial clay is also found in the catchment. As already noted, peat soils are also abundant around the lake. These peatlands are defined as fens /Persson C,1985/.

The lake is shallow with a mean depth of 1.5 m, a maximum depth of 2.6 m and a volume of 0.345 Mm^3 /Brunberg and Blomqvist, 1999/. *Chara* grows on a large proportion of the bottom. The very soft bottom sediment is defined as algal gyttja, gyttja and clay gyttja, and has a maximum depth of about 1.75 m /Bergström, 2001/. The lake is classified as an oligotrophic hardwater lake, a *Chara* lake /Brunberg and Blomqvist, 1999/. Further descriptions of the limnological aspects of the lake are given by /Brunberg and Blomqvist, 1999 and 2000/ and /Brunberg et al. 2002/.

Mean precipitation over the area is 650–700 mm/year, including correction for losses in the measurements, and the runoff is about 200 mm/year, which gives an actual evaporation of 450 mm/year /Söderholm et al. 1983/. Based on this discharge, the total volume of the lake and three theoretical areas of inflow to the lake, a theoretical turnover rate of around 400 days can be calculated.

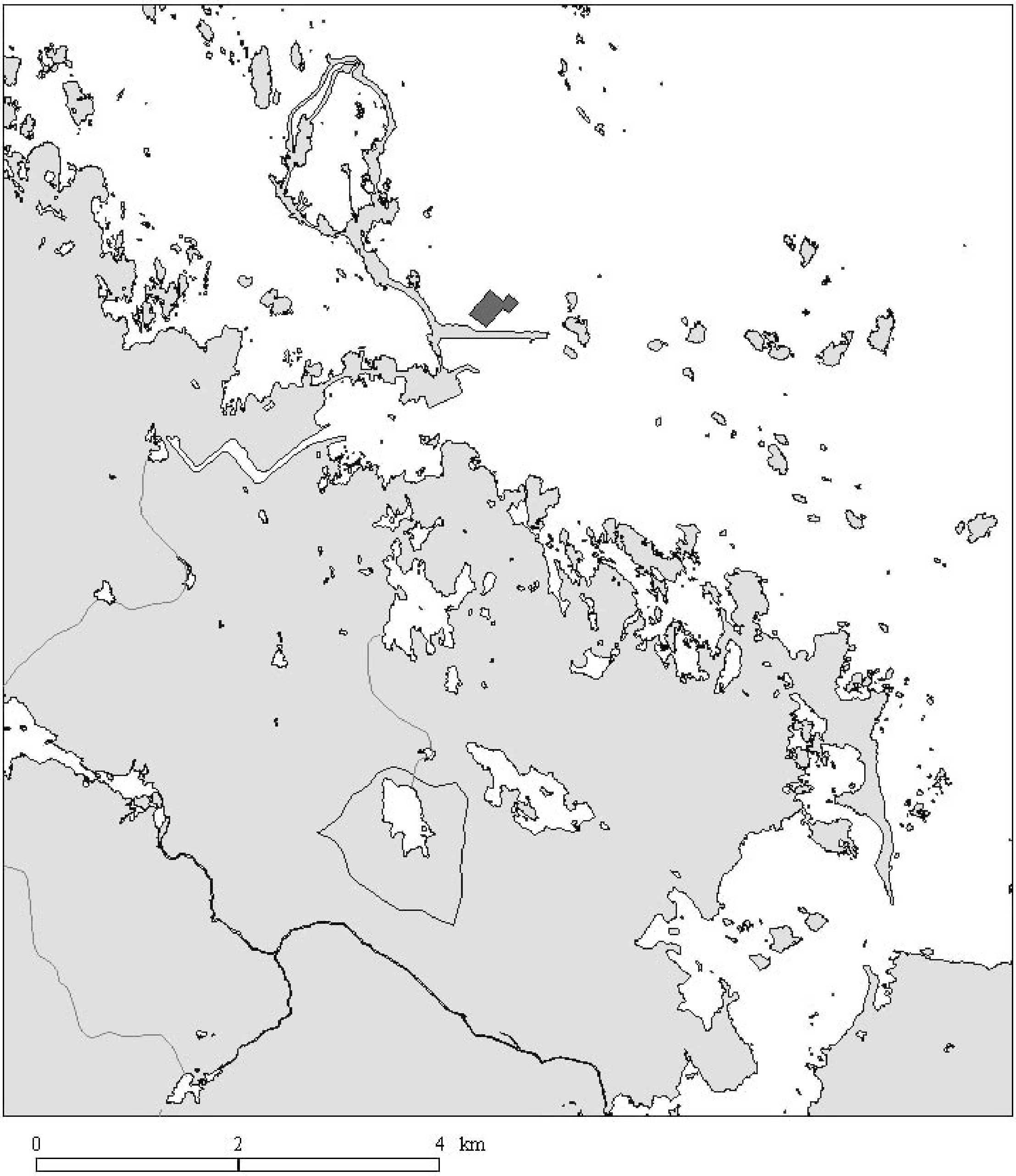

***Figure 2-2.** Map showing Lake Eckarfjärden (the encircled lake) and it's catchment in the Forsmark archipelago. The black formation in the sea shows the location of SFR-1. © Lantmäteriverket (National Land Survey).*

3 Methods

Lake Hällefjärd and its catchment were investigated with many types of field measurements, continuous and short-term surveys from the summer to the end of the year 2000. The continuous measurements were complemented with occasional investigations such as ground penetrating radar (GPR) profiles to further explore the characteristics of the area. Computer simulations were also made to try to calculate the water flow quantities and find their possible paths.

Lake Eckarfjärden was investigated with continuous surveys from the summer to the end of the year 2000.

3.1 Field measurements

3.1.1 Lake Hällefjärd

Continuous measurements were made of the lake level and groundwater levels in the fen just south of the lake, as well as in the neighbouring forest. Precipitation, lake water temperature and water electrical conductivity were also continuously recorded. Additionally a net of groundwater tubes, which were manually recorded once a month or more often, were placed out on the fen.

The measurements in the lake of its level, temperature and electrical conductivity, as well as the precipitation measurement, started on May 19. The groundwater level measurements began on July 3 and 13. Figure 3-1 shows the lengths of the continuous data series as well as an indication of the data quality. For a thorough description of possible measurement errors with emphasis on May 19 to August 29, the reader is referred to /Widén, 2001/.

Campbell data loggers, CR 10, were used. They collected data every minute and saved 10-minute average values, except for precipitation, which was a sum of the 10-minute period. On September 27, the saving interval was changed to 20 minutes. The water levels were measured with Druck PDC 830 Probe, precipitation with a tipping bucket rain gauge and water electrical conductivity and temperature were measured with a Campbell 247 conductivity and temperature probe. The data logger's internal measurement of its temperature was used as a measure of the air temperature.

The lake level measurement was actually a groundwater level measurement on the southern shore, about 30 cm from the open water, with the assumption that the groundwater level there was similar to the lake level. The pressure probe was initially placed in an open hole, with its cable fastened to the pole on which the rain gauge was fixed. On July 3, the pressure probe was moved to a perforated groundwater tube. The rain gauge was placed at some metres distance from the nearest trees to avoid wind interference.

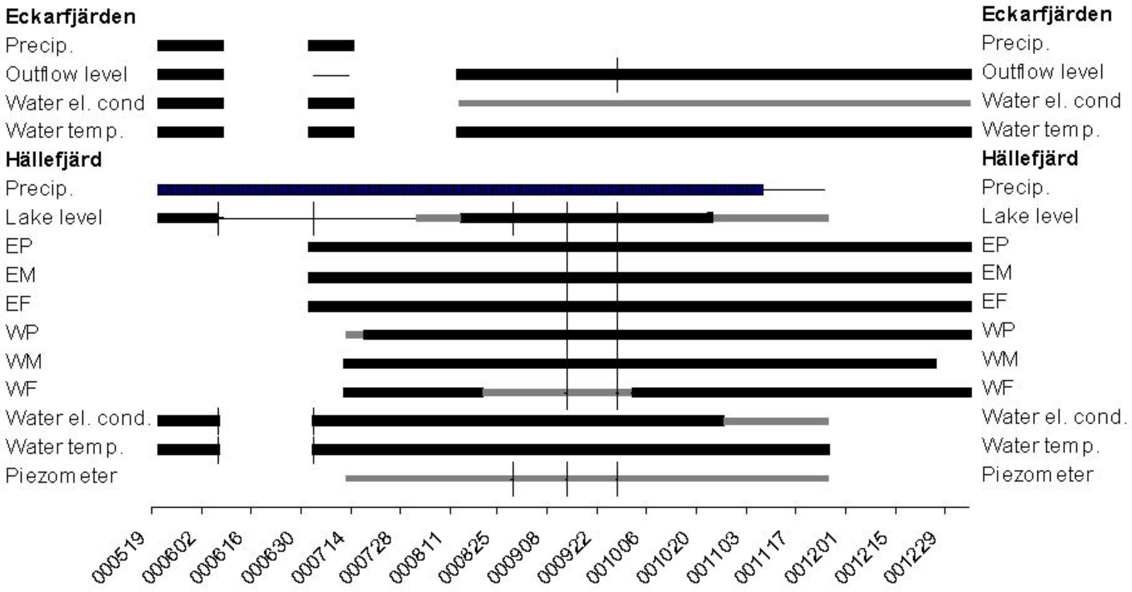

Figure 3-1. The length of the analysed data series at Lake Eckarfjärden and Lake Hällefjärd. A thick black line means good data quality, a thick grey line indicates that there might be uncertainties in the measured data, and a thin line means that data were collected, but the results were very unreliable. The vertical lines mean movement of probes. For explanation of data, see text.

Six groundwater tubes with continuous level measurements were installed, three on each side of the peatland. One was placed in the forest, one on the peatland and one between the others. They are here called EP, EM, EF, WP, WM and WF where E = east, W = west, P = peatland, M = middle and F = forest (Figure 2-1). The groundwater tubes were perforated plastic tubes, inner Ø about 30 mm (no clogging filter). The W probes were calibrated in the laboratory before they were put out but the E probes were not. Groundwater tubes (perforated PVC tubes, inner Ø 17 mm, wrapped with non-woven "fibre cloth" to prevent clogging) for manual measurements were also installed and numbered 1 to 28 and later complemented with six piezometers of the same material but without perforation except at the bottom. The opening was usually at the same depth as the bottom of their neighbouring groundwater tube, 0.9–2.9 m. The tubes were pressed into the soil as deeply as possible with manpower.

All tubes were inserted in a local coordinate system through detailed surveying and point-fixing of the tubes. As no bench point with known coordinates is located in the area, the level of the local bench point was set arbitrarily to 5 m, which is the approximate height above sea level at the site. The measured points were manually inserted on a digitalised map of the area (Figure 2-1). The detailed surveying and point-fixing of most tubes was carried out with the total station Wild T600 on July 3 and of the remaining tubes on October 19. On the second occasion, the lake water level was also measured at many points along the southern shore.

As the pressure probes were moved a few times (Figure 3-1), the data series were manually linked by adjusting measured values to a common reference. Often mean values of the measured values some hour just before and after the movement of the probes were used to reduce the impact of a single value and small oscillations.

The water temperature and electrical conductivity probe was lying on the lake bottom of Lake Hällefjärd close to the water level measurement. The probe was moved on July 3 but at most a few decimetres from the first point. The probe was calibrated for the temperature measurement, but not for the electrical conductivity measurement, before it was put out in the field. Comparison of the measured values to a portable conductivity metre showed agreement on the first two digits. The continuous electrical conductivity data from the lake were also compared every second week with values of the pelagial electrical conductivity /Brunberg et al. 2002/.

Steel rod sounding of the peatland was carried out in June and four GPR (Ground Penetrating Radar) profiles (A–D) were made. The GPR investigations were made with the Pulse Ekko IV sensors and software using a 100 MHz antenna frequency. Measurements were taken every metre using an antenna spacing of 1 metre. GPR data were analysed using the programme PEIV.

3.1.2 Lake Eckarfjärden

Continuous measurements were made at Lake Eckarfjärden of precipitation, outflow water level, water temperature, water electrical conductivity and air temperature with similar equipment as at Lake Hällefjärd. As Lake Eckarfjärden has an outflow, the measurements were made in this flowing water, close to the lake threshold, instead of directly in the lake, as at Lake Hällefjärd. These measurements were also started on May 19, 2000, and continued, with some interruptions, until January 4, 2001 (Figure 3-1).

The lake level measurement probe and the water temperature/electrical conductivity probe were both lying on the bottom of the small stream, and the lake level probe was fastened under a boulder. This probe was moved slightly once during the measurement period. As at Lake Hällefjärd, the precipitation gauge was placed close to the water level metres, also at a few metres distance from the nearest trees to avoid wind interference.

3.2 Meteorological data

3.2.1 Lake Hällefjärd

In the calculations and simulations, hourly measurements of the relative humidity, global radiation and wind speed collected from Geocentrum, Uppsala (59°51’ N, 17°38’ E; 65 km from the site) were used. These measurements were made over grass in urban surroundings. The relative humidity and the global radiation measurements were made at 1.5 m, while the wind was measured at 10 m height. It can be discussed how the wind measurements at Geocentrum correlate to the wind speed at Hällefjärd. However, the data from Uppsala were only used with the purpose of feeding the model with a reasonable input for the evapotranspiration estimates. In the evaporation calculations, the wind measurements from Geocentrum were sometimes reduced by a factor of 0.78 or 0.12. Theese factors were calculated from the assumption that the wind was similar at 100 m height above the ground at Geocentrum and at Hällefjärd, and with different assumptions about the surface roughness at the sites. Different reference heights were used to test the sensitivity on model outputs.

3.2.2 Lake Eckarfjärden

The precipitation metre at Lake Eckarfjärden failed in the autumn, and thus the precipitation measurements from Lake Hällefjärd (about 20 km north-west) or the daily SMHI measurements from Risinge (60°16' N, 18°14' E; about 20 km south) were used instead when comparing the lake level changes and the precipitation.

3.3 Water balance estimates

A lake's water balance, without any overland flow, can be described as:

$$\frac{\Delta S_{lake}}{\Delta t} = q_{\sin} - q_{sout} + q_{gin} - q_{gout} + P_{lake} - E_{lake} \tag{3-1}$$

where ΔS_{lake} is change in lake storage, Δt is time unit, q is water flow, index s means stream water, index g means groundwater, P_{lake} is the precipitation falling on the lake and E_{lake} is the evaporation from the lake surface.

3.3.1 Lake Hällefjärd

As Lake Hällefjärd is lacking visible stream inflow and outflow, Eq 3-1 can be simplified. By calculating $\Delta S_{lake}/\Delta t$, through analysing the difference in the water level between e.g. each hour or each day, and subtracting from it P_{lake}, the changes in lake level caused by the net groundwater flux and the evaporation,

$$\frac{\Delta S_{lake}}{\Delta t} - P_{lake} = q_{gin} - q_{gout} - E_{lake} = q_{gnet} - E_{lake} = \delta \tag{3-2}$$

can be calculated. This calculation was made without any correction factor of the measured $\Delta S_{lake}/\Delta t$ and P_{lake}, thus assuming vertical shores within the level variation interval; that the measured lake level is correct, although it actually is a shore groundwater level; and correct precipitation measurements.

To get a value of $q_{gnet} = q_{gin} - q_{gout}$ lake evaporation has to be calculated. This was done using Penman-Monteith equation, Eq 3-3, /Monteith, 1965/ with the surface resistance r_s set to zero. The reference height z_{ref} was set to 1.5 m, the displacement d was set to zero and different values of the roughness length z_0 were tested. The net radiation R_n was calculated from the measured global radiation at Geocentrum, Uppsala, the actual vapour pressure e was calculated from the relative humidity at Geocentrum and the wind speed u was also taken from Geocentrum, and more or less modified to suit the assumed conditions at Lake Hällefjärd.

$$L_v E_{tp} = \frac{\Delta R_n + \rho_a c_p \left(\frac{e_s - e}{r_a} \right)}{\Delta + \gamma \left(1 + \frac{r_s}{r_a} \right)} \tag{3-3}$$

where

L_v = latent heat of vaporization = 2.45×10^6 J/kg

E_{tp} = potential transpiration [mm/day]

Δ = slope of saturated vapour pressure versus the temperature curve [Pa/°C]

R_n = net radiation available for transpiration [J/(m^{2}day)]

ρ_a = air density [kg/m^3]

c_p = specific heat of air at constant pressure [J/(g°C)]

e_s = vapour pressure at saturation [Pa]

e = actual vapour pressure [Pa]

r_a = aerodynamic resistance [s/m]

r_s = an “effective” surface resistance, canopy resistance [s/m]

γ = psycrometer “constant” = 66 Pa/°C

and where

$$r_a = \frac{\ln^2\left(\frac{z_{ref} - d}{z_0}\right)}{k^2 u} \tag{3-4}$$

where

z_{ref} = reference height [m above the ground]

u = wind speed at reference height [m/s]

k = von Karman’s constant [–]

d = displacement [m above the ground], the level where the wind speed is set to zero

z_0 = roughness length [m above the displacement], a measure of the whirl size

3.3.2 Lake Eckarfjärden

Lake Eckarfjärden does have a stream outflow and thus the same simplification as for Lake Hällefjärd cannot be made here. A difference is also that instead of measuring ΔS here the outflow stream level was measured, which through a rating curve could be recalculated to q_{sout}. As no rating curve was measured, this recalculation was not made. On the other hand, in the analysis of the measurement results, the stream outflow level was sometimes assumed to equal the lake level. This was made although the point of measurement probably was situated slightly after the lake threshold. Also assuming, as for Lake Hällefjärd, vertical shores and no precipitation correction,

$$\frac{\Delta S_{lake}}{\Delta t} - P_{lake} = q_{gin} - q_{gout} + q_{\sin} - q_{sout} - E_{lake} \tag{3-5}$$

can be calculated.

3.4 Computer model simulations, Lake Hällefjärd

To further examine the terms of Eq 3-1, computer models can be used to simulate the inflow to the lake. The Coupmodel, a one dimensional SVAT (soil-vegetation-atmosphere-transfer) model /Jansson and Karlberg, 2001/ was used for this purpose. The model was run with a quasi two dimensional approach, letting the water outflow from one segment be the inflow to the next segment along a slope (Figure 3-2). This approach has previously been used with the Coupmodel by /Espeby, 1992/ and /Stähli et al. 2001/.

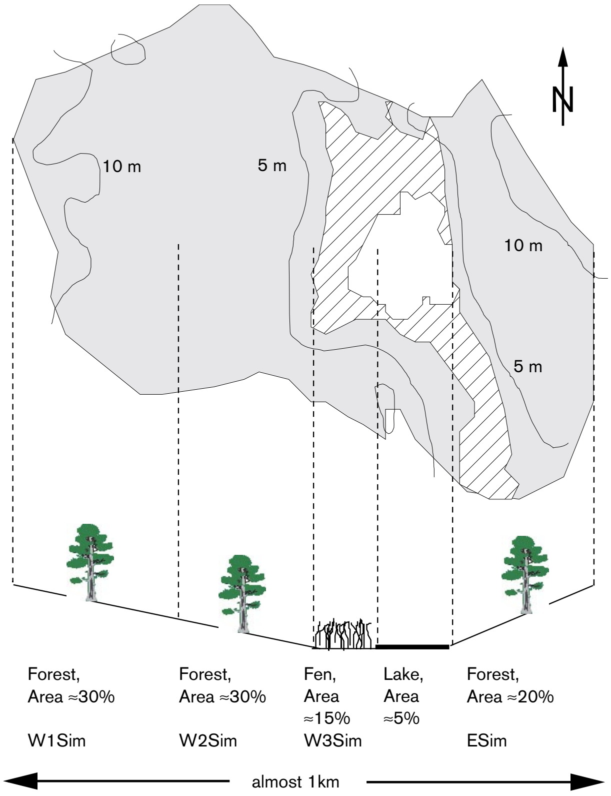

Figure 3-2. *A general sketch of the four simulated 1D-segments at Lake Hällefjärd.*

The model solves Richard's equation (Eq 3-6) for unsaturated water flow coupled with Fourier's law (Eq 3-7) for heat flow combined with the laws of conservation of mass and energy, in each grid point.

$$q_w = -k_w\left(\frac{\partial\psi}{\partial z} - 1\right) \tag{3-6}$$

$$q_h = -k_h\frac{\partial T}{\partial z} + C_w T q_w \tag{3-7}$$

In Richard's equation (Eq 3-6): q_w is total water flow, k_w is the unsaturated hydraulic conductivity, ψ is the water tension, z is depth. In Fourier's equation (Eq 3-7): Heat flow in the soil is the sum of conduction, the first term, and convection, the second term: where the indices h and w mean heat and liquid water, q is flux, k is conductivity, T is soil temperature, C is heat capacity and z is depth.

The saturated water flow is based on a 2D or 3D source/sink term in the saturated layers. The vertical redistribution of water in the profile is calculated based on the assumption that the water content only changes in a boundary layer which is partly saturated and partly unsaturated. The groundwater outflow is calculated with a drainage equation. The one used here is:

$$q_{wp} = \int_{z_p}^{z_{sat}} K_{sat}\frac{z_{sat} - z_p}{d_u d_p}dz \tag{3-8}$$

where q_{wp} is the horizontal flow rate [mm/day], dz is the thickness of each soil layer above the drainage level, K_{sat} [mm/day] is the saturated conductivity of each soil layer, z_{sat} is the depth from the ground level to the groundwater level (negative downwards), z_p is the depth to the drainage level (negative downwards), d_u is the unit length of one horizontal element (always 1 m) in the same direction as d_p and d_p is a horizontal length giving the slope towards the drainage. In this case d_p was chosen so that

$$\frac{z_{sat}[=0]-z_p}{d_p} = s \times 100 \tag{3-9}$$

where s is the slope [%] of the ground surface, e.g. the slope when the groundwater level is at the ground surface ($z_{sat} = 0$), according to /Espeby, 1992/.

Input variables to the model were the measured precipitation at Lake Hällefjärd (with the usual correction factor of 1.07 for measurement errors due to e.g. wind losses) and the measured logger panel temperature as a measure of the air temperature. Net radiation and relative humidity were taken from Geocentrum, Uppsala. The wind speed was also taken from there, and more or less modified to be similar based on the assumed differences between the two sites.

The simulations were calibrated against the measured groundwater levels. Soil properties, using the water retention parameterisation of Brooks and Corey (Eq 3-10), were taken from the database.

$$S_e = \left(\frac{\psi}{\psi_a}\right)^{-\lambda} = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{3-10}$$

S_e is the effective saturation [–], ψ is the pressure head or actual water tension [cm], ψ_a is the air-entry tension [cm], λ is the pore size distribution index [–], θ_s is the porosity [vol%], θ_r is the residual water content [vol%] and θ is the actual water content [vol%].

The hydraulic parameters for the till were, without changes, taken from one profile almost without clay from "Lund, stäket" /Espeby, 1992/ in the database. The peatland soil profile parameters were based on "Bara myr", a peatland that has been quite recently cultivated, but the hydraulic parameters for the upper layers were considerably changed to better suit the assumed conditions at the peatland of Lake Hällefjärd. This meant that the measured properties of the uppermost decimetre were set to be valid also for the following decimetre, and the other properties were pushed downward to 0.4 m depth. In addition, the porosity of the uppermost layer was increased to 97%, the air entry pressure was lowered to 1.44 cm, the volumetric macropore content was increased to 15% and λ (pore size distribution index) was decreased to 0.36. Some smaller changes were also applied to the next soil layer.

Evaporation related parameters for the forest were, with a few changes, taken from Norunda /Jansson et al. 1999/. Transpiration from both forest and fen was simulated using the Penman-Monteith equation (Eq 3-3), as well as the forest soil evaporation. An iterative energy balance was used to simulate the fen soil evaporation.

The model was run with two forest segments (slope 1%), W1Sim and W2Sim, representing the western side of the catchment, followed by a fen segment, W3Sim (Figure 3-2). One eastern forest segment (slope 2.5%) was also simulated, ESim. The fen was simulated with both a varying shallow drainage level, representing the lake level, and with a fixed, slightly deeper drainage level representing the ditch in the southern part of the fen. Simulation was made from May 19 to October 31. The most important settings and parameters are listed in Table 3-1.

Table 3-1. Important parameters and settings in the Coupmodel simulations of the different segments.

Category Setting/Parameter	Upper forest segment, west W1Sim	Lower forest segment, west W2Sim	Peatland W3Sim	Eastern forest segment ESim
Interception				
Direct throughfall (fraction of precipitation) [–]	0.05	as upper	0.05	as west
Max interception storage [mm]	1.2[N]	as upper	0.1–0.6	as west
Within canopy resistance (used for potential interception evaporation) [s/m], r_{sint}	50	as upper	50	as west
Potential transpiration				
Displacement, d	13	as upper	0.7	as west
Surface resistance, plant, r_s [s/m]	60–100	as upper	130–200	as west
Roughness length, plant, z_0 [m]	1	as upper	0.1	as west
Canopy height [m]	18	as upper	1	as west
Meteorological data				
Reference height, z_{ref} [m]	19.5	as upper	2.5	as west
Wind, u [m/s]	Geocentrum	as upper	Geocentrum*0.78	as west
Vegetation				
Plant albedo (relative short-wave reflectance) [%]	8[N]	as upper	20	as west
Leaf area index, LAI [–]	4[N]	as upper	Seasonal varying 1– 2.5 or constant 6	as west
Root depth [m]	–0.7[N]	as upper	0.3	as west
Drainage and deep percolation				
Drainage level, z_p [m]	–4.5	–1.5	Varying 0 to –0.3 m or constant –0.3 m	–3.5
Drainage spacing, d_p [m]	450	150	50 when varying z_p and 300 with constant z_p	140
Water uptake				
Air reduction coeff. (governs plant oxygen need) [–]	4	as upper	0	as west
Critical pressure head for reduction of potential water uptake [cm water]	150[N]	as upper	400	as west
Soil properties				
Based on (database number within brackets)	Lund, stäket (205:4)	as upper	Modified Bara myr (71:11)	as west
Soil profile depth [m]	5 (2 was also tested)	as upper	5 (2 was also tested)	as west
Boundary condition				
Lateral inflow	No	From upper	From western	No
Initial condition				
Initial groundwater level [m]	–3.7	–1	–0.3	–3.2

[N] Parameter value taken from Norunda /Jansson et al. 1999/.

4 Results

4.1 Lake Hällefjärd

4.1.1 Precipitation and temperature

The investigated period included both very rainy periods and long drought periods. During the simulation period, May 19 to the end of October, a total of 427 mm precipitation (uncorrected) fell. All months got more precipitation than normal (average 1961–1990), except August and September, which were drier than usual /SMHI, 2000/. Some large rain events occurred at the end of June, and the second half of July was very rainy. August and September were as mentioned drier as usual, but with a large rainstorm on August 30 that had a big impact on the groundwater levels. The longest rain-free period during the measurement period was September 15 to 30. Another large rain event occurred on October 29. The precipitation measurements failed in November and December, but measurements from the Risinge climate station 45 km from Lake Hällefjärd, as well as the groundwater measurements at Lake Hällefjärd, indicated large rain amounts, especially during the second half of November.

The temperature in the region was warmer than normal in May, but the warm period of that month ended just before the measurements started. The temperature was lower than usual in June and July, around normal in August and September and much warmer than usual during October to December /SMHI, 2000/. A few night frosts occurred in September and some in October, but the daily mean temperature did not fall below zero until the middle of December.

4.1.2 Evaporation

From May 19 to October 31 the calculated and simulated evaporations from the different environments varied between 212 and 382 mm (Table 4-1). The calculated lake evaporation was substantially above the 271 mm reported for Lake Råksjön 60 km away (60°02’N, 17°05’E; area 1.2 km^2) May 7 to October 3, 1995 /Heikinheimo et al. 1999/. In the calculations of the lake water balance, the highest lake evaporation of 382 mm (later referred to as E_L) was used, as well as $0.6E_L = E_{Lmin}$ by which accumulated evaporation is 230 mm as an estimated minimum.

The forest evaporation, calculated with the Coupmodel with parameters mainly according to /Jansson et al. 1999/, varied between the segments on the western side because of different groundwater depths. On the fen, two different types of leaf area index (LAI) were tested. A small LAI gave very high soil evaporation, as more radiation reached the ground, but the effect on the total evaporation was reduced, as not as much transpiration can take place from the smaller leaf area and as less interception water can be trapped on the smaller leaves.

In November and December the evaporation was very low and because of the negative radiation balance, the methods used produced a negative evaporation (condensation).

Table 4-1. Calculated and simulated accumulated evaporation [mm] from different parts of the catchment, May 19 to October 31.

Location	Lowest/Highest evaporation	Assumed difference to obtain the range in evaporation
Lake	343/382 (= EL)	Scaling of windspeed from Uppsala
Fen	313/372	LAI: From 2 to 6
Forest	212/275	Groundwater level from 0.5 to 4 m depth

4.1.3 Lake level dynamics

The lake reacted immediately to the amounts of rain falling directly on its surface with a corresponding increase in its level (Figure 4-1). However, no further rise in the lake level, caused by fast inflow from surrounding areas, could be seen. There was also no obvious delayed inflow from the catchment to the lake. The seasonal evaporation effect was obvious, as δ became less and less negative during September and approached values close to zero (Figure 4-1).

An analysis of the rain-free period, September 15 to 30, showed an accumulated net decrease in $\Delta S/t - P[= 0] = \Delta S/t = q_{gnet} - E_{lake} = \delta$ of about 15 mm, but it varied within ± 1 mm/2h.

The net groundwater flow through the lake depended on the choice of evaporation rate when calculating q_{gnet} from δ (Figure 4-1). With E_L the accumulated q_{gnet} was predominantly positive or around zero. With E_{Lmin} the accumulated q_{gnet} was predominantly zero or negative. The two largest absolute values of the accumulated calculated q_{gnet}, during periods with reliable lake level measurements were a net inflow of about 25 mm/(unit lake area) during the period May 19 to June 6 when E_L was used and a net outflow of about 50 mm/(unit lake area) during August and September when E_{Lmin} was used.

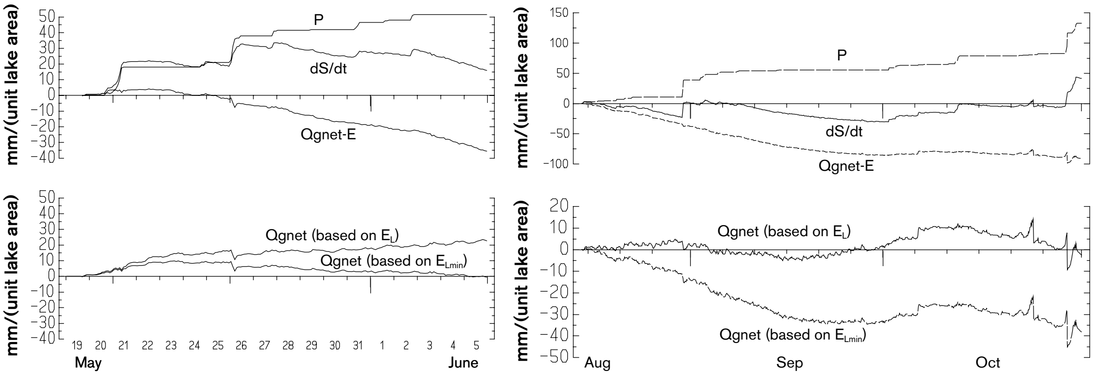

__Figure 4-1.__ Lake Hällefjärd: Calculations based on the measurements of the lake level and the precipitation. In the upper graphs precipitation, lake level change and $q_{gnet} - E = \delta$ of the lake calculated from these. The lower graphs q_{gnet} in the lake, calculated from δ and two different amounts of lake evaporation. Cumulative values May 19–June 5 (right) and cumulative values August 15–October 31, 2000 (left). Note the difference in y-axis.

4.1.4 Hydraulic gradients in the surroundings of the lake

The groundwater gradients in the fen south of the lake were very small, only a few centimetres per 100 m, and the measurement uncertainties were almost in the same range. Differences in absolute values between different measurement series should therefore not be emphasised too much. The largest gradient was around 5 cm/10 m and was directed from the forest measurement point EF towards the fen and occurred during wet periods.

In dry periods, the groundwater level at EF decreased faster than at most of the other locations. Thus the water level at EF almost approached the water levels measured in the fen at the end of the dry periods (end of August and September) (Figure 4-2 and Figure 4-3). On the western side, the forest groundwater level WM decreased below the level of WP and thus a flow reversal occurred in the middle of August as well as in the middle of September, directing the water from the fen towards the forest. Rain on August 30 as well as rain at the beginning of October changed the gradients back to "normal" again.

In the fen there was a small gradient towards the south, possibly resulting in a water flow towards the ditches in the southern part of the fen. It was not obvious that the lake had an outflow in the same direction, as this gradient was not always extending all the way to the lakeshore. Sometimes there was a small groundwater ridge at the southern lake shore, preventing a lake water outflow in the shallow layers of the peat. However outflow could take place if the peat formed a confined layer above a more permeable sand layer. Such behaviour, with a small upward gradient, was observed at all manual piezometer plots on the fen except at point 13.

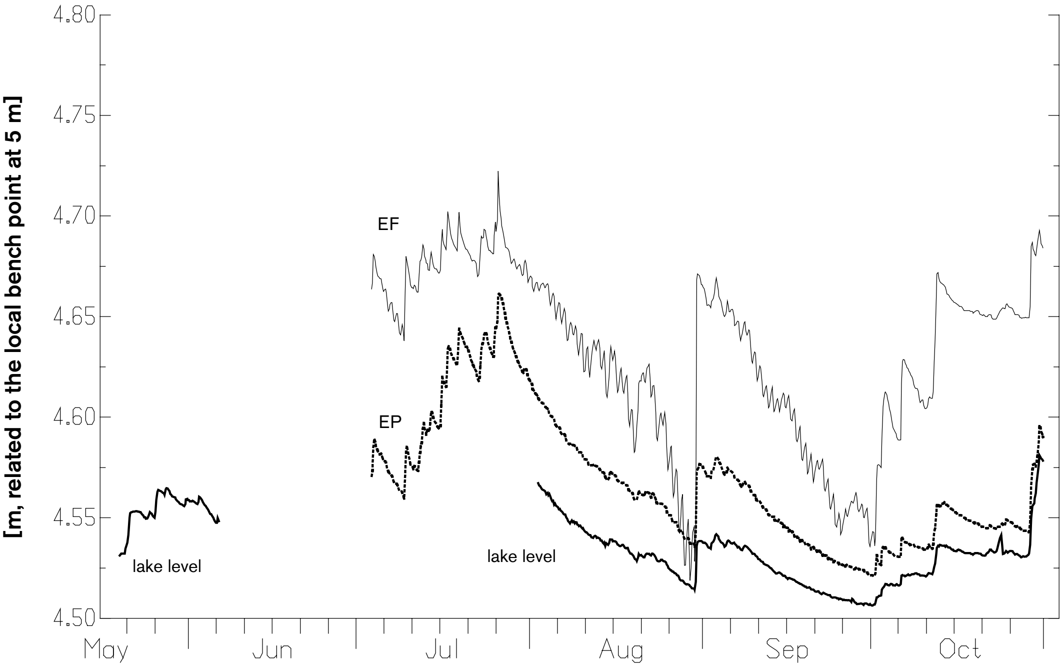

Figure 4-2. Lake Hällefjärd: The lake level and the groundwater levels at EP and EF, related to the local bench point at 5 m, May 19–October 31, 2000, four hour averages. The absolute values of the lake level in May and the beginning of June are unknown and have been arbitrarily set to this level.

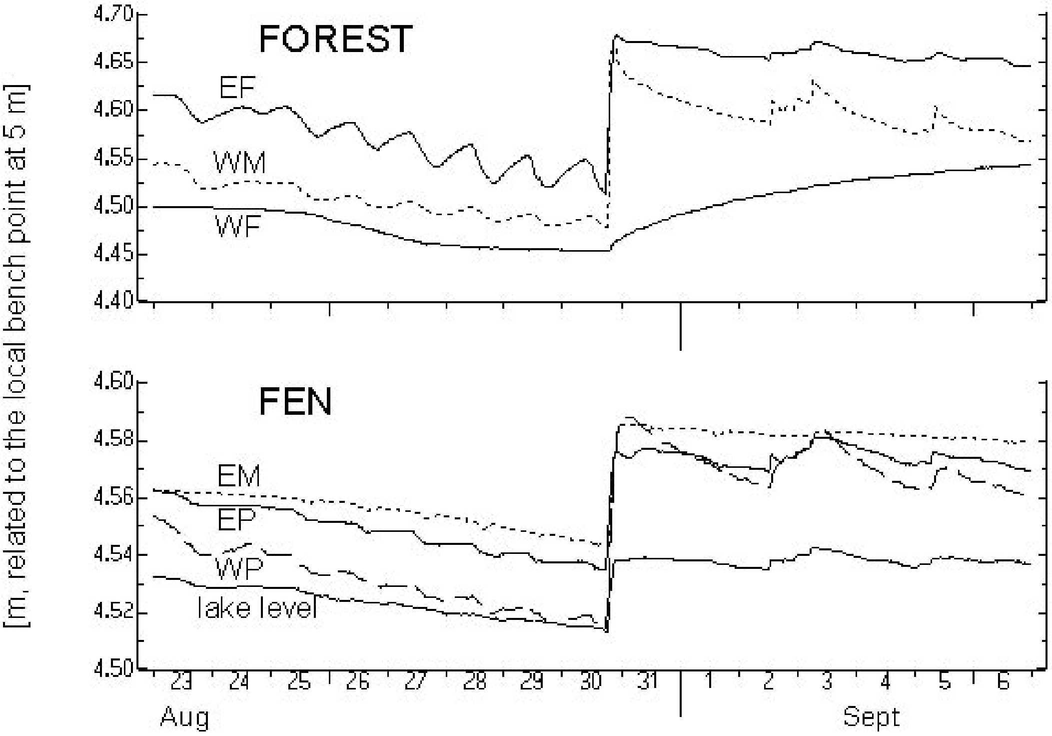

Figure 4-3. Lake Hällefjärd: Close up of all measured groundwater levels as well as the lake level August 23–September 6, 2000, half hour averages. The upper picture shows the forest values and the lower the fen values and the lake level. Values are related to the local bench point at 5 m.

4.1.5 Temporal pattern in groundwater dynamics (both measured and simulated) and lake level dynamics

The measured groundwater levels showed many similarities with the measured lake level, and thus they can be used as indications of the lake level when a measurement of the latter is lacking or unreliable (Figure 4-2). The highest groundwater levels occurred at the end of July, end of August and from the middle of October, as a result of heavy rains.

The groundwater levels responded with greater changes after each rain event than did the lake level. This could also be expected, as the specific storage is less than unity for the soils. The forest groundwater levels usually had the strongest response, followed by the fen groundwater levels, which had a stronger response than the lake level. Of the measured groundwater levels, EF and WF are regarded as forest sites, as well as the western intermediate WM site. The eastern intermediate site EM had a fen behaviour, very similar to EP. The western fen site, WP, usually reacted more to rain events than EM and EP. The 28 mm rain event in the evening of August 30 can be used as an example (Figure 4-3): The lake level rose by 25 mm, EP and EM rose by about 40 mm, WP by 80 mm, EF by 170 mm and WM by 190 mm (WF had a delayed response). If these increases had been caused only by the precipitation falling on that plot, the specific storage would have been 0.85 for EP and EM, 0.43 for WP and about 0.2 for EF and WM. However, this calculation assumes that there is no unsaturated water storage capacity at all above the groundwater level.

Daily fluctuations in the groundwater level caused by evaporation could easily be seen on rain-free summer and early autumn days, especially at EF and sometimes at WM, and some small daily variations could sometimes also be seen at EP, EM and WP. The forest sites EF and WM experienced a night-time rise in their levels (sinusoidal), while the fen sites

sites groundwater levels generally looked more like a stair (i.e. decrease daytimes and constant night-times). The largest evaporation oscillations were observed for EF, August 25 to 30, when there was a 30–40 mm decrease 10 am to 7 pm and a corresponding night-time increase of 15 to 30 mm (Figure 4-3). These variations were very large and implied a small specific storage at this depth, maybe as low as 0.1. The night-time increase at EF, without regarding the specific storage, corresponded to a net inflow of 23 mm/(unit area of the plot)/day during August 1 to 29 and 14 mm/(unit area of the plot)/day during September 15 to 30. In October, when it rained more, and when the evaporation decreased, no daily fluctuations could be seen, and the recession of the groundwater tables after the increase from rain events also seemed to be slower.

The large rain amounts during the second half of the autumn resulted in high groundwater levels and because of almost no evaporation, the levels only very slowly decreased after the rains (Figure 4-4). EF did not vary as much as previously during November and December.

The simulated forest groundwater levels represent sites higher upslope than the low-lying measured sites, and thus they cannot be directly compared, as the groundwater is found at different depths from the soil surface. The uppermost forest simulation segment, W1Sim, with the groundwater level three to four metres deep, had a delayed response to the precipitation events, and also only reacted to the largest precipitation events, which occurred at the end of June, July, August and October (Figure 4-5). The groundwater level in the lower forest segment, W2Sim, varied between –1.1 m and –0.3 m depth and had a much more direct response to the precipitation events than the upper segment. The response seemed to be larger than for the measured groundwater levels. As EF and WM showed, no groundwater level oscillations caused by evaporation could be seen in the simulated groundwater levels.

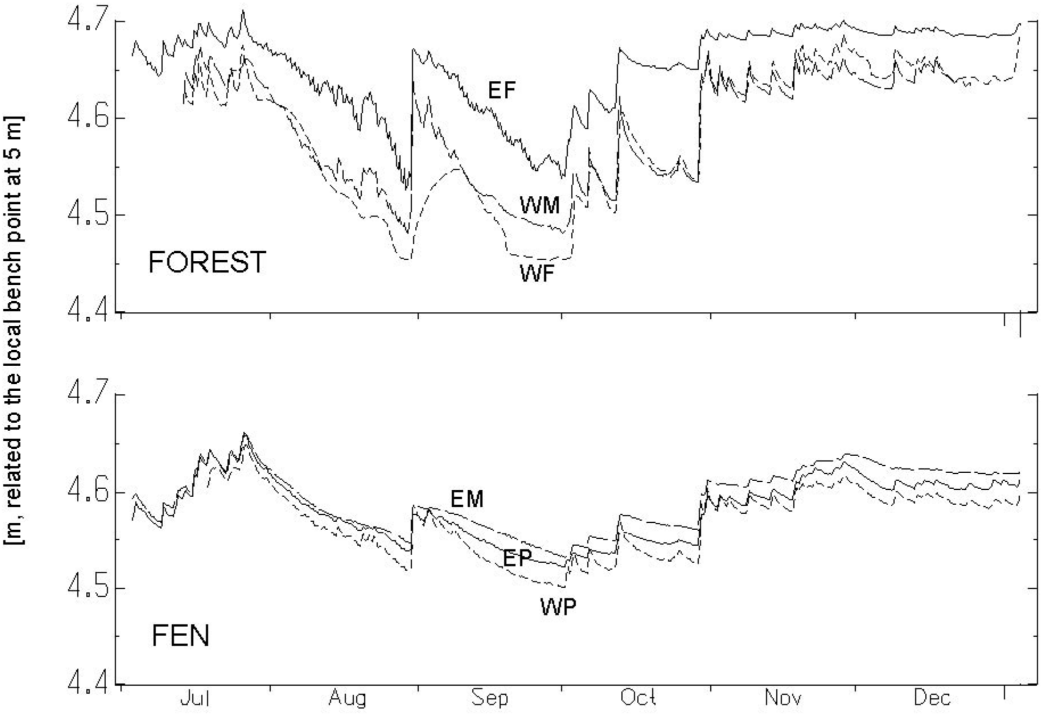

Figure 4-4. Lake Hällefjärd: The continuously measured groundwater levels from July 4, 2000 (EP, EM, EF); July 14 (WM, WF) and July 19 (WP) until December 24 (WM) and January 4, 2001 (the rest), eight hour averages.

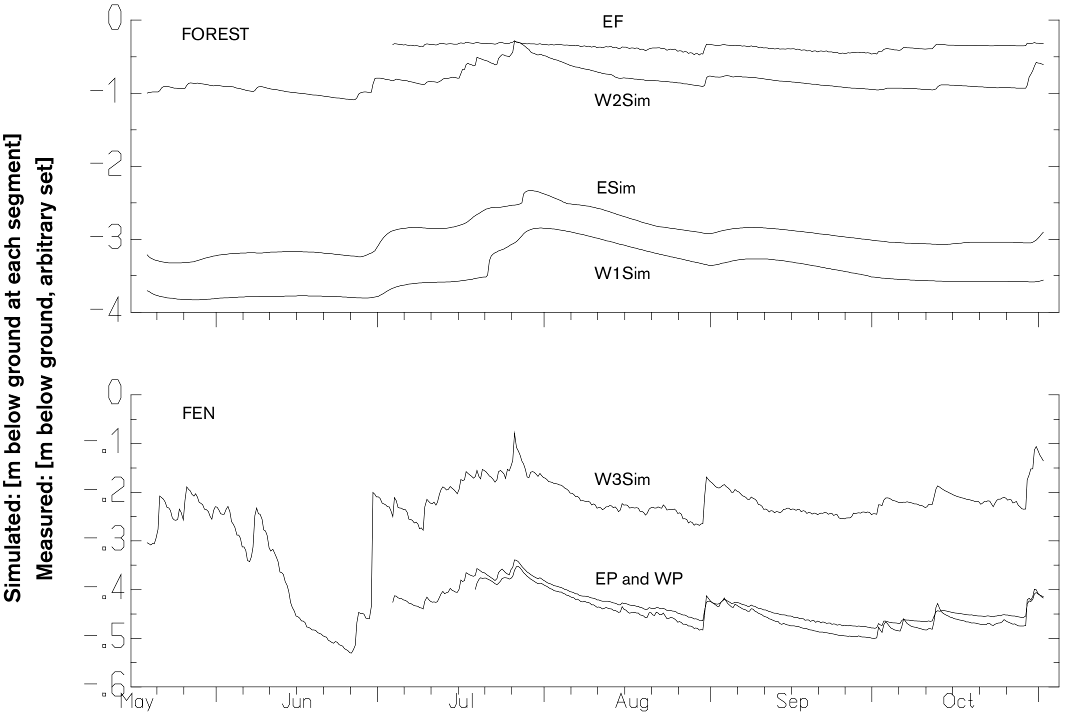

Figure 4-5. *Lake Hällefjärd: Simulated (May 19–October 31, 2000) and measured (July to October 2000) groundwater levels in the forest (upper picture) and the fen (lower). The simulated values are given in metres below the simulation segment ground surface, and the measured groundwater levels are arbitrarily placed at a quite shallow depth below the ground surface. May 19–October 31, 2000, eight hour averages. Please note the different scales on the y-axis.*

The simulated fen groundwater level (W3Sim) agreed best with the measured fen groundwater levels when a fixed drainage level at –0.3 m was used. A fluctuating 0–0.3 m drainage level, corresponding to the lake, resulted in long periods of non-fluctuating surface water for the fen, which does not correspond to the measured fen groundwater levels. This indicates that the fen was not drained by the dynamic lake but by the drain in the southern part of the fen, which represents a fixed level.

The simulated groundwater level decreased by more than was reasonable in June, but during the rest of the simulation period the measured and simulated groundwater levels agreed better, although there were no perfect matches (Figure 4-5). The simulated fen groundwater levels reacted more to a precipitation event than the measured groundwater levels, which cannot only be an effect of an erroneous porosity value, as the same difference was also seen where the porosity was set to 97%.

Running the model without any lateral inflow to the fen yielded a groundwater level that decreased too fast, not only in the beginning of the simulation period, but also in August to October. However, changes in the fen inflow affected the runoff from the segment more than the groundwater level of the segment.

A daily fluctuation pattern in the fen groundwater levels was obtained with the simulations but, as already noted, the measured groundwater levels did not exhibit sinusoidal behaviour.

The simulated large decrease in the fen groundwater level in June could be slightly reduced by applying a high porosity and a low air entry pressure also at the depth 0.2–0.4 m. A too large simulated evapotranspiration, or a too small upland inflow, might also be causes of this decreasing groundwater level. From the middle of August, when a longer period with reliable lake level measurements started, the difference in runoff from different fen simulations was relatively small, given the same inflow.

4.1.6 Water flows

The simulated water flows from the forest and from the fen showed different patterns (Figure 4-6). In drier periods, the outflow from the fen was much less than from the forest. Thus a considerable proportion of the forest water just filled up the fen and did not leave the catchment. After heavy rain, the outflow increased from both the forest and the fen, but the increase was much faster and larger for the fen. It did however also cease faster, as a result of higher hydraulic conductivity.

The maximum daily simulated inflow to the lake was 29 mm/(unit lake area) on August 31 and 44 mm/(unit lake area) on October 31, and only 2–3 mm of this water came from the eastern shore. From August 15 to October 31, the total simulated outflow from the western and eastern shore was 865 mm/(unit lake area), of which the eastern forest gave 225 mm/(unit lake area). During the same period the accumulated calculated q_{gnet} was around zero when E_L was used, and decreased by almost 40 mm when E_{Lmin} was used.

As already noted, the runoff from a segment was mainly influenced by the inflow to that segment. Other factors that affected the outflow from a segment to a greater or lesser extent were the profile depth in the forest, the evapotranspiration, the soil properties and the choice of area representation of each segment.

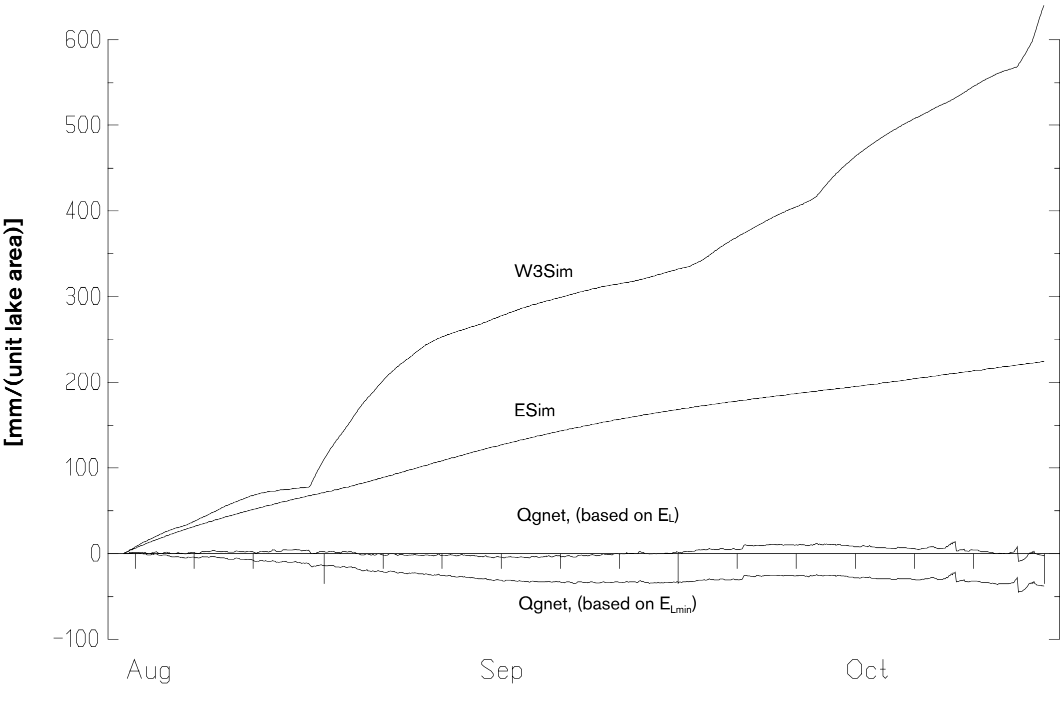

Figure 4-6. Lake Hällefjärd: Accumulated simulated groundwater flow from the fen on the western side (W3Sim) of the lake and the forest on the eastern side (ESim), as well as two possible calculations of the net groundwater flow (q_{gnet}) in the lake (as in Figure 4-1). August 15–October 31, 2000.

The total runoff from the catchment was 45 mm August 15 to October 31, calculated from the total simulated inflow to the lake plus $P– E_L$ of the lake (with E_{Lmin} the total runoff was 47 mm). The total precipitation amount during the same period was 133 mm.

During the measurement period (the year 2000), the outflow drain was only visited on May 19, and it showed at that time an extremely slow flow. The previous summer was drier and then the drain went dry at the end of the summer /Halvarsson, 2001/, implying no surface runoff from the catchment during dry periods.

4.1.7 Water electrical conductivity and water temperature

The electrical conductivity of the lake bottom varied between 25 and 33 mS/m (Figure 4-7). This was about 2–5 mS/m more than the pelagial electrical conductivity, measured every second week or once a month /Brunberg et al. 2002/. Electrical conductivity of the rainwater over the area was more than ten times less than the lake water /IVL, 2001/. Some peaks, rising up to 80 mS/m, were measured in the lake bottom water, especially in May, and although they could be regarded as indications of plug flow groundwater into the lake at precipitation events in drier periods, they are probably error measurements. A better placement of the measurement probe would have been to let it hang more freely in the water and not lie on the bottom, where it was probably more disturbed by sediment particles. Despite the fact that this was a long series with a high time resolution, it did not provide enough data to statistically prove any relationship between precipitation and changes in the electrical conductivity due to inflow of groundwater. The same holds for the continuous water temperature measurement.

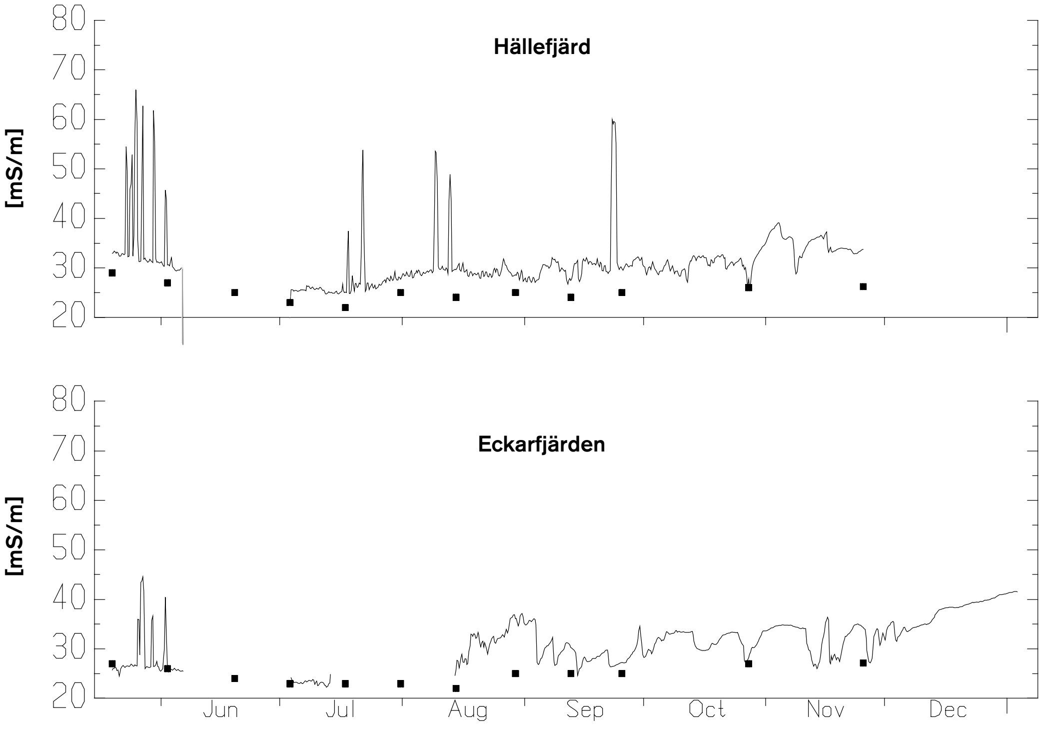

Figure 4-7. Lines: Electrical conductivity continuously measured at the southern shore of Lake Hällefjärd and in the outflow from Lake Eckarfjärden, May 19, 2000–January 4, 2001, six hour averages. Dots: Pelagial measurements made once or twice each month from /Brunberg et al. 2002/. The reliability of the peaks and the oscillations during the autumn is doubted. Six hour mean values are shown here, with the original 10 minutes measured values the highest peaks at Lake Hällefjärd reached about 80 mS/m.

In the beginning of July, the temperature of the nearshore bottom water peaked at 22°C, and at the end of December, the temperature series ended at 5°C. The nearshore bottom water temperature agreed with the pelagial temperature measured by /Brunberg et al. 2002/. The daily mean values of the air temperature and the water temperature followed the same pattern. During the summer and until September, the mean daily lake water temperature was higher than the air temperature. In October and November they were quite similar.

4.2 Lake Eckarfjärden

4.2.1 Climate

Precipitation measurements from Lake Eckarfjärden are available during the two periods May 19–June 6 and July 3–13. The total rainfall amount was 79 mm, of which 53.5 mm fell during the first period and 25.5 mm during the second. The corresponding sums of rain at Lake Hällefjärd were 51.5 mm and 38.5 mm. May 21 got the largest daily rain sum, 15 mm. During the rest of the analysed time period, the precipitation measurements from Lake Hällefjärd (about 20 km north-west) or the daily measurements from Risinge (about 20 km south) had to be used instead.

The air temperature measurements were very similar to those from Lake Hällefjärd (Section 4.1.1).

4.2.2 Stream outflow level

The water flow in the outflow stream was relatively slow, and the bottom gradients were small. Thus it was assumed that the outflow level measurement, although probably situated slightly after the lake threshold, can also be seen as a measure of the lake level. Reliable measurements were obtained during May 19 to June 6 and from August 14 until the end of the year.

The outflow level varied within about 30 cm (Figure 4-8). The lowest values were recorded in May and June, and the highest level occurred in the change from November to December. The general trend was a decreasing level in August and September, increasing in October and November, and decreasing again in December.

Assuming that the outflow level was the same as the lake level, and assuming, as for Lake Hällefjärd, vertical shores and no precipitation correction, $\Delta S/\Delta t - P = q_{gin} - q_{gout} + q_{sin} - q_{sout} - E_{lake}$ could be calculated. At the rain events in May and the beginning of June the lake level clearly rose by more than just the precipitation amounts falling directly on the lake, implying a fast inflow from the surroundings (Figure 4-9). The precipitation measurement failed in the autumn, and thus the precipitation measurements from Lake Hällefjärd (about 20 km north-west) or the daily measurements from Risinge (about 20 km south) had to be used instead when comparing the lake level changes and the precipitation. The storms were not exactly the same at these sites and at Lake Eckarfjärden, and thus it was harder to analyse $\Delta S/\Delta t - P$ in detail. If the lake level rose by more than simply the effect of the rain on the lake itself, this might not only have been due to an extra inflow from the surroundings, but also because the actual rain amounts were larger than the assumed amounts. However, it was generally rare to see the lake level rising by more than just because of the precipitation falling directly on its surface during the autumn, with some exceptions. September 2, October 3 and 12 were days where none of the measured neighbouring precipitation amounts were enough to cause the lake level increase (Figure 4-9). Most rain events however did not seem to cause an extra inflow. In the rainy month November, a steady increase in the lake level occurred, implying a net stream and groundwater inflow to the lake. December, on the other hand, was dominated by a net outflow from the lake.

By performing water flow measurements in the stream outflow, it is possible to make a rating curve, which relates the outflow level to the outflow water flow.

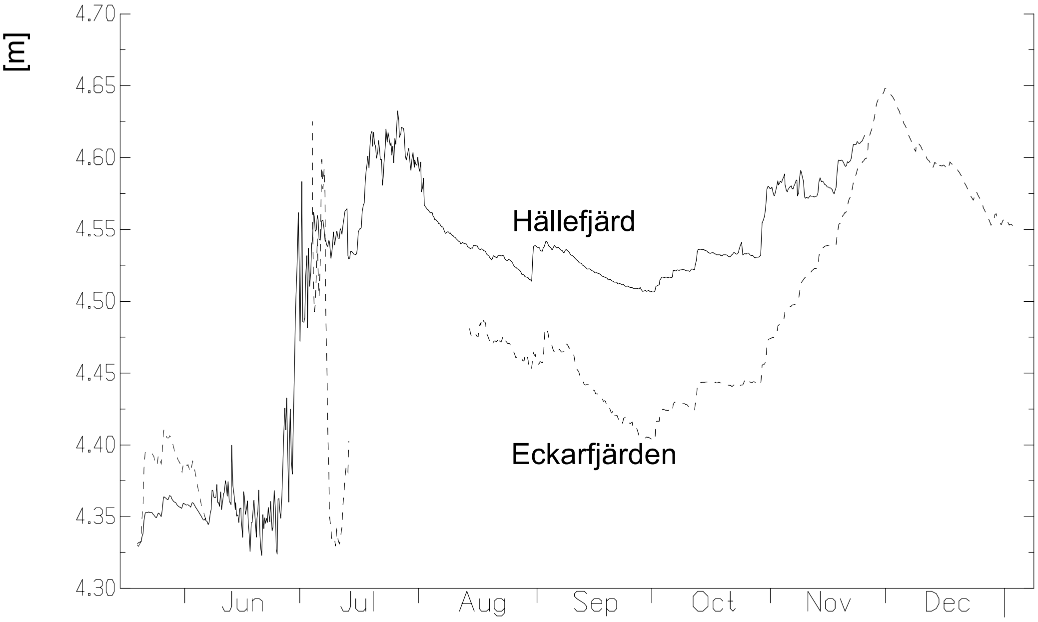

***Figure 4-8.** Measured lake level at Lake Hällefjärd (solid) and outflow level at Lake Eckarfjärden (dotted), 19 May 2000–4 January 2001, including both reliable and unreliable measurements, six hour average. The level at Lake Eckarfjärden is arbitrary placed relative to the level at Lake Hällefjärd. The level of Lake Hällefjärd 19 May to 6 June is set lower than in Figure 4-2.*

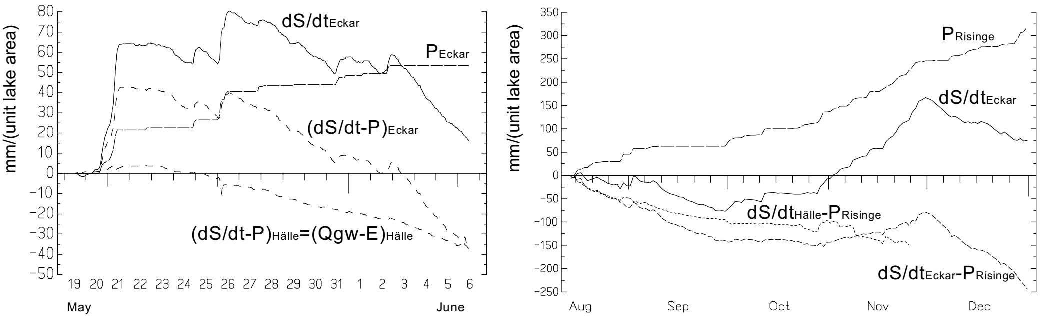

***Figure 4-9.** Calculations based on the measurements of the outflow level of Lake Eckarfjärden and the precipitation. Lake Hällefjärd is included for comparison. The index says which level and which precipitation that have been used. Cumulative values 19 May–5 June and cumulative values 15 August–31 October 2000. Note the scale differences in both axes.*

4.2.3 Water electrical conductivity and water temperature

The electrical conductivity of the outflowing water generally varied between 22 and 27 mS/m in the measurement period May–July (Figure 4-7). These values agree well with the pelagial value measured by /Brunberg et al. 2002/. Some peaks rising up to 50 mS/m occurred during the first measurement period. From August, another oscillating pattern started, where the conductivity varied between 25 and 40 mS/m and where the peaks lasted much longer. The pelagial measurements /Brunberg et al. 2002/ agree with the low values. As for Lake Hällefjärd, a better placement of the measurement probe would have been to let it hang more freely in the water and not lie on the bottom, where it was probably more disturbed by sediment particles.

Electrical conductivity of the rain water over the area was more than ten times less than the lake water /IVL, 2001/.

In the beginning of July, the temperature of the outflowing water peaked at 20°C and at the end of December, the temperature series ended at 1°C. The temperature usually agreed with the pelagial value, measured by /Brunberg et al. 2002/. The daily mean values of the air temperature and the water temperature followed the same pattern. In the measured periods May to July, at a few times in the autumn, and in the second part of December, the daily mean water temperature was clearly higher than the daily mean air temperature. Otherwise during the autumn, the mean daily temperatures of the lake and the water were quite similar.

5 Discussion

5.1 Lake Hällefjärd

The measured lake level variations and the measured precipitation indicated that the dominating water sources and sinks of the lake were the precipitation and the evaporation. The variations in δ, as well as in q_{gnet}, were much smaller than the variations in the lake level and the precipitation at rain events. The estimated lake evaporation determined whether the lake showed a net groundwater inflow or outflow during different time periods. As E_{Lmin} agrees better with the measurements at Lake Råksjön /Heikinheimo et al. 1999/ it is most likely that q_{gnet} is predominantly slightly negative for Lake Hällefjärd, i.e. the diffuse outflow is larger than the diffuse inflow.

Simulated flow versus the lake level variations

The measured lake level variations did not show patterns similar to the simulated groundwater outflow from the eastern forest side or the western fen side. Of the forest and the fen, the smaller water amounts and the quite constant flow from the forest on the eastern side are more similar to the very small lake level variations, than the varying and high flow from the fen on the western side. As an example of the different pattern and amounts between the simulated flow and the measured lake level variations, the accumulated value of $\delta + E_{Lmin}$ (a measure of q_{gnet}) can be studied. It decreased steadily during August and September (i.e. $q_{gin} < q_{gout}$) and if one really tries to see a change due to the large rain event August 30, a very small change towards more negative values of net groundwater flow might be seen, apart from some small oscillations in connection with rain. After this rain, on the other hand outflow was simulated from both the eastern forest and the western fen, but as mentioned, no extra inflow could be seen in q_{gnet}. The possibility that the simulated upland water inflow would just flow through the lake (i.e. $q_{gin} = q_{gout}$), without any temporary accumulation at all seems unlikely as lakes do have a damping effect of inflow peaks floods.

The simulated runoff might be too high, as the simulated forest evaporation was quite small, but also with higher forest evaporation it seems likely that there would be a simulated runoff substantially larger than q_{gnet} at rain events, because of the gradient towards the lake.

Inflow and outflow of the fen compared to the lake

Although the measurements of the lake level did not indicate a groundwater inflow to the lake, the simulated groundwater level of the fen seemed to decrease too fast compared with the measured fen groundwater levels, if it did not receive any upland inflow. One possible reason for this different behaviour is that the fen receives the upland inflow, but the water is trapped there and/or flows on towards the lower levels, without passing through the lake. Another reason might be errors in the simulation parameters regulating the evaporation and the soil properties.

Evaporation and is the fen actually a bog?

The oscillation pattern in the measured groundwater levels due to daytime evaporation with a continuous upland water supply could only clearly be seen at the forest sites EF and WM. Small daily variations occurred at EP, EM and WP too, but scarcely any night-time increase could be seen. No daily pattern at all was noticed in the lake level. Firstly, these differences are caused by different specific storage levels. Secondly, they imply a small evaporation in the fen and the lake and/or a more constant evaporation, as the open water of the fen and the lake also evaporate during the night. /Venäläinen et al. 1999/ compared simultaneous measurements of latent and sensible heat fluxes over the previously mentioned Lake Råksjön and the Norunda forest site. The mean monthly latent heat flux on Lake Råksjön and Norunda forest were reasonably similar, but the forest experienced much larger diurnal variations than the lake. The calculated lake evaporation values E_L and E_{Lmin} used here have a substantial daily fluctuation as calculated by Penman-Monteith's formula without any consideration of the energy storage in the lake. Thus, analysis of q_{gnet} should not be based on daily values but on values accumulated over several days. If the evaporation was not assumed to be almost constant, no upland inflow could be seen in the fen, as the groundwater level did not rise during the night. Thus the peatland would be hydrologically isolated from the upland and would have started to experience the transition from a fen to a raised bog. There were no visible indications of a lagg between the forest and the peatland, which would lead the upland water southward to the outflow ditch.

Flow reversal, groundwater mound and outflow from the lake

Evaporation and a low specific storage in the forest bordering the fen were likely to have caused the flow reversal that seemed to occur, or at least almost occur, on the fen in the rain-free periods at the end of August and the end of September. Such reversals have previously been reported by e.g. /Winter, 1999/. With a more widespread net of groundwater tubes, and less errors in the measurements, it would have been easier to draw conclusions about the lake level compared to the groundwater levels surrounding the lake. Although the lake level seemed to be higher than WM, WF and maybe also WP at the fen flow reversal events, the other groundwater level measurements (continuous and manual) indicated a groundwater mound on the fen south of the lake, hindering the lake water outflow. This mound had disappeared by October 19, or was at least weaker, as the nearshore groundwater tubes had groundwater levels slightly less than the lake level. EP and EF were however still above the lake level at this time. Groundwater mounds often occur at the outflow side of seepage lakes after large groundwater recharge events, such as snowmelt and storms /Winter, 1999; Cheng and Anderson, 1994/. Thus Lake Hällefjärd did not have any near-surface groundwater outflow during the existence of the groundwater mound but it could still have had groundwater inflow and deeper groundwater outflow. If the outflow from Lake Hällefjärd is non-existent or limited to the lake bottom, it does not support the predominantly negative q_{net} calculated with E_{Lmin}. It must however be remembered that the groundwater gradients are very small, and maybe erroneous, and that the main conclusion from the calculated q_{net} is that the groundwater flow to and from the lake is very slow.

The large groundwater level oscillations at EF

One small comment relating to Section 4.1.5, and the two paragraphs above is that the very large oscillations recorded at EF at the end of August could also have partly been influenced by inflow from the fen, as flow reversal occurred during those days.

Soil physical properties and fen surface water runoff

No measurements of the soil physical properties were made. Shrinking, compression, swelling and hysteresis behaviour of the peat is often reported /Persson G, 1985; Price and Schlotzhauer, 1999/ but was not taken into account either in the analysis of the measured groundwater levels or in the simulations. In the simulations made, parameter settings that gave a lot of surface water runoff were rejected, as they could not reproduce the measured groundwater level variations. As water was often standing in the hollows on the fen, the parameters regulating the surface water runoff in the simulations might be wrong. Despite these crude simplifications, general agreement was obtained between measured and simulated water levels.

Lake bottom inflow

At a bottom temperature survey made in Lake Hällefjärd (Appendix 2) in August 2000, no plots with a distinctively lower temperature were found, implying that localised water flow does not exist, which differentiates Lake Hällefjärd from the Norwegian lake investigated by /Norrström and Jacks, 1996/.

Lake chemistry

Although the measurements of the lake levels indicate that the lake only has a minor, if any, exchange of water with the surrounding groundwater, the chemistry of the lake does not support the fact that the lake is only precipitation-fed. Any ions in the lake must either come from:

- groundwater inflow, but if the groundwater inflow is non-existing or very low other possible sources are:
- dry deposition from the Baltic Sea,
- diffusion into the lake from the fen and the lake bottom, caused by osmotic gradients,
- an accumulation of many years of precipitation,
- relicts from previous groundwater inputs which have now ceased and the lake is now slowly turning into a raised bog.

5.2 Lake Eckarfjärden

Fast inflow to Lake Eckarfjärden, probably from the inflow stream, was spotted in May–June when measurements of both the lake level and the precipitation were available. During the autumn, the main trends in the lake level were a slight decrease in August with many variations, a decrease in September, a slight increase in October but also a long period of constant lake level, a large increase in November and again a decrease in December. Removing the effect of direct precipitation on the lake, only November had a net inflow to the lake.

After the rise at a rain event, the lake level of Lake Eckarfjärden usually decreased fast. During the summer this was a combined effect of both outflow and evaporation from the lake surface (Table 5-1). In October, the lake level decreased much more slowly or was almost constant for a longer period. As the evaporation is low in October and as the measured lake level was low, this implies a small outflow equal to the inflow. November and December had high lake levels and thus a large outflow, but the raising lake level in November implies an inflow larger than the outflow. The large inflow amounts in November were a combined effect of large precipitation and almost no evapotranspiration. It is likely that both the stream and groundwater contributed to the inflow in November.

Table 5-1. Analysis of the lake level changes in Lake Eckarfjärden in relation to the precipitation and conclusions about the inflow to the lake. Lake Hällefjärd is also included for comparison.

Lake Eckarfjärden							**Lake Hällefjärd**
When	**Lake level increase at a rain event**	**Lake level change after the increase at a rain event**	**Evaporation**	**dS/dt-P (Risinge)** **Average mm/day**	**Outflow rate (proportional to lake level)**	**Conclusion about inflow**	**dS/dt-P (Risinge)** **Average mm/day**
May/June	> Direct precip on lake	Rapid decrease	High	–7.5 (May 26 to June 6)	Likely low	Fast inflow	–3.5
August			High	–3.5 (14 August to end of August)	Intermediate	Varying	–2.5
September				–2.4	Low	Lower than outflow	–1.5
October		Slowly or const	Low	0	Low	Equal to outflow, i.e. small	–3.0
November			“None”	2.2	High	Higher than outflow, i.e. very high	–1.9
December		Rapid decrease	“None”	–5.2	High	Lower than outflow	

Diurnal variations and evaporation

Diurnal variations in the lake level occurred in the dry period of September. Similar variations were not spotted at Lake Hällefjärd. The lake level was predominantly decreasing, but increased during a few hours in the middle of the day. This is a reverse in behaviour compared to the groundwater levels at Lake Hällefjärd, which had a diurnal behaviour with a daytime decrease due to evaporation and a night-time increase due to a continuous groundwater inflow. Although a nearby lake also evaporated during the night, in contrast to a groundwater site, the daytime evaporation was still slightly higher than the night-time /Venäläinen et al. 1999/. The diurnal variations in the lake level of Lake Eckarfjärden must thus be caused by something other than evaporation combined with water inflow.

Changes in lake level pattern

The change in behaviour before and after September 27 could also have been an effect of probe cleaning.

Other results

The other results from Lake Eckarfjärden are discussed in relation to the results from Lake Hällefjärd in the next section.

5.3 Comparison between the two lakes

5.3.1 Surface and near-surface processes

Inflow to the lakes

Lake Eckarfjärden received a fast water inflow from the catchment, which was never registered at Lake Hällefjärd. The stream inflow to Lake Eckarfjärden is probably the main reason for this difference. The fen surrounding large parts of Lake Hällefjärd might also be important for hindering the water inflow to the lake.

Outflow from the lake and lake evaporation

Comparing the recession events of both lakes, the water level usually seemed to decrease faster in Lake Eckarfjärden than in Lake Hällefjärd. This is reasonable, as Lake Eckarfjärden has a stream outflow, which leads the water out faster than the fen at Lake Hällefjärd. The lake evaporation might also be slightly higher at Lake Eckarfjärden, because its larger area allows slightly higher wind speeds.

Lake water balance, $\Delta S_{lake}/\Delta t - P_{lake}$

As already noted, the extra storm water inflow to Lake Eckarfjärden was mainly spotted in May–June, when precipitation measurements from the lake were also available. During this period, the other precipitation sources (Lake Hällefjärd and Risinge) also indicated an extra water inflow at storm events. Using these other precipitation sources, $\Delta S_{lake}/\Delta t - P_{lake}$ behaved fairly similarly in the first part of the autumn, with negative values in August to September and with values around zero in October. $\Delta S_{lake}/\Delta \mathrm{t} - P_{lake}$ was however slightly more negative at Lake Eckarfjärden than at Lake Hällefjärd. The negative values mean a net decrease in the lake water volume and during this period were mainly caused by evaporation at Lake Hällefjärd, and a combination of evaporation and stream outflow at Lake Eckarfjärden. It must be remembered that Lake Eckarfjärden most likely also had a stream inflow during this period with net volume decrease. In November, on the other hand, $\Delta S_{lake}/\Delta t - P_{lake}$ was positive for Lake Eckarfjärden, while still negative for Lake Hällefjärd, although the lake level measurement at Lake Hällefjärd was not reliable in this month. It is predictable that Lake Eckarfjärden received an extra water inflow during this very rainy month, when the evapotranspiration must have been almost zero. The outflow was also very large, but not as large as the inflow. In December $\Delta S_{lake}/\Delta t - P_{lake}$ was again negative for Lake Eckarfjärden, i.e. the water volume was decreasing, but now mainly through the outflow stream, and not by evaporation. It is worth noting that the high water levels in December gave a larger net outflow of Lake Eckarfjärden than in the middle of August and September when the outflow consisted of both stream outflow and lake evaporation. It can be speculated that the lake level decreased very fast at the beginning of August after the large rains at the end of July, as a combined effect of high stream outflow and high evaporation.

Electrical conductivity

The electrical conductivity of both lakes implied a groundwater inflow.

5.3.2 Possible exchange with deep groundwater

The measured lake level of Lake Hällefjärd implied a very small groundwater inflow, if any, and thus the amounts of deep groundwater entering the lake are likely to be very small. The limited exchange with shallow groundwater does not support a dominant exchange with deeper groundwater. It is likely that the hydraulic conductivity of the lake bottom sediments is low.

Lake Eckarfjärden does have a water inflow, probably mainly through the stream, but likely also a groundwater inflow. It cannot be excluded that a small exchange with a deep groundwater may exist.

For a better knowledge of the deep groundwater exchange with the lake water is information about the hydraulic properties of the deep bedrock needed. It is also important to further investigate the surface parts and the contact with the biosphere. It is not known if the closeness to the sea makes the area a discharge area for regional groundwater, or if any regional water flow is directly diverted to the sea, without approaching the surface at the lakes. The conclusion that the groundwater inflow to the lakes is likely to be small, especially at Lake Hällefjärd, could not without further investigations be generalised to other lakes.

6 Future research

Even if many types of measurements have already have been tested within the project so far, there are many other measurements it would be interesting to carry out. The following chapter describes possible new and additional measurements.

6.1 Tracer experiments

Tracer experiments could be used to make an independent check of the conclusions drawn about the lake turnover time, by providing information about water flow paths and water flow quantities. The experiments must however be carefully designed, as the water flow rates are probably small. It would be most interesting to determine whether the water flow from the till slopes is going into the lake or whether it is being diverted around Lake Hällefjärd. The possible water flow rate in and out of both Lake Hällefjärd and Lake Eckarfjärden would also be very interesting. Additionally, it would be of interest to find out whether the Lake Hällefjärd catchment outflow really occurs through the drain or not.

Preferably, one would like to use methods such as O-18 analysis, which do not require the addition of substances. Protection of the valuable ecosystem at Lake Hällefjärd makes it inadvisable to add any tracers, and additions of radioactive tracers are also unsuitable at Lake Eckarfjärden because of its closeness to the SFR-1.

Another type of tracer experiment would be to regularly measure the resistivity around the lakes, to examine the changes with time.

6.2 Inflow and outflow spots of the lake bottom

6.2.1 Piezometer

To determine whether water is flowing into or out of the lake, or whether there is any vertical flow at all, piezometers could be inserted into the lake bottom. A water level in the piezometer higher than the lake water level would indicate a groundwater inflow spot.

Fixing the levels of piezometers in the lake might be complicated, but by always measuring both the piezometer and the lake water levels, the piezometer water level could be related to the other water levels through the lake level, thus making point-fixing unnecessary.

If a new lake bottom temperature measurement were to be made, results from that could be used to identify interesting points for piezometer measurements. Generally, and given no new measurements, points close to the shore are most interesting /McBride and Pfannkuch, 1975; Shaw and Prepas, 1990/ although the small size of especially Lake Hällefjärd implies that also the centre of the lake could have a small “nearshore” seepage.

It is interesting to select both suspected inflow and outflow areas for the piezometer locations. For the latter, the area closest to the outflow of Lake Eckarfjärden and the southern part of Lake Hällefjärd are relevant. It might also be interesting to have piezometers placed outside both forest (till) and peatland shores.

A group of piezometers penetrating the lake bottom to different depths on the same spot would show if there is any shallow confining layer under the lake. Such a measurement would however disturb the sediment, and potentially change the hydrological conditions.

6.2.2 Seepage metres

Seepage metres can be used to measure the flux of groundwater into or out of a lake bottom. The method is described by e.g. /Shaw and Prepas, 1990/. Computer simulations of /McBride and Pfannkuch, 1975/ provided the theory that groundwater inflow is largest close to the shore, and decreases exponentially towards the middle of the lake. This theory has been verified in many lakes (although not in all the lakes investigated) by seepage metre measurements /e.g. Shaw and Prepas, 1990/. Guided by this, seepage metres should mainly be placed close to the shore, to find the maximum inflow, but also in the central part of the lake to be able to integrate the inflow over the whole area.

Coarse lake bottoms that consist of stones or boulders could not be investigated with this method and it might also be problematic to fasten the seepage metres in the very soft bottoms of Lake Hällefjärd and Lake Eckarfjärden.

/Norrström and Jacks, 1996/ used seepage metres to measure water inflow and outflow from macropores and as well as diffuse seepage through the lake bottom. No localised flow paths were found in the bottom temperature survey of Lake Hällefjärd, but it would be good to make another survey before deciding where to put the seepage metres.

6.3 Continuation of measurement series

The continuously collected data have been shown in this report to be very useful for the rough estimation of the turnover time and inflow to the lakes. As always, prolonged time series are interesting.

Some variables were not reliably measured, for more or less well-known reasons. It is important to examine the whole equipment in the laboratory again, before re-installing it in the field, to see if some gauges/probes were altered during the previous field campaign. One should also carefully think of ways to reduce the different problems that occurred. An easy way to check the absolute value of the lake water level given from the logger, is to make manual level recordings using a gauge in the lake at each field trip.

6.4 Groundwater levels

For better simulations and better knowledge about the groundwater gradients, groundwater level measurements higher up on the till slope should be made. It is not as easy to penetrate the till with groundwater tubes as it is to penetrate the peat, so somewhat more advanced tubes would be needed. The number of tubes and the choice between manual and automatic logger recording is a question of money.

6.5 Stream water flows

To determine the runoff from the catchment, water level measurements should be made in the outflow drain of Lake Hällefjärd. /Halvarsson, 2001/ reported that the drain went dry at the end of the summer 1999, which needs to be taken into account when designing this measurement. Water flow measurements at different water levels to get a rating curve of the drain at Lake Hällefjärd and the inflow and outflow streams of Lake Eckarfjärden are also needed. A relatively small current metre is likely needed, because of the often small water flows.

6.6 Evaporation

For a better understanding of the water balances of the lakes, measurements of parameters related to the evapotranspiration would be useful.

So far, evapotranspiration has been calculated using the panel temperature from Lake Hällefjärd and global radiation and humidity from Uppsala. The wind speed from Uppsala has also been used, sometimes recalculated based on different assumptions of roughness lengths. Different assumptions of roughness have also been included in the evapotranspiration calculations, and have often been manipulated to get evapotranspiration values reasonably close to literature data.

There are many different techniques to measure evapotranspiration parameters (many ways to calculate the evapotranspiration) and one should carefully investigate which method is most useful in this case. It is recommended that the lake energy storage (lake temperature) is taken into account when calculating the lake evaporation /Price, 1994b/.

If some meteorological variables have to be represented by measurements from other sites, it would probably be more accurate to use the measurements made at the nearby Forsmark nuclear power station rather than the measurements from Uppsala.

6.7 Soil and bedrock properties

Different soil properties, such as water retention curves, swelling/shrinking characteristics, hydraulic conductivities etc would probably provide better simulation results. As these characteristics vary a lot spatially, it is preferable to use measurement methods which cover a larger area, but which are not as accurate as point measurements. Studies of the exchange with deep groundwater would also need information about the hydraulic properties of the bedrock at different depth.

6.8 General concern

If the measurement programme at Lake Hällefjärd is to be continued, one should carefully design a protection system for the fen with e.g. suspended walkways. It was noticed during the field trips that a path developed though the Phragmites even if only two people walked the same way twice. The Phragmites was bent to the sides and the peat was compacted and the path was filled with water. Thus new surface water flow paths and small gradients might have developed. The impact on the fen should be minimised, both because of the general protection value of this type of natural ecosystem as well as the risk of artificial impacts on the hydrology which is being studied.

7 Conclusions

The water level measurements and the simulations have given some first insights into the hydrology of both a Swedish seepage lake and a Swedish drainage lake. Lake Hällefjärd, the seepage lake, seems to be dominated by precipitation and evaporation, and has only a minor groundwater exchange with the surroundings. Thus the lake turnover time is long, and closer to the 4.4 years calculated with no groundwater inflow, than the about 100 days that are calculated from the normal recharge in the region. The high resolution data collected are useful in understanding the hydrology of the lake although it do not fully capture the diffusive groundwater flow in and out of the lake. It is concluded that the groundwater flow through the lake is slow and quite constant and thus delayed. Tracer experiments may be useful to enable an independent check of this conclusion. Lake in some storms, gets a fast water inflow from the surroundings. The turnover time of Lake Eckarfjärden is thus likely closer to the theoretical 400 days, calculated with the recharge in the region, as opposed Lake Hällefjärd. Conventional water flow measurements in the inflow and outflow stream of Lake Eckarfjärden to produce a rating curve would be useful in providing more information about the water flow quantities, and thus providing a picture of the size of the groundwater inflow.

Given the very small groundwater inflow at Lake Hällefjärd, the amount of deep groundwater inflow is likely to be very low. After rating curves are made to get an estimate of the groundwater inflow at Lake Eckarfjärden, it will be possible to say more about the possible amounts of deep groundwater inflow.

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References

Bergström E, 2001. Late Holocene distribution of lake sediment and peat in NE Uppland, Sweden. SKB R-01-12, Svensk Kärnbränslehantering AB.

Bradley C, 1996. Transient modelling of water-table variation in a floodplain wetland, Narborough Bog, Leicestershire. J. Hydrol., 185, p 87–114.

Branfireun B A, Roulet N T, 1998. The baseflow and storm flow hydrology of a precambrian shield headwater peatland. Hydrol. proces., 12, p 57–72.

Brunberg A-K, Blomqvist P, 1998. Vatten i Uppsala län 1997. Beskrivning, utvärdering och åtgärdsförslag. Upplandsstiftelsen, Rapport nr 8/1998, Uppsala, Sweden (in Swedish).

Brunberg A-K, Blomqvist P, 1999. Characteristics and Ontogeny of Oligotrophic Hardwater Lakes in the Forsmark Area, Central Sweden. SKB R-99-68, Svensk Kärnbränslehantering AB.

Brunberg A-K, Blomqvist P, 2000. Post-glacial, Land Rise-induced Formation and Development of Lakes in the Forsmark Area, Central Sweden. SKB TR-00-02, Svensk Kärnbränslehantering AB.

Brunberg A-K, 2001. Pers comm.

Brunberg A-K, Nilsson E, Blomqvist P, 2002. Characteristics of oligotrophic hardwater lakes in a post-glacial landrise area in mid-Sweden. Freshwater Biol., 47, p 1,451–1,462.

Brydsten L, 1999. Shore line displacement in Öresundsgrepen. SKB TR-99-16, Svensk Kärnbränslehantering AB.

Brydsten L, 2000. Pers comm.

Carlsson L, Gidlund G, 1983. Evaluation of the hydrogeological conditions at Finnsjön. Svensk Kärnbränsleförsörjning, SKBF/KBS Technical Report 83–56, Stockholm, Sweden.

Cheng X, Anderson M P, 1994. Simulating the influence of lake position on groundwater fluxes. Water Resources Res., 30 (7, July), p 2,041–2,049.

Dall'O M, Kluge W, Bartels F, 2001. FEUWAnet: a multi-box water level and lateral exchange model for riparian wetlands. J. Hydrol., 250, p 40–62.

Eser P, Rosen M R, 1999. The influence of groundwater hydrology and stratigraphy on the hydrochemistry of Stump Bay, South Taupo Wetland, New Zeeland. J. Hydrol., 220, p 27–47.

Espeby B, 1990. Tracing the origin of natural waters in a glacial till slope during snowmelt. J. Hydrol., 118, p 107–127.

Espeby B, 1992. Coupled simulations of water flow from a field-investigated glacial till slope using a quasi-two-dimensional water and heat model with bypass flow. J. Hydrol., 131, p 105–132.

Haglund E, 1972. Naturvårdsinventering av Uppsala län, del VIII: Tierps kommun, norra delen. Länsstyrelsen i Uppsala län (Uppsala County Administration). Uppsala, Sweden (in Swedish).

Halvarsson E, 2001. Hällefjärd – en kalkoligotrof sjö i Norduppland. M.S.Thesis. Dept. of Limnology, Uppsala University, Scripta Limnologica Upsaliensia 2001 B:11, Uppsala, Sweden (in Swedish).

Heikinheimo M, Kangas M, Tourula T, Venäläinen A, Tattari S, 1999. Momentum and heat fluxes over lakes Tämnaren and Råksjö determined by the bulk-aerodynamic and eddy-correlation methods. Agr. Forest Meteorol., 98–99, p 521–534.

IVL, 2001. Miljödata. [Web]. Data från miljöövervakningen, http://www.ivl.se/miljo/ [Accessed 2001-07-03] (in Swedish).

Jansson P-E, Cienciala E, Grelle A, Kellner E, Lindahl A, Lundblad M, 1999. Simulated evapotranspiration from the Norunda forest stand during the growing season of a dry year. Agr. Forest Meteorol., 98–99, p 621–628.

Jansson P-E, Karlberg L, 2001. Coupled Heat and Mass Transfer Model for Soil-Plant-Atmosphere Systems. Royal Institute of Technology, Dept. of Civil and Environmental Engineering, Stockholm, 325 pp, (ftp://www.lwr.kth.se/CoupModel/CoupModel.pdf)

McBride M S, Pfannkuch H O, 1975. The distribution of seepage within lakebeds. J. Res. U.S. Geol. Surv., 3, p 505–512.

Mitsch W J, Reeder B C, 1992. Nutrient and hydrologic budgets of a Great Lakes coastal freshwater wetland during a drought year. Wetlands Ecology and Management, 1(4), p 211–222.

Monteith J L, 1965. Evaporation and environment. In: Fogg G E (ed.) The State and Movement of Water in Living Organisms, 19th Symp. Soc. Exp. Biol., Cambridge: The Company of Biologists, p 205–234.

Nilsson E A, 2001. A preliminary carbon budget for two oligotrophic hardwater lakes in the Forsmark area, Sweden. SKB R-01-24, Svensk Kärnbränslehantering AB.

Norrström A-C, Jacks G, 1996. Water pathways and chemistry at the groundwater/surface water interface to Lake Skjervatjern, Norway. Water Resources Res., 32 (July 7), p 2,221–2,229.

Persson C, 1985. Jordartskartan 121 Östhammar NO, Sveriges Geologiska Undersökning (Swedish Geological Survey), Serie Ae No 73, Uppsala, Sweden (in Swedish).

Persson C, 1986. Jordartskartan 13I Österlövsta SV, Sveriges Geologiska Undersökning (Swedish Geological Survey), Serie Ae No 77, Uppsala, Sweden (in Swedish).

Persson G, 1985. Markfysikaliska undersökningar på några organogena jordar i Kronobergs län. Naturvårdsverket (Swedish Environmental Protection Agency) Rapport 3057, Solna, Sweden (in Swedish).

Price J S, 1994a. Water exchanges in a shoreline Thypha marsh on Lake Ontario. J. Hydrol., 161, p 181–195.

Price J S, 1994b. Evapotranspiration from a lakeshore Thypha marsh on Lake Ontario. Aquatic Botany, 48, p 261–272.

Price J S, Schlotzhauer S M, 1999. Importance of shrinkage and compression in determining water storage in peat: the case of mined peatland. Hydrol. proces., 13, p 2,591–2,601.

Rodhe A, 1989. On the generation of stream runoff in till soils. Nordic Hydrology, 20, p 1–8.

SGU, 2000. Sveriges Geologiska Undersökning (Swedish Geological Survey). [Web]. Brunnsarkivet (Well archive). http://www.sgu.se/databaser/brunnsark_index.htm [Accessed December 2000].

Shaw R D, Prepas E E, 1990. Groundwater-lake interactions: II. Nearshore seepage patterns and the contribution of ground water to lakes in central Alberta. J. Hydrol., 119, p 121–136.

SMHI Swedish Meteorological and Hydrological Institute, 2000. Väder och vatten No 5 to No 12. (also available as "Månadens väder", (http://www.smhi.se/sgn0102/n0203/manvaed.htm) (in Swedish).

Söderholm H, Müllern C-F, Engqvist P, 1983. Beskrivning och bilagor till hydrogeologiska kartan över Uppsala län. Sveriges Geologiska Undersökning (Swedish Geological Survey). Serie Ah Hydrogeologiska översiktskartor i skala 1:250,000, No 5, Uppsala, Sweden (in Swedish).

Stähli M, Nyberg L, Mellander P-E, Jansson P-E, Bishop K H, 2001. Soil frost effects on soil water and runoff dynamics along a boreal transect: 2. Simulations. Hydrol. Process., 15, p 947–941.

Vanek V, 1991. Riparian zone as a source of phosphorus for a groundwater-dominated lake. Water Res., 25 (4), p 409–418.

Venäläinen A, Frech M, Heikinheimo M, Grelle A, 1999. Comparison of latent and sensible heat fluxes over boreal lakes with concurrent fluxes over a forest: implications for regional averaging. Agr. Forest Meteorol., 98–99, p 535–546.

Widén E, 2001. Groundwater Flow Into and Out of Two Lakes Partly Surrounded by Peatland. M.S.Thesis, Thesis Report Series 2001:6. Division of Land and Water Resources, Royal Institute of Technology, Stockholm, Sweden.

Winter T C, 1999. Relation of steams, lakes, and wetlands to groundwater flow systems. Hydrogeol. J., 7, p 28–45.

Appendix 1

Monitoring of bedrock and deposits at Lake Hällefjärd

Methods

Even though visual impressions were recorded at each visit to the lake a walk around each lake was also made to note some hydrogeological characteristics. At Lake Hällefjärd the peatland was investigated by manual rod steel sounding in June, while four GPR (Ground Penetrating Radar) profiles (A–D) and two resistivity profiles (E–F) were made in August and September (Figure 2-1).

The GPR investigations were made with the Pulse Ekko IV sensors and software using a 100 MHz antenna frequency. Measurements were taken every one metre using an antenna spacing of 1 metre. GPR data were analysed using the programme PEIV.

In addition, two resistivity profiles were carried out using ABEM Terrameter 4000 and System Lund. The collected resistivity values were modelled in RES2INV (2 dimensional) and presented in ERIGRAPH.

Results

Steel rod sounding

The steel rod sounding was carried out entirely on the peatland south, west and north of Lake Hällefjärd. Thus between 50 and 250 cm peat was found at each point. Below 5–90 cm, sand and gravel were found, until the probe could not be pushed any further down. At a few points stones were also found. At one point, in the peatland south of the lake, soft material resembling clay was found.

Ground Penetrating Radar (GPR)

The peat and till thickness, as well as the bedrock level, can be found on all GPR profiles from Lake Hällefjärd (Figure 2-1, Figure A1-1 to Figure A1-4). At a few sites there are two possible interpretations of the bedrock level. Note that the length scale in Figure A1-1 to Figure A1-4 is valid for peat only. The radar velocity in till and bedrock is double the peat radar velocity and thus the thickness of till and bedrock is double the thickness given by the length scale.

North of the lake the maximum peat thickness is 3.6 m, which occurs in the eastern peatland part of profile A-A’. At the same point the maximum depth to the bedrock of this profile, about 6.6 m, is found. Profile A-A’ begins on bare rock east of Lake Hällefjärd and ends on big blocks in the west. Profile B-B’, along a small gravelled road, does not pass through much peat. The maximum peat thickness is about 1.6 m and is found in the western part of the profile as well as in the middle, where profile C-C’ crosses it. The maximum depth to the bedrock, 7 m, is found about 80 m from the eastern end of the profile and probably also in the middle of the profile. The short profile C-C’ is only over peat, with a maximum thickness of 2 m in the initial, southern part. The maximum depth to the bedrock, 3.6 m, is also found here. The filling material of the road can be seen south of the lake, in profile D-D’ where the maximum peat thickness is 2 m and the maximum depth to the bedrock is probably 5.2 m.

Beneath the peat, south of the lake, layered sediments are found. This indicates that here, there has been open water, lake or sea, which has been overgrown by peat. The till in the eastern part of the profile also shows some type of layers.

Resistivity

The two resistivity profiles show a big difference in the conductivity of the ground. For the water flow, the low resistivity region is of interest. The peatland parts of the profile naturally show the lowest resistivity values. The bedrock has the highest resistivity.

Clay also has low resistivity, but at Lake Hällefjärd there does not seem to be much clay. It is at least not present in the GPR profiles. Low resistivity values here therefore indicates the high water content (high porosity) in the ground. High porosity has sometimes a connection to high hydraulic conductivity, but this is not always the case. The most interesting low resistivity region on the eastern shore, profile E-E', is found where the clear-cut area begins, about 80 m from the start point. Here, both the modelled values from ERIGRAPH and RES2INV show that below the topsoil, with a relatively high resistivity, comes a layer with lower resistivity, somewhat lower than the modelled values in the rest of this profile, except for the peatland. High resistivity values close to the soil surface are also found just before the peatland. These seem to correspond to high values on the western shore too. On the eastern shore, three false values have been deleted. Below the part with pine and Labrador-tea (*Rhododendron tomentosum* or *Ledum Palustre*) the measured and modelled deeper resistivity values are lower than in the topsoil.

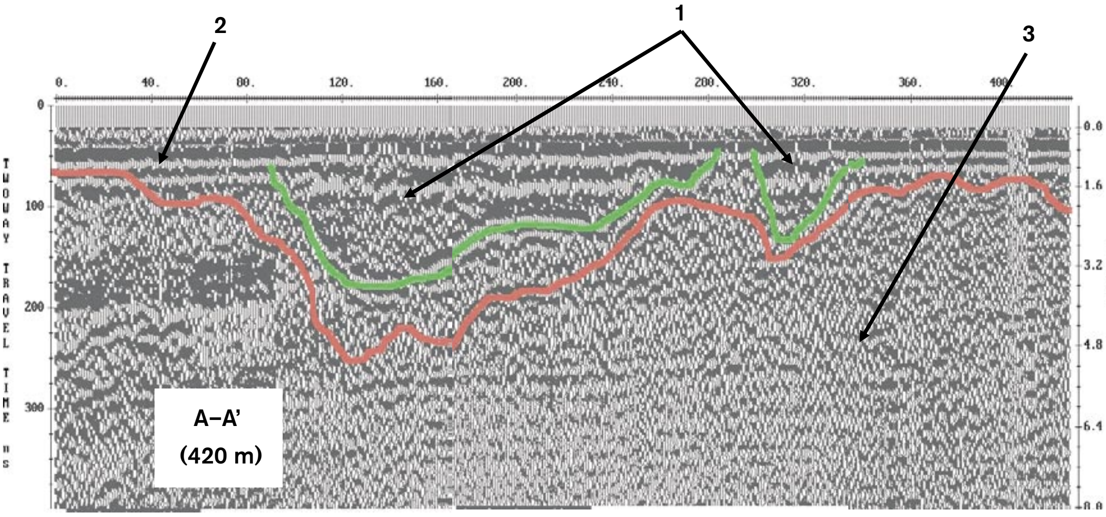

Figure A1-1. *GPR profile A-A', August 2000 at Lake Hällefjärd. The distinct borderlines are interpretations, drawn by hand. Dashed lines mean that the interpretation of that border is not clear. 1 = peat, 2 = till, 3 = bedrock, 4 = road filling material, 5 and 6 layered sediments where the history of 5 is unknown but 6 must be old lake or sea sediments. The depth of the profiles (8 m) corresponds to the peat radar velocity. The profiles are in reality deeper as the radar velocity is about the double in till and bedrock. The transects have different lengths and the figures do not have exactly the same scale.*

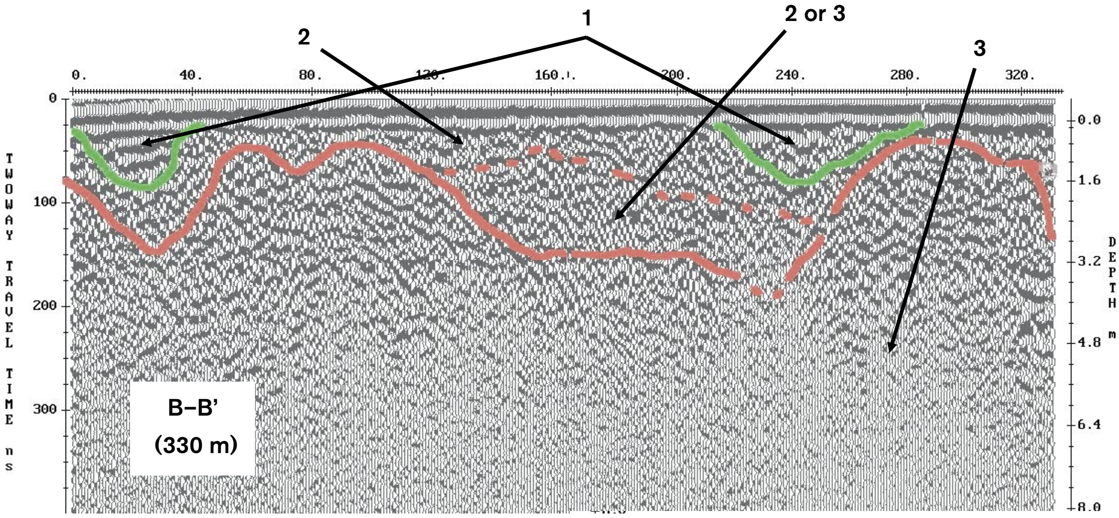

Figure A1-2. *GPR profile B-B' at Lake Hällefjärd. Explanations in Figure A1-1.*

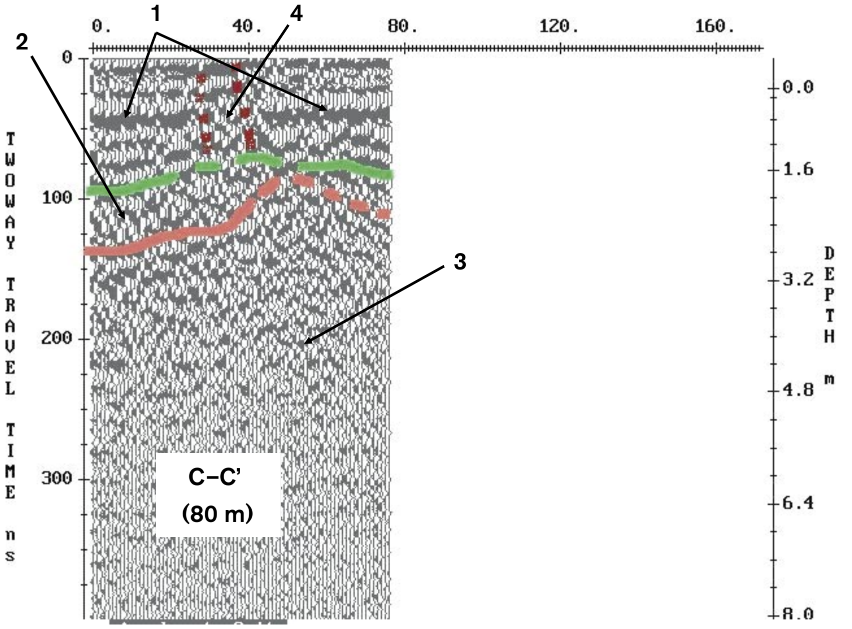

Figure A1-3. *GPR profile C-C' at Lake Hällefjärd. Explanations in Figure A1-1.*

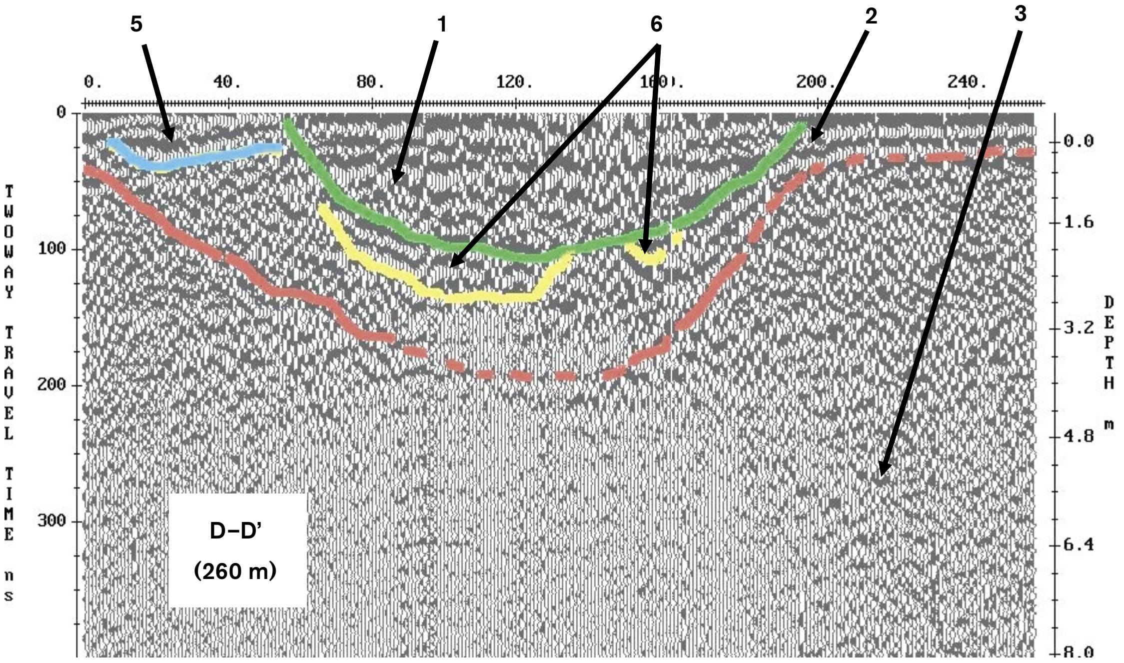

Figure A1-4. *GPR profile D-D' at Lake Hällefjärd. Explanations in Figure A1-1.*

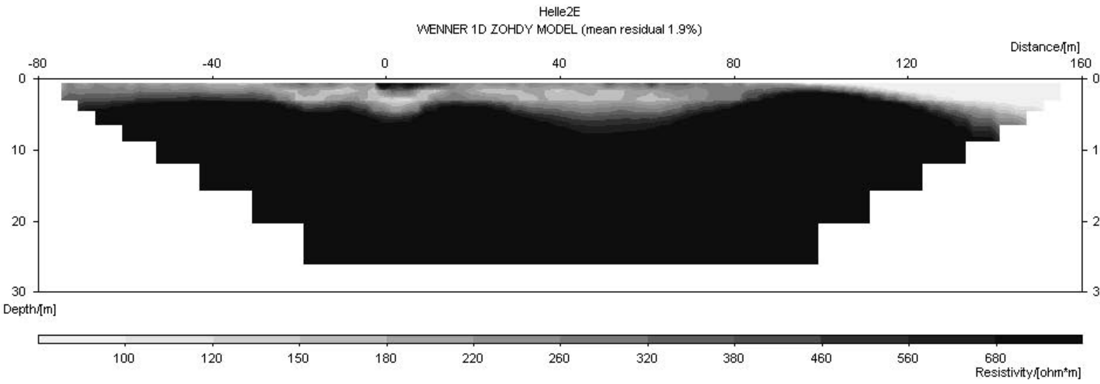

Figure A1-5. *Resistivity profile E-E', on the eastern shore of Lake Hällefjärd (N-S). The profile is on till except in the south where it reaches the peatland. (Modelled in RES2INV, presented in ERIGRAPH).*

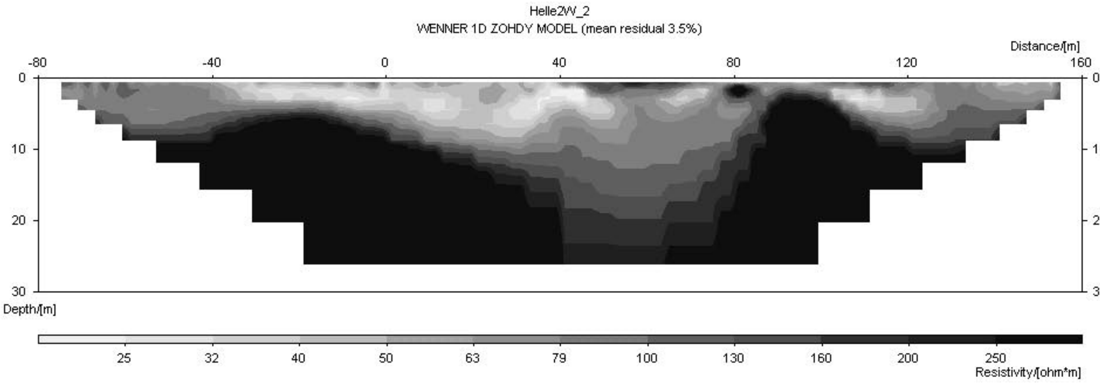

Figure A1-6. *Resistivity profile F-F', on the western shore of Lake Hällefjärd (N-S). The profile is mainly on peat, which was mostly quite wet.*

Discussion

Ground Penetrating Radar (GPR)

North and south of the lake there are smooth depressions in the hard rock. The lake and the peatland are thus topographically formed. An alternative definition of the aerial extent of the lake might be to include the peatland. The latter has been tested in some of the HBV simulations.

The peat connection to the adjacent catchment in the north, investigated with profile B-B’ and C-C’, is probably not of any major importance. There could however be some water flow, and thus the groundwater ridge is not completely impermeable and not completely fixed.

The soft material found with the steel sounding at a point south of the lake is probably the same as the layered sediment found on the GPR profiles.

The layers found on the eastern shore in profile D-D’ are not found on any of the other transects. The only visible difference between this area and the other sites is that the forest has been clear-cut. The layered structure is perhaps a result of changed moisture content in this soil and maybe the groundwater level can be seen. There may however also be a geological difference here, coinciding with the clear-cut area.

Resistivity

The low resistivity region underlying a higher resistivity region on the eastern shore might be an indication that there may be some type of localised flow. On the western shore a similar phenomenon is found, below the area with pine and Labrador-tea. There, localised flow might also occur. This low-resistivity region seems in the 2D-model (Figure A1-6) to be connected to a quite big cross-sectional area of low resistivity. With a one-dimensional model this south-lying region of low resistivity seems to be a bedrock crack, going from the surface deeper into the ground in a northward direction. Steel sounding was done at two points in the small pine and Labrador-tea area. They reached around 300 cm deep, which is however not as deep as the low resistivity region. The main constituent of the two profiles is peat, followed by sand and gravel. In one point as much as 120–130 cm sand and gravel could be felt before the probe stopped. It must be quite loosely packed, probably with a very high water content, for it to be possible to drive the stick so deep into that material. The establishment of the pines is probably a result of the drier topsoil.

Appendix 2

Monitoring of spatial pattern of groundwater inflow to Lake Hällefjärd

Methods

Searching for groundwater inflow points, the lake bottom temperature was measured every metre along a west-east transect across the lake (Figure 2-1). The temperature was also measured around a big part of the shoreline. Two additional temperature depth profiles were investigated, at the maximum depth point close to the eastern shore and at a point close to the western shore. By the end of the summer the temperature difference is generally at its highest between lake water and groundwater and therefore outflow points are most likely to be found. This measurement was performed from a rowing boat, on August 2, with a temperature probe Pt-100 connected to a Campbell data logger CR 21. The time constant of the probe was about half a minute. An instant value was collected after an inspection to check that the measured level did not change too much. The time between the measurements was about 0.5 to 2 minutes including movement of the boat along the west-east transect. During the row around the shoreline many measurements per minute were made. The conductivity, together with another temperature measurement, was also measured using a Campbell 247 Conductivity and Temperature probe. However, the time constant of this probe (about 5 minutes) was longer then the adaptation time at each registration. The probes were kept at a constant height above the bottom whenever possible.

Results

Only minor irregularities of water temperatures were found on the lake bottom. There was an obvious temperature decrease with depth, especially in the bottom sediment (Figure A2-1). The decrease in the temperature corresponded to an increase in the conductivity.

On the west-east transect (Figure 2-1) there were three main spots with 0.5–2°C lower temperature than the surroundings (Figure A2-2). These were at both shores and in the middle of the transect.

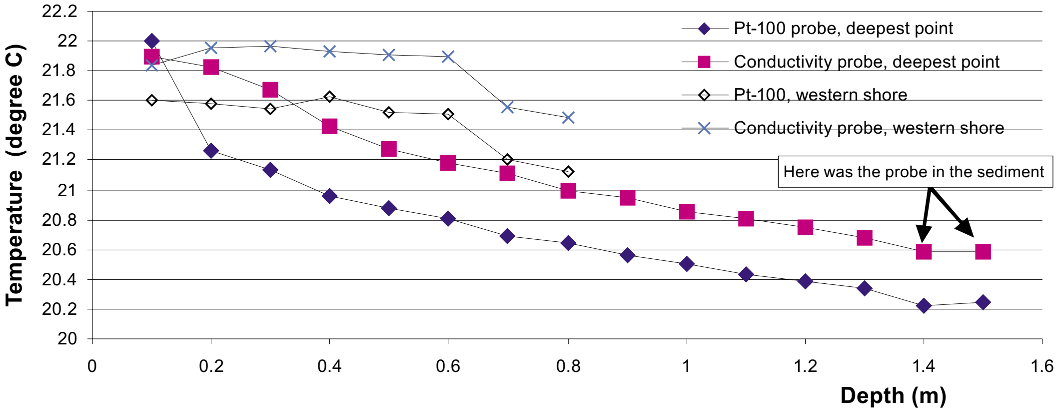

Figure A2-1. *Temperature decrease with depth at the deepest point and a point on the western shore (less deep) at Lake Hällefjärd, August 2, 2000. Two temperature probes were used, the fast reacting Pt-100 and a slower reacting combined conductivity and temperature probe.*

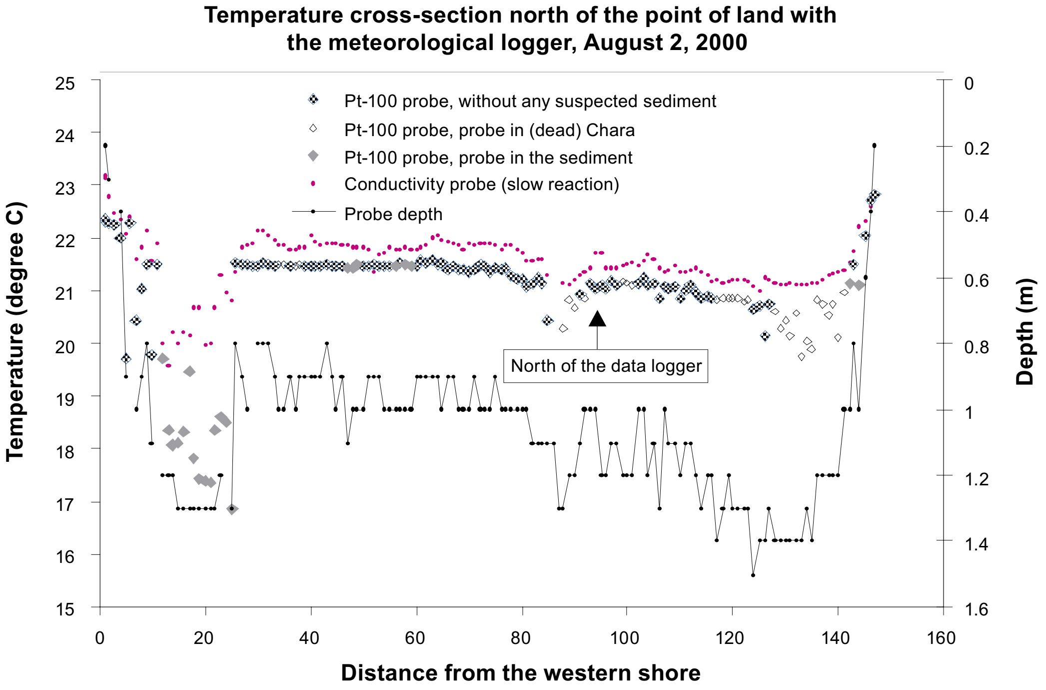

Figure A2-2. *Lake bottom temperature, west-east cross-section at Lake Hällefjärd, August 2, 2000. Two different probes were used, the Pt-100 (squares) with a fast time constant and a conductivity and temperature probe with a slow time constant (dots). The intention was to hold the probes just above the sediment, but this was not always possible. Thus the Pt-100 squares have different colours as an indication of whether the temperature is lower because the probes were in the bottom sediment. When the probes were in (dead) Chara, it was impossible to see if the probes were also in the sediment or not. The depth of the probes is indicated in the figure. The data logger mentioned is the one first installed, with e.g. precipitation measurements.*

At the transect around the lakeshore, a small decrease in the temperature occurred after about 80 m, which was somewhere in the northwestern corner of the lake. A very small conductivity increase could also be seen there. Some small irregularities in the temperature and in the conductivity occurred during the rest of the transect.

Discussion

All the three spots (adjacent to the shore and in the middle) that had slightly lower temperature were also somewhat deeper, which might have caused the temperature decrease. Groundwater inflow is however likely to occur close to the shore /e.g. Shaw and Prepas, 1990/ so the temperature decrease here can also really be an effect of groundwater inflow. The measurements on the eastern shore are more reliable than those on the western shore, where the measurements started and where it took a while along the transect to identify the best way to hold the probes just above the bottom. The water temperature also seemed to be lower when the probe was in dead *Chara*. It might then have touched the bottom, but that was impossible to see through the dense *Chara*. The temperature difference can however be caused by an inflow of groundwater.

The small temperature differences indicate that if there is a groundwater inflow to the lake, it is probably spread out in the sediment and is not flushing in through any macropores in the sediment. A new measurement is suggested to clarify if any persistent patterns of inflow exist.