THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Groundwater Chemistry affected by Underground Construction Activities

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ABSTRACT

A leaking underground construction increases the groundwater recharge and decreases the residence time of the groundwater. If groundwater of a certain chemical composition dominated the location inside the bedrock of a planned tunnel prior to the construction phase, this water is likely to be replaced by water of a different chemical type because of leakage of water into the tunnel during the construction and operational phases. The changes in hydrological and hydrochemical conditions may in turn result in changed chemical processes and interaction between the water and the bedrock/fracture minerals. The processes that may be altered include acid-base, redox and ion exchange processes.

This thesis presents experience from one field study, three case studies and numerous studies mentioned in the literature. The field study and the three case studies show that underground constructions are likely to cause changes in the water chemistry. The hydrochemical changes have largely been seen to be dependent on geological conditions.

Common changes in water chemistry often include acidification and decreased alkalinity as a result of the oxidation of sulphide in wetlands or in fracture minerals that form sulphuric acid. This hydrochemical process has been seen to be triggered, thereby causing more aggressive hydrochemistry during the construction phase of for example the Hallandsåsen and Romeriksporten rail tunnels. Changes in the concentration of calcium and magnesium through cation exchange following acidification have been observed, primarily in the field experiment at Lake Gårdsjön.

Underground constructions often cause an increase in organic matter in the bedrock groundwater, which is measured as organic carbon. Decomposition of organic matter may lower the redox potential. Furthermore, the use of cementitious grout is likely to increase the pH near an underground facility. Changes in redox potential and pH are likely to have an impact on the redox state of iron and manganese. A more reducing environment may cause iron and

manganese to become dissolved while a rise in the pH may lead to precipitation. The precipitation of iron and manganese is the most common cause of clogging of the drainage system in underground facilities.

Underground constructions have been seen to cause changes in the chloride concentrations. These observed concentration changes include an increase through the upconing of brine waters or inflow of marine waters. However, a reduced chloride concentration through deeper penetration of shallow meteoric water has also been observed.

The hydrochemical changes may have implications for construction materials, such as steel bolts, waterproofing grout and shotcrete, as well as for drainage systems in the underground constructions. However, hydrochemical changes that may shorten the lifespan of the construction materials can be limited through grouting and thereby the hydrological impact of the construction activities in sensitive locations. There is a need to establish and implement models to predict the prevailing hydrochemical conditions in the construction and operational phase of a facility based on information from the pre-construction phase.

LIST OF PAPERS

This thesis includes the following papers, referred to by Roman numerals:

I. Mossmark, F., Hultberg, H., Ericsson, L. O., 2007. Effects on water chemistry of groundwater extraction from chrystalline hard rock in an acid forested catchment at Gårdsjön, Sweden. Applied Geochemistry (vol. 22, 1157-1156).

II. Mossmark, F., Hultberg, H., Ericsson, L. O., (2008). Recovery from an intensive groundwater extraction in a small catchment with crystalline bedrock and thin soil cover in Sweden. The Science of the Total Environment (vol. 404:1-3 (2008) 253-261).

Fredrik Mossmark wrote the entire text of the two articles under supervision. Lars O Ericsson and Hans Hultberg edited the text and gave advice to improve the articles.

ACKNOWLEDGMENTS

This thesis presents the results of work that has been carried out in three different projects over a period of eight years and more people than what is usual for a licentiate thesis have been involved in different phases of the work. I would like to thank Lars O. Ericsson and Malin Norin for their supervision and mentorship during the writing of this thesis. I thank Lars-Olof Dahlström and Gunnar Gustafson for their helpful comments and encouragement. I would like to thank Hans Hultberg for his supportive co-operation and inspiration to continue my research work. I would also like to thank Jan Sundberg and Elke Myrhede at Geo Innova/Vectura for their support and understanding. My thanks also to Otto Graffner and Siri Knape Hansén for getting me involved in the exciting Gårdsjön experiment.

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PAPERS I - II

1 INTRODUCTION

The interaction between underground constructions and water chemistry is complex and the resulting groundwater chemistry in the vicinity of a underground constructions may be influenced by many factors. A knowledge gap related to groundwater chemistry, underground construction and the practice in the construction industry was identified and the studies presented here were initiated to gain further knowledge.

After the conductance of a literature review, it was understood that several studies of the subject had previously been carried out. However, most of the previous studies had been done related to the planned storage of spent nuclear fuel and were not considering ordinary facilities. Furthermore, none of the studies were conducted with a holistic view of the systems and were not including all the aspects that influence the chemical composition of the groundwater and its importance for and interaction with underground constructions such as tunnels.

In nature, every location is unique and the hydrological, geological, geochemical, climate and biological conditions always differ resulting in a variety of hydrochemical conditions. Anthropogenic influence to water chemistry is also of importance, especially since many underground constructions are being built in urban areas. In order to predict and understand groundwater chemistry, it is therefore of importance to include the significant factors that have an impact on the chemical composition of the water.

The construction of an underground structure causes hydrological changes through leakage into the structure. The leakage is usually larger during the construction phase than during operational phase. The flow towards the structure may cause changes in the chemical composition of the water through bringing water with different origin towards the structure.

This thesis presents results from investigations carried out within the framework of a separate research project as well as from literature. The project has included a field study of the hydrological and hydrochemical impact from groundwater extraction as well as database studies of two tunnelling projects and one field experiment. The literature review has mainly included investigations carried out in Sweden and Norway, However, studies from Austria, Australia, Japan, U.S.A., Canada, China (Taiwan) and the Republic of Korea (South Korea) were also included. Databases for non-peer-review publications from authorities in primarily Sweden and Norway have also been browsed for information.

At the time of the conductance of this study, the professionals dealing with underground construction generally view the chemical properties of the groundwater as static. Swedish authorities for road and railroad administration currently use methods to establish if complementary protection for the construction material is needed based on chemical properties of water sampled prior to the construction phase of an underground structure. There is a general need for the development of methods to predict hydrochemical conditions in conjunction with underground constructions.

2 OBJECTIVES

The objective of the studies presented in this thesis is to highlight the dynamics of groundwater chemistry in relation to underground construction, in the context of geological and hydrogeological conditions.

The work is intended to create a foundation for further work with the objective of creating models for the prediction of the groundwater chemical properties during the construction and operational phases of an underground structure based on information collected in the pre-construction phase. One further objective is to study the relation between hydrochemical conditions and the durability of the construction materials used in underground construction and the potential clogging/occlusion of drainage channels.

Conceptual models that connect geological conditions to hydrochemistry will be presented as a foundation for further studies. The potential use of these models to limit the impact to hydrochemistry from underground constructions will be discussed as well as the implications to the durability and lifespan of underground construction materials.

3 SCOPE OF WORK

This thesis presents a literature review and four in-depth studies concerning the impact on water chemistry of underground construction activities. The in-depth studies included one comprehensive field investigation of groundwater extraction from boreholes in crystalline rock, data from two underground facilities and one field experiment. The site for the field investigation was at Lake Gårdsjön on the west coast of Sweden. The other in-depth study included the Hallandsås rail tunnel in southern Sweden, the Äspö Hard Rock Laboratory and a field experiment conducted in the northern part of the island of Äspö.

Conceptual models describing the hydrochemical properties based on geological and hydrological conditions have been established. Three of common geological conditions in what are primarily formerly glaciated areas are presented and the resulting hydrochemical conditions are discussed.

3.1 In-depth studies

Four in-depth studies related to underground construction were evaluated and are presented as case studies. Within the work for the licentiate degree, a field investigation of one of the in-depth studies (Lake Gårdsjön) was carried out. The remaining three in-depth studies were carried out as desk studies, including comprehensive database studies.

3.1.1 Lake Gårdsjön

The field studies at Lake Gårdsjön included groundwater extraction that was carried out in a small watershed in Western Sweden over four and a half years. Run-off volumes, groundwater levels, extracted volumes, and water chemistry were monitored. The area was monitored for three years prior to the start of groundwater extraction. Following extraction, the recovery was monitored for three years.

The data collected from the experiment has been evaluated with the aim of understanding the impact of groundwater extraction and underground construction. Hydrological modelling has been carried out. Results from the field study at Lake Gårdsjön are presented primarily in Papers I and II.

3.1.2 The Hallandsås rail tunnels

The construction of the Hallandsås rail tunnels started in 1992 and they are due to be completed in 2015. Two 8.6 km-long tunnels are being constructed through a horst that consists primarily of Precambrian igneous and metamorphic rock types. The Hallandsåsen mountain comprise granitic gneiss that has been exposed to tectonic forces, dolerite intrusions and superficial weathering (Annertz, in prep.). The mountain includes fracture zones that have been shown to make the construction of the tunnels more difficult than what was expected at the initiation of the construction phase. The completion date has been postponed on several occasions. Hydrochemical data from groundwater, leaking water in the tunnel as well as surface water have been linked to information about construction progress to assess the impact on water quality.

3.1.3 The Äspö Hard Rock Laboratory

The laboratory was built in the early 1990s as a rehearsal for the future construction of a repository for spent nuclear fuel. In the pre-construction, construction and operational phases of this facility the groundwater chemistry was monitored closely. A large number of publications have been published regarding the hydrochemical impact on the groundwater of the bedrock from the facilities. In this thesis, a limited evaluation of published data was made with a focus on parameters important to construction materials.

3.1.4 Groundwater extraction in the northern part of the island of Äspö

In the northern part of the island of Äspö an experiment with groundwater extraction from boreholes in the bedrock was carried over two years from 1999 to 2001. Similar to the Lake Gårdsjön experiment, monitoring of groundwater chemistry, groundwater levels and run-off volumes was conducted prior to the start of the extraction and during extraction. However, in contrast to the experiment at Lake Gårdsjön, the recovery period was not monitored. In this thesis, a database study of previously presented hydrological (Graffner, 2005) and hydrochemical data (Knape Hansén, 2002) has been carried out.

3.2 Forecasting water chemistry through conceptualisation

Simple methodology to forecast the chemical composition of the groundwater that will prevail during the construction and operational phases of an underground structure based on information collected in the pre-construction phase will be presented in this thesis. Conceptual models that describe typical geological conditions in a recently glaciated area (such as Scandinavia and the northern parts of North America) are presented with an emphasis on historical events, such as previous marine and lacustrine transgressions.

The methodology should be seen as a discussion contribution and the conceptual models will be used as a simplification. The forecasting models will need future improvements to offer more reliable information that can be used more readily as a decision basis in conjunction with the design of underground structures.

3.3 Limitations

The case studies mainly refer to projects carried out in crystalline bedrock, projects that have been carried out in sedimentary rock is briefly discussed in the literature review chapter. There are a large number of hydrochemical parameters that may be affected by underground construction and in turn may affect the performance of construction materials. In the work presented in this thesis, the analyses have been limited to the following parameters: pH, alkalinity, sodium, chloride, sulphate, potassium, magnesium, calcium, iron, manganese and oxygen. The scope of work focuses on underground constructions built for civil infrastructure located mainly in rural areas and excludes the presentation and evaluation of data from mining and urban locations. This thesis emphasizes on the impact from hydrochemical conditions to underground constructions and does not cover all relevant health related perspectives concerning the use of groundwater resources for potable water.

4 BACKGROUND TO HYDROLOGY, GROUNDWATER AND WATER CHEMISTRY

4.1 The hydrological cycle

The hydrological cycle describes how water transforms from one type to another, see Figure 4-1. Water evaporates from the oceans (where it leaves the salinity behind), lakes and land surfaces to the atmosphere. Biota contributes to the atmosphere through transpiration. From the atmosphere, the water is redeposited to the earth mainly as rain or snow. Some of the water that is deposited stays in the so called interception storage in the vegetation before it is often directly evaporated back to the atmosphere. Most of the water that is deposited reaches the ground, the water that falls as snow is kept in snow storage awaiting melting. The water that reaches the ground as fluid is either absorbed by the vegetation, runs off as surface water or infiltrates to groundwater. The water that was absorbed by the vegetation can be transpired back to the atmosphere. The surface water is transported to larger streams and lakes before it reaches the ocean (or less likely, is evaporated on the way to the ocean). Only a small fraction of the deposited water infiltrates to become groundwater.

The water budget for a watershed can be summarized as:

$$P - E = RS + RG \pm \Delta M$$

Where

P = Precipitation
E = Evapotranspiration
RS = Surface runoff
RG = Groundwater baseflow
ΔM = Changes to storage

For long observational periods, the changes to storage (ΔM) can be neglected. Figure 4-1 describes the water budget with somewhat more detail than in the equation. The storage term included in the equation combine the storage of surface water, groundwater, soil water, storage on land surface as well as interception storage in biota.

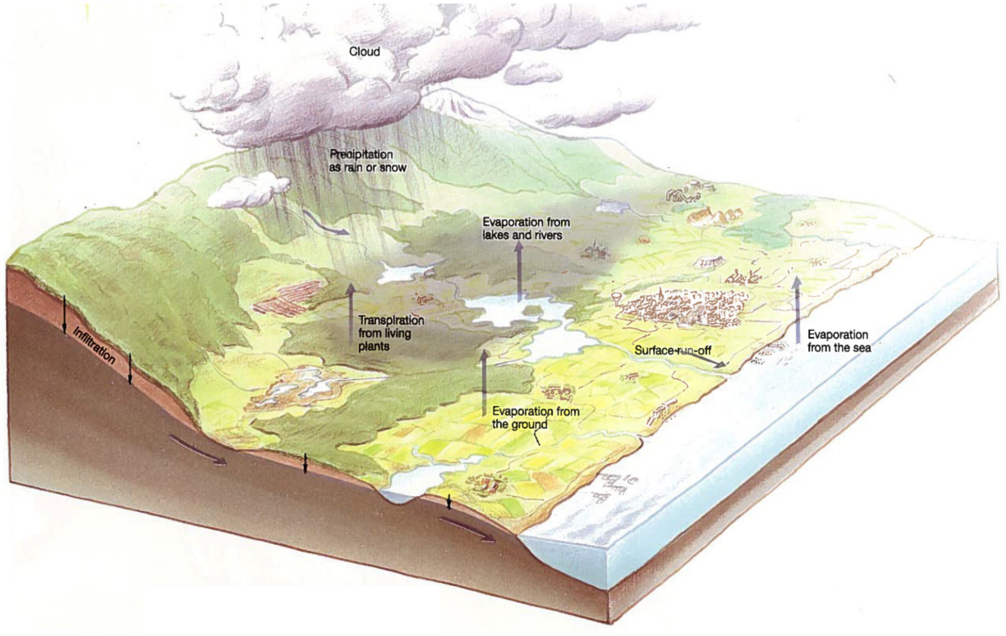


Figure 4-1. The hydrological cycle presented schematically. Drawing by Hans Sjögren, from the National Atlas of Sweden/Geology (1994).

4.2 Hydrochemistry under unaffected conditions in crystalline rock

The hydrochemical conditions in deeply located groundwater (more than 20-30 m) are often stable due to long turnover times. The hydrochemical properties of bedrock groundwater derive from the minerals found in bedrock that can react with the groundwater and also from processes to which the water is exposed during earlier transport – percolation through the soil layer for example. Deeply located bedrock groundwater is often characterised by high ionic strength as it has been in contact over a long period with the different minerals that make up the bedrock. The pH value and buffer capacity of the groundwater are affected by processes involving the available minerals and organic material. Figure 4-2 describes common changes to water chemistry as the water flows from a recharge to a discharge area. This introductory chapter deals with the following processes:

- Acid-base processes
- Ion exchange processes
- Redox-related processes
- Microbial processes
- Weathering processes

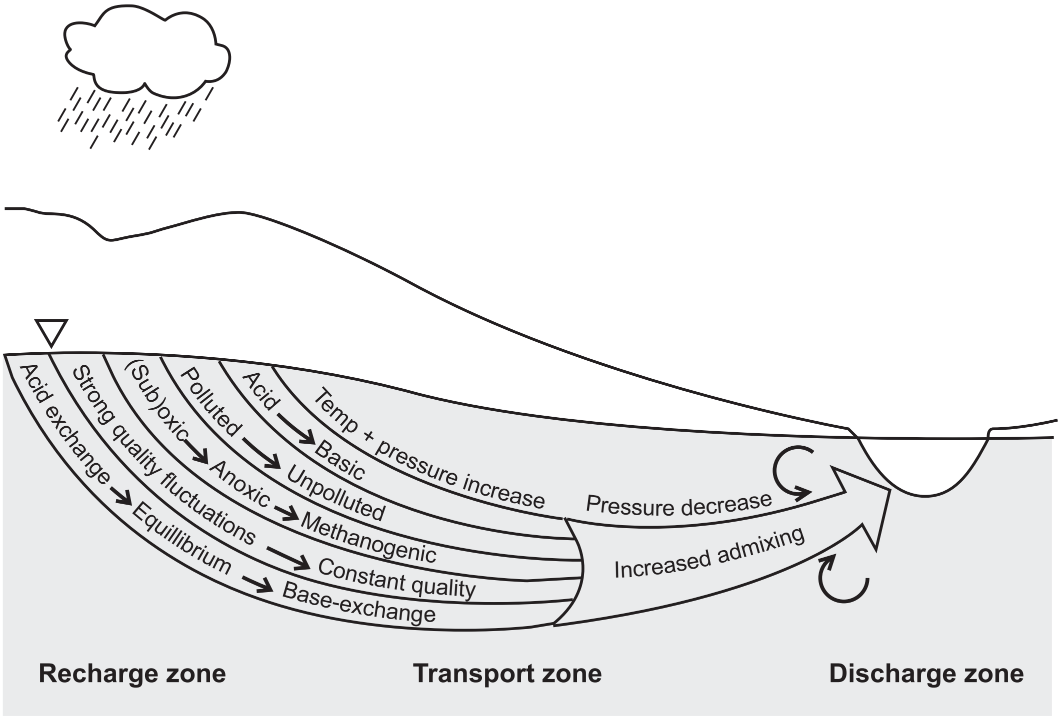


Figure 4-2. *Changes to hydrochemistry as the water flows from a recharge area to a discharge area, modified after Knape (2001).*

4.2.1 Acid-base

The carbonate system is one of the acid-base systems that give natural water its character. Other acid-base systems involve sulphide, phosphate and silicic acid. Each system comprises two or three compounds that can release or take up free hydrogen ions. The different compounds in each system have equilibrium conditions related to the pH. At a certain pH only two of the possible compounds in an acid-base system occur. These are known as acid-base pairs, where one compound can release a free hydrogen atom (acid) and the other can take up a hydrogen atom or another cation (base). Acid-base systems act as a buffer system against acidification in the fact that the base can neutralise with the addition of hydrogen ions (acidification) (Deutsch, 1997). It should be noted that the balanced reactions are temperature- and pressure-dependent. The atmospheric partial pressure of carbon dioxide has an effect on the carbonate system (Mattheß, 1994).

Reversible reactions of the carbonate system (Drever, 1988):

$H_2CO_3 <=> HCO_3^- + H^+$ *Formula 4-1*

$HCO_3^- <=> CO_3^{2-} + H^+$

At a pH of 6.4 the concentration of HCO_3^- and H_2CO_3 will be the same whilst the concentration of CO_3^{2-} is negligible. On the other hand, at a pH of 10.33 the concentrations of HCO_3^- and CO_3^{2-} are the same whilst the concentration of H_2CO_3 is negligible. HCO_3^- and CO_3^{2-} are bases that counteract acidification. Total alkalinity is the sum of the bases that can be titrated using a strong acid, e.g. hydrochloric acid.

The most common geological source/sink of carbonate is calcium carbonate or calcite. Formula 4-2 describes the chemical reaction where calcium carbonate is either dissolved or precipitated. When water that contains calcium carbonate reaches a surface, the carbonate acid is released as a gas to the air and calcium carbonate is precipitated.

$CaCO_3 + H_2O + CO_2 <=> Ca^{2+} + 2HCO_3^-$ *Formula 4-2*

The bases in the carbonate system make up the majority of these bases in natural water. Other base pairs for phosphate, sulphide and silica are given in Formula 4-3 (Drever, 1988).

$HPO_4^{-2} + H^+ = H_2PO_4^-$ *Formula 4-3*

$PO_4^{-3} + 2H^+ = H_2PO_4^-$

$SiO(OH)_3^- + H^+ = Si(OH)_4$

$H_2S = HS^- + H^+$

4.2.2 Ion exchange processes

Ion exchange processes are a type of adsorption/desorption on surfaces that are negatively or positively charged. In geological material, ion exchange takes place mainly on clay minerals but also on organic material such as humus. As clay mineral often has a negative charge in its surface layer structure, it is mainly adsorption/desorption of positively charged ions, cations, that takes place. At a low pH the surfaces available on clay minerals and humus are used for ion exchange, mainly hydrogen ions. At a higher pH, and thus with lower concentrations of free hydrogen ions, the available surfaces for ion exchange are used to a greater extent by the base cations in water, such as magnesium and calcium (Deutsch, 1997).

4.2.3 Redox-related processes

Oxidation and reduction involve an element's take-up or release of valence electrons. Oxidation or reduction can, but not necessarily, mean both take-up and release of oxygen atoms. The solubility of many elements in groundwater and surface water depends on the redox conditions and the prevailing pH. For some elements, such as arsenic and chromium, the toxicity depends on the redox species. Cr(VI) is more toxic than Cr(III) and As(III) is more toxic than As(V) (Deutsch, 1997). The different redox species, for arsenic for example, are regarded as the redox pairs which through take-up and release of electrons create equilibrium. Often, however, redox reactions occur with the involvement of more than one redox pair. To illustrate in which redox species the substance occurs under different redox and pH conditions, an Eh-pH graph is drawn (Deutsch, 1997). An example of such a graph, for iron, is shown in Figure 4-3.

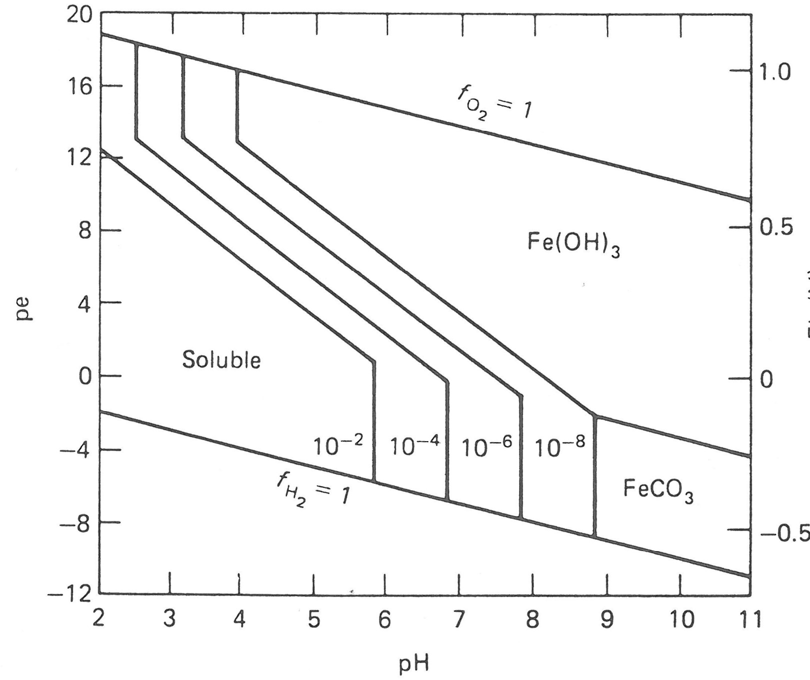


Figure 4-3. Iron species and contours of dissolved iron activity under different redox (Eh) and pH conditions, $PCO_s=10^{-2}$ and no dissolved sulphur present (Drever, 1988).

A reducing chemical environment can be created through oxygen-consuming processes, such as the degradation of organic material such as humus. An oxidising chemical environment can be created through dissolved oxygen being transported in water e.g. during periods of major groundwater build-up (Deutsch, 1997). Which iron species dominates at a certain redox potential is largely dependent on the pH, where a change in pH can result in iron either dissolving or falling out (Figure 4-3). As with the balances in the acid-base reactions, redox potential is temperature-dependent (Mattheß, 1994).

According to Drever (1988) all surface waters contain organic compounds. Processes that affect the redox conditions occur during degradation of the organic compounds. If oxygen is available in the water, it may be consumed in a reverse photosynthesis during the degradation process. The consumption of oxygen may cause anaerobic conditions and result in a decrease of the redox potential. The amount of organic compounds are usually measured as dissolved organic carbon (DOC). The organic matter is considered as dissolved if it passes through a 0.45 µm filter, if the same analysis are carried out on an unfiltered it measures the content of total organic carbon (TOC).

4.2.4 Microbial processes

Microorganisms in groundwater have been noted in deep-lying crystalline rock, up to depths in excess of 1,000 m (Pedersen, 2000). The primary chemical effect of groundwater is in the form of changes in redox conditions (Pedersen, personal communication). There is a large variety of species of microorganisms in groundwater and mapping takes place on a continuous basis (Pedersen, 2000). It has been noted that microorganisms can both reduce and oxidise sulphur, iron and manganese in groundwater. Figure 4-4 shows how iron-oxidising bacteria form a reddish brown mass in the surface water. It has been noted that sulphur-oxidising bacteria could oxidise sulphide to sulphate in groundwater where pyrite (FeS_2) is present (Botrell et al., 2000).

Figure 4-4. Iron oxidising bacteria at Äspö HRL (Photo: SKB).

4.2.5 Weathering processes

As stated previously, chemical and mechanical weathering of mineral soils and rock has a significant effect on the chemical composition of the groundwater. Even if it is the chemical weathering that has a direct impact on the water chemistry, there is often an interaction between mechanical and chemical weathering (see, for example, Tarbuck and Lutgens, 1999). Several of the stated chemical processes contribute to chemical weathering. According to Mattheß (1994) it is mainly ion exchange processes, hydrolysis, redox processes and dissolution in water, that interact in the chemical weathering. Increased access to organic and inorganic acids results in increased weathering.

According to Mather (1997) and Knape (2001), it is primarily the following reactions that contribute to the volume of dissolved ions and consequently the chemical weathering in the saturated groundwater zone:

Dissolution of carbonates and silicates through hydrolysis:

$$\text{Carbonate minerals} + \text{Hydrogen ions} = \text{Cations} + \text{Hydrogen Carbonate}$$

Silicate minerals + Hydrogen ions = Cations + Silicic acid ($H_2SiO_3^-$)

Aluminium silicate minerals (e.g. caolin) + Hydrogen ions = Cations + Silicic acid ($H_2SiO_3^-$) + Secondary minerals (e.g. clay mineral)

Soluble salts in the groundwater e.g.
Gypsum, halite, anhydrite etc.

Redox reactions e.g.

Fe_2O_3 (s) + $6H^+ + 2e^- = 2Fe^{2+} + 3H_2O$
MnO_2 (s) + $4H^+ + 2e^- = Mn^{2+} + H_20$

Cation exchange takes place mainly in conjunction with changes in pH. When the pH falls, bound calcium, magnesium and potassium ions, for example, are replaced by the binding of free hydrogen ions instead and the base cations are dissolved. If the pH rises again and the concentration of free hydrogen ions falls, there is once again scope for the base cations to be bound to the minerals or the construction material. Sometimes, however, the dissolved cations have been removed by the groundwater.

4.3 Hydrochemical character of bedrock groundwater

The chemical character of bedrock groundwater in Scandinavia is described in quite a large number of publications, including Eriksson (1970), Aastrup et al. (1995), the Swedish Environmental Protection Agency (1999), Knape (2001), Eklund (2002) and Frengstad (2002). Aastrup et al. (1995) describe how the composition of the groundwater varies in different parts of Sweden.

Eklund (2002) studied how the chemical composition of groundwater differed between nine typical defined hydrogeological environments. The typical environments included defined environments in rock and soil. The wells that form part of the study were affected to a limited extent by human activity. One typical environment was defined for sedimentary rock whilst there are two different typical environments defined for crystalline rock: one for crystalline rock located above the highest coastline after the most recent glacial period (Weichsel) and one for rock located below the highest coastline. The evaluation of hydrochemical data for groundwater for these three typical groundwater environments was based on 1,181 analyses of crystalline rock below the highest coastline, 112 analyses for crystalline rock above the highest coastline, and 245 analyses from sedimentary rock (Eklund, 2002). Chemical data characterising the different environments are for the counties of Södermanland and Östergötland. Typical geological conditions below and above the highest coastline are shown in Figure 4-5.

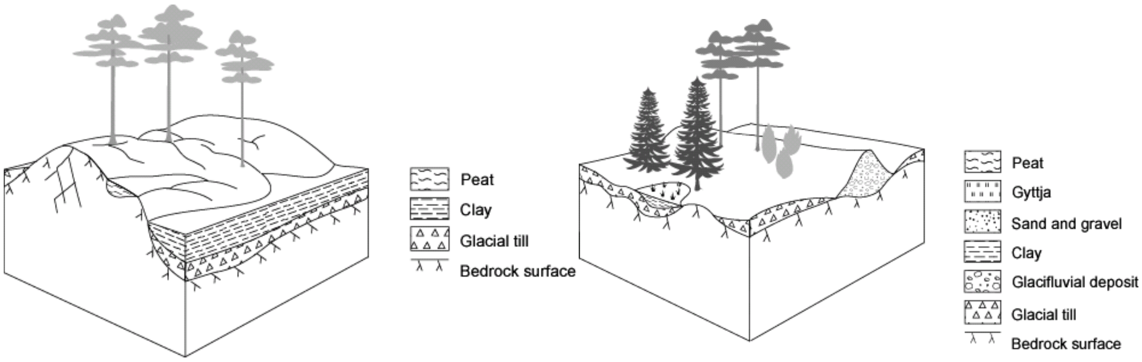


Figure 4-5. Typical geological cross-sections with crystalline bedrock below (left) and above (right) the highest coastline following the most recent glacial period (Eklund, 2002).

Figure 4-6 shows how pH, alkalinity and sulphate vary geographically in bedrock groundwater in Sweden. High sulphate concentrations in the bedrock groundwater are often linked to the existence of rocks containing sulphur, such as pyrite, and thus occur in areas with ore deposits (Aastrup et al., 1995). In areas in Sweden with sedimentary bedrock, it is mainly alum shale that contributes to the high sulphate content in the groundwater. Gypsum is also a source of high sulphate concentrations although it occurs to quite a limited extent in Sweden. According to Eklund (2002) high sulphate concentrations are to be found in crystalline rock and are higher in sedimentary rock compared with crystalline rock that has not been subject to marine transgressions. The groundwater below the highest coastline was probably affected by marine sulphur from sea water.

Highly alkaline bedrock groundwater in Sweden occurs mainly in areas where the bedrock contains lime, such as the limestone areas in Skåne, on the islands of Öland and Gotland, in Jämtland, around Lake Siljan in Dalarna and in the sedimentary bedrock in Västergötland (Figure 4-6). Soils containing lime have been formed from limestone, mainly as a result of glacial erosion, which was then transported into the surroundings. These have also contributed to the alkalinity in bedrock groundwater in areas where the bedrock is lime-deficient. In Uppland and Mälardalen there are lime-rich soils that have been transported from limestone in what is now the Gulf of Bothnia, contributing to the alkalinity and the relatively high pH, see Figure 4-6 (Aastrup et al., 1995). According to Gustafson et al. (2009), the bedrock groundwater in highland areas in southern Sweden that have not been exposed to transgressions following the most recent, Weichselian, glaciation has generally low alkalinity.

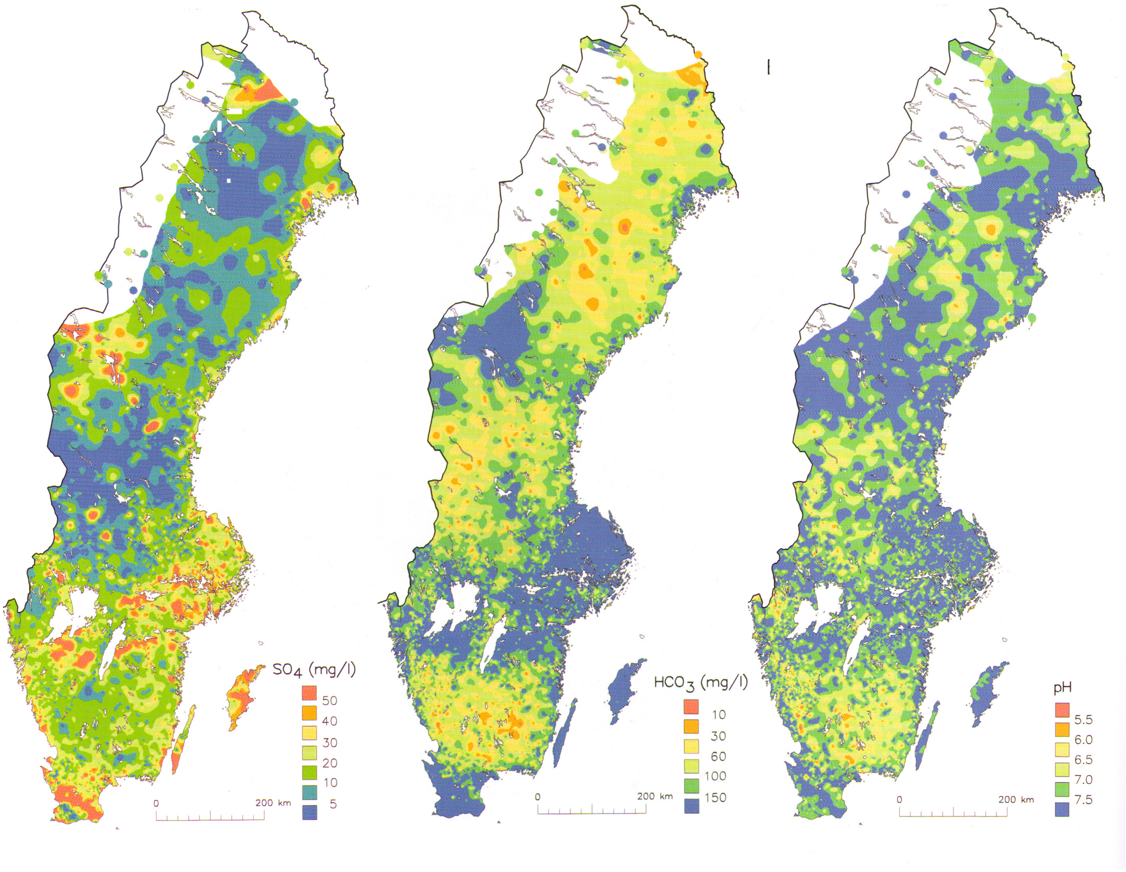


Figure 4-6. Sulphate, alkalinity and pH in the bedrock groundwater in Sweden (Aastrup et al., 1995).

According to the Swedish Environmental Protection Agency (1999) the highest chloride levels for bedrock groundwater in crystalline rock are to be found below the highest coastline. This is confirmed by the collation of chloride concentration carried out for *the National Atlas of Sweden*, *Geology* (the National Atlas of Sweden, 1994). According to Figure 4-7, the highest chloride concentrations are to be found in rock in low-lying parts of Sweden – areas that were consequently below the highest coastline following the more recent glacial period. According to Eklund (2002), 25% of the wells in crystalline rock below the highest coastline have chloride concentrations in excess of 40 mg/L. In a typical sedimentary rock environment there are chloride concentrations similar to those found in crystalline rock below the highest coastline. Account should be taken, however, of the fact that all sedimentary bedrock included in the survey is located below the highest coastline. For the 25% of the wells in crystalline rock above the highest coastline that had the highest chloride content, the level was only just over 15 mg/L, which is considerably lower than for the rock wells below the highest coastline.

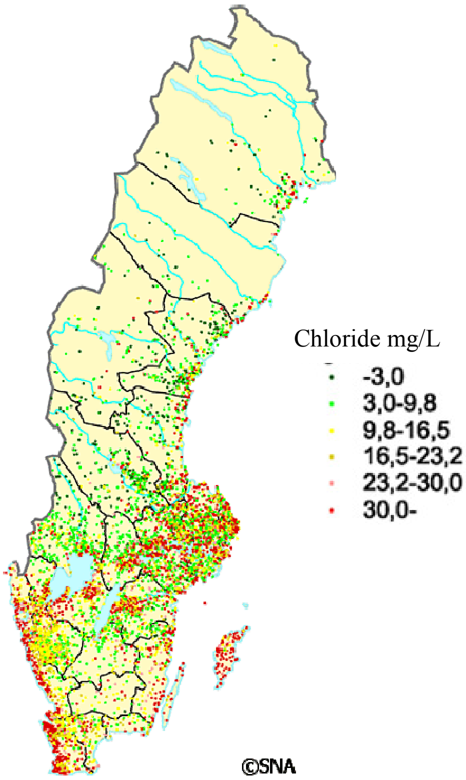


Figure 4-7. *Chloride concentration in rock wells in Sweden (the National Atlas of Sweden, Geology (1994)).*

5 BACKGROUND TO UNDERGROUND CONSTRUCTION

5.1 Different underground facilities

There are underground facilities for a large number of purposes although the construction techniques used to reinforce and counteract hydraulic contact between a facility and bedrock groundwater are often similar. The types of construction presented in this chapter can therefore be regarded as being of a general nature. The following are a number of common underground constructions:

- Road and rail tunnels.
- Hydroelectric power tunnels.
- Fresh water and sewer tunnels.
- Tunnels for other infrastructure installations, such as electricity, telecommunications, mining, oil and gas lines.
- Caverns for storage of oil and gas.
- Emergency shelters.

5.2 Designs used in conjunction with underground construction

The supporting system in tunnels comprises a construction designed to minimise leakage of water into the tunnel and to secure the tunnel to prevent rock fall or collapse. Deciding which parts of the construction are chosen to achieve the stipulated requirements for safety and impact on the surroundings depends on the geological conditions. The conditions often vary along the tunnel and consequently the construction of the tunnel can differ from one part to another (Vegvesen, 2006).

In normally fissured hard rock, stability problems are mainly due to rock wedges falling from the roof or sliding out from the side of the tunnel (Lindblom, 2001). The rock is reinforced with bolts or injection cement to prevent collapse. When excavating tunnels using a traditional drill or blast method, an examination at the tunnel front is often carried out to acquire information about the rock quality in the next section. The information obtained is used to decide what form reinforcement and water sealing will take in the next section of the tunnel (Vegvesen, 2006).

5.2.1 Reinforcement bolts

For reinforcement, three main types of bolt are used: fully grouted rockbolt, pre-tensioned rock bolts and split set bolts (Lindblom, 2001). The grouted bolts are not normally pretensioned and are generally fully grouted. When fitting grouted bolts, a cement grout is forced into a pre-drilled hole after which the bolt is inserted, see Figure 5-1 a. This method can be automated and is effective. An alternative to fully grouted bolts used previously is the split set-method, which uses two halves of a pipe filled with cement paste. The bolt is placed between the two halves of the pipe, see Figure 5-1 b. The split set method cannot be automated and is used primarily when a small number of bolts are to be fitted. Pre-tensioned, end-secured bolts are used to achieve immediate bearing capacity. The final bearing capacity is often low if the bolts are not subsequently grouted in cement paste.

A common end-secured, pre-tensioned bolt is the expansion bolt, see Figure 5-1c. Friction bolts combine the function of the grouted bolts and the pre-tension bolts with strength and good ultimate bearing capacity. A common type of friction bolt is the Swell-friction rockbolt (see Figure 5-1 d) which comprises a steel pipe that is inserted into the borehole that is to be reinforced. The pipe is then pressed against the wall of the borehole by means of water under high pressure (Lindblom, 2001).

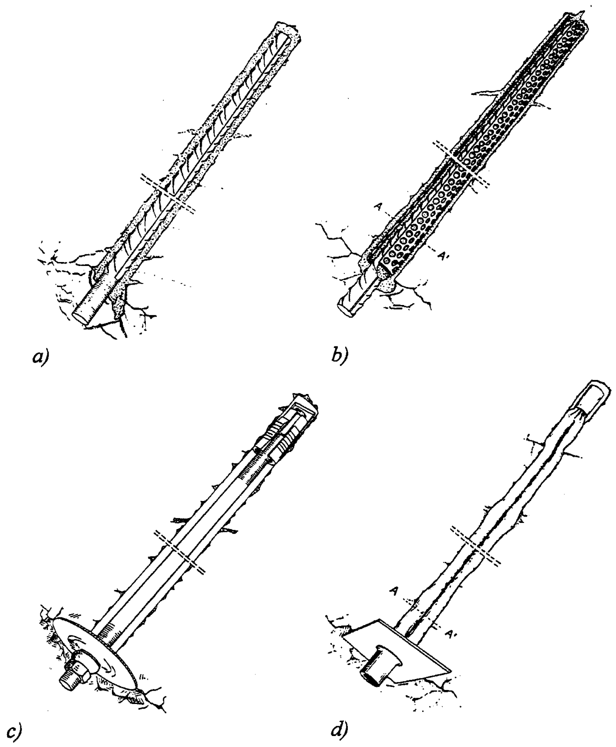


Figure 5-1. *Common types of bolt for rock reinforcement: a) Fully grouted rockbolt b) Split set rockbolt c) Expansion bolt d) Swell-friction rockbolt (Lindblom, 2001).*

When constructing tunnels in rock of poorer quality, pre-bolting is sometimes carried out before a section of tunnel is blasted (Holmøy and Aagard, 2002). In conjunction with pre-bolting, bolts are fitted at an angle forwards from the front of the tunnel to prevent roof fall during blasting or when transporting material from the tunnel. The bolts that are used for pre-bolting are in completed tunnels temporary and are subsequently replaced with other, permanent reinforcements although a method where the bolts are made permanent in conjunction with pre-bolting is considered. In the completed tunnels the bolts have not been protected against corrosion, which is necessary if the bolts are to be used as permanent reinforcement (Holmøy and Aagard, 2002).

5.2.2 Shotcrete

Shotcrete is used to reinforce tunnels. Often shotcrete is used together with bolting to achieve the desired stability in the tunnels in normally fissured crystalline rock. Both reinforced and non-reinforced shotcrete is used. For reinforcement, either normal reinforcement with steel fibres or reinforcement steel is used. Steel fibre reinforcement means that steel threads, approximately 20-30 mm long, with a diameter of 0.5 mm, are added to the cement before it is shot (Lindblom, 2001).

5.2.3 Cement lining

For tunnel sections through low-strength rock, cement lining can be used as permanent reinforcement (Vegvesen, 2006; Lindblom, 2001). The lining is carried out at the tunnel front and shuttering is used as necessary. Cement lining can be made both reinforced and non-reinforced depending on the reinforcement requirement (Vegvesen, 2006). Mobile moulds are used for continuous cement lining in longer tunnel sections (Lindblom, 2001).

5.2.4 Grouting

In Sweden, pre-grouting is used as a rule for sealing tunnels with supplementary post-grouting as necessary (Vägverket, 2000). Pre-grouting is carried out by drill holes in the tunnel front as a fan after which the boreholes are grouted (Lindblom, 2001). The advantage of pre-grouting compared with post-grouting is that it can be carried out under high pressure (Vägverket, 2000).

Figure 5-2 shows a sketch for pre-grouting. In the case of road tunnels in Norway, only pre-grouting is used as there is a risk of damage to the tunnel or other problems caused by water leaking into the tunnel or if there are regulations stipulating maximum leakage volumes (Vegvesen, 2006).

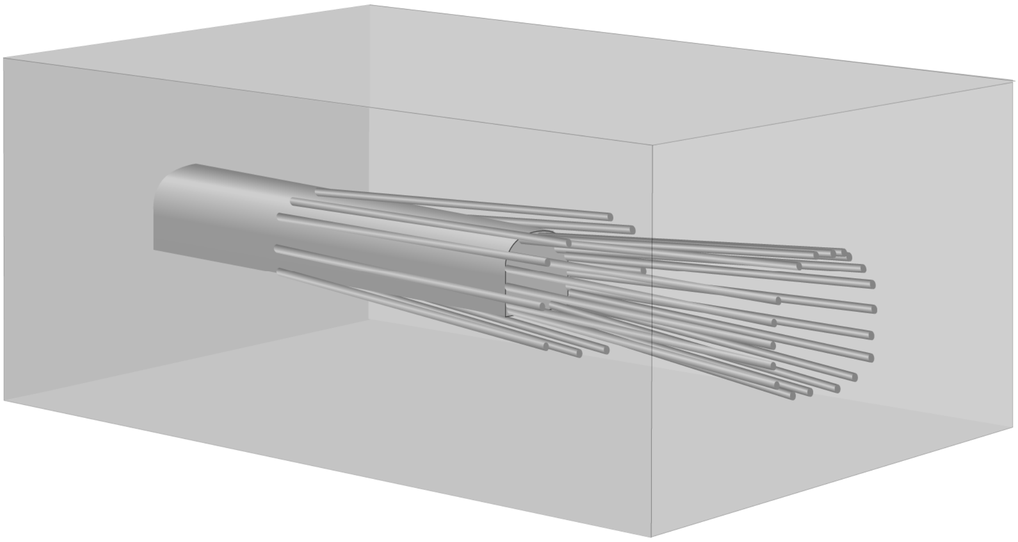


Figure 5-2. Pre-grouting sketch; the left-hand part of the figure shows the tunnel front with a grouting fan.

For grouting, a cement-based grout is commonly used although different types of grout are being developed. The most commonly used so called chemical grout is the water-soluble silica sol, sodium silicate (a silicate-based material and a cement accelerator) and the non-water-soluble substance polyurethane (Lindblom, 2001).

5.2.5 Drainage system for leaking water

In infrastructural tunnels that are covered with shotcrete cement, wall drains are built to channel leaking water down to the drainage system under the pavement in the tunnel. The aim of the drains is to create a dry environment in the tunnel in a way that does not affect long-term durability. According to Vegvesen (2006) the final location of the drains is decided when tunnel construction has been completed and the points at which water is leaking are located. Figure 5-3 shows a modern wall drainage design. A wall drainage system comprises a channel created inside the shotcrete in a tunnel by placing a distance pipe between the tunnel wall and the shotcrete. Insulation is also placed between the shotcrete and the drainage channel to counteract frost erosion.

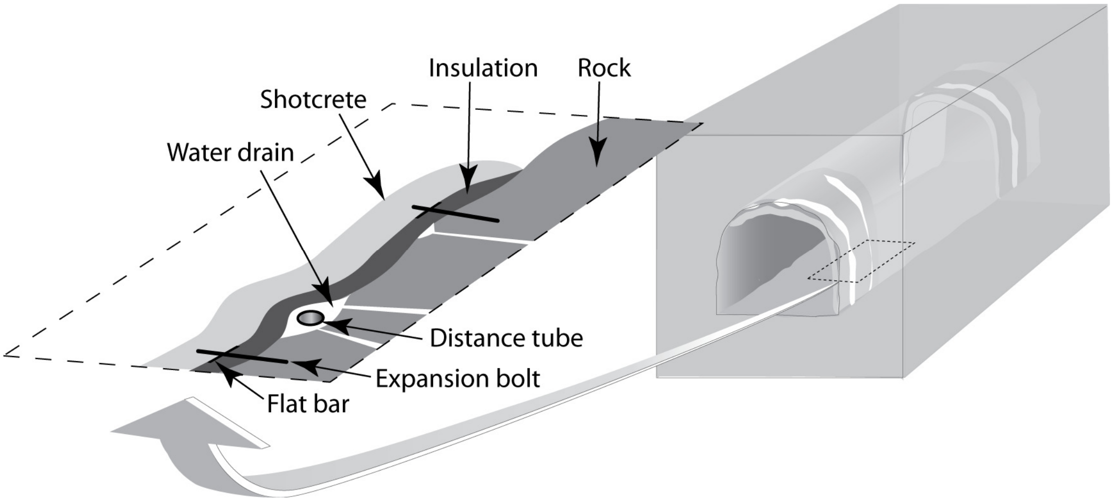


Figure 5-3. Water drain to deal with leaking water in a tunnel.

6 GROUNDWATER AND HYDROCHEMICAL INTERACTION WITH UNDERGROUND CONSTRUCTIONS

Underground constructions generally cause increased groundwater recharge, assuming that there are leakages. The increased groundwater recharge can for example cause new flow patterns for groundwater in rock. The flow can cause changes in hydrochemical properties of groundwater, also in the vicinity of the underground facility. This is partly caused by flow towards the underground facility of groundwater with a different composition than the original groundwater.

The groundwater of the bedrock usually has long residence times, from a few years to thousands of years (Knutsson and Morfeldt, 2002). The residence time from recharge to discharge can be drastically shortened from the influence of underground construction. In the late 1990's a 15 km-long railroad tunnel, Romeriksporten, was built in the vicinity of Oslo. A tracer test was carried out where a tracer was injected in shallow groundwaters above the tunnel. According to Pedersen (1997), a breakthrough of the tracer into the tunnel was observed after only six hours and a maximum concentration of the tracer was measured after 25 hours. The vertical distance from the surface to the tunnel was approximately 200 m. The test exemplifies how the construction of underground facilities can shorten the residence times of the groundwater of the bedrock.

A lowering of the groundwater level has been observed in numerous cases caused by the construction of tunnels. However, groundwater chemistry is not usually monitored during the construction phase of road tunnels in Sweden (Windelhed, pers. Comm.). According to Gustafson (2009), the drawdown of the groundwater level due to underground construction is dependent on boundary conditions and hydraulic conductivity. For fractured aquifers, the connectivity of the fractures is also of importance (Gustafson, 2009). The importance of the boundary conditions were also stressed in Olofsson (1991) noting that only a small drawdown is achieved when a fractured aquifer is connected to a large reservoir such as surface waters or an aquifer in a gravelly sediments.

Governmental authorities have established hydrochemical standards for underground construction as well as groundwater production wells. In Norway and Sweden, these guidelines are generically formulated and consider groundwater chemistry as static. According to the Norwegian road administration, *Vegdirektoratet,* complementary protection against corrosion of rockbolts is needed when building tunnels in the seawater zone of the groundwater. The guidelines for tunnel construction also stipulate the need for complimentary protection in corrosive environments. However, standard values for the chemical composition were not established (Vegvesen, 2006). The Swedish authorities for railway (Banverket) respectively road administration (Vägverket) have established guideline values for the requirement of complementary protection against corrosion. The guideline recommends complementary protection for construction materials of steel (e.g. rockbolts) if specified hydrochemical requirements for a number of parameters are not met (Vägverket, 2004; Banverket, 2005). The threshold values have been established for the following parameters:

- pH < 6.5
- Total hardness < 20 mg/L Ca
- Alkalinity < 1 mEq/L (equivalent to 61 mg/L HCO_3^- approximately)
- Electrical conductivity > 100 mS/m

The National Food Administration in Sweden has established guideline concentrations for the hydrochemical composition of groundwater to be used for potable water. The guideline values emphasize on health aspects of the water, but also includes aspects concerning the durability of water pipes and pumping systems (Livsmedelsverket, 2001). The aspects that are related to the durability of the system stipulate that the water may limit the durability of the system if:

- Iron > 0.1 mg/L
- Chloride > 100 mg/L
- Electrical conductivity > 100 mS/m
- Manganese > 0.05 mg/L
- Sodium > 100 mg/L
- Sulphate > 100 mg/L
- Alkalinity > 60 mg/L
- Calcium 20 – 60 mg/L

According to the Swedish National Road Administration (1999) sulphate-resistant cement is used for grouting if the sulphate-sulphur concentration in the groundwater exceeds 200 mg/L. The Swedish Standards Institute has established a standard for construction materials that take water chemistry into consideration (SS-EN 206-1, 2001). The standard describes the need for more durable composition in hydrochemical environments with high sulphate concentrations.

6.1 Impact from underground constructions on surface waters and groundwater in the overburden

A drawdown of the groundwater levels and the drying up of streams have been observed as the consequence of underground construction. During the constructional phase of the Romeriksporten railroad tunnel outside of Oslo, the water level of a nearby lake decreased by more than 5 m as displayed in Figure 6-1 (Brettum och Løvik, 2005). The drawdown caused chemical oxidation following the previously anaerobe conditions and sulphate was became oxidized to form sulphuric acid. In the deepest parts of the affected lake, sulphate concentrations increased to almost 400 mg/L during the year of 1998.

During the period of acidification, pH decreased to a minimum value of 3.3 (Figure 6-2). The Southern Puttjern Lake was monitored and constituted a reference to the affected Northern Puttjern. During the pre-construction phase of the Romeriksporten railroad tunnel, the two lakes had similar hydrochemical composition. Figure 6-2 reveals the sulphate concentrations and pH in water samples collected in the two lakes. For the Lake Southern Puttjern, the chemical composition was unchanged. During the year of 1998 Lake Southern Puttjern had neutral pH (ca 7.0) and sulphate concentrations below 10 mg/L (Brettum och Løvik, 2005).

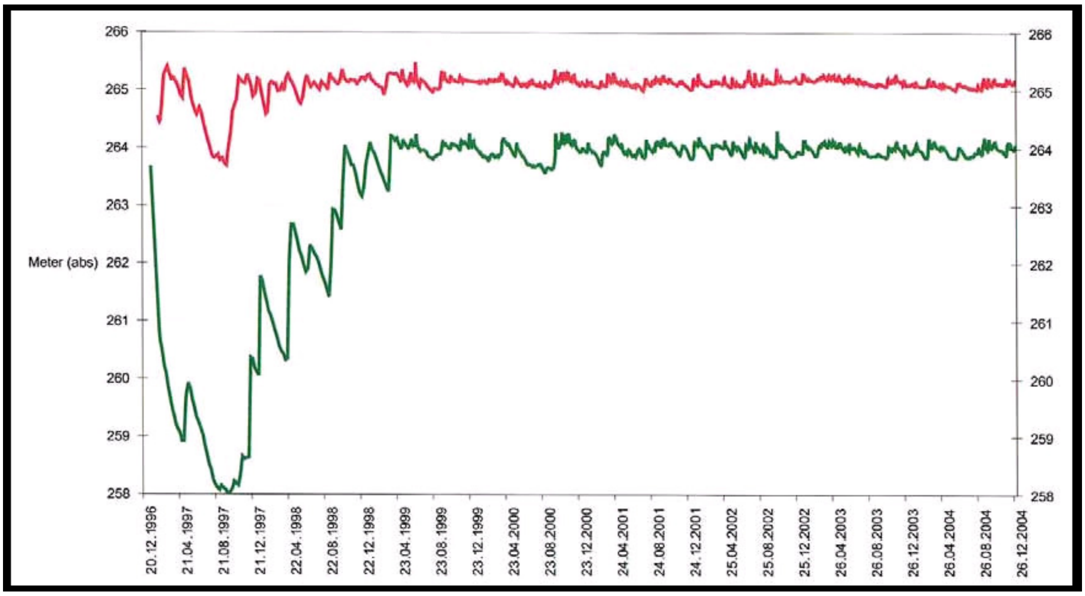


Figure 6-1. *Water levels in the Southern Puttjern (red line) and in the Northern Puttjern (green line) during the constructional and operational phases of the Romeriksporten railroad tunnel (Brettum och Løvik, 2005). During the summer of 1997, the water levels of the Northern Puttjern decreased by nearly 6 m. The construction of the tunnel was completed in 1999.*

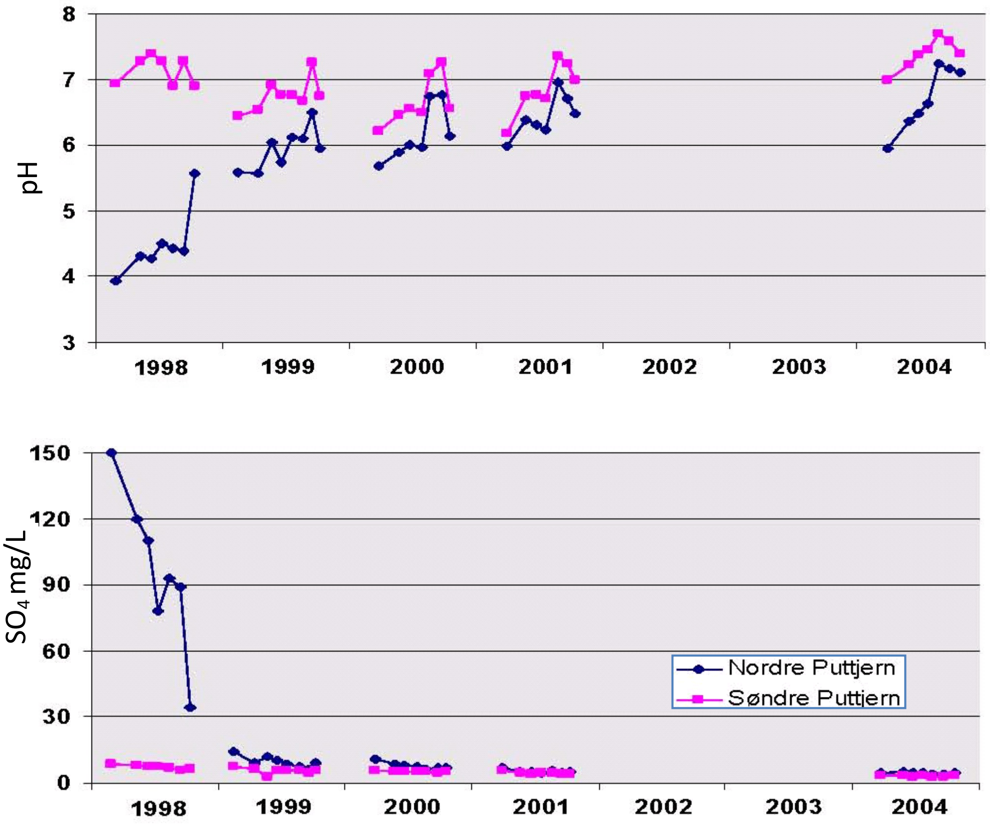


Figure 6-2. Concentrations of sulphate and pH values in the water of the lakes Northern Puttjern (marked with a line of blue colour) and Southern Puttjern (marked with a magenta coloured line) during the constructional and operational phases of the Romeriksporten Railroad tunnel (Brettum och Løvik, 2005).The construction period ended in 1999.

6.2 Hydrochemical impact to the groundwater in the bedrock

Alike for the shallow groundwater in the overburden and for surface waters, the water leakage into a tunnel can also affect the chemical composition of the groundwater in rock aquifers. A leaking tunnel will cause a flow towards the tunnel, possibly from all directions. Groundwater systems that under unaffected conditions have long residence times with water being from a few years to several thousand years could be affected to have residence times of only a few days. Shallow, meteoric water as well as deeper brine waters may flow towards a tunnel because of the leakage. Under certain circumstances, underground constructions may cause upconing of saline waters. The construction activities may cause changes of pressure that changes the stratification between meteoric and saline waters. The water that flows towards a tunnel may consequently have a different composition than the original water that dominated the in the rock mass at the location of the tunnel prior to the construction phase. Observations made during tunnel construction in different parts of the world describe hydrological and hydrochemical changes. The observed examples range from the Romeriksporten railroad tunnel in Norway to the Tsukuba tunnel in Japan.

The chemical composition of the tunnel water was monitored during the construction phase of Romeriksporten (Traaen and Berge, 1999). Chemically, the water was characterised mainly by substances that originated from the water-sealing system in the tunnel (grouting and Acrylamide) and from the explosives (nitrogen compounds). A slight increase in the sulphate content was measured in the drainage water in the tunnel as well as the presence of humus, which could be attributed to vertical transport from shallow groundwater and surface water. During the construction of Romeriksporten the groundwater levels were monitored (Snilsberg, 1998; Snilsberg and Kværner, 1999). The water levels in the boreholes closest to the tunnel fell by between 20 m and 45 m compared with unaffected conditions. Kitterød et al. (2000) simulated the inflow into the tunnel and the effect of an infiltration facility that was installed to reduce the drop in the groundwater level. The simulation mainly highlighted the continued and significant need for infiltration (Kitterød et al., 2000).

Shimada and Ishii (1986) studied how water chemistry was affected over a three-year period by the construction of the Tsukuba Tunnel, located approximately 100 km north-east of Tokyo in Japan. Apart from the chemical analysis, an isotope analysis was also made of tritium and oxygen in order to determine the age and origin of the infiltrating water. As part of the investigation, water infiltrating into the tunnel was analysed as well as surface water and shallow groundwater. According to Shimada and Ishii (1986) the pH in the tunnel was not affected by cement-based grout. The investigation revealed a gradual increase in alkalinity and calcium concentrations. In the isotope analysis of infiltrating water in the tunnel, Shimada and Ishii (1986) also observed that a gradually increasing proportion of the water was made up of water that had recently infiltrated from shallow groundwater. However, there was a considerable difference in the measurement results for the points where the water had been analysed for isotope conditions. At one of the test points almost all infiltrating water was surface water whilst at other sampling points the proportion of surface water was between 20% and 50% (Shimada and Ishii, 1986).

Olofsson and Ericsson (1985) studied how the groundwater chemistry is affected in the long-term in conjunction with groundwater extraction from both glacial deposits, glacifuvial deposits and bedrock aquifers. Hydrochemical changes during the operation of eighteen groundwater reservoirs in rock were evaluated. According to Olofsson and Ericsson (1985) there is a gradual increase over time in the electrical conductivity i.e. higher ion strength. An increase in sulphate concentrations was noted in four of the 18 boreholes whilst 13 had relatively unchanged sulphate concentrations. Rising calcium and magnesium concentrations were noted in almost half of the boreholes. In the majority of the boreholes no change in the pH took place over time. A change was noted in only three boreholes. In two of the three boreholes with a change in pH, the borehole characteristics deteriorated during the observation period. This led to one of the boreholes being deepened and one being blasted clean using compressed air (Olofsson and Ericsson, 1985).

Changed groundwater levels can cause oxidation of rocks containing sulphide and minerals such as pyrite, other iron sulphides and muscovite gneiss, which in turn causes acidification (Karlsrud et al., 2003). East of Kristiansand in Norway a 38 km section of the E18 highway has been brought up to motorway standard. Along this section of the road seven tunnels have been built, totalling 5.9 km in length (Vegvesen, 2007). Sulphur is present in the bedrock along parts of this section of road, mainly in muscovite gneiss. This means that surface water could have high levels of sulphate and a low pH. According to Hindar and Lydersen (2002) sulphate concentrations in the surface water of almost 100 mg/L and a pH as low as 4.5 were measured before the road construction phase commenced. Based on the investigation in Hindar and Lydersen, the Norwegian Public Roads Administration, Vegvesen, proposed limits for emissions from the road facility, including its tunnels, which in a few cases means that the surface water recipient is permitted to have sulphate levels of up to 100 mg/L (Vegvesen, 2006).

Laaksoharju and Gurban (2003) describe how the water chemistry in the groundwater is affected by the storage of low- and medium-active nuclear waste by SFR, Swedish Nuclear Fuel and Waste Management Company (SKB), at the operating stage. Unfortunately, the evaluation does not include any hydrochemical data from the period before the facility was constructed or from the construction phase. The facility is located beside the Forsmark nuclear power station and is built 50 m below the bed of the Baltic Sea in crystalline bedrock. The facility was constructed between 1983 and 1988. Monitoring of the groundwater chemistry and chemical modelling are to be found in Laaksoharju and Gurban (2003) for the period 1989-2000. According to Laaksoharju and Gurban (2003), the groundwater chemistry at SFR is characterised by the Weichsel glaciation and the subsequent stages in the development of the Baltic

Sea. The groundwater around SFR changed gradually during the monitoring period from older to younger marine groundwater. A gradual decrease in the chloride content of the groundwater was noted where all the water with a high chloride content from the Littorina Sea period was replaced by water from the Baltic Sea. In one of the boreholes a gradual increase in the influence of glacial water was noted during part of the monitoring period (Laaksoharju and Gurban, 2003).

Laaksoharju et al. (2009) studied the hydrogeochemical effects in the excavation damage zone of underground structures in the planning process for a deep repository. This study was mainly based on observations from the Äspö HRL. One of the main findings in the study was that calcite precipitation caused a decrease of hydraulic conductivity adjacent to an underground structure. Although the decrease was found to be less than 2% per ten years, this decrease will have an impact for constructions with a long lifespan.

In the deep sea tunnels to Hitra (depth 264 m) and Frøya (depth 150 m) in Norway the infiltrating water was mainly of a seawater composition and no relict water was observed (Hem et al., 2002). Marine waters usually have an impact on the hydrochemical composition beneath the seabed and infiltrates through the higher density of saline waters compared to meteoric groundwater that originates from the shore.

6.3 Hydrochemical influence to the durability of underground construction

6.3.1 Durability of reinforcement bolts

According to Windelhed and Lagerblad (2002), bolts embedded in cement, if done so properly, offer good protection against corrosion. The protection is due to the fact that the cement creates an alkaline environment with a high pH, which results in a low risk of corrosion. A high buffer against acidification and high calcium concentrations in the water protect against corrosion (DIN 50929). When cement with a low water-cement ratio is used, the protection against corrosion is improved in those cases where the cement comes into contact with water. With a low cement-water ratio there is a surplus of cement grains which during the pouring process did not come into contact with water. If water were to come into contact with the embedding cement at a later stage, the cement would react with the water and water-bearing fractures could in that case become self-sealing (Windelhed and Lagerblad, 2002).

There is a risk of corrosion when a bolt is not covered completely during pouring. Even in such a case the risk is due largely to hydrochemical conditions, which primarily takes the form of access to oxygen and water although a reduction in the pH also contributes to a corrosive environment. A reduction in the pH can take place when the water turnover near the bolt is high or if there are geological conditions that contribute (Windelhed and Lagerblad, 2002). Water flow along a bolt towards a tunnel does not need to cause corrosion if the groundwater generally is alkaline or if microbial conditions do not exist for creating a corrosive environment. It also ought to be taken to account that bolts can also be exposed as a result of rock movements.

Further hydrochemical parameters affect the corrosion when an unprotected bolt comes into contact with water. High chloride and sulphate concentrations in the water contribute to corrosion of bolts. Microorganisms can also contribute to a corrosive environment. According to Minick (1987) it is mainly organisms that oxidise sulphide into sulphuric acid that contribute to corrosion. DIN 50929 states that anaerobic water is corrosive although according to Windelhed and Lagerblad (2002) this presupposes that the water contains sulphate-reducing bacteria. These bacteria are a prerequisite for corrosion in oxygen-free water (Windelhed and Lagerblad, 2002).

The risk of corrosion caused by aggressive groundwater can be reduced if the bolts are given a protective coating. Where appropriate, the bolts have been coated with epoxy and powder paint. As embedding normally provides good protection, the coating ought to be used only if there is a risk that bolt embedment will fail (Windelhed and Lagerblad, 2002). Figure 6-3 shows a reinforcement bolt protected using epoxy and powder paint.

Figure 6-3. A reinforcement bolt with a protective coating of powder paint and epoxy in the Frøya Tunnel in Norway (Photo: Fredrik Mossmark).

Pells and Bertuzzi (1999) have compiled a summary of different reinforcement designs and corrosion of bolts in conjunction with a rock construction in Sydney. The authors searched for the use of coating of rock bolts with epoxy to achieve satisfactory protection against corrosion, which could give the bolts a lifespan of between 50 and 100 years. According to Pells and Bertuzzi (1999) in the case of bolts protected solely by cement only the term permanent bolts can be used, assuming that 'permanent' refers to a lifespan of less than 25 years. Pells and Bertuzzi (1999) do not take into account hydrochemistry in their analyses of the durability of bolts and instead assume that the hydrochemical conditions are relatively unknown.

According to Blindheim et al. (2005) bolts in the subsea tunnels in Norway have a supplementary protective coating as the hydrochemical environment is often corrosive. In the Eiksund Tunnel hot-dip galvanised expander bolts were used, protected by an epoxy coating, a plastic casing and embedded in cement to ensure protection against corrosion (Blindheim et al., 2005). Andersson et al. (2001) present results from investigations of the durability of bolts, shotcrete and grouting in the Muskö Tunnel and SKB's repository for medium-active nuclear waste at Forsmark. In the Muskö Tunnel, which was completed in 1963, no corrosion was noted in any of examined bolts that were embedded according to the norms at the time. A further bolt, which was not correctly embedded, was examined and revealed slight corrosion. No corrosion of bolts was noted at the SFR facility (Andersson et al., 2001).

During the construction stage of the Löttinge Tunnel in Stockholm, groundwater with a relatively low pH (6-7) was observed. According to the National Road Administration classification system this meant that the groundwater was assessed to be aggressive and that supplementary protection of the bolts is required. During the construction phase dispensation was granted from the requirement for supplementary protection although investigation is required of the durability of the bolts by taking core samples (Windelhed, personal communication)

In the Vardø Tunnel in northern Norway a corrosion investigation of the reinforcement bolts has been carried out since the construction phase of the tunnel in 1980 (Pedersen, 1993). Eight bolts made of different types of steel and with varying forms of rust protection were placed unprotected in boreholes in the tunnel wall. Two of the bolts disappeared in 1988 and after that the corrosion investigation continued with just six bolts. Samples were taken from the water in the tunnel and their chemical composition was considered to be similar to sea water. The environment in the tunnel was assessed to be corrosive. Of the eight bolts, four were made from different grades of stainless steel whilst four were hot-dip galvanised reinforcing steel bolts, of which three had varying degrees of supplementary epoxy protection and with treatment of the nuts. Three of the four stainless steel bolts had distinct signs of rust attack. The bolts that did not have any rust were considered to be made of better grade steel with a molybdenum content of around 5%. Of the four reinforcement steel bolts, the bolt that did not have any epoxy coating had the lowest level of rust attack. This bolt had, however, a specified thickness for the protective zinc layer whilst the other three, which were protected with epoxy, had an unspecified zinc layer thickness.

An examination of the durability of different types of bolt was carried out at the Kvarnstorp sandstone mine (Helfrich and Finkel, 1989). The environment in the mine was not considered to be corrosive although no extensive chemical analysis of the water was made. The water in the mine had a neutral pH, seepage was considered low. Different types of bolt were examined from the point of view of durability: cement-embedded bolts, bolts covered in plastic and Swellex expander bolts. Helfrich and Finkel (1989) maintained that the bolts in the mine often lacked satisfactory protection against corrosion. The plastic-covered and cement-embedded bolts had often not been embedded completely and parts of them were thus unprotected. In the survey, all types of bolt had been affected by corrosion (Helfrich and Finkel, 1989).

Experience from the Kvarntorp sandstone mine is similar to the experience from the Vardø Tunnel, where bolt protection did not have the desired effect. In both cases where the corrosion protection did not have the desired effect on the corrosion process it is uncertain whether the bolts were coated completely. The reason for the increased corrosivity in conjunction with the use of anticorrosion measures ought to be studied further. The results from the Kvarntorp sandstone mine and the Vardø Tunnel could be explained by the hydrochemically heterogeneous setting, which for a steel construction part in earlier studies was shown to stimulate corrosion (Norin and Vinka, 2003). A hydrochemically heterogeneous environment can be created when a bolt has not been completely embedded or if the protective zinc or epoxy layer does not cover the bolt entirely.

6.3.2 Steel reinforcement and steel fibre reinforcement in shotcrete

Nordström (2005) presents results from examinations of durability in steel fibre reinforcement. According to Nordström (2005) steel fibre reinforcement of shotcrete entails a reduced risk of corrosion compared with when conventional steel reinforcement is used. Nordström (2005) carried out both field and laboratory studies of steel fibre reinforcement. On inspection of fractured shotcrete, a low level of corrosion was noted even in hydrochemical environments which were assessed to be aggressive with high chloride concentrations. In the field studies, the chloride concentration in the concrete was measured. Those locations that were considered to be exposed to an aggressive environment based on a high chloride concentration, had more than 0.2% chloride per kilo of cement. In the laboratory setting, steel fibres were exposed to water with 3.5% chloride. However, in an examination where fractured shotcrete with steel reinforcement was exposed to water containing chloride, the diameter of the steel fibres in the fractures in the concrete decreased by 15-25% over five years. According to Nordström (2005), long steel fibres had a greater propensity to corrode than short steel fibres. For each increase of 10 mm in the length of the steel fibre, the loss due to corrosion of steel fibre diameter in a fracture in the shotcrete that was exposed to water with a relatively high chloride concentration increased by 5%.

It was noted that the use of stainless steel fibres offers good protection against corrosion and the use of galvanised fibres resulted in a delay in the time before the fibres began to corrode but did not provide any long-term protection. The fracture width in the fractured shotcrete was of significance to the corrosion. When steel-reinforced shotcrete was exposed in the field to water containing chloride, corrosiveness increased when the fracture width exceeded 0.1 mm. When the shotcrete was exposed to water with a low chloride content in the laboratory experiment, the corrosiveness in the steel fibres increased when the fracture width exceeded 0.5 mm. The water used in the laboratory test to represent low chloride content was tap water and the chloride concentration was unknown. According to Nordström (2005) the use of accelerators in the shotcrete also affected the durability of the steel fibres. When the concrete reinforced with steel fibre was exposed to water with a low chloride content there was better protection against corrosion when a sodium silicate accelerator was used in the shotcrete. However, no improved corrosion protection was noted in conjunction with the use of sodium silicate when the concrete was exposed to water with high chloride concentrations (Nordström, 2005). Nilsson (2003) describes the difficulty of dimensioning the reinforcement of tunnels with fibre-reinforced shotcrete anchored in rock but agrees that it is possible that reinforcements in tunnels are often over-dimensioned.

6.4 Construction elements made of cement-based materials

6.4.1 Hydrochemical influence on cement that protects bolts

The use of cement which is resistant to sulphate has increased gradually since the 1960s. Cement which is not resistant to sulphate can, on the addition of sulphate after the cement paste has hardened, acquire ettringite formation ($Ca_6Al_2[(OH)12(SO_4)3]\cdot 26\ H_2O$). This leads to swelling and fracturing of the cement, which means that the groundwater can come into contact with the bolts and in doing so reduce the durability of the cement (Windelhed and Lagerblad, 2002).

If the cement is exposed to acidic groundwater, there is a risk that it can be dissolved. At a pH lower than 4.0, there is a risk of acidic attack with degradation of the cement paste. Such a low pH can only occur in bedrock groundwater under special geological conditions, such as in the presence of rock rich in pyrite and sulphide (e.g. sulphide gneiss). When the groundwater contains bicarbonate, this can react with calcium ions in the cement paste and form calcite. This could result in a reduction in the pH value of the water, which makes the water environment more corrosive to any exposed bolts. A reaction between the cement paste and the carbon dioxide in the air could result in a significant reduction in the pH and lead to corrosion of the bolts (Windelhed and Lagerblad, 2002). Chloride can penetrate the cement paste by means of diffusion to a protected bolt and if there is access to oxygen this could lead to the bolt corroding.

In an examination of the durability of bolts, grouting and shotcrete in the subsea tunnel leading to the island of Muskö (Andersson et al., 2001) the cement around the embedded bolts was also examined. During the examination it was noted that contact between the bolts and the cement had decreased, mainly due to the fact that calcite had formed nearest the bolts. In the transition between the rock and the cement, calcium leaching was noted. According to Andersson et al. (2001) the chemical changes in the cement that protect the bolts could result in a serious reduction in tunnel reinforcement.

6.4.2 Shotcrete

Shotcrete has proved to have more sensitive properties than normal concrete through abnormal fracturing at drains (Lagerblad et al., 2006). In, among other places, the Södra Länken tunnels in Stockholm, the shotcrete revealed shrinkage fractures. According to Lagerblad et al. (2006) shotcrete containing alkali accelerators is sensitive to sulphate attack. When water and sulphate are present, the formation of ettringite can take place, leading to swelling. Even sulphate-resistant shotcrete becomes sensitive to sulphate attack if it contains alkali accelerators (Lagerblad et al., 2006). With alkali-free accelerators, sensitivity to sulphate is avoided although a larger build-up of ettringite was noted (Fjällberg and Lagerblad, 2003). The extensive formation of ettringite was noted in particular when grouting agents rich in aluminium were used (Lagerblad et al., 2006).

In conjunction with an examination of tunnels in the Swiss Alps, sulphate attacks on cement were noted (Romer et al., 2003). Contrary to experience in Sweden, the sulphate attacks mainly resulted in a build-up of thaumasite. According to Romer et al. (2003) degradation of cement into thaumasite takes place mainly through contact with groundwater with a low mineral concentration (calcium, carbonate and sulphate). According to Romer et al. (2003) degradation of cement into thaumasite takes place over a period of 20-30 years.

During an examination of the shotcrete in the Muskö Tunnel it was noted that the cement paste was leached due to the aggressively brackish seepage water. The cement paste had disappeared almost completely from the surface of the shotcrete and the concrete's ballast was visible. In 1995, it was noted that the contact between the shotcrete and the rock was reduced in sections of the tunnel. According to Andersson et al. (2001) calcium carbonate, ettringite, calcium/dolomite and gypsum had formed between the shotcrete and the rock. The results from the examination of the shotcrete were compared with analyses of the tunnel water. At locations where the cement paste had leached out, it was shown that the seepage water had a composition that had a greater propensity to leach out of the cement paste than along less affected locations. Even at locations with reduced contact a correlation with the chemical composition of the seepage water was observed. Andersson et al. (2001), however, do not present any data from hydrochemical analyses to substantiate their conclusions.

6.4.3 Durability of cement-based grouting agents

According to observations in a large number of tunnels, seepage of groundwater often decreases gradually during operation (Hem, 2002). Reduced seepage in tunnels during operation has been noted at, among other places, Äspö HRL (Laaksoharju, personal communication), the SKB facility for medium-active nuclear waste (Andersson et al., 2001), the Hitra Tunnel (Hem, 2002) and the Göta Tunnel (Albino, personal communication). According to Hem (2002) processes that cause natural water sealing in the tunnel can be divided into three groups: chemical deposits, biological processes and mechanical processes. A further contributing factor to a gradual reduction in seepage in tunnels during operation is the fact that a gradual fall in the pressure gradient can arise towards the tunnel, thus reducing the inflow (Andersson et al., 2001). The leakage into an underground facility may cause significant hydraulic gradients. According to Bockgård (2004), unsaturated hydraulic conditions may occur if the bedrock is heterogeneous. The unsaturated conditions decrease the effective hydraulic conductivity and thereby decrease the leakage into a tunnel.

Even if the majority of experience indicates that the flow of groundwater into tunnels during operation gradually decreases, there are also processes that degrade cement-based grouting agents. According to Pusch et al. (1988) the primary degrading processes are leaching, sulphate attack and calcite formation. When water with a neutral pH comes into contact with cement-based grouting, an acid attack can take place as the cement is alkaline (Lagerblad, 2001). In the case of high sulphate concentrations in the groundwater, sulphate attacks can occur on cement-based grouting agents. The sulphate-resistant grouting agents have a higher resistance to sulphate attacks but do not offer complete protection (Lagerblad, 2001). According to Damidot et al. (1992) more than 400 mg/L of sulphate-sulphur in the groundwater is required for a sulphate attack to take place, presupposing bedrock containing sulphur e.g. where pyrite or gypsum are included.

6.5 Construction parts made of other material

6.5.1 Chemical grouting agents

Jakubowicz (1992) examined the durability properties of the grouting agent polyurethane. According to Jakubowicz (1992) the durability of the polyurethane deteriorated in the case of a high pH and at high temperatures. An alkaline hydrochemical environment, which occurs naturally in limestone or with concurrent use of cement grouting, can have a negative effect on the durability of polyurethane. According to Jakubowicz (1992) there are major differences between different types of polyurethane grouting agent.

Axelsson (2006) contains a literature study of the durability of the grouting agent silica sol. The literature study summarises the results from other studies by stating that the durability of silica sol depends on the pH and the concentration of silicon in the water. According to Axelsson's (2006) summary, the durability of silica sol decreases in conjunction with a high pH. When using silica sol in combination with a cement-based grouting agent this could lead to durability problems for silica sol as the cement-based grouting agent creates a basic environment. According to Björnström (2005) the durability of silica sol is good at a high pH assuming that the water is saturated with silicon. According to Axelsson (2006), there is a general link between the durability of silica sol and silicon concentrations in the surrounding groundwater where higher silicon concentrations result in better durability.

6.6 Durability of drainage systems

Durability problems in drains can be attributed in part to the issues dealt with regarding the durability of cement and steel material but also to filling problems. According to Ekliden (2008) clogging of drains is caused mainly by iron and manganese precipitates. Iron and manganese, which are dissolved in the groundwater, can oxidise and thus precipitate when they reach the tunnel drain. Oxidation can take place either chemically or through microbial activity (Ekliden, 2008). According to Pedersen (personal communication) microbial oxidation of iron means that a slimy mass is formed which comprises both precipitated iron and organic material. The volume becomes considerably larger than if iron alone had been precipitated chemically. The microbial oxidation is thus most problematic. According to observations based on experience presented in Hargelius (2006) the greatest risk of microbial oxidation of iron in drains is when the pH is between 5.5 and 7.0. If the pH falls below 5.5, precipitation will not occur and if the pH is above 7.0 it is mainly chemical oxidation that takes place (Hargelius, 2006). In a comparison with Figure 4-3, which describes different redox forms of iron depending on the redox potential and pH, the observations made by Hargelius (2006) concur well. Hargelius (2006) recommends observations at the construction stage of the tunnel to identify locations where problems can occur for drains. Such a procedure could be necessary for an underground facility to be completed within a reasonable time. The procedure does not take into account, however, the fact that hydrochemical conditions can change over time. According to Mattheß (1994), chemical oxidation of manganese generally occurs at a higher pH than for iron.

7 Results from the field study at Lake Gårdsjön

At Lake Gårdsjön, the effect of groundwater extraction was studied with monitoring of two similar catchment areas. One of the catchment areas was studied under pristine conditions for three years and for four and a half years during groundwater extraction. The recovery from the impacts of the groundwater extraction was then studied during the following three years. The other catchment area was used as an unaffected reference. Findings and results from the experiments at Lake Gårdsjön are presented in Paper I and in Paper II. Furthermore, findings from the initial three years of monitoring under pristine conditions have been published in Knape (2001), data from the extraction period have been published in Graffner et al. (2005) and Knape Hansén (2002) with an evaluation presented in Paper I. Results from the recovery period have also been published in Mossmark et al. (2008a) and in Paper II.

7.1.1 Instrumentation and monitoring

In the experimental and reference catchments, several physical parameters were measured. Groundwater levels were measured with transducers in the experimental catchment as well as in the reference catchment. Piezometric heads in both deep drilled boreholes in the bedrock as well as in filter wells in the overburden were measured. In the experimental catchment, the runoff volume was monitored in three weirs. The instrumentation of the experimental catchment is presented in Figure 7-2. For the reference catchment, only one weir was used to measure runoff volume. Air temperature, precipitation, air moisture, wind speed and wind direction were measured using two climate stations. The extracted groundwater volume was also measured continuously. A photo of the Thomson weir that was used for the measurement of runoff volume is presented in Figure 7-1.

The monitoring also included a regular sampling program for chemical analysis. Shallow groundwater (at an approximate depth of 2 m) from the two catchment areas was collected six to ten times per year, while extracted groundwater and runoff water were sampled every fortnight. The groundwater in the bedrock was sampled four to eight times annually, the samples were collected at a depth of approximately 30 m. The sampled water was analyzed for pH, Electrical Conductivity (EC), and major constituents. In the extracted groundwater, pH, EC as well as redox potential was measured and logged continuously.

Figure 7-1. V-notched weir with water level recorder at the F3 catchment. An automatic water sampler (on top) and a pH and EC logger are installed at this weir.

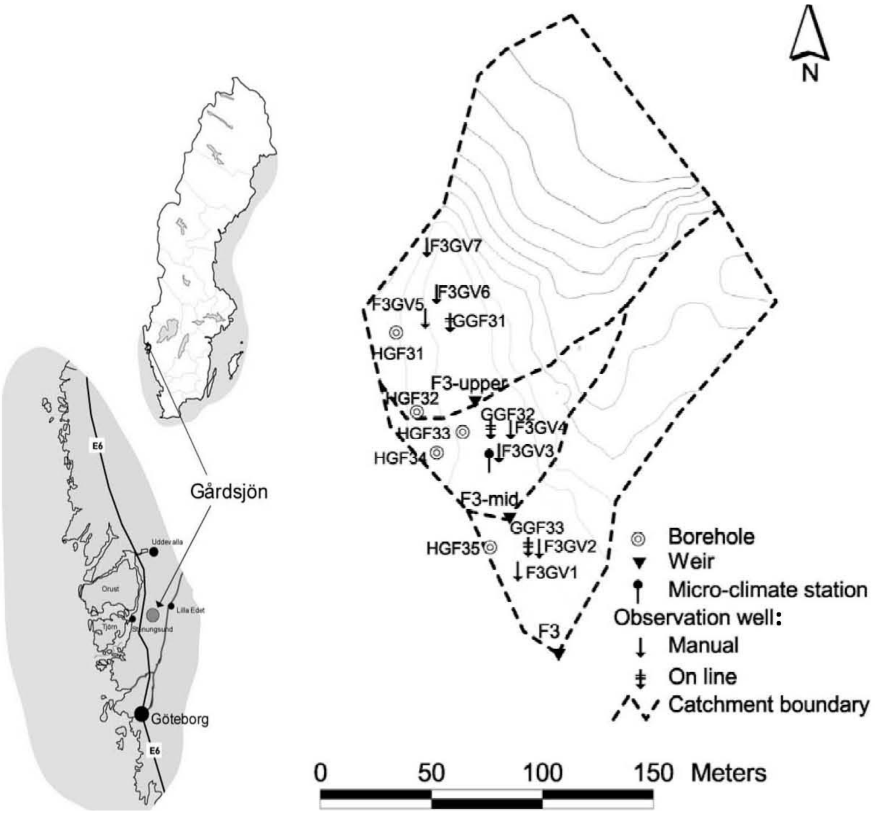


Figure 7-2. Location of the Lake Gårdsjön area and instrumentation of the experimental catchment. The borehole HGF33 was used for water extraction during the period December 2000 to April 2005. Extraction from HGF31 was carried out during the period April 2004 to April 2005.

7.1.2 Geological and hydrological conditions

The area is characterized by crystalline bedrock, a thin layer of overburden consisting of glacial till, wetlands (sphagnum peat), coniferous forest (Scots pine and Norway spruce) and relatively high annual precipitation (approximately 1100 mm annually). The geological and hydrological conditions of the area are described in more detail in Olsson et al. (1985), Nilsson (1985), Samuelsson (1985), Fredén (1986) and Andersson et al. (1998).

The annual precipitation during the monitored years is presented in Figure 7-4. The precipitation was higher during the years prior to the start of the groundwater extraction, 1998 to 2000, compared to the extraction period, 2001-2005. The annual precipitation was again higher during the recovery phase, 2006-2007.

The bedrock in the Lake Gårdsjön area mainly comprises gneissic granodiorite (Samuelsson, 1985) covered by thin layers of regolith (mainly glacial till) and podzol and organic soils. According to Fridh och Hayling (1980) a fracture zone in the rock exists beneath the central wetland of catchment area F3 in a north-south direction and another fracture zone crosses the F1 catchment area. Fridh and Hayling (1980) described the metamorphosed bedrock to include several sets of joints and fractures. The bedrock of the Gårdsjön area has fractures and fracture zones that are connected and are water-bearing and thereby contain a fractured aquifer (Paper II).

The overburden has largely been formed through processes related to glaciation, the most recent ice sheet withdrew approximately 14000 B.P. The ice sheet deposited crushed geological material formed from eroded rock and previous regolith as thin layers directly on top of the crystalline rock, a deposit type referred to as glacial till. This deposit type forms the surface of more than 60% of the experimental catchment area F3 and more than 50% of the reference catchment area F1 (Olsson et al., 1985). The quaternary geological map (Figure 7-3) reveals mainly bedrock outcroppings in the area. This indicates that the thickness of the glacial till in most locations is less than 50 cm.

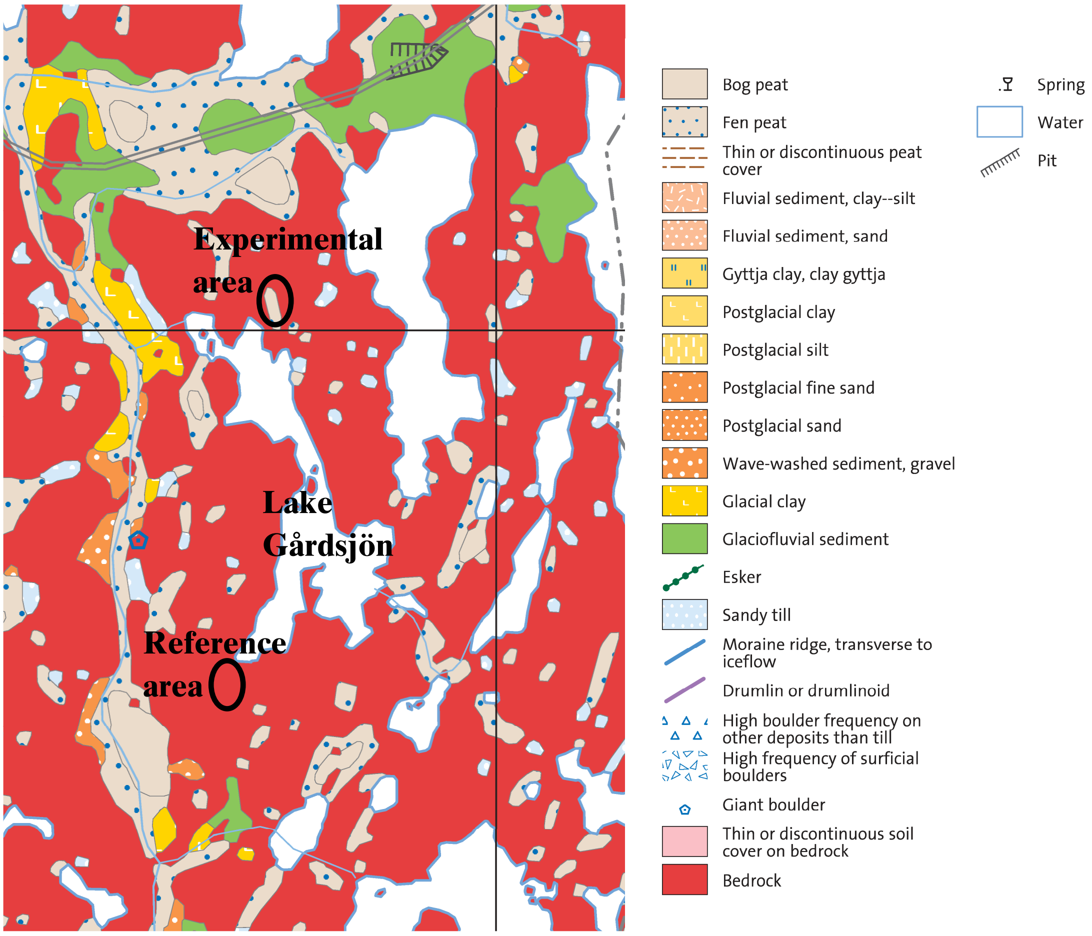


Figure 7-3. *Quaternary deposits in the Lake Gårdsjön area. Most of the surface in the area is mapped as "Bedrock" (outcropping). However, this indicates that the thickness of the overburden is less than 50 cm. Thin layers of glacial till cover most of the areas mapped as bedrock outcropping. © Geological Survey of Sweden.*

After deglaciation, several marine transgressions took place. Areas that were inundated during the transgressions typically have deposit types sedimented in water, which means material that is quite sorted in terms of particle size and in some cases thick layers. The Gårdsjön area is located at an elevation of between 110 to 130 m above sea level (asl) and, according to Fredén (1986), the highest shoreline is 125 m asl. However, only very thin layers of fine silt to sand have been found on top of the till in the experimental wetland. Organic wetland soils cover approximately 5% of the area of the experimental catchment area F3 (Nilsson, 1985). The F1 reference catchment area also includes a wetland (Andersson et al., 1998) similar in extent to the F3 wetland. The wetlands in the two catchment areas consist primarily of sphagnum peat.

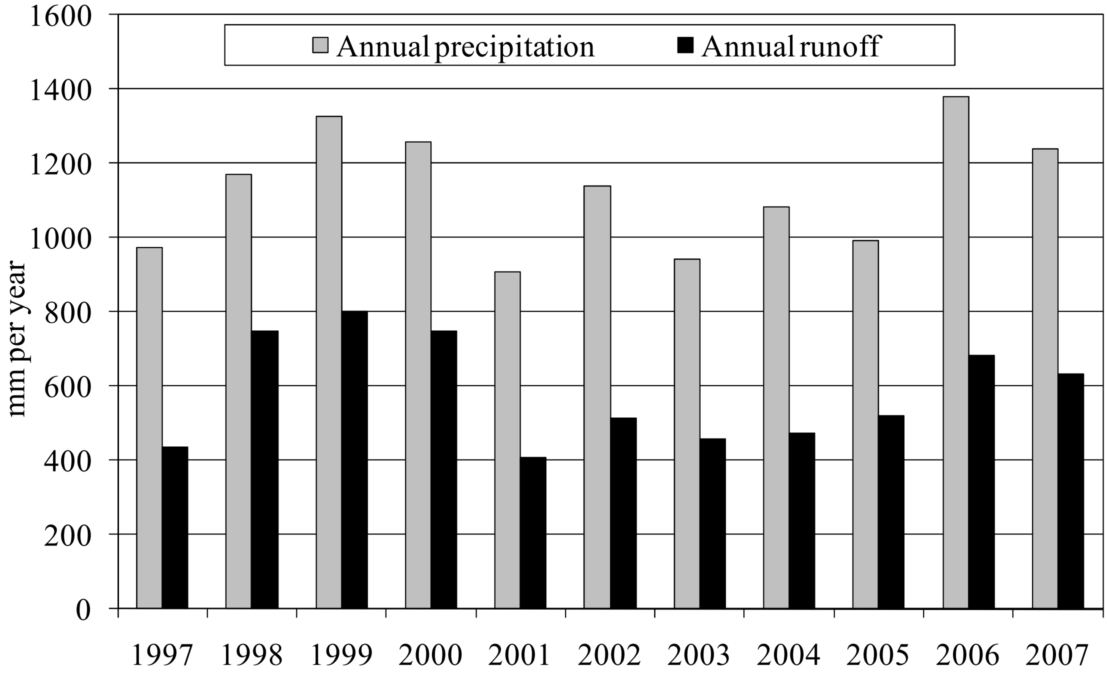


Figure 7-4. *Annual precipitation measured at Lake Gårdsjön as well as runoff from the reference catchment F1.*

As in most recently glaciated areas in Scandinavia, the entities bedrock and overburden are easily defined. In the results and discussions chapter for the Gårdsjön project, three different water bodies are defined:

- Surface water, meaning streamwater or any water above the land surface.
- Groundwater in the overburden (wetland or glacial till).
- Groundwater in the bedrock.

7.1.3 Hydrological and hydrogeological effects

The groundwater extraction was carried out from two different drilled boreholes (HGF31 and HGF33) in the bedrock, the boreholes were approximately 50 m deep. Groundwater extraction occurred from borehole HGF33 during the period December 2000 to April 2005. During the last year of groundwater extraction, from April 2004 to April 2005, borehole HGF31 was also used for extraction. From February to April 2004, there was an intermission in the groundwater extraction. The borehole HGF33 had a sealed off section through the use of an inflatable packer during most of the extraction period. However, HGF31 was used as an open borehole. The extraction caused a lowering of the groundwater table by 5-20 m in the bedrock and by up to 5 m in the soil cover compared to unaffected levels. During the extraction period, the runoff volume decreased by nearly 50 % (Figure 7-5). The extracted volume corresponded to the decrease in runoff volume in the experimental area. This indicates that the extracted water mainly consisted of water that had been recharged within the F3 catchment area and consequently that the boundaries of the groundwater aquifer would not exceed the water divide of the catchment area.

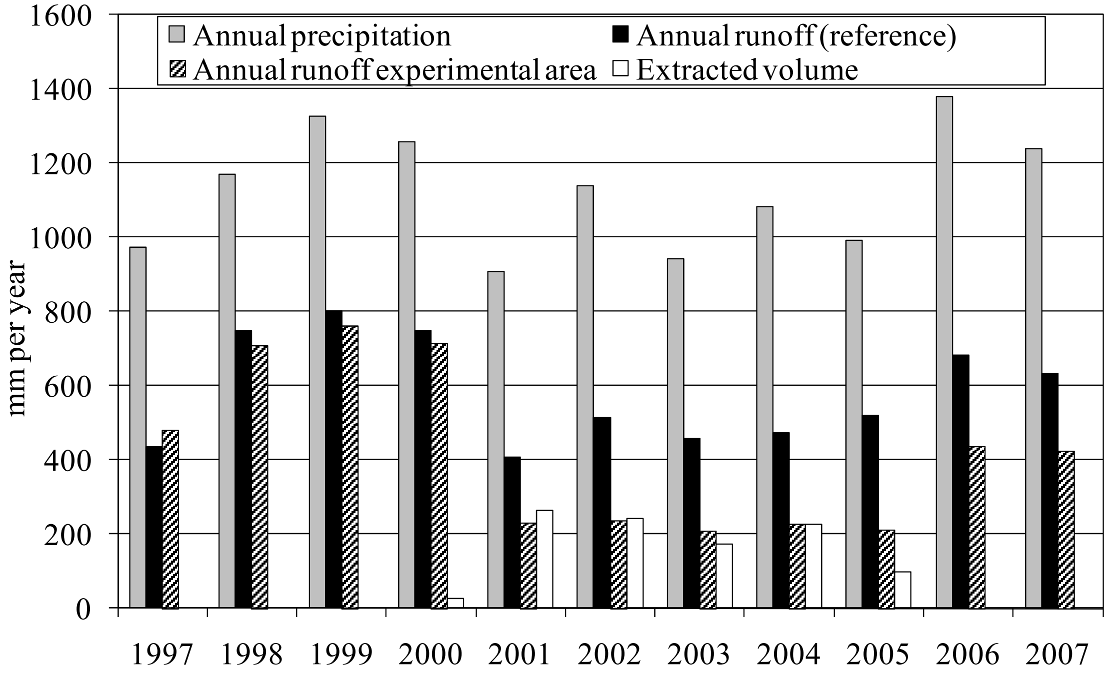
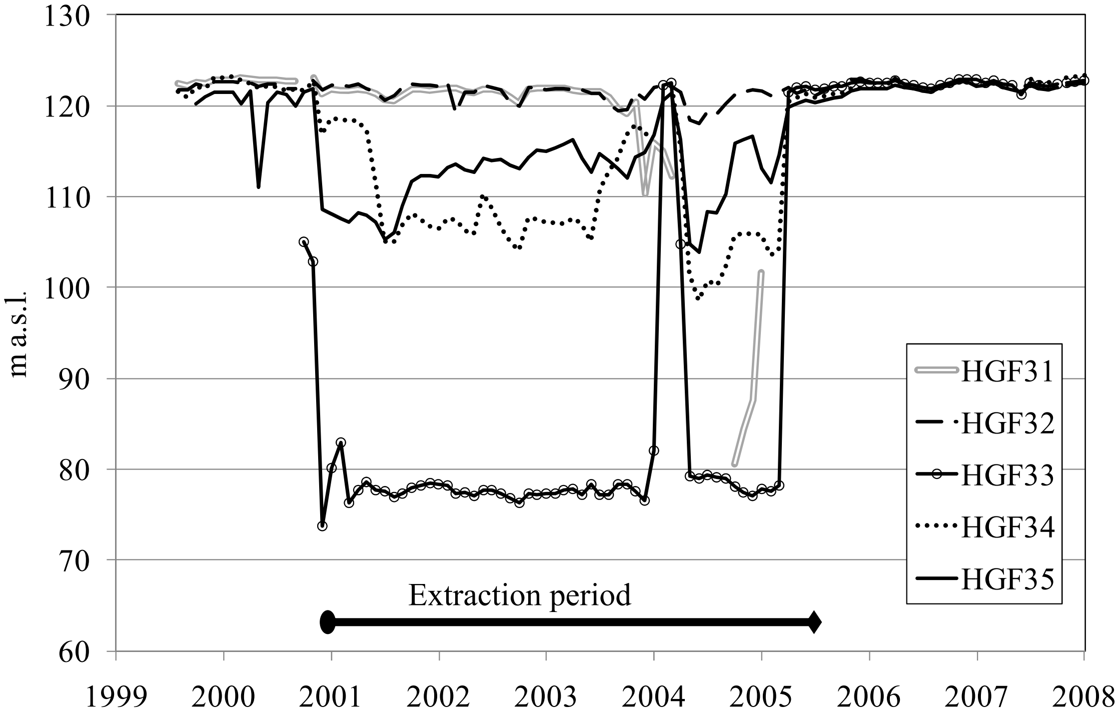


Figure 7-5. *Annual precipitation in the Lake Gårdsjön area,as well as runoff from the experimental and reference catchments and extracted groundwater volume from the experimental area.*

The level of shallow groundwater in the wetland and the drilled boreholes in the bedrock was subject to greater seasonal fluctuations during extraction. Figure 7-6 reveals that seasonal fluctuation in shallow groundwater is up to 2.5 m (GGF32). The groundwater levels in the wetland have fluctuated less since the experiment. For the groundwater in the bedrock, seasonal fluctuation became evident in some of the boreholes (HGF31 and HGF32) during extraction. The pattern of fluctuation was a lowering of the groundwater level during the summers of 2001, 2002 and 2003. Other boreholes showed a more permanent decrease in the groundwater level (HGF34 and HGF35) throughout the period of groundwater extraction. Since the experiment was concluded all boreholes have exhibited stable groundwater levels (Figure 7-6).



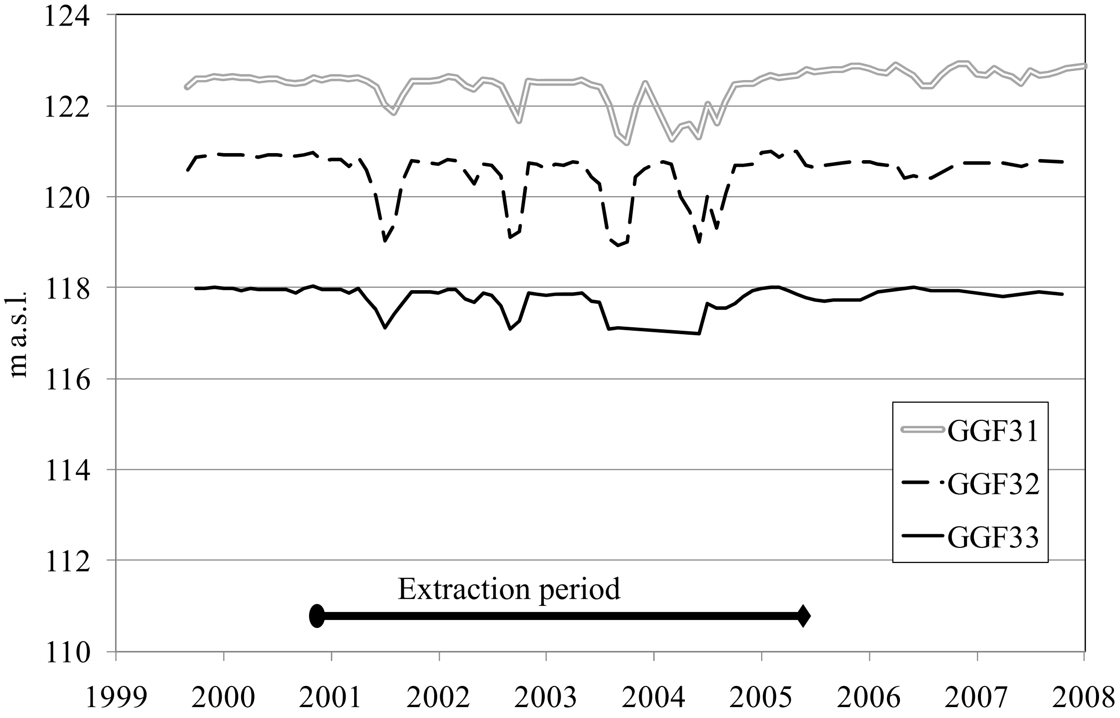


Figure 7-6. *Groundwater levels in the experimental catchment F3. The upper graph reveals levels in the bedrock, the lower displays levels in the overburden. Groundwater extraction was carried out from borehole HGF33 during the period from December 2000 to April 2005, from April 2004 to April 2005 extraction was also carried out from borehole HGF31.*

7.1.4 Hydrological modelling and evaluation of Lake Gårdsjön

A scoping hydrological modelling has been presented in Mossmark et al. (2008a). For the modelling, the software Mike 11 from DHI (DHI, 2007) was used. The software code uses reservoir boxes and can automatically calculate values of parameters to present calculated runoff volume that fits to the measured runoff volume. In the modelling, the following reservoirs were used:

- Snow reservoir
- Interception reservoir
- Reservoir in the unsaturated zone
- Groundwater reservoir (2)

The model also takes evapotranspiration into account, however, this need to be estimated by manual calculation (Penman equation was used). The input data to the model also comprised precipitation, observed runoff volumes, temperature and extracted volume of groundwater. The automatic calibration of the rainfall-runoff (RR) module of Mike 11 was used. The runoff model was primarily calibrated to match accumulated runoff volume rather than instantaneous flow.

The parameters used in the model correspond to the following properties according to DHI (2007):

CQof determines the share of the precipitation that runoffs compared to the share that infiltrates. The value for this parameter is between 0 and 1. A low value indicates that most of the water infiltrates.

CK_{12} describes the shape of the hydrograph and reflects the time delay of the impact from a precipitation event to the runoff volume.

CK_{BF} is a time constant that describes the runoff flow formed through groundwater effluence.

For the reference area F1, the entire time series from 1999 through 2007 was used for the simulation. The accumulated observed and simulated runoff volume is presented in Figure 7-7. For the experimental area it was more difficult to fit parameters for the entire monitoring period, and the simulated runoff volume differed more from the observed runoff volume compared to for the reference catchment. The observed and simulated runoff volumes when the same characterizing parameters were used for the entire period are presented in Figure 7-8.

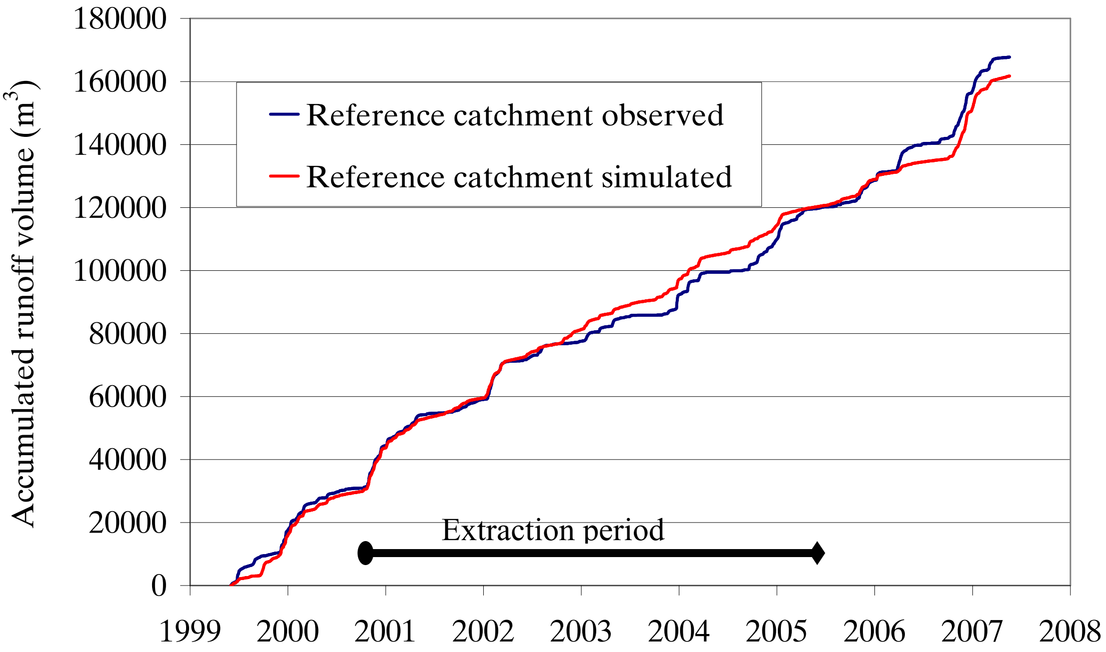


Figure 7-7. *Accumulated runoff volumes from the reference catchment. The observed runoff volume is compared to the simulated runoff volumes from the Mike11 hydrological modelling.*

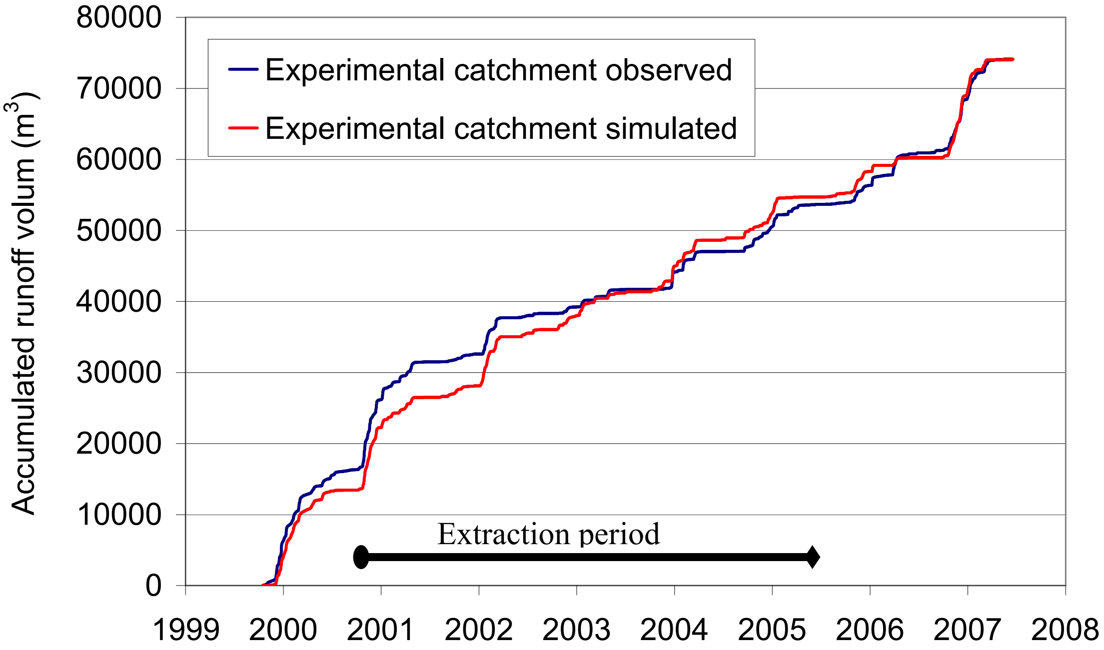


Figure 7-8. *Accumulated runoff volumes from the experimental catchment. The observed runoff volume is compared to the simulated runoff volumes from the Mike11 hydrological modelling.*

To decrease the difference between the simulated and the observed runoff volumes two separate simulations were carried out for the experimental catchment. One simulation was carried out for the initial period, the years 2000-2003, and one for the period 2004-2007. The modelling results indicate a gradual change in runoff characteristics for the experimental catchment, as presented in Table 7-1. Because of the changing characteristics of the catchment, two modelling periods were used.

Table 7-1. Generated parameter values through the fitting of runoff volumes using the RR-module of the modelling software.

Parameter	F1 (Ref.)	F3 (Experimental) entire period	F3 2000-2003	F3 2003-2007
CQof	0.77	0.62	0.66	0.52
CK1	30.5	20.7	24.7	10
CKBF	2973	400	400	1600

The generated values for the parameters CK1 and CKBF indicate that the experimental catchment F3 has a quicker hydrological response following precepitation events compared to the reference area F1. The value for the parameter CQof was higher in the reference catchment F1 than in F3, this indicates that precipitation that falls within F1 to a higher extent runs off in the surface than in the experimental catchment F3.

The difficulties to fit parameter values that are relevant for the entire period indicate a change in hydrological characteristics of the experimental catchment. Such a change is also indicated by the measurement results of the runoff volumes from the experimental catchment. Despite the quick recovery of the groundwater levels, the recovery of the runoff volumes from the area affected by extraction was slow. The runoff volume from the experimental catchment is compared to the reference catchment in Figure 7-9.

Before the groundwater extraction commenced, the runoff volumes from the two catchments were fairly similar. During the period of extraction, the runoff volume from the experimental catchment fell to 50 % compared to the reference catchment. During the recovery phase, after the groundwater extraction, the runoff volumes increased slowly. During the first two years after the groundwater extraction was terminated, the runoff volumes from the experimental catchment were 35 % lower than from the reference catchment. During 2008 the runoff volumes from the experimental catchment F3 had increased further in comparison to the reference catchment. However, the volumes were still lower from the experimental catchment than from the reference as presented inFigure 7-9.

The results reveal a delayed (several years) recovery for runoff. In comparison, the measured groundwater levels recovered quickly. However, it should be observed that the groundwater levels in the bedrock were measured in open boreholes and the interpretation of the results are therefore difficult. Changes in runoff volumes and groundwater levels are further discussed in Paper I and in Paper II.

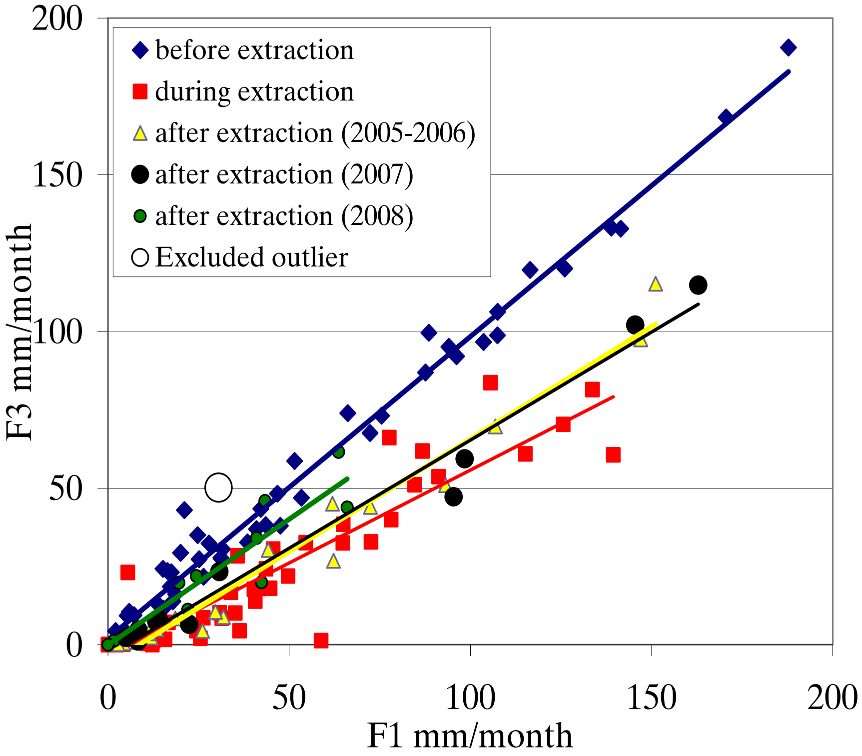


Figure 7-9. *Monthly runoff from the experimental catchment F3 compared to the reference catchment F1. The three phases before, during and after the groundwater extraction are compared. The figure shows a gradual recovery for runoff, a complete recovery may take from five to ten years.*

7.1.5 Water chemistry

During the experiment with groundwater extraction, the increased seasonal fluctuation in the groundwater level led to aeration of the shallow organic soil layers of the wetland of the experimental catchment F3. The seasonal aeration caused the sulfide bond in the wetland to oxidize to sulfate causing a sulfate surge and resulted in a subsequent acid pulse when the groundwater levels rose in the autumn. The effect of the experiment was gradual acidification of the wetland.

The concentrations of the cations magnesium and calcium in the shallow groundwater of the wetland paralleled those of sulfate with high concentrations in the autumn during the extraction period at Lake Gårdsjön. Afterwards, concentrations of magnesium in the groundwater of the wetland were lower than pre-experiment levels. This could be explained by the higher mass fluxes of magnesium in runoff water from the experimental catchment compared to the reference catchment during the experiment period (Paper I).

The chemistry of surface runoff water displayed a pattern similar to the shallow groundwater. The increase in sulfate and base cation concentrations during the experiment was slightly lower in run-off compared to the shallow groundwater. The chemical changes for runoff observed during the experimental period have been reversed since extraction was terminated. The hydrochemistry of shallow groundwater in the glacial till surrounding the wetland was, however, unaffected by the experiment (Paper I).

During the experiment, the chemistry of the groundwater in the fractured bedrock became more similar to that of the wetland and surface water (Paper I). Effects of changes in water chemistry in shallow groundwater in the wetlands were also reflected in the rock groundwater. The sulphate surges in the wetland groundwater were observed in boreholes that were quickly recharged by shallow wetland water as revealed in Figure 7-10. The elevated concentrations of sulphate in the bedrock groundwater during the experiment recovered quickly when the experiment was terminated. The increased recharge from shallow water also caused an induced acidification of more than 0.5 pH units in boreholes where low buffer capacity (e.g. HGF31) was measured (Paper I). Sulphate surges caused by natural variations in the groundwater level have been observed in the reference catchment at Lake Gårdsjön (Mossmark et al., 2008a) as well as in a number of catchments in Finland (Åström and Björklund, 1997). However, the groundwater extraction made this process more significant.

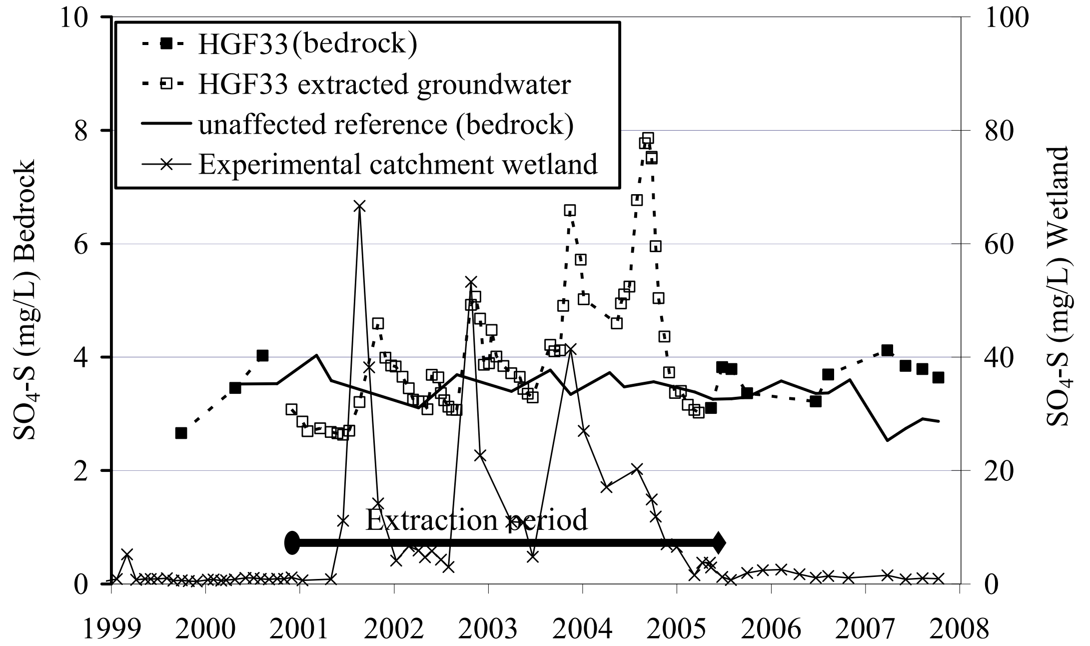


Figure 7-10. *Concentrations of sulphate in the groundwater of the bedrock and in a wetland affected by the groundwater extraction compared to the groundwater of the bedrock in a nearby reference catchment.*

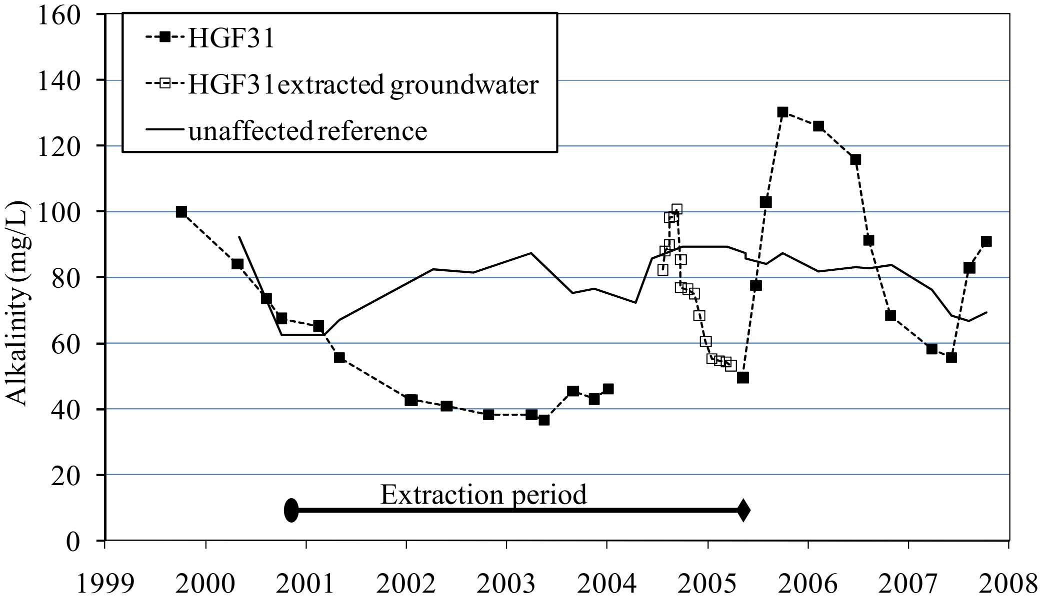


Figure 7-11. *Concentrations of Alkalinity in the groundwater of the bedrock in the catchment area affected by the groundwater extraction compared to a nearby reference. During the period from December 2000 to early 2004 the alkalinity in HGF31 decreased. There was a short intermission for the extraction during March 2004 when the alkalinity in HF31 recovered.*

After extraction was intensified in 2004 through the use of two boreholes, a decrease in pH also occurred in borehole HGF33 (Paper I). During this intensive final year of extraction, alkalinity also decreased in HGF33, whereas HGF31 exhibited a decreasing trend throughout the experiment (Paper I). The redox potential of the extracted groundwater from HGF33 increased throughout the extraction period, while chloride concentrations and electrical conductivity remained fairly unchanged (Mossmark et al., 2008a).

During the first three years after the groundwater extraction at Lake Gårdsjön was stopped, a pH recovery has been noted and sulphate surges have been absent. However, according to Paper II the concentrations of sulphate have persisted at slightly higher levels after the experiment compared to pre-experiment levels. In the reference catchment area F1, the concentrations of sulfate decreased during the same period (Paper II).

7.1.6 Conclusions from the Gårdsjön experiment

The extraction of the groundwater from the bedrock affected both hydrology and water chemistry within the experimental catchment. The resulting hydrochemistry is highly affected by the geological setting, Lake Gårdsjön is located approximately the same altitude as the maximal transgression following the most recent glaciation. Wave washing processes may have had an impact, but there has not been a sufficient sea depth for thick marine deposits, e.g. marine clays to form. The hydrological changes that were observed during the extraction period can be summarized as follows:

- Decreased surface runoff volumes.
- For the bedrock groundwater of the fracture zone underneath the wetland, a constant lowering of the groundwater table was observed.
- The groundwater table in the wetland displayed increased seasonal level fluctuations compared to the unaffected conditions. The groundwater levels became lower during the dry season (summer), but fully recovered every autumn and winter.
- The decrease in runoff volume was similar to the extracted groundwater volume. This indicates a local groundwater flow cell where the influence area has a relatively small extension.

When the groundwater extraction was terminated, the following changes were observed:

- The observed groundwater levels in the wetland and in the bedrock recovered within three to six months after the termination of the groundwater extraction.
- The runoff volume recovered gradually during the years after the groundwater extraction was stopped. After four years of recovery, the runoff volumes had still not recovered.

The decrease in runoff from the experimental catchment during the period with groundwater extraction was likely caused by increased groundwater recharge.

The following changes were observed for water chemistry during the extraction period:

- When the recovery of the water levels in the wetland occurred during the autumns, a steep increase in sulphate concentrations was observed in the groundwater. The high concentrations of sulphate gradually declined to slightly higher than pre-experimental levels during the springs.
- The high sulphate concentrations were accompanied by lower pH and steep increases for base cations such as calcium and magnesium in the groundwater of the wetland.
- For the groundwater of the bedrock, seasonal increases for sulphate were observed at the same occasions as for the shallow waters.
- During the extraction period pH and alkalinity in the bedrock groundwater decreased while the redox potential increased.
- The chloride concentrations and the electrical conductivity remained relatively unchanged compared to the unaffected conditions before the extraction.

During the extraction period, the dry season left some of the wetland dry and aeration could occur. When the water levels rose during the autumn, previously bond sulphur was likely oxidized and sulphuric acid was produced and released. The production of sulphuric acid caused acidification and magnesium and calcium were released through ion exchange with hydrogen ions.

The groundwater extraction caused an increase of groundwater recharge to the bedrock. During the pre-experimental phase, the groundwater of the bedrock likely had a residence time of many years. The groundwater extraction caused an increase of the groundwater recharge and induced a water flow towards the extraction point. The shortened residence time and the water flow towards the extraction point caused the chemical composition of the groundwater of the bedrock to become more influenced by the shallow waters. This explains the decrease for alkalinity and pH as well as the seasonal variations of sulphate concentrations that mirror the variations in the shallow waters.

8 DESCRIPTION AND RESULTS FROM IN-DEPTH DESK STUDIES

Three objects were studied through desk studies within the scope of this licentiate thesis. The studied objects included the Hallandsåsen railroad tunnel, a limited database from the Äspö Hard Rock Laboratory and an experiment with groundwater extraction in the northern parts of Äspö. The desk studies were primarily carried out as database studies of hydrochemical data with the inclusion of data for hydrological and geological conditions as well as biota for evaluation purposes.

8.1 Hallandsåsen rail tunnel

The project involves the construction of two parallel rail tunnels through a horst located in southern Sweden. Each of the two tunnels is 8.6 km long and completion is planned for the year of 2015. Construction commenced in 1992, but the progress has been significantly delayed during the construction phase on two occasions due to unexpected technical problems.

8.1.1 Timeline of the tunnelling project and construction method

The construction of the tunnels commenced in 1992 from the northern side of the Hallandsåsen ridge. In the initial phase a tunnel boring machine (TBM) was used. However, the TBM was soon found to be unfit for building a tunnel through the superficially weathered northern slopes of the Hallandsåsen ridge. The construction method was changed to regular drill and blasting.

The advantage of the drill and blasting method compared to the use of one TBM was the ability to construct the tunnel from more than one front. The two tunnels were built from both the northern and southern sides of the ridge. An additional adit halfway between the southern and northern slopes of the ridge was also opened to shorten the construction period. The construction came to a halt in 1997 after two groundwater related obstacles occurred. Leakage into tunnel during construction had depleted the groundwater supply in some production wells on the ridge. The grout that was used to improve the waterproofing system of the tunnel to address the depletion of the water supply caused acrylamide contamination of the groundwater and, in some instances, also of surface waters.

The construction activities were halted for remediation until 2003, when preparation for the completion of the tunnel commenced. The construction of the tunnel resumed in 2005 through the use of a tunnel boring machine. With the current use of one tunnel boring machine, construction is only carried out at one location at the time. The completion of the eastern tunnel is expected in the autumn of 2010 (Banverket, 2009).

8.1.2 Description of the area

The two tunnels are built through a horst which stretches in a south-easterly to north-westerly direction in the north western parts of the Scania Province in the south of Sweden. The horst is approximately 40 km long, 5 to 10 km wide and its maximum altitude is 226 m a.s.l..

The horst consists of crystalline rock, primarily granitic gneiss with dykes of dolerite as displayed in Figure 8-1. The dykes are generally oriented along the longitudinal direction of the horst, in a south-easterly to north-westerly direction (Annertz, 2009). The dolerite dykes have almost vertical dip. The matrix rock, the granitic gneiss, is generally fractured in the vicinity of the dolerite intrusions with fracture zones on both sides of the nearly vertical sheets of dolerite. The dolerite as well as the granitic gneiss have weathered surfaces and are fairly water-bearing at shallow depth. However, at larger depth the dolerite dykes have generally few water bearing fractures (Gynnemo, personal communication).

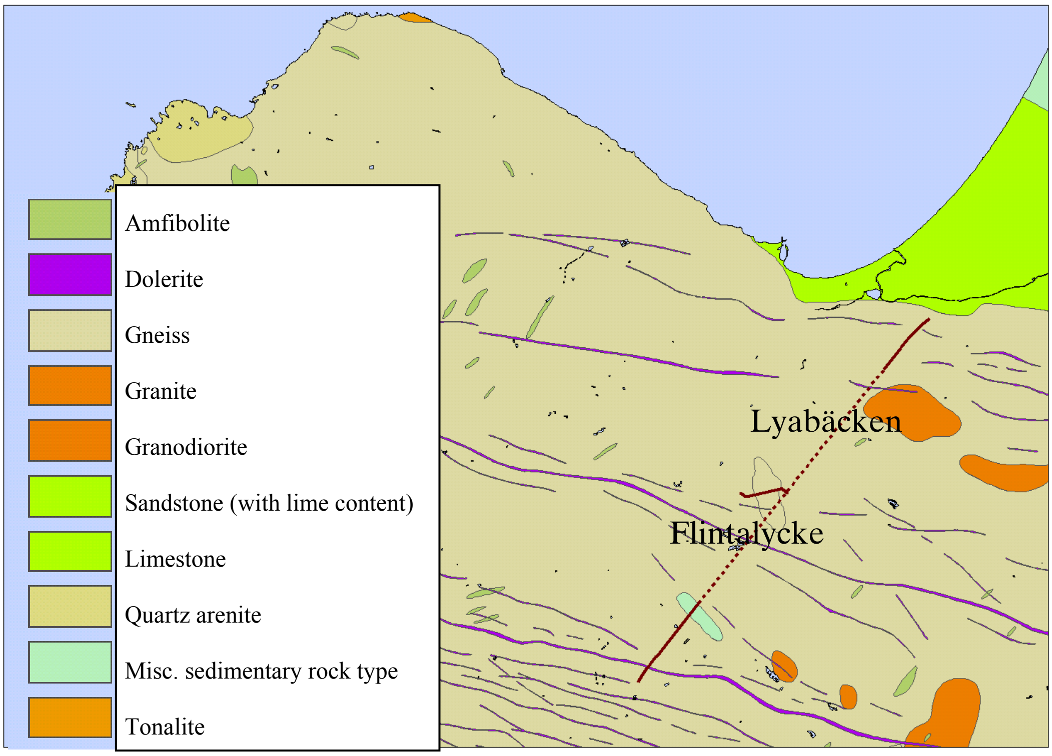


Figure 8-1. *Geological map displaying the bedrock at the Hallandsåsen horst. © Swedish Geological Survey.*

Alike many recently glaciated areas, the horst has an overburden that mainly constitutes of a thin layer of glacial till as displayed in Figure 8-2. Among other glacial deposits, glacifluvial sediments are also present, primarily along the Sinarpsdalen Valley to the west.

Along the slopes of the horst, wave washed sediments are present. However, areas with higher elevation have not been subject to marine transgressions following the most recent glaciation. According to the National Atlas of Sweden (1994), the most extensive transgression following the most recent glaciations period submerged areas situated below 50-60 m a.s.l. in the area of Hallandsåsen. Wetlands consisting of fens and bogs are present in hollows that constitute local groundwater discharge areas, these are common also within highland areas of the ridge. Hollows are commonly located above fracture zones since the fractured areas exhibit less resistance towards superficial weathering than the surrounding bedrock.

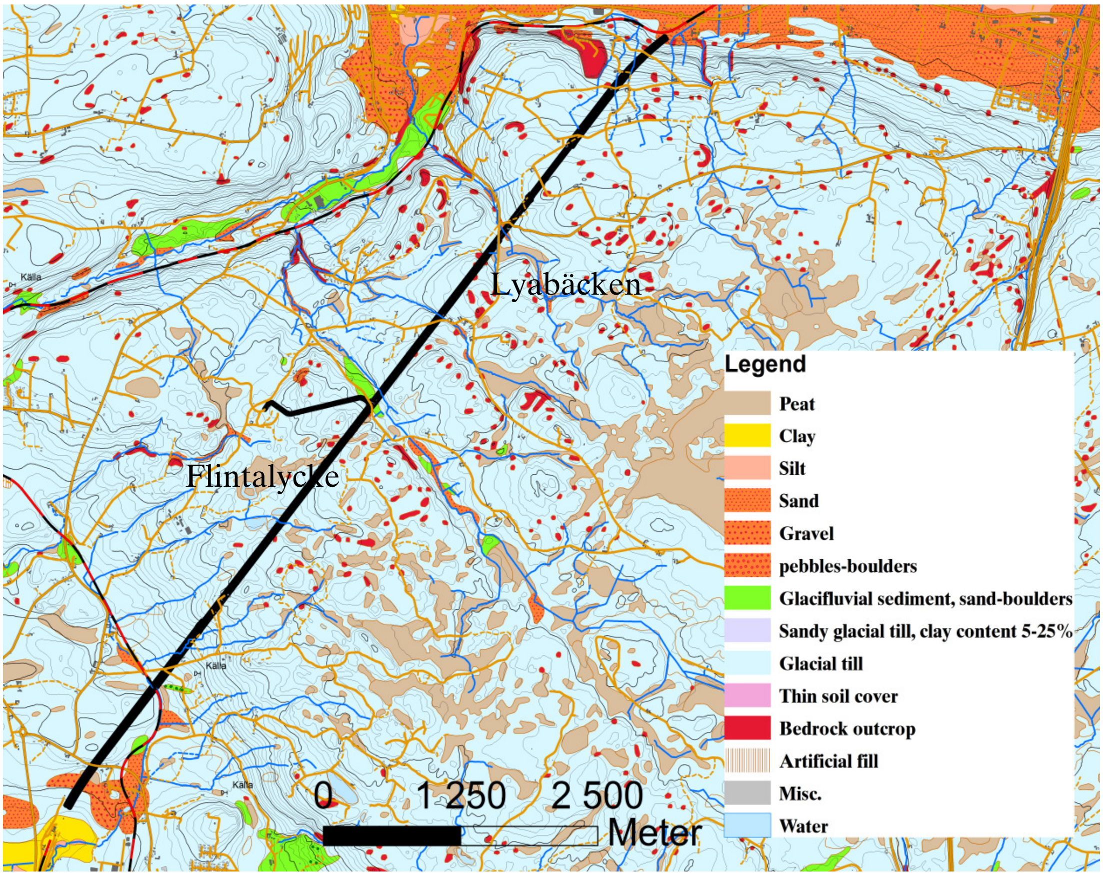


Figure 8-2. Quaternary deposits at the Hallandsåsen horst. © Swedish Geological Survey.

8.1.3 Impact to hydrology

Groundwater levels, surface water levels and runoff volumes have been affected by the tunnel construction. Some of the areas have been affected since the early years of construction (Björkman, in prep.). The construction resumed in the year 2005 using a tunnel boring machine. The most affected at the time of resumption were in the north and at the mid adit as displayed in Figure 8-3.

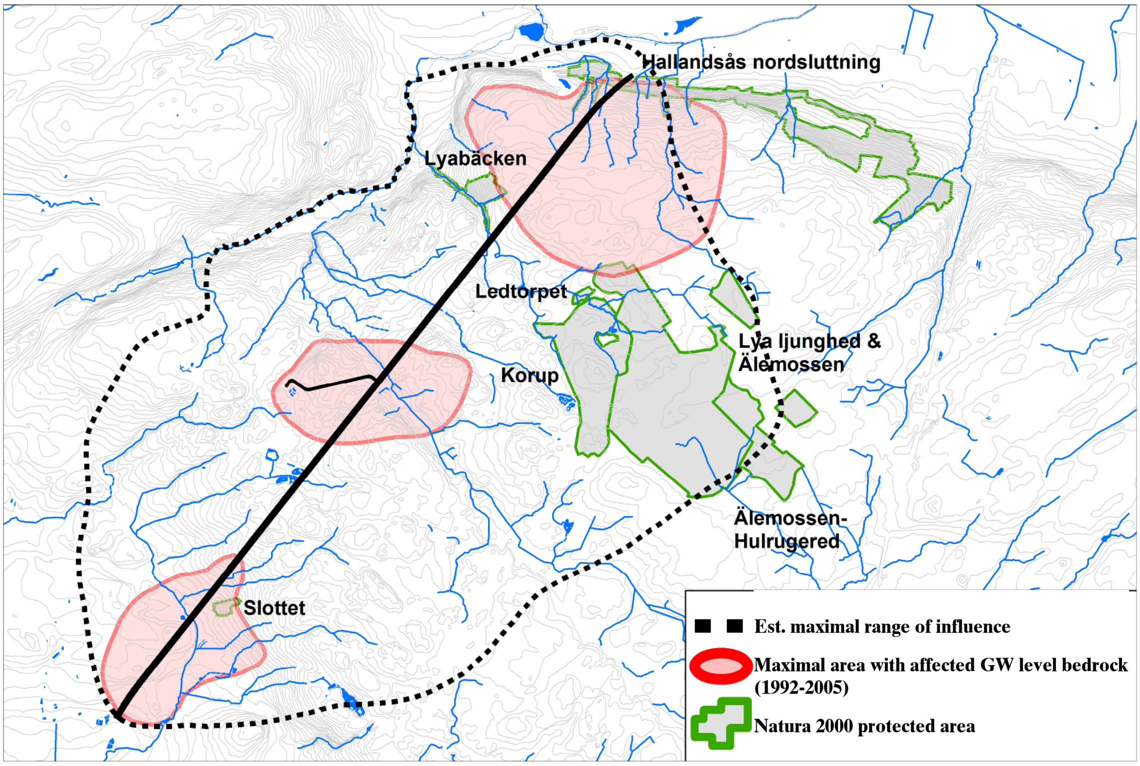


Figure 8-3. Areas with affected groundwater levels before the resumption of the tunnel construction in 2005 (Björkman, in prep).

The recent period with construction using the tunnel boring machine, the impact to groundwater and surface waters is more easily evaluated compared to the periods with drill and blasting since construction only occurs at one location at any time. Generally, the drawdown of the groundwater level at a location increases when the TBM and consequently the tunnel front approaches. When the tunnel front has passed and the waterproofing systems have been installed, a recovery of the groundwater levels to near pre-construction levels usually occur. The groundwater levels in three deep drilled boreholes along the tunnel are displayed in Figure 8-4. The levels in the three boreholes were affected when the TBM approached and recovery occurred when the TBM had passed and the waterproofing system had been installed.

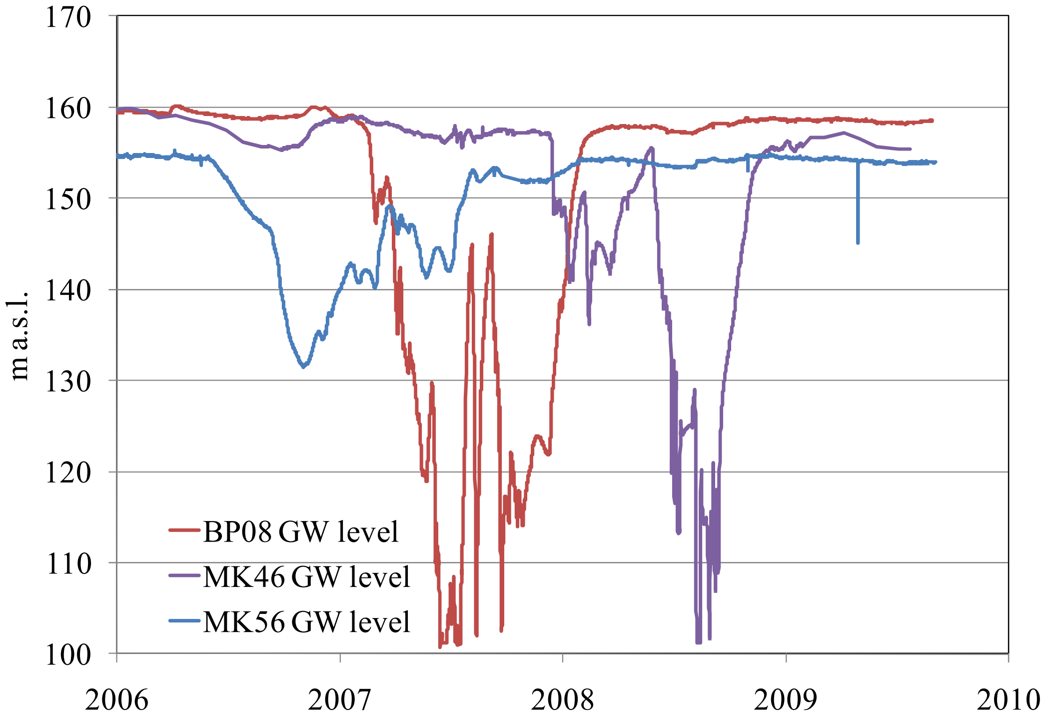


Figure 8-4. *Groundwater levels in three deep drilled boreholes located along the stretch of the tunnel. The groundwater levels decreased when the tunnel front passed and recovered after the water proofing systems in the tunnel were built. For some of the boreholes, e.g. BP08, the groundwater level did not fully recover during the presented monitoring period.*

The impact to the groundwater levels from the construction of the eastern tunnel with the use of the TBM during the years 2005 through 2010 has been discussed in Björkman (in prep.). Different parts of the ridge were affected as the tunnel was built from the south to the north. Figure 8-5 to Figure 8-8 display the different areas that were affected from leakage to the tunnel.

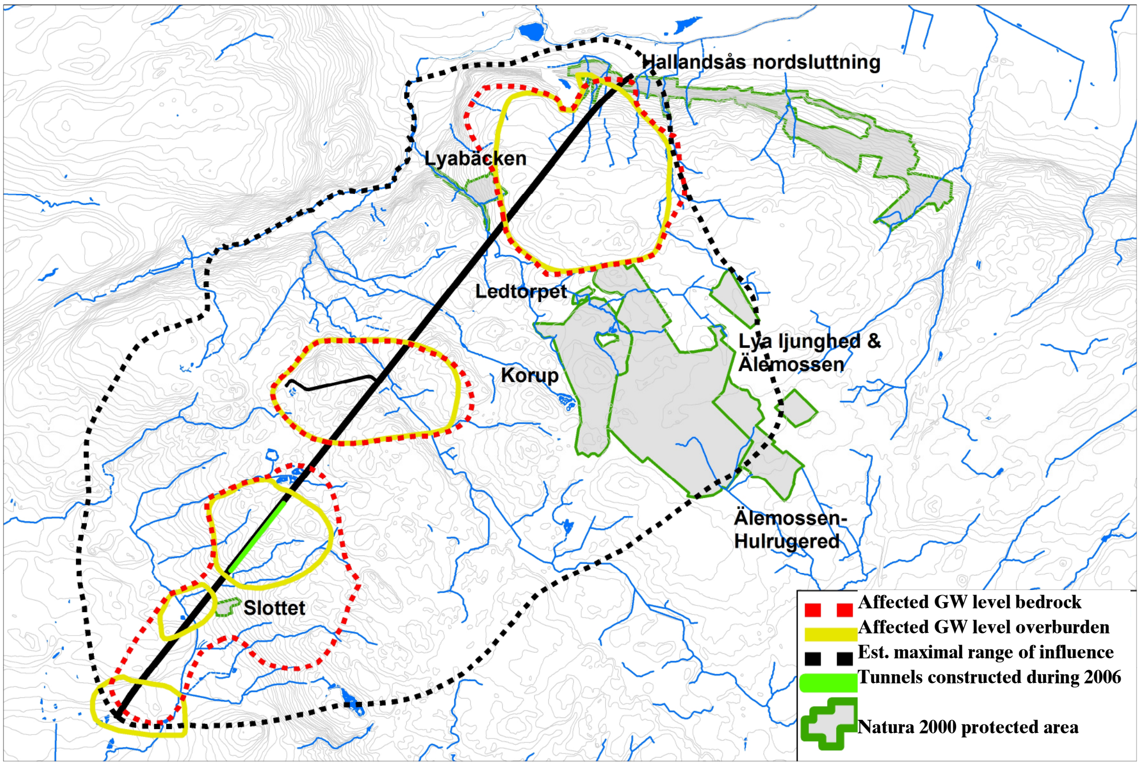


Figure 8-5. *Areas with affected groundwater levels in the bedrock as well as in the overburden during the year 2006 (Björkman, in pep).*

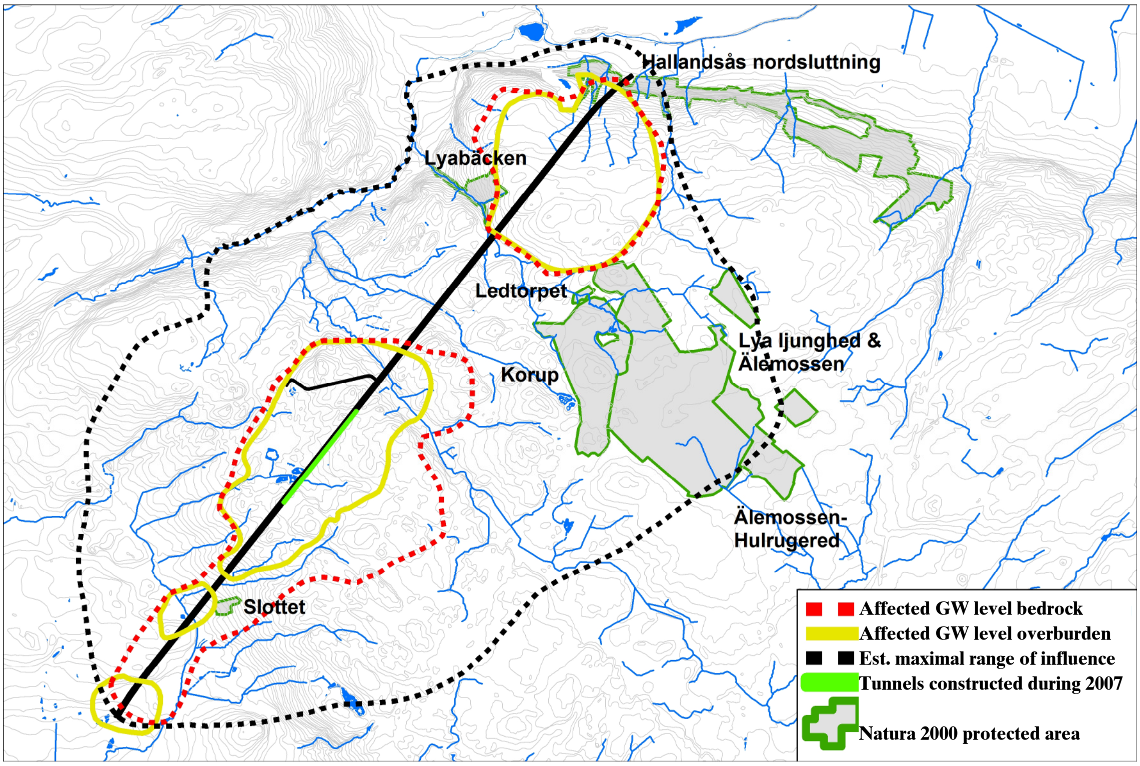


Figure 8-6. *Areas with affected groundwater levels in the bedrock as well as in the overburden during the year 2007 (Björkman, in prep.).*

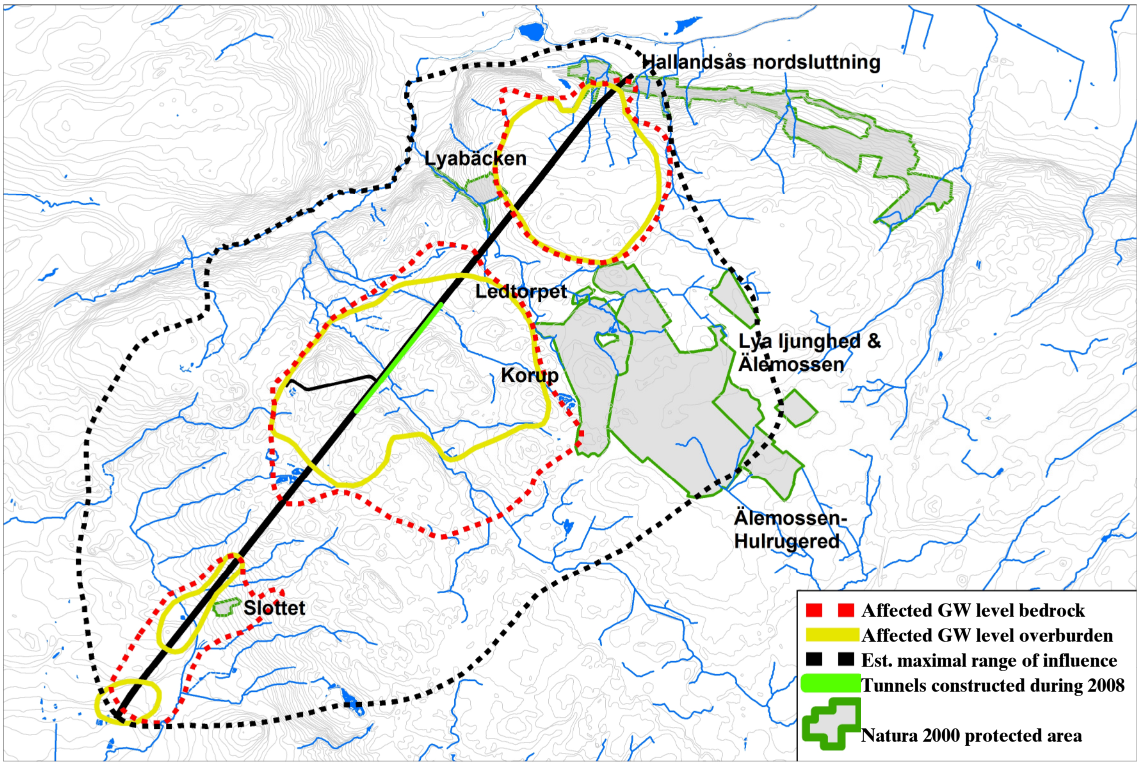


Figure 8-7. *Areas with affected groundwater levels in the bedrock as well as in the overburden during the year 2008 (Björkman, in prep.).*

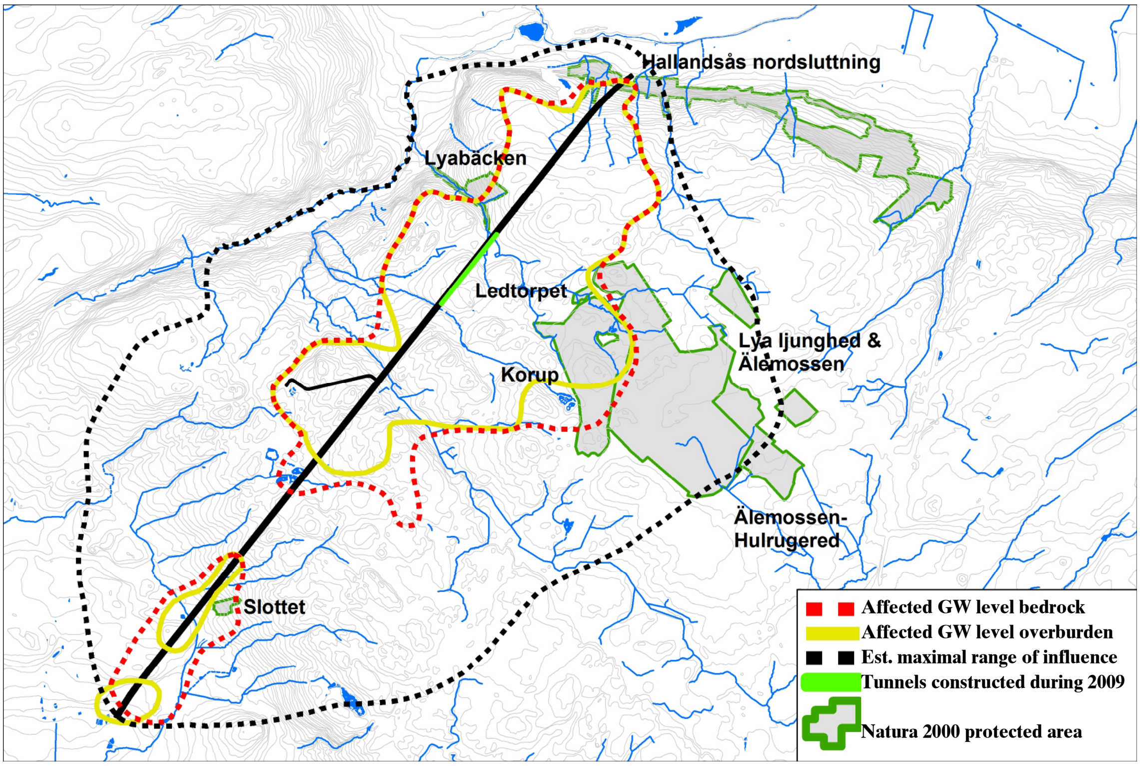


Figure 8-8. *Areas with affected groundwater levels in the bedrock as well as in the overburden during the year 2009 (Björkman, in prep.).*

8.1.4 Impact to water chemistry

The impact from the hydrological changes to the water chemistry is dependent on the surrounding environment. Factors that affect the resulting water chemistry include the original hydrochemical conditions as well as geological, biological and hydrological conditions. Notable changes to water chemistry have been observed in the vicinity of important fracture zones that intersect the tunnel.

8.1.4.1 Flintalycke

The groundwater aquifer in the bedrock in the Flintalycke area is affected by leaky boundary comprising an approximately 55 m thick dolerite dyke. Figure 8-1 and Figure 8-2 present the location of Flintalycke from a geological perspective. The contact zone with the matrix rock (gneiss), however, comprises a fracture zone with water bearing fractures (Björkman, in prep.).
Figure 8-9 shows the approximate location of a fracture zone and a wetland that were affected by the construction of the tunnel.

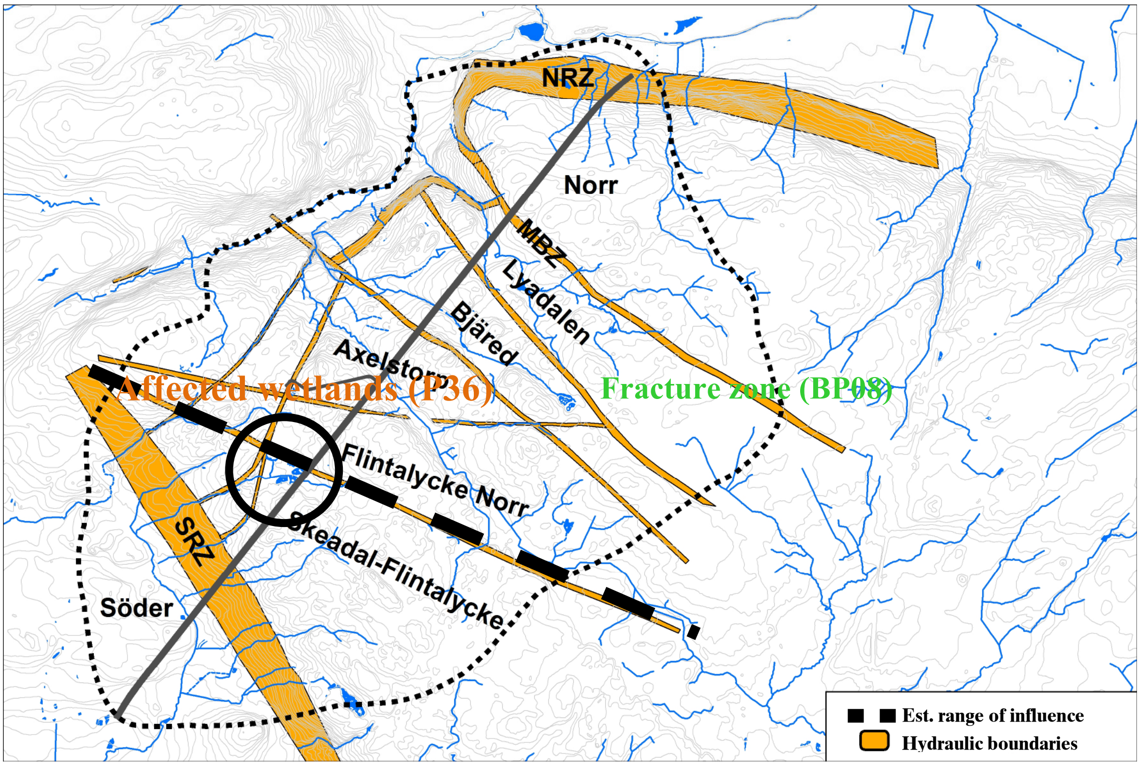


Figure 8-9. The figure displays zones with low permeability (marked yellow), the affected wetlands and the approximate location of the fracture zone (Björkman, in prep.).

The construction of the tunnel lowered the groundwater level in the fracture zone and in the wetland. The borehole BP08 intersects the fracture zone (Gynnemo, personal communication). Figure 8-10 reveals the lowering of the groundwater levels that occurred when the TBM passed the Flintalycke area during the year 2007. The construction of the tunnel also caused a lowering of the water levels in the wetland (Klingberg Annertz, personal communication).

The aeration of the wetlands likely caused oxidation of sulphur and the formation of sulphuric acid. The acid decreased pH in the surface waters (P36) as revealed in Figure 8-10. The groundwater of the bedrock was also affected with increased sulphate concentrations and lower pH as a result from groundwater flow from the wetland to the bedrock. The concentrations of TOC increased in the bedrock groundwater during the sulphate surge indicating a contact with shallow waters. A concentration increase for Total Organic Carbon (TOC) indicates influence from shallow waters.

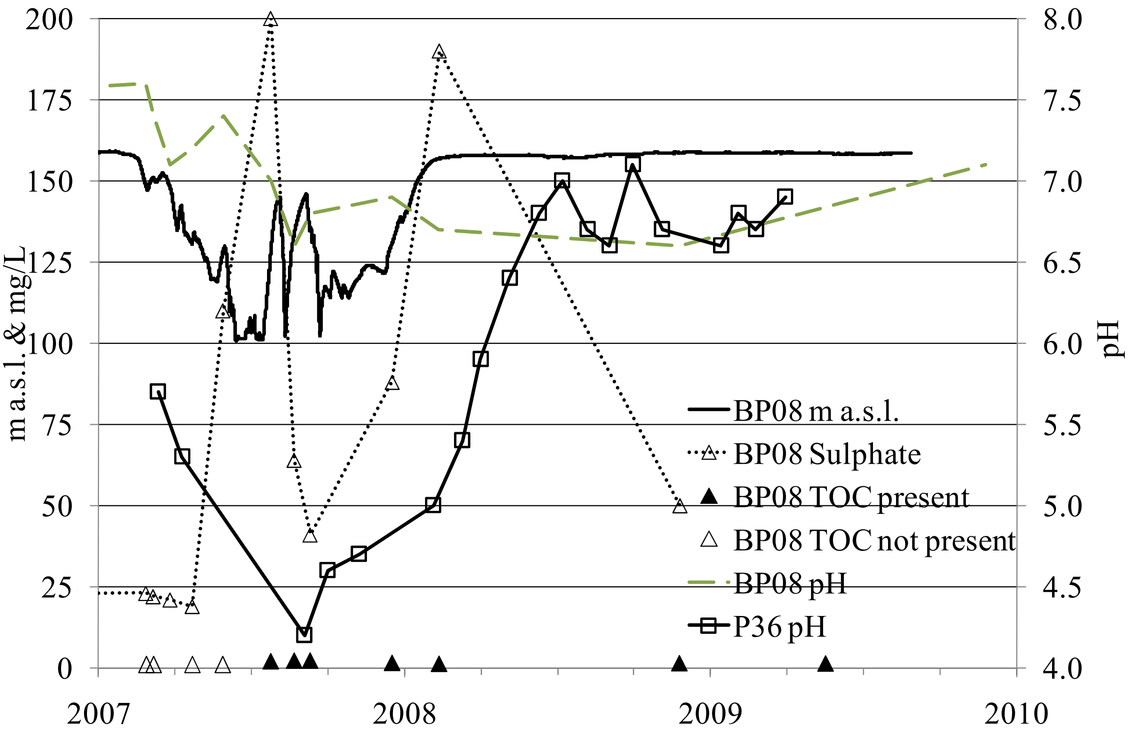


Figure 8-10. *Oxidation of a wetland in the Flintalycke area caused hydrochemical changes in surface waters as well as groundwater. Sulphur became mobilized and cause d a sulphate surge and acidification. The detection limit for TOC in the chemical analysis was 1 mg/L.*

8.1.4.2 Lyabäcken

The tunnel boring machine penetrated the Bjäredsbäcken zones in late 2008 and early 2009, the location of Lyabäcken is presented in geological context in Figure 8-1 and Figure 8-2. According to Björkman (in prep.) these zones comprise negative hydraulic boundaries. As the tunnel front passed the zone, the groundwater levels in the bedrock on the northern side became affected. Recovery of the groundwater levels occurred when the TBM penetrated another zone comprising a negative hydraulic boundary south of the Lyabäcken brook and the waterproofing system of the tunnel between these two boundaries were completed. The zones comprising the negative boundaries are displayed in Figure 8-11.

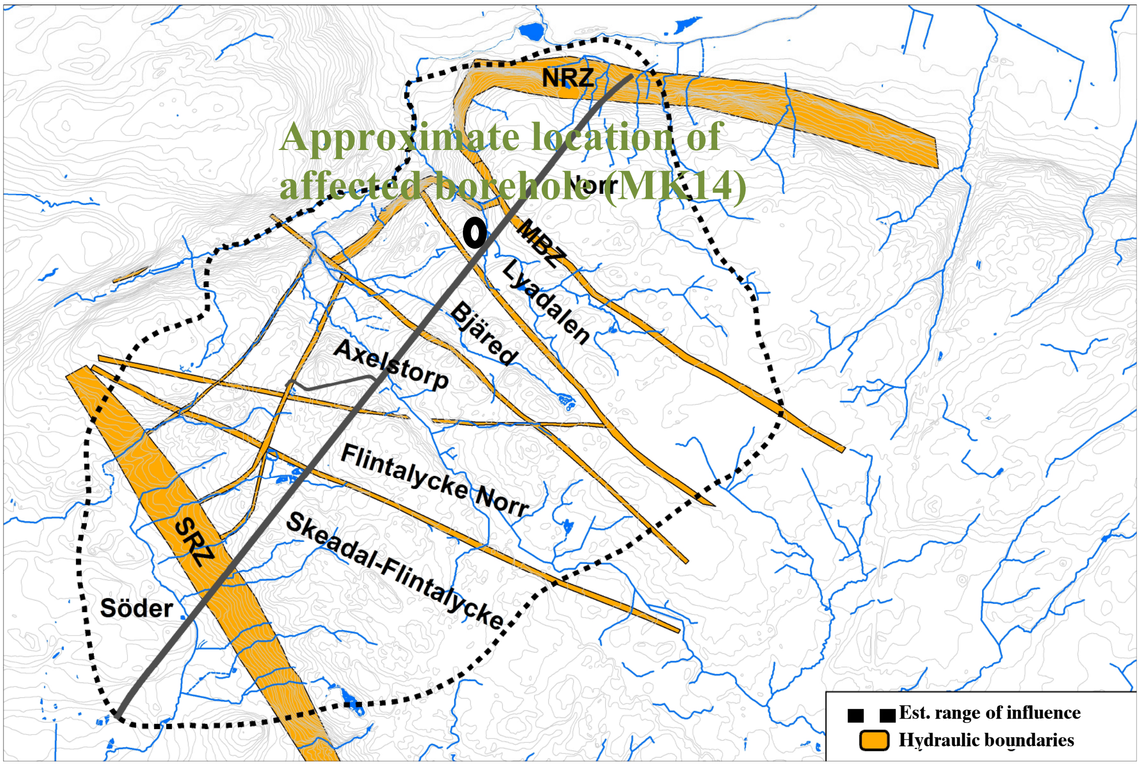


Figure 8-11. *The area south of Lyabäcken was hydrochemically affected during the construction phase of the eastern tunnel.*

The groundwater levels of the affected borehole are presented in Figure 8-12. During the period when the recovery of the groundwater levels occurred in mid 2009, a sulphate surge was observed. A decrease in pH levels was also observed. Chemical analysis presented content of TOC in the bedrock groundwater at the same time as the sulphate concentrations increased, before the sulphate surge the TOC content was undetectable. The presence of TOC indicate significant recharge of shallow waters. However, unlike at Flintalycke large wetlands that could constitute significant sulfur pools are not present in the vicinity of MK14. A possible explanation of the sulphate surge could be an oxidation of sulphide containing fracture minerals that were observed during the drilling of the borehole (Klingberg Annertz, personal communication).

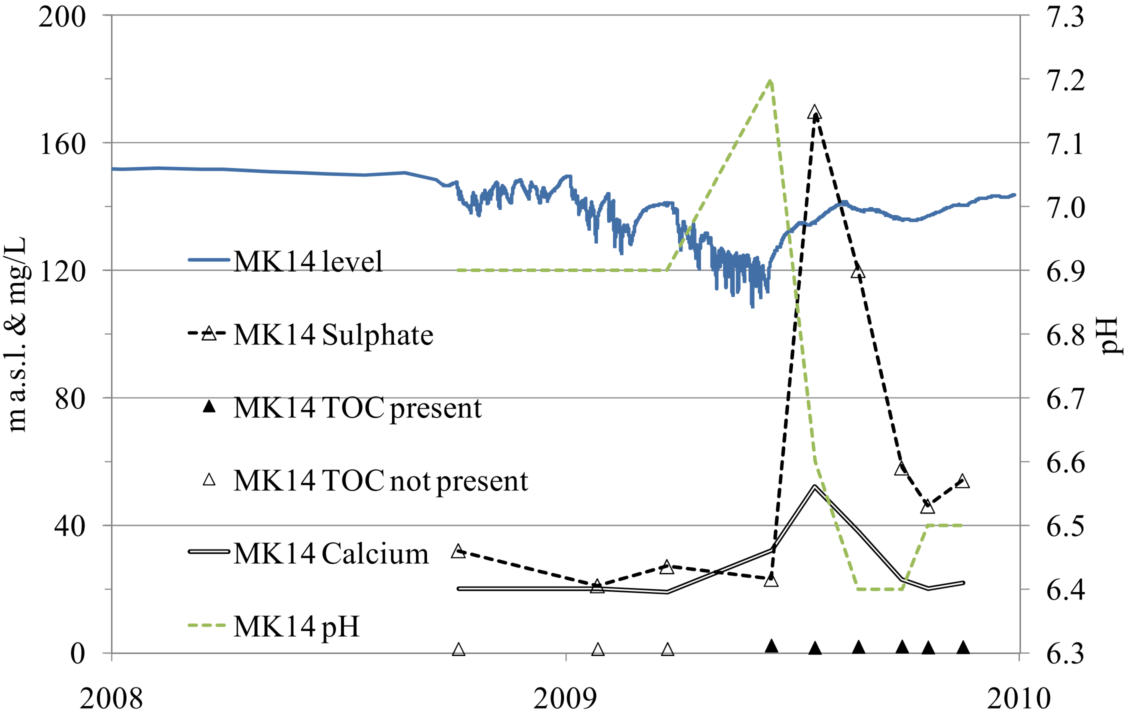


Figure 8-12. *Groundwater levels, sulphate concentrations, TOC and pH in an affected deep drilled borehole (MK14) located south of the Lyabäcken zone. The detection limit for TOC in the chemical analysis was 1 mg/L.*

8.1.5 Conclusions for the Hallandsåsen rail tunnel

The most significant impact to groundwater levels and water chemistry were found for locations that comprise discharge areas under the pre-construction phase. For those areas, the direction of the water flow was changed. Furthermore, these areas are often associated with wetland or streams at the surface and with fracture zones in the bedrock. However, under specific geological conditions, groundwater recharge areas were also significantly affected.

Wetlands constitute deposits of nutrients and sulphur as well as a diverse biota. These areas are sensitive to hydrological changes such as a lowering of the groundwater level. The surface waters as well as the groundwater of the bedrock in one such area were observed to become acidified when the tunnel front passed.

The location (Flintalycke) exemplifies a discharge area that has not been subject to a marine transgression following the most recent glaciation period.

An important negative impact to the water quality was also observed in a groundwater recharge area in the Lyabäcken area. Pyrite (contains sulphur) in the fractures was oxidised and sulphuric acid formed, leading to decreased pH.

8.2 The Äspö Hard Rock Laboratory

A repository located at large depth in hard rock is the method suggested by the Swedish Nuclear Fuel and Waste Management Co for the storage of nuclear fuel from Swedish nuclear energy reactors during the time of the decay of nuclear activity. The Äspö Hard Rock Laboratory was built during the 1990's as a rehearsal for such repository.

The structure of the laboratory consists of a tunnel that exits on the mainland to the south. In the northern parts of the facility, the tunnel spirals down to an approximate depth of 460 m. In the centre of the spiral, a vertical elevator shaft has been constructed. The elevator shaft exits on the southern parts of the island of Äspö (SKB, 2008).

8.2.1 Description of the area

The petrology and mineralogy of the island of Äspö has been mapped and reported in gradually more detail during the last 25 years. According to Lundegårdh et al. (1984) and Gustafson (1989) the dominant rock type on the island of Äspö is a medium grained reddish-grey granitoid. The granitoids has intrusions of granites, pegmatite, dolerite and mylonite (Gustafson, 1989). According to Tullborg (1997), calcite and chlorite are the two most common fracture minerals. However, water bearing fractures also contain epidote, fluorite, hematite, Fe-oxyhydroxides and clay minerals (Tullborg et al., 1991).

According to Påsse (1997), the most recent glaciation ended 12150 BP and was followed by a regression of the Baltic sea. The highest shoreline after the most recent glaciation is located at approximately 100 m a.s.l.. The succession of different environments following the most recent glaciation has been decisive for the composition of the overburden as well as the chemical composition of waters at various depth.

For the formation of the overburden, the ice sheet primarily deposited a crushed inorganic soil type directly above the bedrock (glacial till). After the retreat of the ice sheet, it was followed by transgressions with marine and lacustrine environments. During this period well sorted deposits such as clays were formed. During the coastal regression, previous sediments were subject to wave washing processes. After the regression, primarily organic soils such as sphagnum peat have formed in the groundwater outflow areas.

During the glacial period, primarily during the melting period when the border of the ice sheet retreated high water pressure from the ice sheet injected meltwater into the groundwater (Laaksoharju, 1999). After the retreat of the ice sheet, transgressions with periods of both marine (or brackish) and lacustrine waters occurred (Påsse, 1997). According to Laaksoharju (1999), injection of saline water occurred during the periods with brackish water. The cause of the injection was the higher density of the saline waters of the sea compared to the less saline groundwater. During the period of the Littorina Sea (8000 BP to 2000 BP), the salinity of the sea was up to twice as high compared to the Baltic sea of today. Consequently, the density force for the injection as well as the penetration depth of the seawater into the groundwater reached its maximum during the Littorina period. After the regression of the sea from the island of Äspö, a shallow groundwater zone of meteoric water was formed like pillow on top of the more saline deep groundwaters (Laaksoharju, 1999). Brine waters with older origin than the Littorina Sea has also been observed.

8.2.2 Hydrogeochemical impact from the construction of the HRL

According to Banwart et al. (1999), the groundwater recharge increased fifty times and residence times decreased during the construction phase of the Äspö HRL compared to the pre-construction period. During the construction and operational phases of the laboratory, the leakage of groundwater has caused increased water flow, mainly towards the facilities. Figure 8-13 displays a model of the different groundwater types in the vicinity of the laboratory.

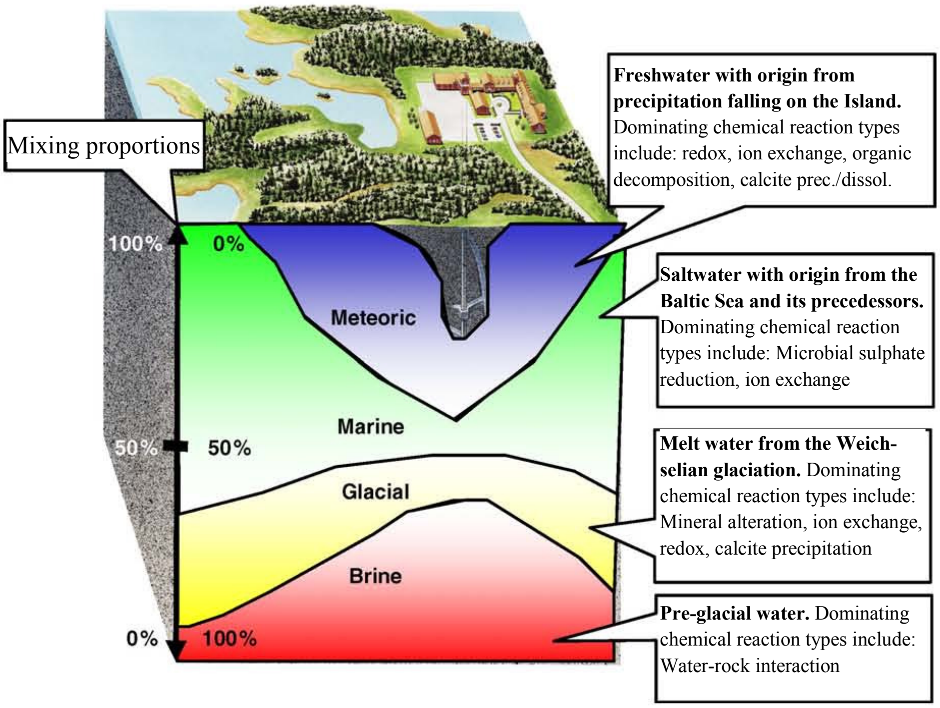


Figure 8-13. Model of the different groundwater types and the primary geochemical reactions in the surroundings of the Äspö Hard Rock Laboratory (modification applied to Laaksoharju et al., 2008).

Upconing of deep brine waters were observed during the construction and operational phases of the Äspö HRL as displayed in Figure 8-14 (Laaksoharju, 1999). The chloride concentrations have gradually increased in the deeper parts of the laboratory (Laaksoharju, pers. Comm.). Furthermore, the shallow waters of meteoric origin penetrated deeper into the bedrock (Laaksoharju, 1999)

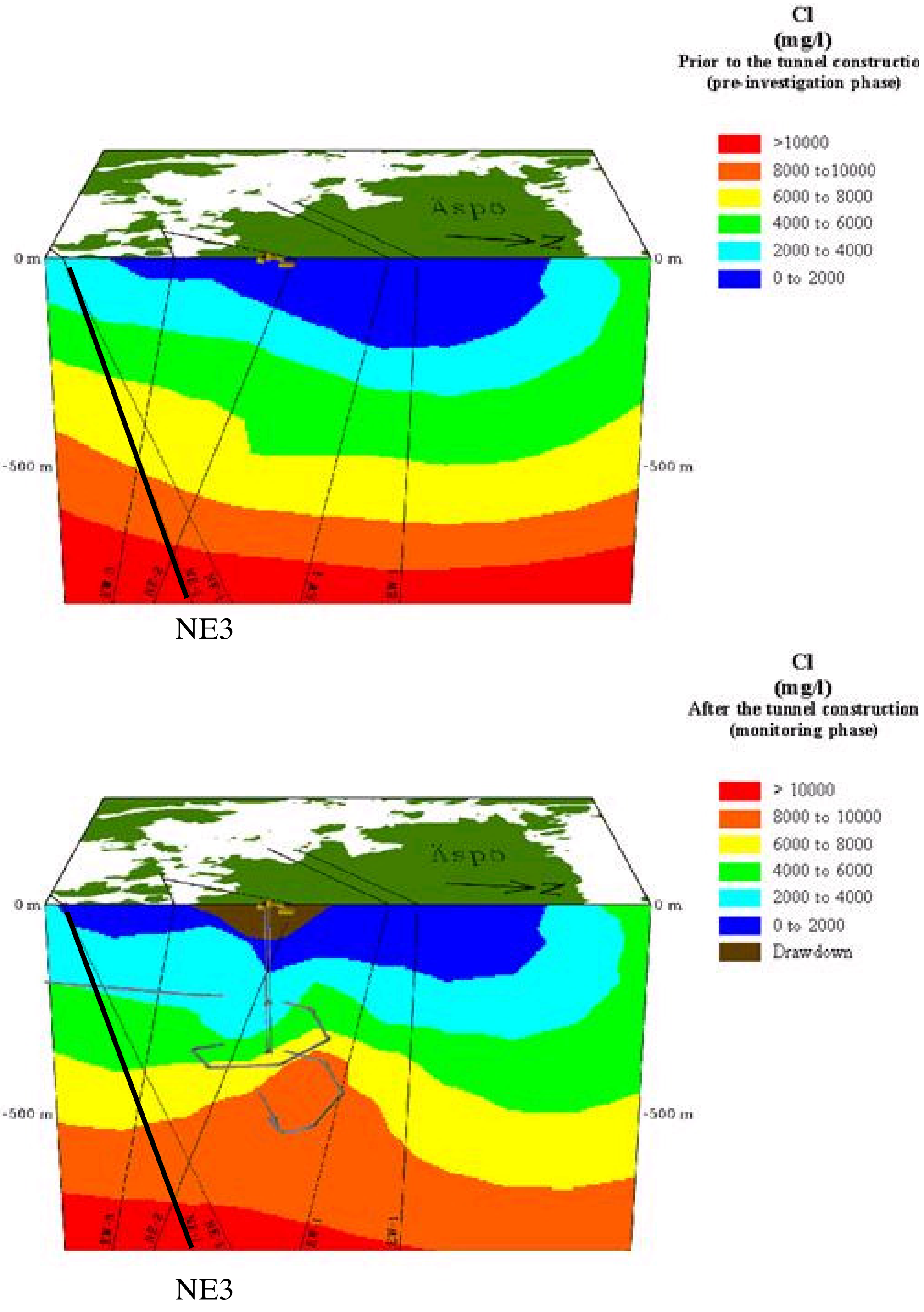


Figure 8-14. *The construction of the Äspö HRL caused upconing of saline waters and deeper penetration of shallow meteoric waters (Laaksoharju et al., 1999). The models also describe the locations for some of the studied fracture zones, Bockholmen is located to the south of the area included in the model where the tunnel runs at a more shallow depth.*

According to Banwart et al. (1999), the increased groundwater recharge caused a raised concentration of Dissolved organic carbon (DOC) in the groundwater of the bedrock. The concentration of DOC represents the content of organic compounds, which are representative for shallow waters. The recharge also caused vertical flow of more oxidized waters. However, the increase of concentrations of DOC caused an increase in microbial activity. The microbes consume oxygen and anaerobe conditions remained in the deep groundwater (Banwart et al., 1999).

During the construction phase of the HRL, changes to water chemistry were monitored. The results have been presented in several reports, among others in Rhén et al. (1997). In a percussion borehole crossing the fracture zone NE3 (location presented in Figure 8-14), six groundwater samples were collected during the construction phase. As indicated by Figure 8-13 and Figure 8-14, the fracture zone is in connection with different types of water and intersects the tunnel at an approximate depth of 150 m below sea level. According to Rhén et al. (1997), a gradual increase of shallow meteoric water content was observed, at the same time the previous dominance of water with origin from the Baltic Sea decreased. Figure 8-15 reveals a decreasing trend for Magnesium and an increasing trend for sulphate. The decreasing trend for magnesium may be caused by shallow waters replacing Baltic sea water (with high magnesium content).

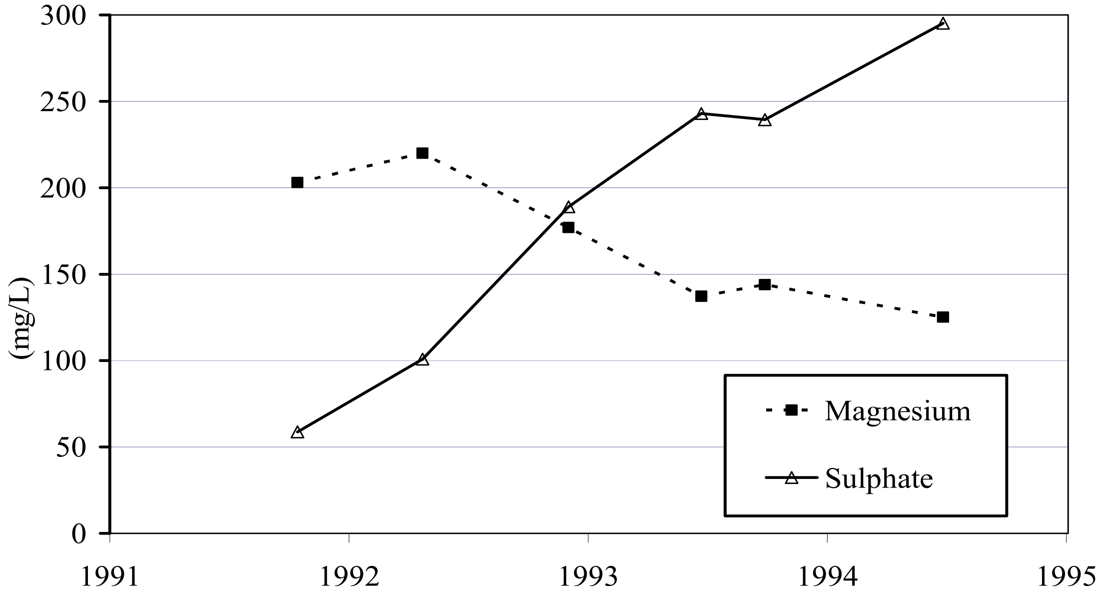


Figure 8-15. The construction of the Äspö HRL caused decreasing magnesium and increasing sulphate concentrations in the NE3 fracture zone (Rhén et al., 1997).

The sulphate concentrations in NE3 were lower than expected in the pre-construction phase. According to Rhén et al. (1997), the likely reason for this was microbial reduction of sulphate to sulphide. The initially low values for sulphate increase gradually to match the expert judgement made prior to the construction phase.

At a location where the depth to the tunnel from the land surface is shallower (approximately 70 m below sea level), beneath the island of Bockholmen, the water chemistry responded differently to the construction activities compared to at the NE3 fracture zone. During the initial construction phase, the magnesium and sulphate concentrations increased. After the tunnel front had passed this location, the concentrations decreased (Figure 8-16). According to Rhén (1997), similarly, the chloride concentrations at this location increased steeply when the tunnel front passed this location. The concentrations of chloride decreased when the tunnel front had passed. The increased concentrations of sulphate, magnesium and chloride indicate influence from marine waters during the initial period of the construction phase.

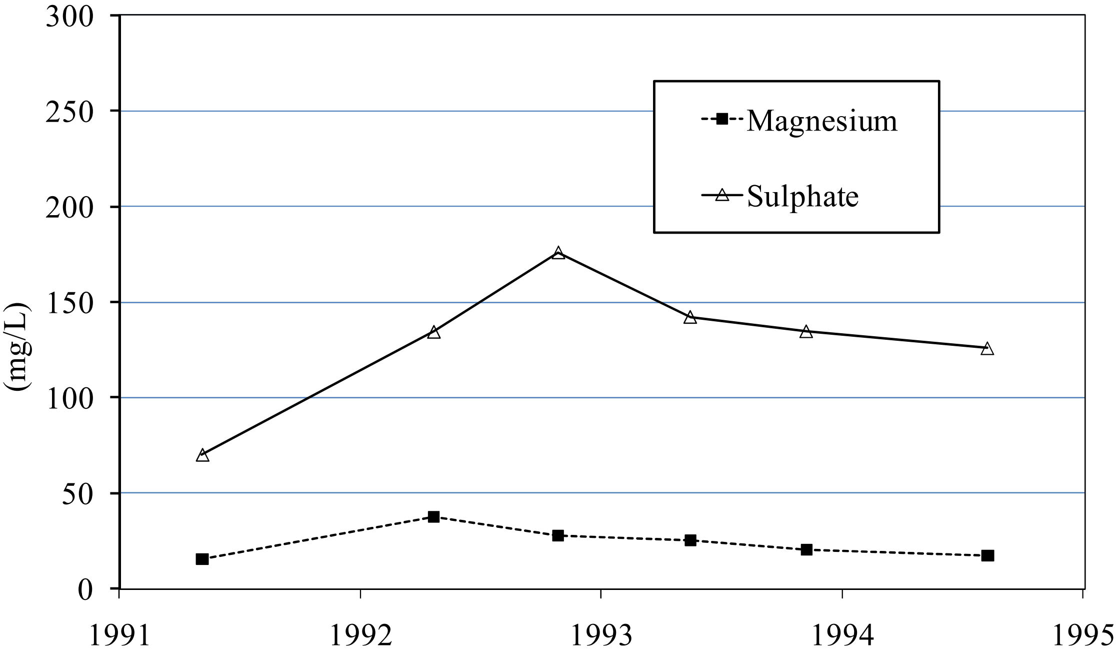


Figure 8-16. The construction of the Äspö HRL caused an increase of magnesium and sulphate concentrations in the bedrock below the island of Bockholmen (Rhén et al, 1997).

The monitoring at the island of Bockholmen was carried out with the purpose to monitor changes to the redox conditions. It was expected that shallow oxidized water would reach the tunnel within a timespan of 1.5 days to 5 years. However, the redox front did not reach the tunnel beneath the island of Bockholmen during the monitoring period of the experiment due to biological oxygen consumption (Rhén et al., 1997).

8.2.3 Conclusions from the studies at Äspö HRL

During the constructional and operational phases of the laboratory, the leakage of water into the facilities caused hydrological and hydrochemical changes. Groundwaters of different origin and of different composition are present in the bedrock in the vicinity of the facilities. Two important hydrochemical changes were an upconing of saline brine waters to the deeper parts of the laboratory (approximately 500 m below sea level) and a deeper penetration of shallow meteoric waters from the island of Äspö.

Where the tunnel passed beneath the island of Bockholmen in the Baltic sea at relatively shallow depth (less than 100 m below sea level), the influence from marine waters increased compared to the pre-constructional conditions. The construction of the facilities caused increased groundwater recharge to the bedrock with shallow water that naturally contained more organic matter (measured as DOC) and oxygen. However, the degradation process of DOC consumed most of oxygen and may have caused a reduction of sulphate. The redox conditions in the groundwater remained largely unchanged.

The Äspö HRL exemplifies a location that has been exposed to marine (and lacustrine) transgressions following the most recent glaciations period. However, the area of the Äspö HRL is also currently located at the shore of the Baltic Sea, which has an influence to the groundwater chemistry. The hydrochemical changes that have been observed include those that make the groundwater more aggressive towards the construction materials with e.g. increasing concentrations of sulphate and chloride in some locations. However, the changes at some other locations have been observed to make the less aggressive, e.g. with decreasing chloride concentrations.

8.3 Groundwater extraction in the northern part of the island of Äspö

A study of the hydrochemical and hydrological impact from groundwater extracxtion was carried out on the northern part of the island of Äspö. The study was similar to the one carried out at Lake Gårdsjön. Prior to the initiation of the groundwater extraction, two small watersheds were studied in an unaffected state for two years. Groundwater was extracted during two and a half years, from mid 1999 through the end of 2001.

The results and analysis from the study of hydrochemical variations prior to the initiation of the extraction have been presented in Knape (2001). Hydrochemical results from the period with groundwater extraction from inside one of the two watersheds has been presented in Knape Hansén (2002). Results for hydrology, hydrogeology and climatic measurements have been presented in Graffner (2005).

8.3.1 Description of the area

The experiment with groundwater extraction was carried out in the vicinity of the Äspö Hard Rock Laboratory (HRL). The area has similar geological conditions to the HRL, but the experiment affected a smaller area than the laboratory. As mentioned in chapter 8.2.1, the bedrock of the area constitutes Småland-Värmland granitoids, this includes quartzsyenite, granite and granodiorite (Lundegårdh et al., 1985). The most recent glaciation ended 12150 B.P. (Påsse, 1997) and has followed by a regression of the Baltic sea. The highest shoreline after the most recent glaciation is located at approximately 100 m a.s.l.. The succession of different environments following the most recent glaciation has been decisive for the composition of the overburden. The ice sheet that primarily had deposited a crushed inorganic soil type directly above the bedrock (glacial till), was followed by transgressions with marine and lacustrine environments. During this period well sorted deposits such as clays were formed. During the coastal regression, previous sediments were subject to wave washing processes. The area is located a few metres above the sea level. After the regression, primarily organic soils such as sphagnum peat have formed in the groundwater outflow areas.

About two thirds of the surface area of the two watersheds that were studied consisted of uncovered bedrock. Glacial till constitutes the surface of 10 % to 15 % of the two areas, and clay constitutes about 5 %. Organic wetlands constitute the most common soil type in the surface, constituting between 10 % to 20 % (Knape, 2001). It should be noted that as a result of the historical sequence of different environments of the area following the glaciation, clay can in some cases be found as a sublayer beneath the organic soils. Glacial till can in some locations be found as a sublayer to both clay and organic soils. Figure 8-17 describes the topography at the two watersheds that were monitored.

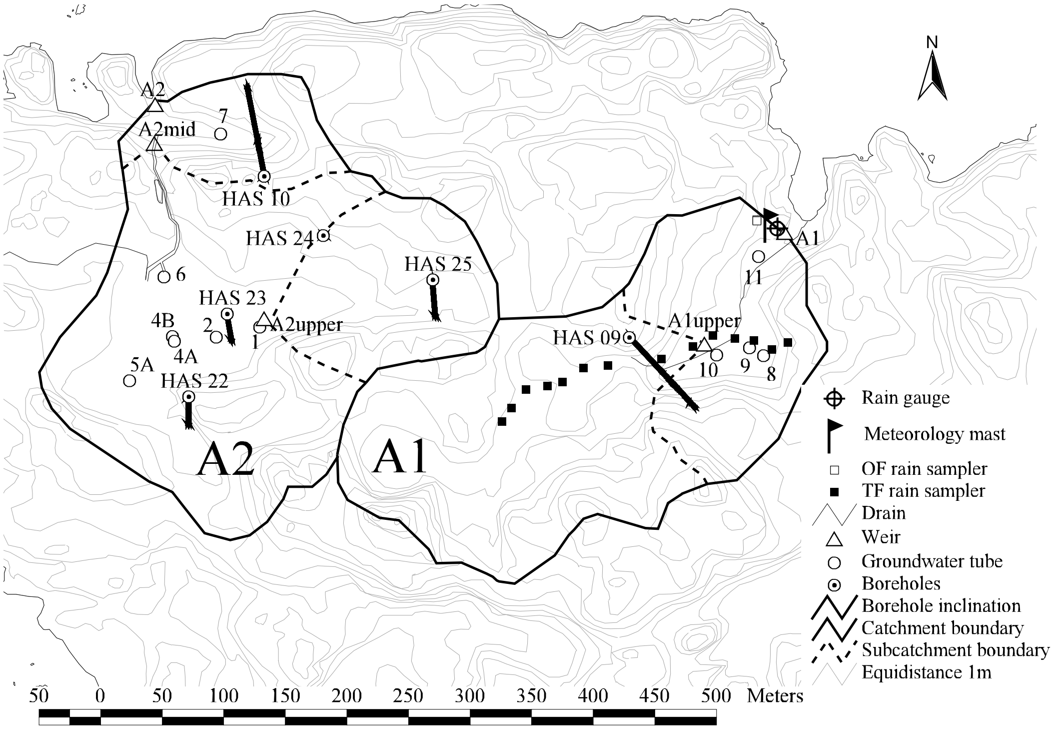


Figure 8-17. Topographical map revealing the instrumentation at the location for the groundwater extraction at the island of Äspö (Knape Hansén, 2002).

8.3.2 Results

According to data presented in Graffner (2005), the groundwater extraction had a small impact on the annual runoff volume. As displayed inFigure 8-18, the runoff from the area with groundwater extraction was smaller than from the reference area during the two years with the largest extraction volume. The impact on groundwater levels in the overburden was also small. However, one of the boreholes in the bedrock located nearby the one borehole used for groundwater extraction was affected.

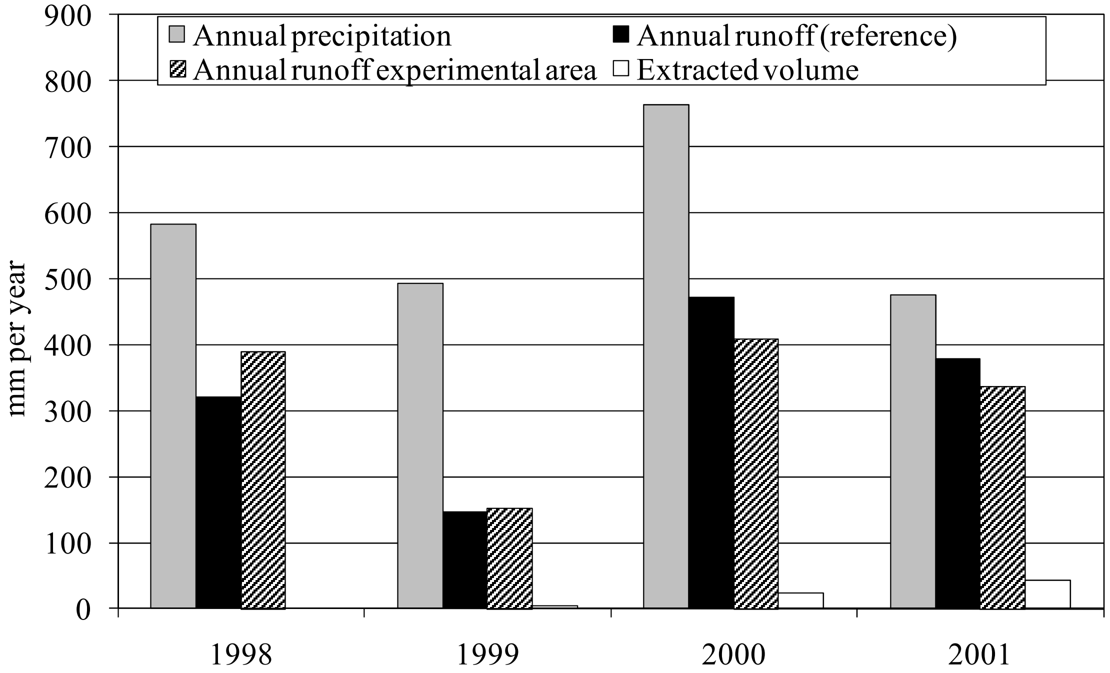


Figure 8-18. Water budget for the two monitored watersheds located on the island of Äspö. Data according to Graffner (2005). Groundwater extraction was carried out from mid 1999 to the end of 2001.

The extraction caused more evident changes for hydrochemistry than for hydrology. The groundwater chemistry of the extraction borehole came to resemble the chemistry of the shallow waters. Figure 8-19 displays an increase of sulphate concentrations in the extracted groundwater. The time based variations of the sulphate concentrations of the borehole mimic those of the shallow filter well GV5. Concentrations of chloride and pH also indicated that the groundwater of the bedrock became more similar to shallow waters as displayed in Figure 8-20 and Figure 8-21. Figure 8-22 displays time based hydrochemical changes in the extraction borehole in a multi-axis Piper graph (Mossmark, 2003).

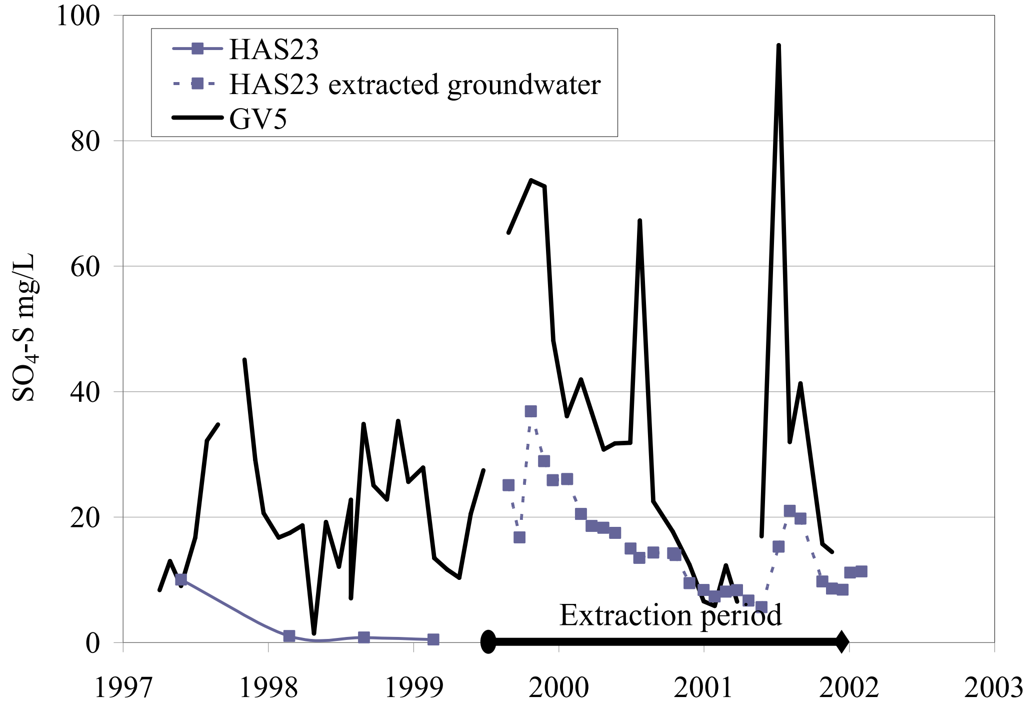


Figure 8-19. *The groundwater extraction caused an increase of sulphate concentrations in the extraction borehole. The time based variations in the borehole mimics those in the shallow groundwater (GV5). Data according to Knape Hansén (2002).*

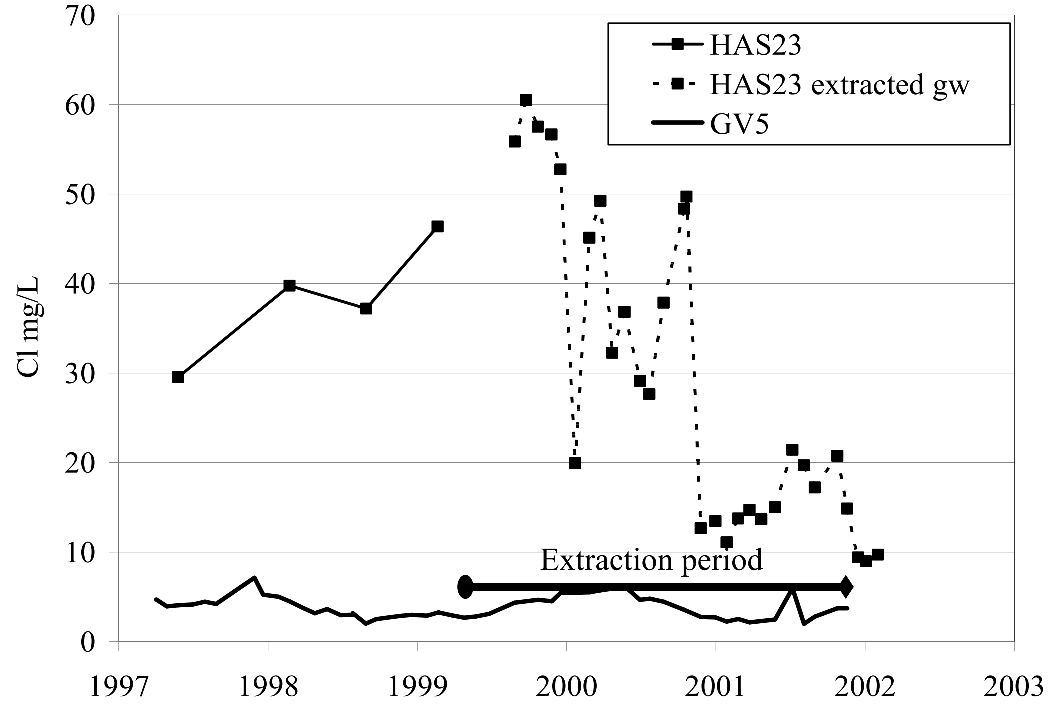


Figure 8-20. *Decreasing chloride concentrations in the extracted groundwater. Data according to Knape Hansén (2002).*

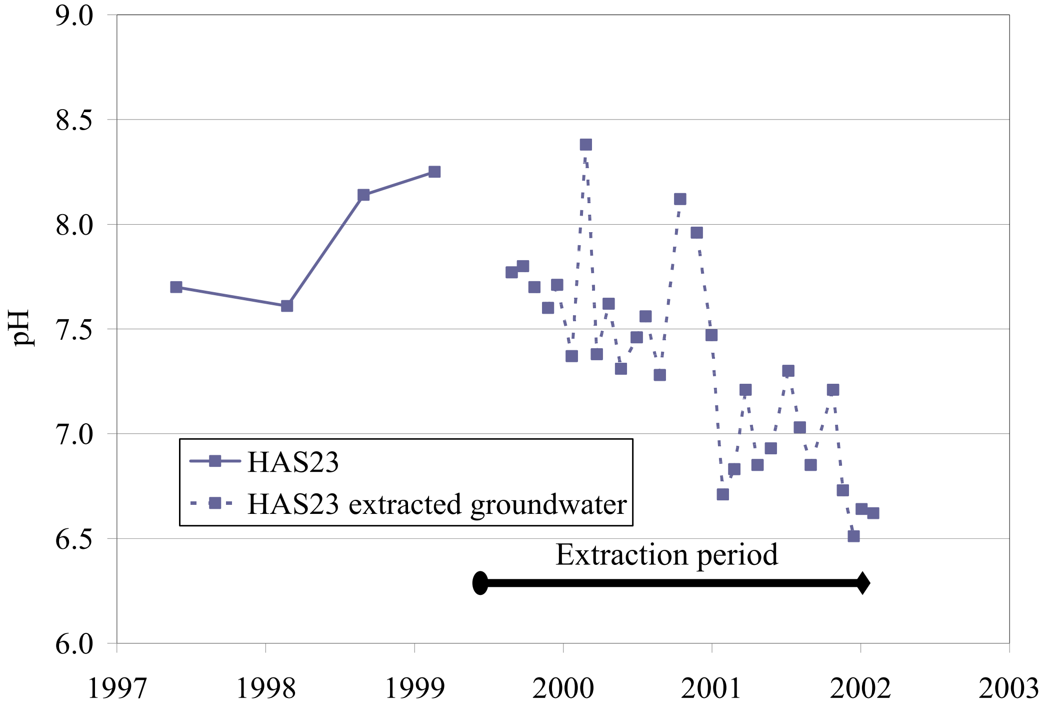


Figure 8-21. *During the period with groundwater extraction, pH gradually decreased in the extraction borehole. According to Knape (2001), pH of the shallow groundwater is usually between pH 4 and pH 6.*

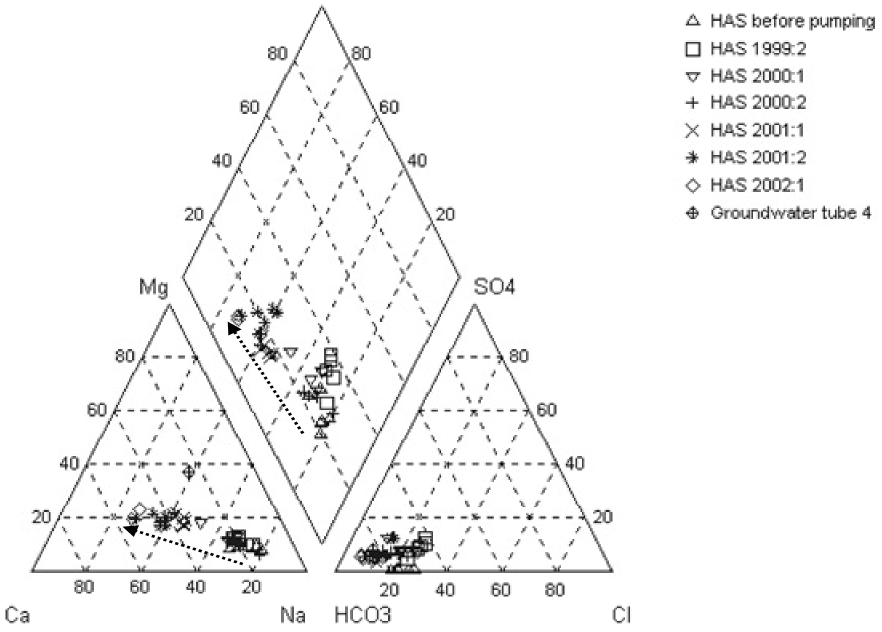


Figure 8-22. *Hydrochemical facies of the groundwater of the extraction borehole HAS23 (Mossmark, 2003). The arrows describe the changes of the composition over time.*

8.3.3 Conclusions from the Äspö groundwater extraction experiment

The extraction of groundwater caused notable changes of the composition of the bedrock groundwater. However, unlike the results from the groundwater extraction at Lake Gårdsjön, the impact to the groundwater chemistry of the shallow waters as well as to the water budget was relatively small.

Despite the small hydrological impact, the chemical composition of the bedrock groundwater became more similar to the shallow groundwater. Sulphate concentrations increased and followed the concentration variations in the shallow systems. Chloride concentrations and pH decreased in the groundwater of the bedrock. According to Knape Hansén (2002), increased influence from shallow waters to the extraction borehole HAS23 was also evident through increased DOC concentrations. In some aspects, the changes to the groundwater chemistry at the island of Äspö meant a composition that was less aggressive towards construction materials used in underground facilities, e.g. with lower chloride concentrations.

Compared to the Lake Gårdsjön experiment, the borehole for extraction yielded less water since it did not intercept any major waterbearing fracture zones. The small volume of water that was extracted limited the hydrological impact to the runoff volumes. However, the hydrochemical changes were notable but less significant compared to the Lake Gårdsjön experiment.

9 FORECASTING WATER CHEMISTRY THROUGH THE USE OF CONCEPTUAL MODELS

The chemical composition of the groundwater is mainly dependent on geological and hydrological conditions, as well as biota. In this thesis three conceptual models are presented to exemplify the vulnerability to hydrochemical composition based on geological conditions. The conceptual models include three typical geological settings that have been subjected to recent (Weichselian) glaciations with resulting shallow layers of overburden. In the conceptual models, transgressions following the most recent glaciations are important factors. The highest shoreline following the Weichselian glaciations is defined by the largest transgression.

9.1 Groundwater discharge areas that have not been subjected to recent marine transgressions

The results from the field and case studies identify the groundwater discharge areas with wetlands being vulnerable to hydrochemical changes caused by underground constructions. Some geological differences apply depending on whether a discharge area has been subject to transgressions or not. In locations above the highest shoreline (during the transgression), it is common to find organic wetlands (peat) immediately overlaying glacial till, see Figure 9-1.

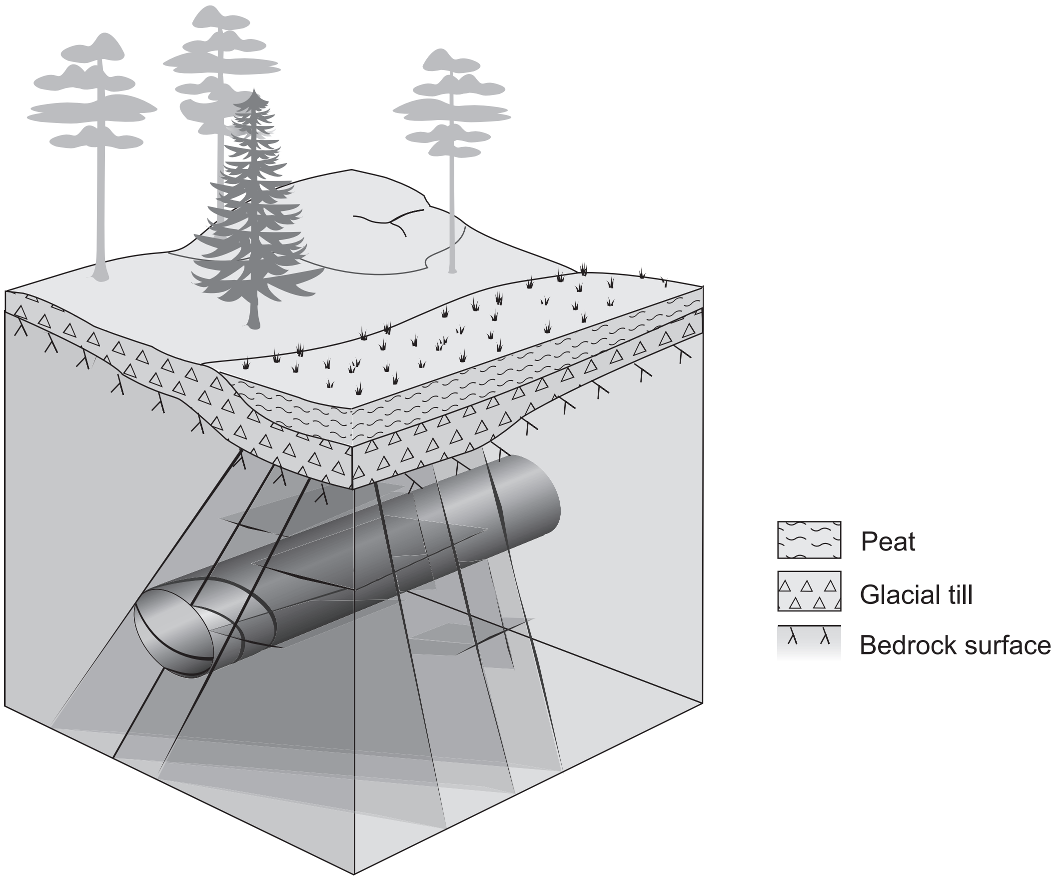


Figure 9-1. *Groundwater discharge area that has not been subject to marine transgressions. The glacial till is immediately overlaid by peat. In the figure, a fracture zone intersects the tunnel and the wetland (indicated with a dark grey geometrical shape).*

In the geological setting described in Figure 9-1, the construction of the tunnel is likely to affect the peat wetland. Wetlands are usually located in topographical depressions. The depressions commonly represent weakness zones in the bedrock, such as fracture zones. Locating the fracture zone in the wetland is therefore justified. The fracture zone will constitute a hydraulic connection and we are likely to see the following changes:

- Water flow will increase in the fracture zone, flowing from the wetland to the tunnel. The wetland may transform into a recharge area and may dry up partially or entirely. It may be subject to increased seasonal variations in the groundwater level.
- The water in the vicinity of the tunnel is in chemical terms likely to become more similar to the shallow groundwater in the wetland.

- Oxidation processes may cause the formation of sulphuric acid in the wetland, which in turn may lower the pH and cause the release of base cations such as calcium and magnesium.
- The groundwater in the bedrock is likely to see an increase in organic matter. Whereas the shallow water that flows towards the tunnel is likely to be more oxidised, decomposition of the organic matter will counteract this process through the consumption of oxygen.

9.2 Groundwater recharge areas that have not been subjected to recent marine transgressions

The field and case studies indicate that groundwater recharge areas are, in most cases, relatively invulnerable to underground construction activity. In the recently glaciated areas, the overburden in the recharge areas is dominated by glacial till, se Figure 9-2.

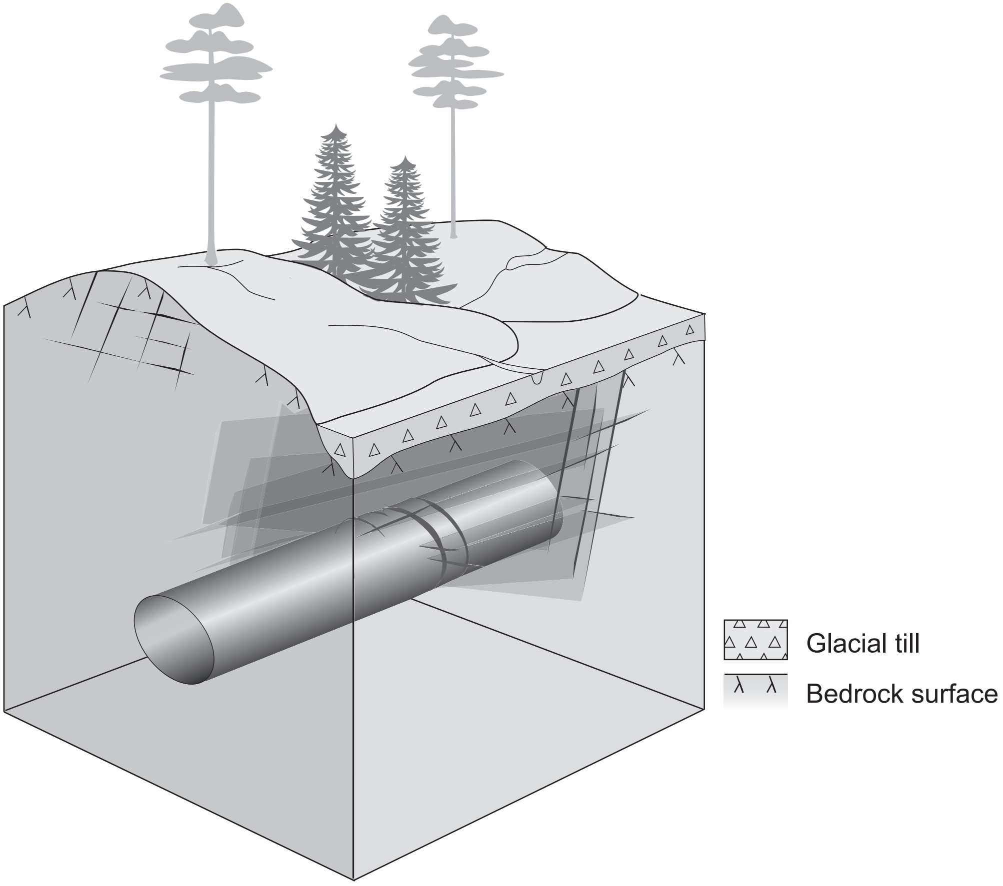


Figure 9-2. Geological model in a groundwater recharge area that has not been subjected to marine transgressions. Glacial till is immediately overlaying the bedrock.

The following hydrological and hydrochemical aspects relevant to underground constructions have been identified for groundwater recharge areas as presented in Figure 9-2:

- Unlike in the wetland, there are no sulphur pools available that may be exposed to oxygen and form sulphuric acid.
- Leakage to the tunnel may cause changes to the redox potential, this may have an importance to, in particular, manganese and iron.

9.3 Areas that have been subjected to recent marine transgressions

For groundwater discharge areas that have been subject to transgressions, it is common to observe marine/post-glacial clays overlaying the glacial till. As seen in Figure 9-3, peat may also have been formed, overlaying the clay layer. This model may also represent a groundwater recharge area that has been subject to marine transgressions. Fine-grained sediments such as marine clays are deposited at fairly large depths in water. However, through land uplift the hydrogeological function as a groundwater discharge area may have shifted and the area instead becomes a recharge area.

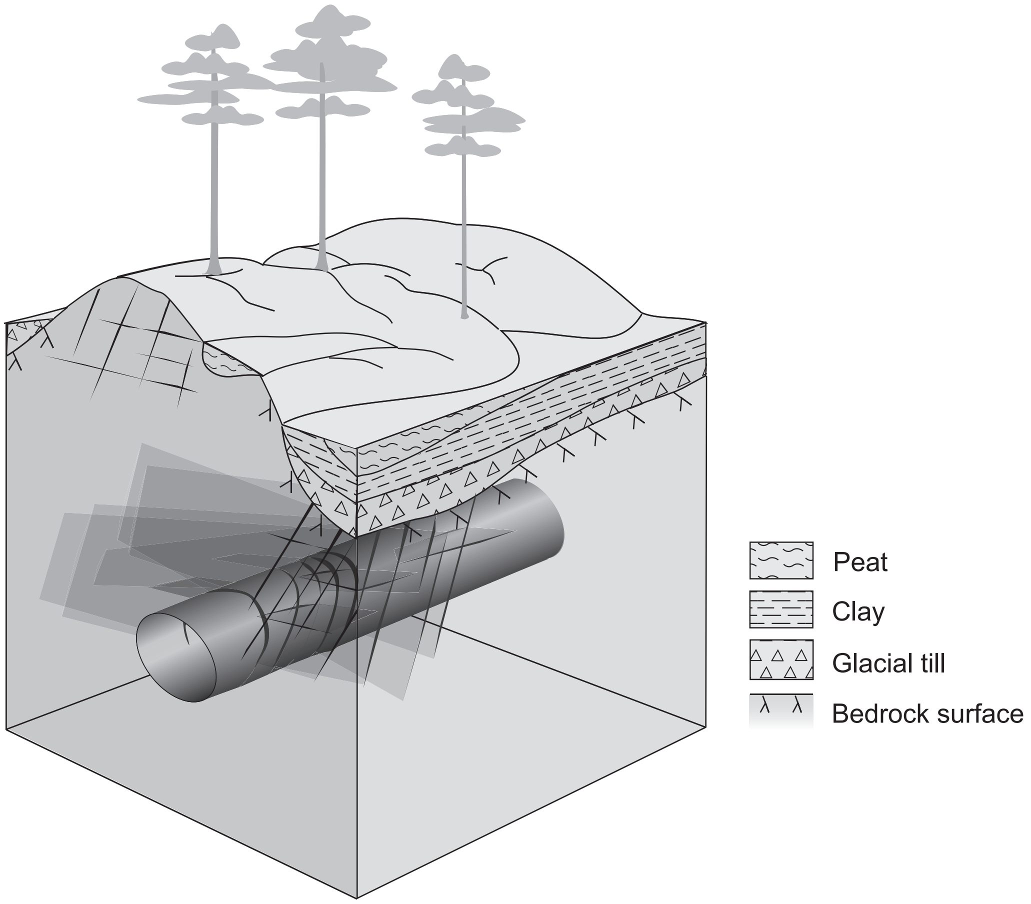


Figure 9-3. Typical geological conditions at an area that has been previously subject to marine transgressions. In the figure, a fracture zone intersects the tunnel and the wetland (indicated with a dark grey geometrical shape).

The impact of tunnelling in a geological setting that has been exposed to transgressions (Figure 9-3) can be similar to a geological setting that has not been subject to transgressions (Figure 9-1). The following aspects should be considered:

- A clay layer may limit the hydraulic interaction between the groundwater of the bedrock and the groundwater of the wetland.
- The clay layer, especially if it is of marine origin, is likely to contain a substantial pool of chloride and sulphur. The sulphur may be subject to oxidation and the formation of sulphuric acid.
- Chloride is likely to be present in the groundwater at higher concentrations compared to the areas that have not been subjected to marine transgressions. Furthermore, there is commonly chloride readily available in fine grained deposits such as marine clays.

The in-depth studies, as well as case studies in the literature, included groundwater discharge areas with wetlands located both above and below the highest shoreline formed by the largest transgression following the Weichselian glaciations. The studies show that underground construction may alter the hydrological system and cause groundwater discharge areas to become recharge areas. In this process, organic wetlands, such as sphagnum peat, which under unaffected conditions are submersed, may become drained and aerated. At a later stage, when the water levels rise again, it is likely that the wetland has become oxidised and sulphur bonded as sulphide in the wetland may be released during the formation of sulphuric acid. In observed cases (Hallandsåsen, Romeriksporten and the Gårdsjön field study) the aeration of wetlands has caused sulphur surges, acidification and observed changes in the concentration of base cations.

According to the results from the in-depth studies, the greatest hydrochemical impact on wetlands from underground constructions has been observed in areas located above the highest shoreline (unaffected by transgression following the Weichselian glaciation). A clay layer, which is common in areas subjected to transgressions, may limit the hydraulic interaction between the groundwater of the bedrock and the groundwater of the wetland. However, the number of studied locations that have been exposed to transgressions is limited. The marine clays are likely to be rich in sulphides and oxidation of the clays could have an amplifying effect on the acidification caused by oxidation of an adjacent wetland. Further studies are deemed necessary to draw further conclusions.

9.4 Influence to hydrochemistry from fracture minerals

The presence of fracture minerals has been identified as an important factor in the vulnerability to hydrochemical changes caused by underground constructions. One of the in-depth studies shows the possible impact of sulphide minerals, such as pyrite. The hydrological changes caused by underground constructions, such as tunnels, may cause the groundwater in the fractures of the bedrock to become more oxidised. The pyrite minerals are easily affected by the oxidation, which may be caused by sulphuric acid.

Calcium carbonate is one of the most common types of fracture minerals. The solubility of calcium carbonate is highly dependent on carbon dioxide pressure.

Leakage into an underground facility may cause the hydrochemical conditions of the groundwater to change with aerobic decay of organic matter. Such a process results in an increase in carbon dioxide pressure, which may cause calcium carbonate fracture minerals to become dissolved (Drever, 1988). Dissolved calcium ions may later precipitate to once again form calcium carbonate when the groundwater is later discharged into the underground facility if the carbon dioxide pressure of the water is higher than in the atmosphere (Eriksson and Holtan, 1974).

Interaction between the water and silicate minerals is also of importance to water chemistry, e.g. through weathering of feldspars. However, these processes are significantly slower than for pyrite and calcium carbonate.

10 DISCUSSION

The changes in water chemistry that will occur during the construction and operational phases of underground constructions are mainly dependent on the geological conditions and the construction methods. The impact of underground construction on water chemistry has been observed to be positive in some cases, but negative in most cases from a construction material durability point of view. However, all studies show that underground constructions cause the groundwater chemistry to become more dynamic. One important process caused by the leakage into underground constructions that is of importance to construction materials was chemical oxidation of sulphide in wetlands and in fracture minerals to form sulphuric acid. The main processes that influence the water chemistry have been summarised previously in Figure 4-2. The studies included in this thesis show that underground constructions disturb the natural processes and that the resulting water chemistry is difficult to predict in detail (Figure 10-1). However, general hydrochemical changes may be predicted based on data describing the geological and hydrological conditions.

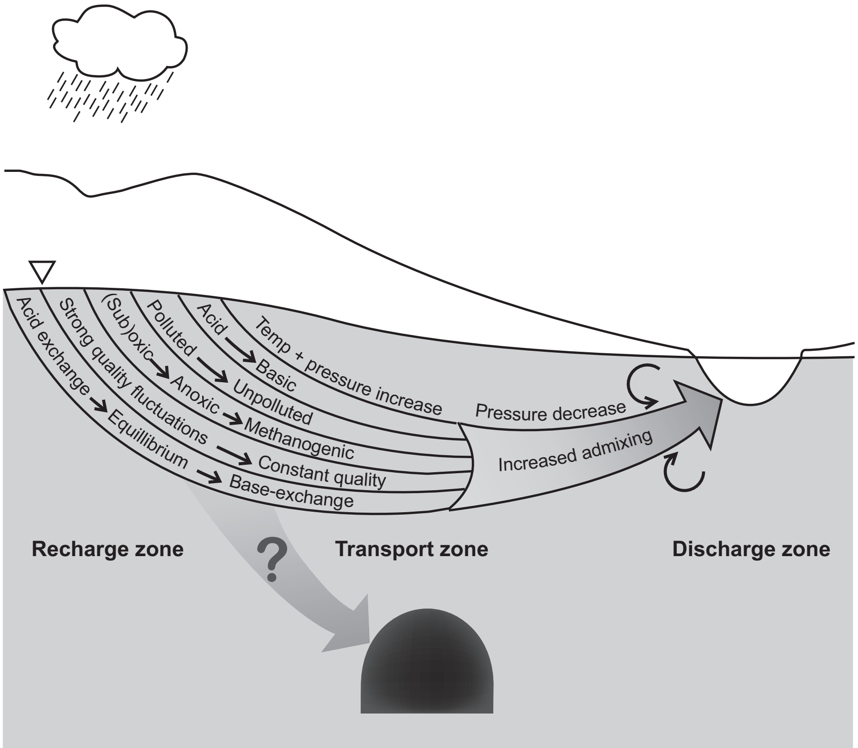


Figure 10-1. The natural hydrochemical processes are influenced by the construction of underground facilities.

Some of the results from the in-depth studies show that the hydrochemical changes that occur during the construction and operational phases of an underground construction may have negative implications for the durability of construction materials. Figure 10-2 reveals a decrease in alkalinity in the groundwater in the bedrock during groundwater extraction within the field study at Lake Gårdsjön. The alkalinity drops below the limit established by the Swedish authorities for aggressive water, set at 61 mg/L HCO_3^-. Meanwhile, the alkalinity in the nearby reference displays little time-based variation.

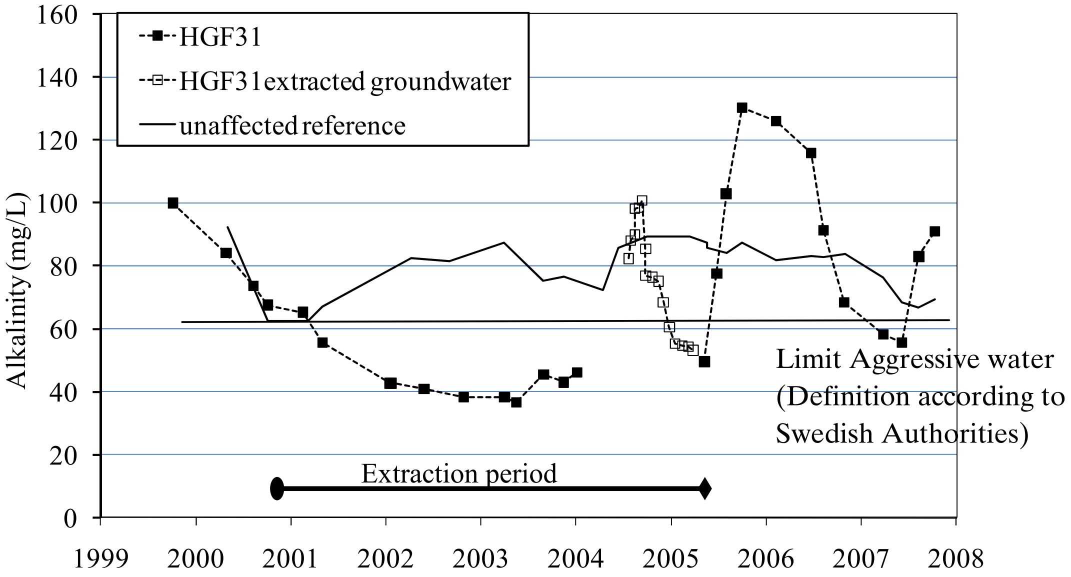


Figure 10-2. *Results from the field experiment at Lake Gårdsjön show that groundwater extraction caused the alkalinity to decrease. According to definitions established by the Swedish Authorities, the water became aggressive.*

Hydrochemical changes with negative implications for the durability of construction materials were also observed during the construction phase of the Hallandsåsen rail tunnel. A relevant example is shown in Figure 10-3 where the pH decreases below the criteria value of 6.5 for aggressive water.

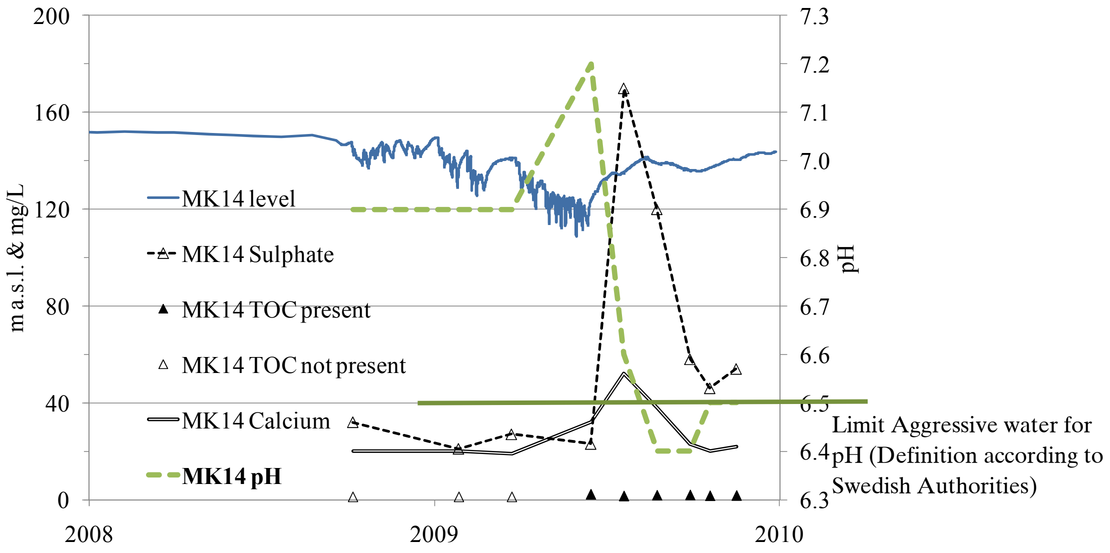


Figure 10-3. *The groundwater in the bedrock became aggressive during the constructional phase of the Hallandsåsen rail tunnel. The measurement results for pH fell below the definition for aggressive water established by the Swedish Authorities.*

The examples presented in Figure 10-2 and Figure 10-3 show similar results for underground construction activities in two different geological conditions. At Lake Gårdsjön, the decrease in alkalinity was most likely caused by oxidation of sulphur to sulphuric acid in a wetland. The water in the wetland infiltrated to the bedrock where the alkalinity was consumed. In the Hallandsåsen rail tunnel, the acidification was most likely caused by oxidation of sulphur into sulphuric acid in the fracture mineral pyrite, which was followed by acidification of the groundwater in the bedrock.

The results from Lake Gårdsjön show that the redox changes and the related oxidation of sulphur also have an impact on many other relevant parameters. The oxidation of sulphur causes the formation of sulphuric acid and consequently a response with alkalinity, a possible decrease in pH, and a subsequent release of the base cations. The impact of an acidification caused by oxidation of fracture minerals should trigger the same processes as from the oxidation of sulphur in a wetland that was observed at the Lake Gårdsjön.

In two of the in-depth studies, changes in chloride concentration were also observed. Increasing chloride concentration due to upconing of brine waters was observed at the Äspö HRL. In contrast, during the field investigation with groundwater extraction on the northern parts of the island of Äspö, decreasing chloride concentrations were observed. Chloride is not prone to be involved in chemical reactions and the changes are most likely caused by groundwater flow only. Changes in chloride concentration, particularly through upconing of brine or inflow of marine waters, are identified as a process that could potentially make the groundwater more aggressive to construction materials.

In this thesis three types of conditions have been identified that may contribute to changes in hydrochemical conditions with a negative impact on the durability of construction materials:

- Wetlands (and groundwater discharge areas)
- Sulphide minerals in the bedrock
- Marine and brine waters

Through pre-investigation during the pre-construction period of an underground construction, locations that may be sensitive to hydrological changes could be identified. At such locations, steps could be taken to improve the life span of the construction materials. It is suggested that grouting, and in particular pre-grouting, should be carried out with precision at such locations to minimise the hydrological, and hence hydrochemical, impact. A less preferred method would be to select construction materials with complementary protection at such locations.

The cases studied in this thesis mainly involve rural settings, although the processes are general. In Scandinavia, many of the tunnels are built in urban areas. The hydrological impact with a lowering of the groundwater table from the construction of tunnels in urban areas has been described in Persson (2007). Lekander (1991), Norin et al. (1998) and Mossmark (2003) studied the hydrochemical composition of the shallow groundwater in Gothenburg. Aastrup et al. (1997) presented a similar study for Stockholm. According to Mossmark (2003), sulphur surges were observed due to seasonal hydrological variations that caused changes in the redox conditions. The hydrological changes in the groundwater in urban areas caused by underground constructions, as presented in Persson (2007), are likely to cause changes to the redox conditions. As in the rural settings studied in this thesis, leakage into underground constructions during their construction and operational phases may cause changes in the chemical composition of the groundwater in the bedrock. The water may become more aggressive towards the construction materials. Furthermore, the leakage could cause contamination of the groundwater in the bedrock through recharge from shallow contaminated waters in an urban area.

The completion of the construction phase with successful waterproofing through grouting will often result in almost full recovery of groundwater levels. In observed cases, the water chemistry of the groundwater in the bedrock may become less aggressive during the operational phase than during the construction phase. However, if degradation of the construction materials is initiated during the construction phase, the durability and resistance to further degradation of the materials could be decreased.

There are ongoing discussions about whether the current methods for waterproofing tunnels in rural areas should be changed. The limits for leakage into tunnels have been set to primarily combat subsidence of buildings in urban areas. In the discussions it has been suggested that more water should be allowed to leak into a rural tunnel than what is currently permitted. This thesis shows that such a change in the waterproofing methods could make the hydrochemical impact greater. The water chemistry would need to be considered more carefully in the design of an underground facility.

11 CONCLUSIONS

Leakage into underground constructions such as tunnels causes flow from all directions and decreased residence time for the groundwater. The construction of underground facilities often causes changes in the hydrochemical conditions of the groundwater in the bedrock. The hydrochemical conditions that occur during the construction and operational phases of underground constructions may be more aggressive to construction materials compared to unaffected conditions.

The geological conditions have been identified as having a major influence on whether hydrochemical changes that have a significant impact on construction materials will occur. Important changes have been observed in areas that are both groundwater discharge areas as well as recharge areas in unaffected conditions. However, groundwater discharge areas such as wetlands have been identified as being particularly sensitive.

For some of the objects studied, the changes in the hydrological regime caused redox conditions to change with more oxidised water reaching deeper into fracture aquifers in the bedrock or into wetlands (discharge areas in unaffected conditions). The changes in redox led to the oxidation of sulphide where available: in the wetlands or in sulphide-containing minerals in the bedrock, e.g. pyrite. The oxidation of sulphide caused the formation of sulphuric acid and where there was insufficient buffer capacity this led to acidification. Ion exchange reactions caused the release of calcium and magnesium in exchange for hydrogen ions.

The leakage during the construction and operation phases of underground facilities has been observed to increase the concentration of organic matter in groundwater in the bedrock. During decay the organic matter will have an impact on the water chemistry. If aerobic conditions prevail, the decay will consume oxygen and cause the carbon dioxide pressure to increase, which may cause dissolution of calcium carbonate. However, if the decay of the organic matter occurs in anaerobic conditions, sulphate may be reduced to hydrogen sulphide and the alkalinity of the groundwater will increase.

Some of the observed hydrochemical changes have a possible negative impact on the durability of the construction materials. For steel-based construction materials, i.e. steel bolts and reinforcement in shotcrete, the following hydrochemical changes are of importance:

- Increased groundwater recharge may cause a more oxidised environment.
- Sulphides, available in the overburden and in the bedrock, may be oxidised to sulphuric acid and may cause a lowering of the pH.
- Increased concentrations of decaying organic matter in the groundwater of the bedrock and acidification have in some observed cases caused dissolution of calcium carbonate in the bedrock (in e.g. calcite fracture fillings).
- Increased recharge of shallow waters of low ionic strength may also cause decreased concentrations of calcium and alkalinity.
- The chloride concentrations in the groundwater may increase through upconing of saline waters or through the influence of marine waters. The chloride concentrations may decrease through the increased influence of shallow meteoric waters.

The following changes, which have a significant impact on the durability of cement-based materials, have been observed:

- Sulphate attack on concrete may occur although the concrete is characterised as sulphate-resistant. As mentioned for steel-based materials, high sulphate concentrations may occur when constructing underground facilities in geological conditions where sulphide is present.
- If the groundwater has high sulphate concentrations, there is an increased risk that ettringite will form. This process causes swelling.
- The precipitation of calcite may cause a decrease in the permissible load for rock bolts.
- Leaching of the concrete may occur. Decay of organic matter in an oxidised environment may be the cause. However, it is also possible that calcium carbonate will precipitate near an underground structure through the release of carbon dioxide into the air.

The grouting agents polyurethane and silica sol have exhibited reduced durability in alkaline environments. However, for silica sol this durability issue is avoided if the water has reached saturation for silica.

The precipitation of iron and manganese may cause clogging of the drainage channels that deal with the water leaking into underground constructions. The precipitation occurs when iron or manganese is oxidised, often through microbial activities. The solubility of manganese and iron is also dependent on the pH. Increasing pH may cause iron and manganese to precipitate. This is a relevant aspect as cement-based grout, which is commonly used for waterproofing underground facilities, causes an alkaline environment. The cement-based grout may thus cause iron and manganese that is dissolved in the groundwater to precipitate, thus leading to clogging. This may either mean decreased leakage into the facilities through the clogging of fractures or it may negatively influence durability if the clogging occurs in the drainage system. Calcite may also form and cause clogging of the drainage system when carbon dioxide is released to the air.

The results from this thesis identify the geological conditions as a decisive factor for hydrochemical conditions. The durability of an underground facility is influenced by groundwater chemistry. It is therefore recommended that the groundwater chemistry is predicted in the pre-construction phase of major tunnelling projects. Suitable tools for hydrochemical modelling should be presented and methods should be established for the prediction of the future hydrochemical conditions during the construction and operational phases based on data collected in the pre-construction phase. The results of such predictions should be used to design the waterproofing grout and in the selection of construction materials.

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Effects of groundwater extraction from crystalline hard rock on water chemistry in an acid forested catchment at Gårdsjön, Sweden

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Abstract

Atmospheric deposition of S in Sweden has decreased by some 80% over the last 15 a, resulting in a general reduction of SO_4 concentrations in ground and surface water. This project, however, shows that artificial hydrological alteration in an acid wetland can reverse this trend and increase acidity and SO_4 concentrations. The experiment involved the monitoring of two catchments in relatively virgin conditions. In one of the catchments, an experiment with intensive groundwater extraction from the bedrock was carried out. During the experiment, the runoff from the catchment decreased by 50%. Furthermore, the extraction of groundwater resulted in increased seasonal aeration of the centrally located wetland, leading to oxidation of reduced S bound to the soil layers of the wetland. The S changed to solute SO_4, with a subsequent SO_4 surge. Thus, the experiment resulted in an induced acidification of the wetland and runoff waters. The extraction of groundwater significantly increased the recharge of water from the overburden, glacial till and organic soils to groundwater in the bedrock, which in turn reduced the retention time in the bedrock aquifer. These changes resulted in the chemical signature of the groundwater in the bedrock becoming similar to those of the wetland. The findings revealed deterioration in the water quality in the bedrock due to increased concentrations of dissolved organic C and SO_4, as well as a decrease in pH.

1. Introduction

Atmospheric deposition of S in Sweden has decreased by some 80% over the last 15 a (Hultberg and Ferm, 2004), resulting in a general reduction of SO_4 concentrations in ground and surface water. However, in order to interpret the ongoing trends and development of the macroelement and S concentrations in water in subsurface strata, it is important to understand the hydrochemical effects caused by natural hydrological changes or groundwater withdrawal.

This study was initiated to examine how an alteration in hydrological conditions including a lowering of the groundwater level in a small catchment with thin soil layers and crystalline bedrock affects

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the hydrochemistry. Such alterations can be caused by underground construction work and tunnelling or cuttings for roads and railways, which are common in the Nordic countries Finland, Norway and Sweden. A lowering of the groundwater level can also be caused by extraction of groundwater for drinking water. Knowledge of the hydrochemical effects of such alterations is sparse but necessary due to the increase in underground construction activity and use of groundwater resources. Possible effects of a lowering of the groundwater level are a shortage of drinking water, a negative impact on tunnel reinforcements and waterproofing systems (Axelsson, 2006), in addition to biota damage due to acidification.

2. Hypothesis

Prior to the experiment, the following hypotheses of the effects of artificial groundwater extraction were assumed:

- Extraction causes an alteration in hydrological conditions as it removes approximately 10–50% of surface runoff to groundwater recharge of the bedrock.
- Increased recharge of groundwater in the bedrock and hence increased vertical flow caused by extraction leads to decreased concentrations of macroelements and an increased concentration of dissolved organic C (DOC).
- The O_2 levels in the groundwater increase and cause oxidation of sulphide to SO_4 and consequently lower pH. Concentrations of base cations are increased in shallow ground and surface water.
- The assumed runoff decrease is not compensated for by the increased concentrations of several major constituents of mass fluxes. The total amount of mass fluxes is hence decreased.

3. Description of experimental setup and studied catchments

In order to test the hypothesis, two fairly identical small catchments in the Lake Gårdsjön watershed on the west coast of Sweden were selected (Fig. 1). One of the catchments was used for the experiment (catchment F3) while the other served as a reference (catchment F1), the distance between the two catchments is 1.3 km. The experiment consisted of groundwater extraction from the bedrock by means of a percussion borehole (HGF33) in catchment F3 (Fig. 1). General information on the F1 catchment has previously been presented in Andersson et al., 1998.

The study included the monitoring of hydrological conditions and frequent ground and surface water sampling for chemical analysis. Both catchments had been monitored for several years before the experiment was initiated in catchment F3. Catchment F1 is 37000 m^2 while F3 measures 28000 m^2 (Olsson et al., 1985).

3.1. Geological and hydrological conditions

The bedrock mainly consists of gneissic granodiorite (Samuelsson, 1985) covered by thin layers of regolith and soil. A fracture zone in the rock is assumed to exist beneath the central wetland of catchment F3 in a north to south direction.

The most recent glacial period existed in the Lake Gårdsjön area from approximately 100 ka to 14 ka B.P. The glacier deposited crushed inorganic material formed from eroded rock and previous regolith as thin layers directly on top of the crystalline rock, a soil type referred to as glacial till. This soil type forms the surface of more than 60% of the experimental catchment (Knape, 2001).

Following glaciation, the sea level regressed in relation to the land mass. Areas located at the highest point of the shore line and below the highest point thereby became exposed to wave washing. Furthermore, these areas typically have soil types sedimented in water, which means well sorted material in terms of particle size and in some cases thick soil layers. The experimental areas are located at an elevation of approximately 115 m above sea level (asl) and, according to Fredén (1986), the highest shore line is 125 m asl. However, only very thin layers of soil, from fine silt to sand, have been found on top of the till in the experimental wetland. Organic wetland soils constitute no more than approximately 5% of the area of the experimental catchment F3 (Nilsson, 1985).

The total annual net precipitation is around 1100 mm/a and approximately 50% is removed by means of evapotranspiration. The climate has been classified as maritime temperate; according to the Köppen-Geiger system, a mild, humid climate without dry seasons. Vegetation mainly consists of a mixture of Norway spruce and Scots pine (Olsson et al., 1985).

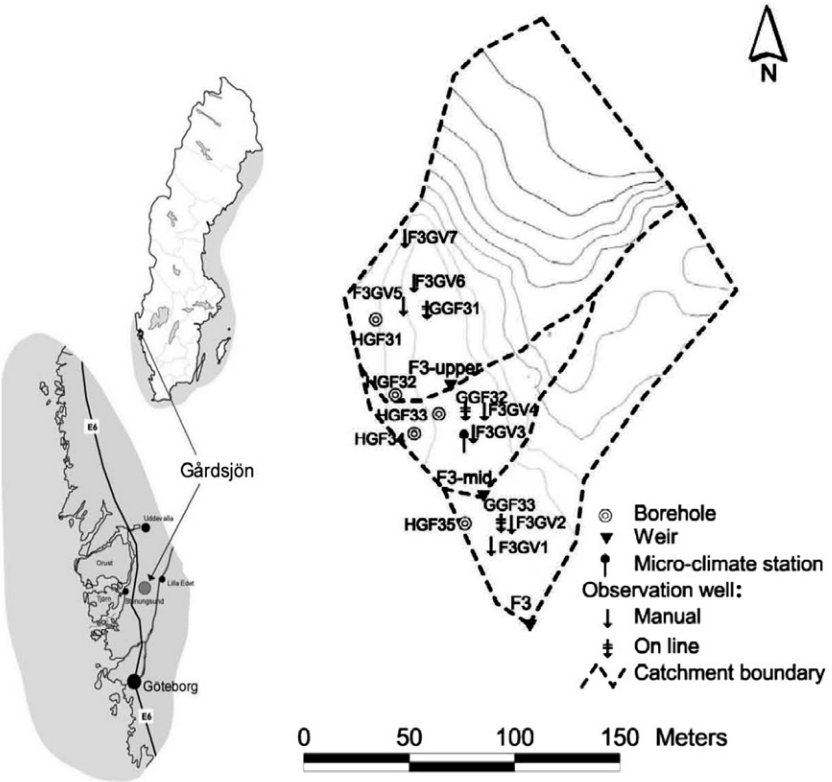

Fig. 1. Geographical location of the two catchments and instrumentation setup in experimental area F3. The reference catchment F1 had similar instrumentation to that in F3 but runoff was only monitored at one weir (Web-ref 1; Graffner et al., 2005).

3.2. Experiment and monitoring approach

The experiment in catchment F3 involved the constant withdrawal of groundwater at a depth of 50 m in a percussion drilled borehole (HGF33) from December 2000 to April 2005. A brief interruption in groundwater extraction occurred during February and March 2004. From April 2004 until April

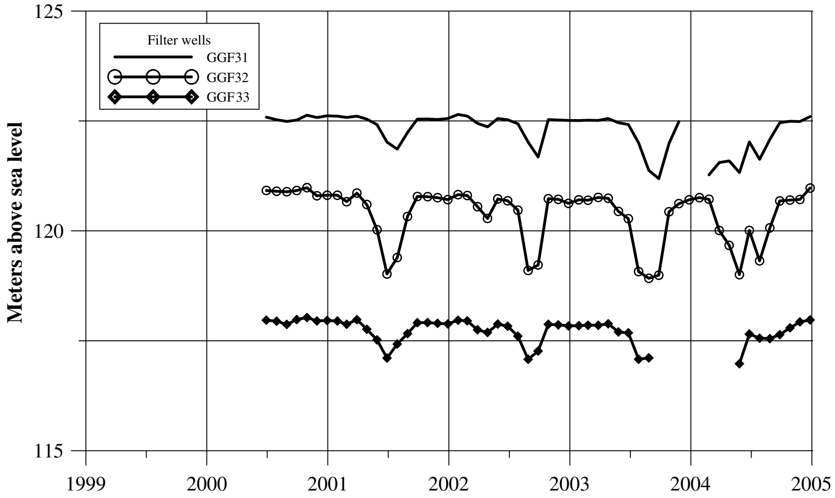

Fig. 2. Groundwater levels in the organic soils of the F3 catchment from June 2000 to 2004.

Table 1
Hydrological conditions for the two catchments, F1 and F3, during the monitoring and the experimental period

Year	Precipitation (mm/a)	Runoff unaffected ref. catchment F1 (mm/a)	Extracted groundwater from rock in F3 (mm/a)	Runoff experimental catchment F3 (mm/a)
1997	972	436	–	481
1998	1169	748	–	707
1999	1327	802	–	762
2000	1258	749	25 (Dec. 1–31, 2000)	713
2001	909	408	265	230
2002	980	514	243	237
2003	943	458	208	174
2004	1082	474	196	225

2005, borehole HGF31 was also used for groundwater withdrawal in order to increase the impact. The extracted water was emptied into Lake Gårdsjön. The boreholes were drilled to an approximate depth of 70 m, and HGF31, HGF33 and HGF35 were inclined with an angle of 20° from the vertical line.

A logging system regularly recorded data on extracted water volumes, surface runoff, weather conditions, and groundwater levels in the bedrock and regolith/soil layers. Furthermore, pH and electrical conductivity (EC) of the extracted groundwater and surface runoff were continuously measured. The location of the equipment in F3 is shown in Fig. 2.

The monitoring included a regular sampling program for chemical analysis. The sampled water was analysed in order to determine pH, EC, major constituents, DOC, Fe, Mn and Al. Shallow groundwater from the two catchments was collected once a month, while extracted groundwater and runoff water were sampled every fortnight. The groundwater in the bedrock was sampled four times per year to a depth of 30 m by means of a submersible electrical pump with plastic tubing.

4. Results and discussion

The groundwater extraction caused a significant alteration in the hydrological system of the F3 experimental area, which in turn affected the hydrochemical situation of the ground and surface waters.

4.1. Hydrological changes

Before the start of the experiment, the two studied catchments exhibited similar hydrological properties regarding runoff volumes. After the initiation of groundwater extraction, an approximate decrease of 50% in runoff volume in the F3 experimental area was revealed (Table 1). The decrease in runoff in F3

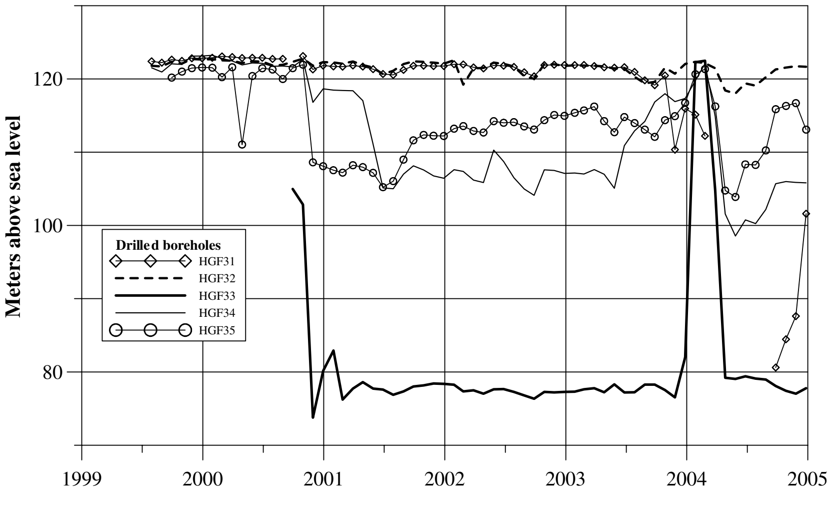

Fig. 3. Groundwater levels in the bedrock boreholes of the F3 catchment between 1999 and 2004.

compared to the reference area F1 corresponded well with the extracted water volume. This indicates that the extracted water mainly consisted of water recharged within the F3 catchment.

The level of shallow groundwater in the wetland and the drilled boreholes was subject to increased seasonal fluctuation. Fig. 2 reveals that seasonal fluctuation of groundwater is up to 2.5 m (GGF32). The seasonal variations of the groundwater in the bedrock (Fig. 3) became more evident in some of the boreholes (HGF31 and HGF32), while others revealed a more permanent decrease in groundwater level (HGF34 and HGF35). The groundwater level in HGF33 was held constant by varying the level of groundwater extraction (Fig. 3).

4.2. Chemical changes in shallow groundwater and surface water

The increased seasonal fluctuation in the groundwater level led to aeration of the shallow organic soil layers of the wetland. The seasonal aeration caused the groundwater to become more oxidized when groundwater levels started to increase again in the autumn. Sulphide bound to the soil layers changed to soluble SO_4 leading to a SO_4 surge and subsequent acid pulse during the autumn (Fig. 4).

As can be observed in Fig. 4, the weak trend towards increased pH that was apparent prior to the start of the experiment ceased. The effect of

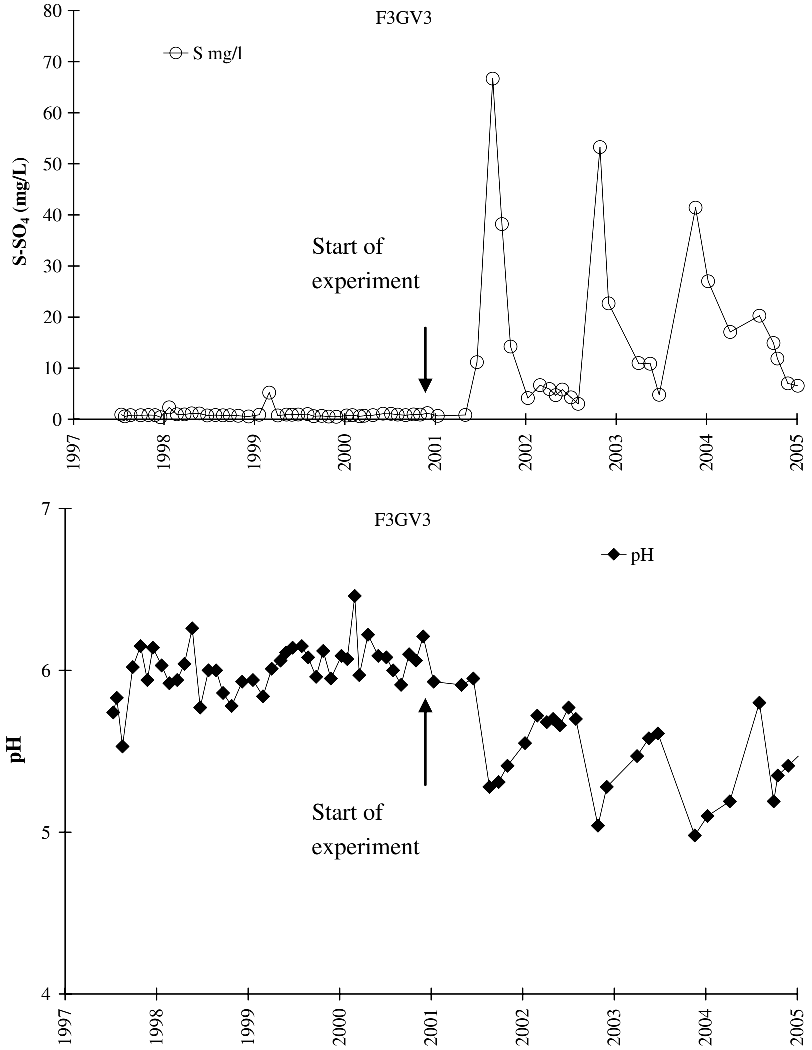

Fig. 4. Time series describing S concentrations and pH in the shallow well F3GV3 located in the organic soil of the wetland in catchment F3.

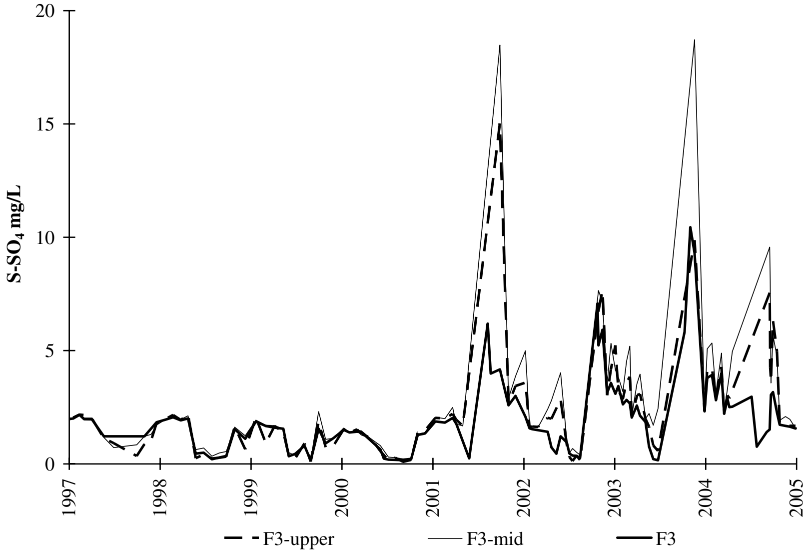

Fig. 5. Time series of SO_4 in runoff water in the three weirs of catchment F3.

the experiment was gradual acidification of the wetland. The chemistry of the runoff water had a similar, albeit slightly weaker, development of SO_4 concentrations (Fig. 5). In the case of runoff water, pH exhibited a weak but nevertheless obvious tendency to decrease. It should be noted that S deposition at Lake Gårdsjön has decreased by nearly 80% over the past 15 a (Hultberg and Ferm, 2004), which makes the induced development quite remarkable. The hydrochemistry of shallow groundwater in the glacial till surrounding the wetland was, however, unaffected by the experiment.

The induced acid pulses and seasonal aeration also had an impact on several other major constituents, most notably the concentrations of the divalent base cations Mg and Ca paralleled that of SO_4, with significant pulses during groundwater level recovery in the autumn. In the case of Fe, a weak seasonal increase during the autumn was observed in the wetland, but not in runoff waters.

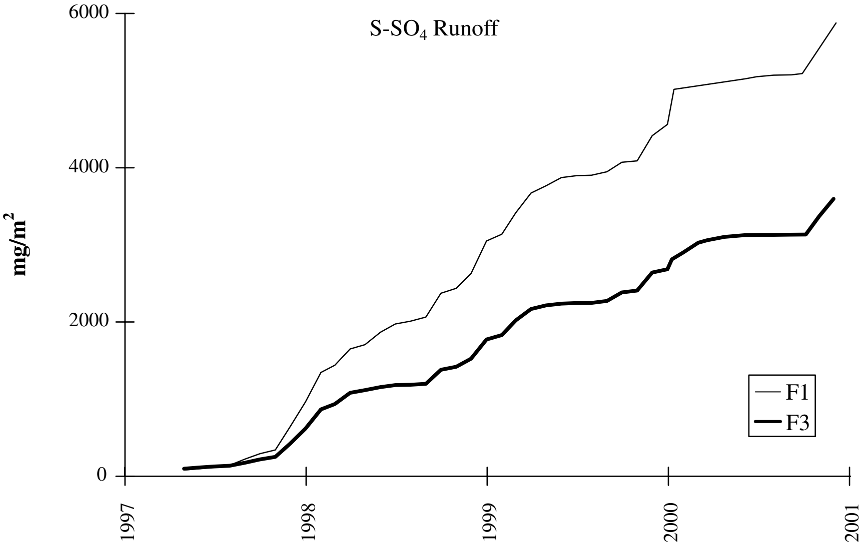

Fig. 6. Cumulative mass fluxes of SO_4 from the reference catchment F1 and the experimental catchment F3 before the experiment started.

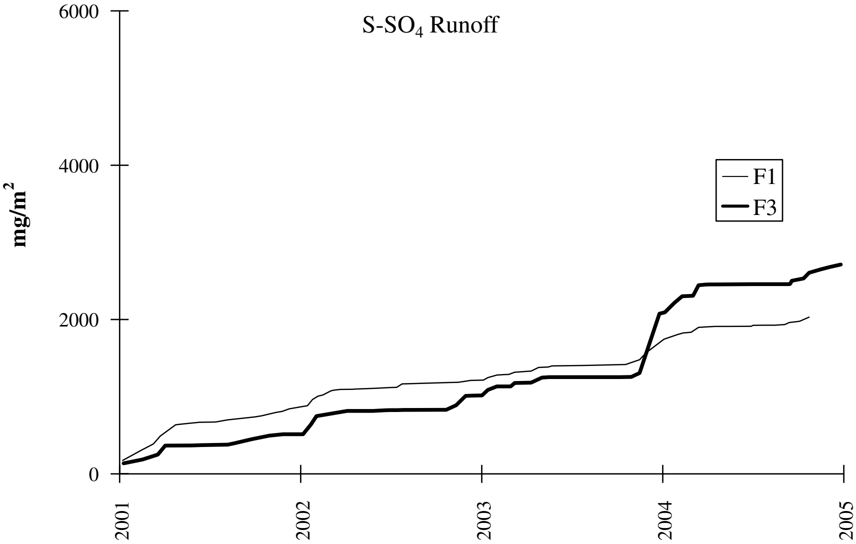

Fig. 7. Cumulative mass fluxes of SO$_4$ during the experimental period.

4.3. *Mass fluxes of runoff water*

As shown in Table 1, the precipitation and consequently the runoff from the unaffected catchment were higher during the monitoring period than during the experiment. Mass fluxes from an unaffected catchment will be smaller during a dry year compared to one with high precipitation due to decreased runoff flow. However, the reference and experimental periods can be compared when the two catchments are related to each other.

The similarity in hydrological behaviour between the two catchments was important for the study of accumulated mass fluxes. When summarizing the runoff for the 4 a before the start of the experiment, the total runoff from catchment F1 was 2735 and 2681 mm from F3 (including 25 mm of groundwater extracted in December 2000). During the experiment, the total runoff from F1 was 1854 mm, while the sum of total runoff and extracted groundwater from F3 was 1773 mm.

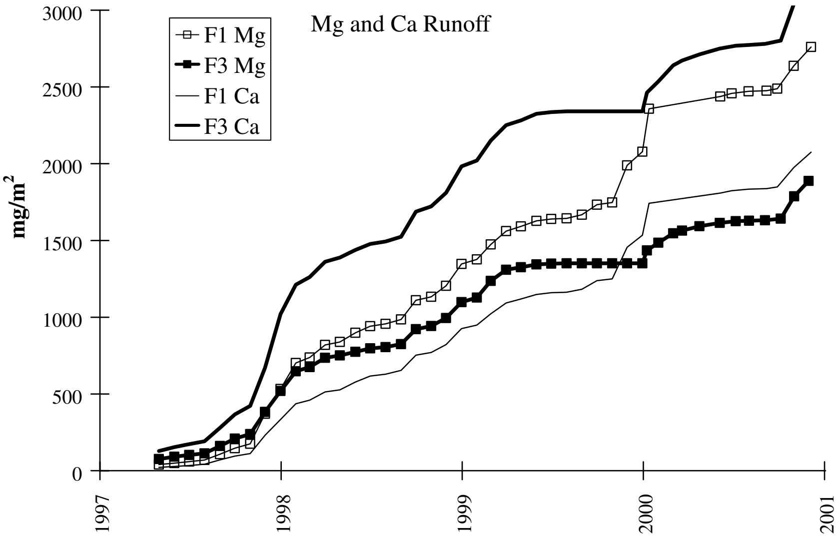

Fig. 8. Cumulative mass fluxes of Ca and Mg from the F1 reference catchment and the F3 experimental catchment during the monitoring period.

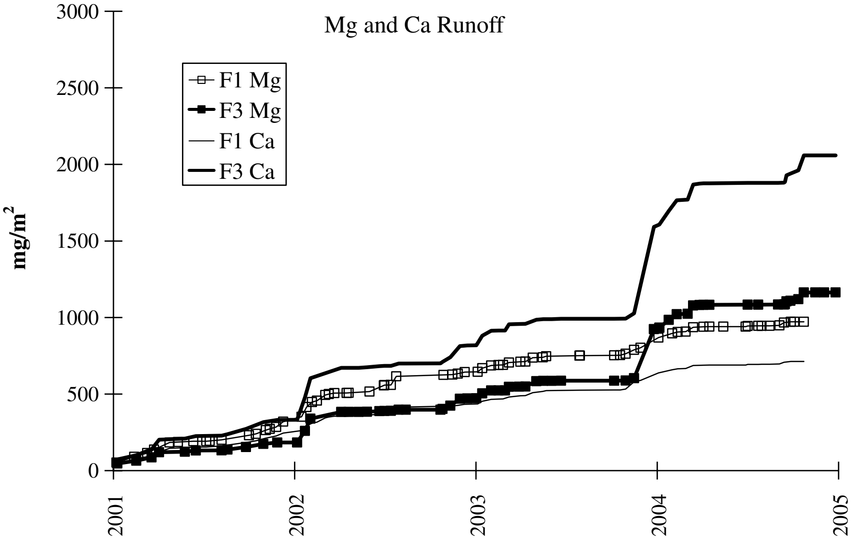

Fig. 9. Cumulative mass fluxes of Ca and Mg from the two studied catchments during the experimental period.

During the monitoring period before the experiment started, the total mass flux of SO_4 in runoff water from catchment F1 was approximately 50% higher than that of F3 (Fig. 6). The higher concentrations of SO_4 from F1 compared to F3 during the monitoring period could be due to previous felling of parts of the F3 area (Olsson, 1985). Reynolds et al. (1995) found lower concentrations of SO_4 in runoff from areas where conifer forest has been felled. After the groundwater extraction experiment was initiated, the mass flux from the F3 experimental area became similar to that of the F1 reference area (Fig. 7). A SO_4 surge in 2004 makes the mass flux from F3 even higher than that of F1.

A similar increase was observed for Ca and Mg. Before the experiment started, the mass flux for Ca in runoff water from F3 was approximately 50% higher than in that of F1 (Fig. 8). During the experiment, the mass flux in F3 increased threefold in comparison to F1 (Fig. 9).

4.4. Chemical alterations of groundwater in fractured bedrock

The chemistry of the groundwater in the fractured bedrock became more similar to that of the wetland and surface water. The increased recharge from shallow water caused an induced acidification

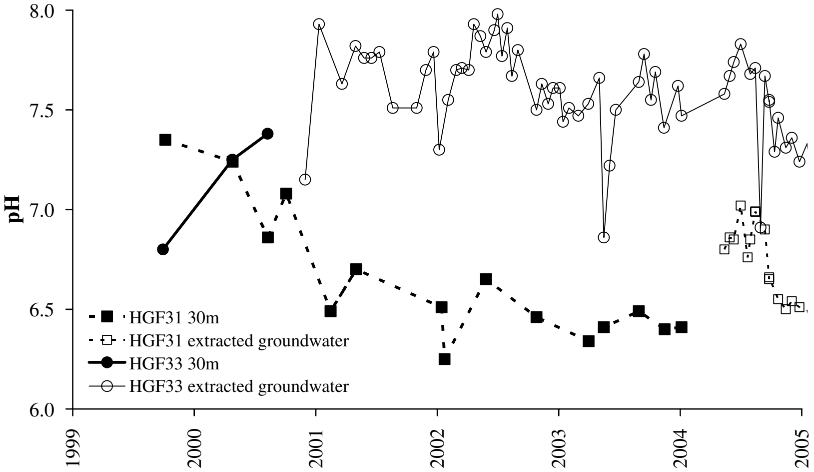

Fig. 10. Time series of pH in groundwater of boreholes HGF31 and HGF33 located in the fractured bedrock.

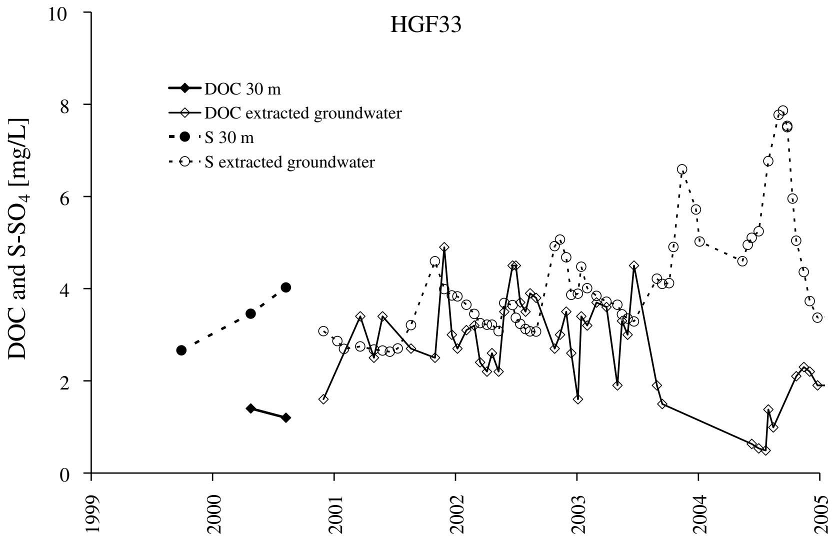

Fig. 11. Time series of SO_4 and DOC in HGF33 before and during the groundwater extraction.

of more than 0.5 pH units in boreholes where low buffer capacity (e.g., HGF31) was measured, while boreholes with higher buffer capacities (e.g., HGF33) exhibited stable pH values (Fig. 10). No decrease in alkalinity or other macroelements was noted in the majority of observation boreholes, although one of the drilled boreholes did show such tendencies. The increased recharge was, however, evident through the increase of DOC concentrations (Fig. 11).

The powerful effects of oxidization on water chemistry in shallow groundwater in the wetlands also had an effect on the rock groundwater. The S surges can be observed in boreholes that were quickly recharged by shallow water. Fig. 11 illustrates how the SO_4 concentrations double at the same time of year as the SO_4 surges were observed in the wetland and surface waters. The increase in sulphate concentrations can affect cations such as the Ca bound to the rock in the fractures and cause them to become soluble. As a result of this process, the increased S concentration could be the reason why levels of macroelements such as Ca remain fairly constant rather than decrease when the rock groundwater was recharged by ionically weak shallow waters (Fig. 12).

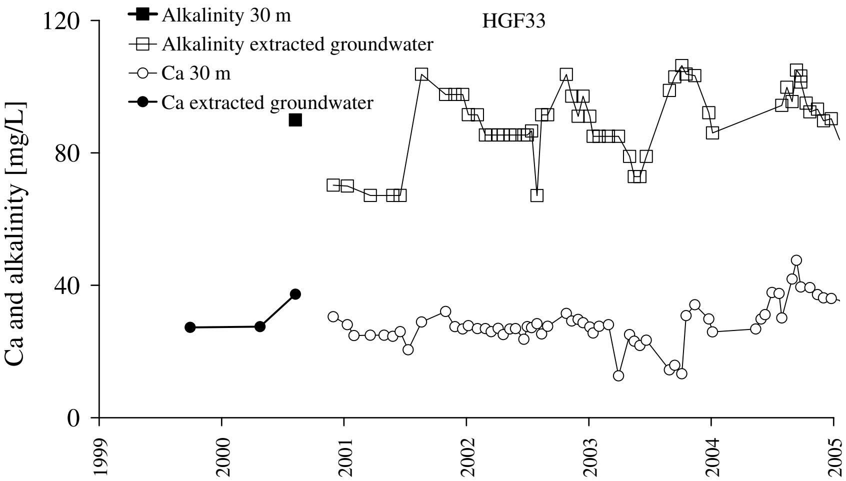

Fig. 12. Time series of alkalinity and Ca concentrations in groundwater from HGF33.

5. Conclusions

The extraction of groundwater resulted in approximately 50% of the water that would otherwise appear as runoff, infiltrating and recharging the groundwater in the bedrock. The groundwater extraction caused seasonal aeration of the shallow soil layers, which led to a release of SO_4 and a subsequent SO_4 surge. During this induced oxidation and acid pulse, divalent base cations (Ca and Mg) also increased in shallow groundwater and runoff. The groundwater of the bedrock was affected by the increased recharge and resulting reduction in retention time in the form of lowered pH and increased DOC. The increased S concentration in surface waters had a significant impact on the deep groundwater chemistry; the SO_4 concentration increased, and consequently other macroelements such as Ca did not decrease as expected, but remained fairly constant throughout the experimental period.

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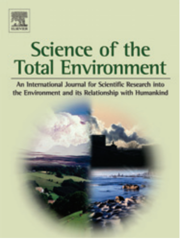

Recovery from groundwater extraction in a small catchment area with crystalline bedrock and thin soil cover in Sweden

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ABSTRACT

An experiment has been in progress since 1997 in a small catchment area (28,000 m^2) with crystalline bedrock and thin soil cover to study the conceivable impact on groundwater conditions of tunneling and the use of groundwater. The impact on hydrology and hydrochemistry from intensive extraction of groundwater at a depth of 50 m in the bedrock has been studied at Lake Gårdsjön in Sweden. The catchment area was first monitored under pristine conditions, followed by four and a half years of extraction and then a recovery phase. The geological conditions result in a low buffer capacity and high sensitivity to acidification. During the period of extraction, the surface runoff decreased by approximately 50% compared to a nearby reference area. The groundwater extraction caused increased fluctuation in groundwater levels in a wetland, which in turn caused oxidation of reduced sulfur to sulfate. The sulfate concentrations increased almost 100-fold in some instances, causing a lowering of the pH by one unit in shallow groundwater. Since extraction of the groundwater was discontinued, the pH has gradually risen and the sulfate concentrations have decreased. However, the concentration of sulfate in groundwater in the wetland has remained stable at approximately double the pre-experiment levels. Magnesium concentrations were lower after the experiment, caused by exhaustion of the magnesium pool in the wetland through acidification. The extraction of water from the bedrock shortened the retention times and increased the recharge of groundwater in the bedrock. After extraction was terminated, the groundwater levels in the boreholes recovered within a month to levels similar to those before extraction. The hydrochemistry of the bedrock groundwater, which was strongly affected by the hydrochemistry of shallow groundwater during the experiment, has also gradually begun to regain its pre-extraction signature. However, the surface runoff has remained low during the first 2 years of recovery, at about 60% of the volume compared to the unaffected catchment area. This could be explained by delayed recovery in resaturation of the shallow rock that was unsaturated during the experiment.

1. Introduction

This study was initiated to examine how changes in hydrological conditions, including a lowering of the groundwater level, in a small catchment area with thin soil cover and crystalline bedrock affect the hydrochemistry. Similar geological conditions are common in Canada, Finland, Norway, Sweden and more regions worldwide. Changes in hydrology

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can be caused by underground construction work and tunneling or cuttings for roads and railways. Examples of groundwater-related issues that could occur as a result of tunneling and underground construction projects have previously been described for the Romeriksporten tunnel in Norway (Kværner and Snilsberg, 1999; Kitterød et al., 2000; Beitnes, 2005; Brettum and Løvik, 2005), and for underground laboratories in Canada (Gascoyne, 2004), Sweden (Laaksoharju et al., 1999) and the USA (Glassley et al., 2003). A lowering of the groundwater level can of course also be caused by extraction of groundwater for domestic or industrial use. Knowledge of the hydrochemical consequences of such changes is sparse (Olofsson and Ericsson, 1985) but necessary due to the increase in underground construction activity and use of groundwater resources. Possible effects of a lowering of the groundwater level are a shortage of drinking water and a deterioration in the quality (Hultberg and Johansson, 1981), a negative impact on tunnel reinforcements and waterproofing systems due to changes in water chemistry (Parkinson, 1975; Axelsson, 2006), and biota damage due to acidification.

In this study, one catchment area was studied under pristine conditions for three years and for four and a half years during groundwater extraction. The recovery from extraction is currently being studied. Findings and results from the initial three years of monitoring under pristine conditions have been published in Knape (2001) and findings from the extraction period have been published in Graffner et al. (2005), Hultberg et al. (2005) and Mossmark et al. (2007).

The aim of this project is to study the recovery of hydrogeology, hydrology and water chemistry from the groundwater extraction experiment. Findings for two years of the recovery phase are presented in this paper. The focus of this paper is to identify, quantify and discuss the persistence of some of the negative chemical and hydrological effects of groundwater extraction on surface waters, shallow groundwater and groundwater in the bedrock (Mossmark et al., 2007). This paper should be seen as a conceptual discussion with a focus on pH, alkalinity, sulfate and base cations. More chemical parameters have been measured although the results are not presented in this article.

2. Description of the experimental set-up and the studied catchment areas

This project was carried out in two small, fairly identical catchment areas in the Lake Gårdsjön watershed on the west coast of Sweden (Fig. 1). One of the catchment areas was used for the experiment (catchment area F3) while the other served as a reference (catchment area F1). The distance between the

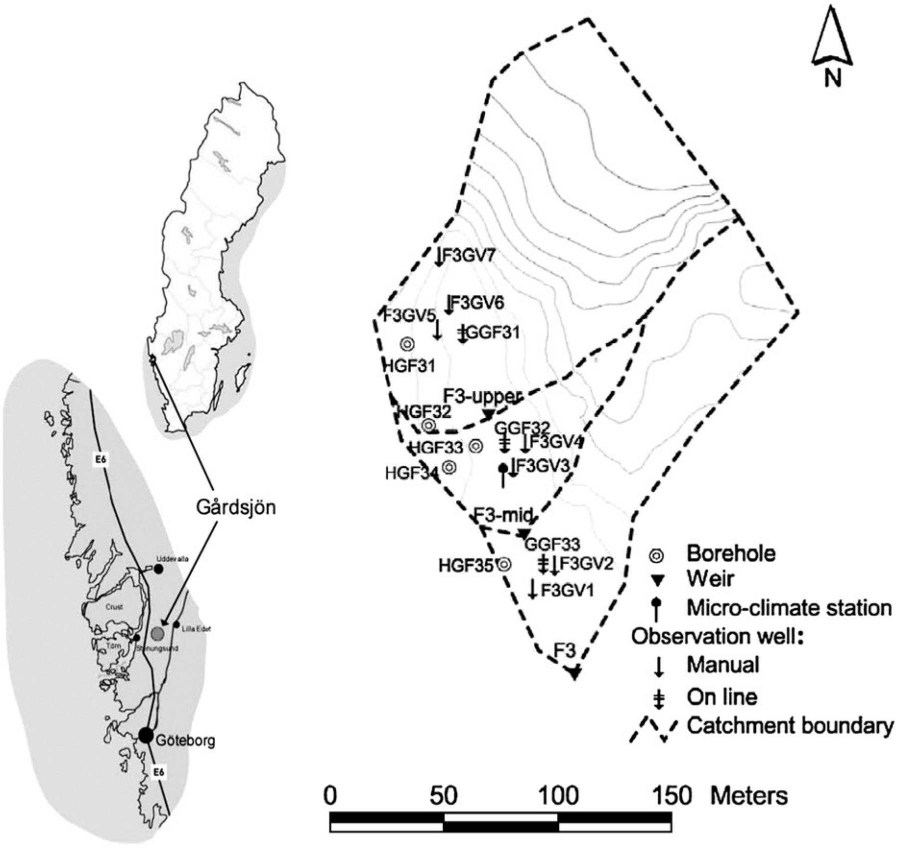

Fig. 1 – Geographical location of the two catchment areas and the instrumentation set-up in experimental area F3. The reference catchment area F1 had similar instrumentation to that in F3 although runoff was only monitored at one weir (www.gardsjon.org and Graffner et al., 2005).

two catchment areas is 1.3 km. The experiment consisted of groundwater extraction from the bedrock by means of two percussion boreholes (HGF31 and HGF33) in catchment area F3 (Fig. 1). A submersible pump was installed in each borehole at a depth of approximately 50 m. The extracted water was pumped to the nearby Lake Gårdsjön, outside the catchment area. For general information on the F1 catchment area see Andersson et al. (1998).

The study included the monitoring of hydrological conditions and frequent ground and surface water sampling for chemical analysis. Both catchment areas had been monitored for several years before the groundwater extraction experiment was initiated in catchment area F3. Catchment area F1 is 37,000 m^2 in size and F3 is 28,000 m^2 (Olsson et al., 1985).

2.1. *Geological and hydrological conditions*

The bedrock mainly consists of gneissic granodiorite (Samuelsson, 1985) covered by thin layers of regolith (mainly glacial till) and soil. According to Melkerud (1983) a fracture zone in the rock exists beneath the central wetland of catchment area F3 in a north–south direction and another fracture zone crosses the F1 catchment area. According to Fridh and Hayling (1980) the metamorphosed bedrock includes several sets of joints and fractures. The bedrock of the Gårdsjön area has fractures and fracture zones that are connected and are water-bearing and hence contain a fractured aquifer. The bedrock aquifer boundaries for F1 and F3 were initially assumed to be equal to the water divides for the surface water catchment areas.

The Weichselian-formed glacial period occurred in the Lake Gårdsjön area from approximately 100,000 years BP and the last glacial retreat occurred 14,000 years BP. The glacier deposited crushed inorganic material formed from eroded rock and previous regolith as thin layers directly on top of the crystalline rock, a deposit type referred to as glacial till. This till forms the surface of more than 60% of the experimental catchment area F3 and more than 50% of the reference catchment area F1 (Olsson et al., 1985).

After deglaciation, several marine transgressions took place. Areas located below the highest point of the shoreline thus became exposed to wave washing. Furthermore, these areas typically have deposit types sedimented in water, which means material that is quite sorted in terms of particle size and in some cases thick layers. The experimental areas are located at an elevation of approximately 115 m above sea level (asl) and, according to Fredén (1986), the highest shoreline is 125 m asl. However, only very thin layers of fine silt to sand have been found on top of the till in the experimental wetland. Organic wetland soils cover approximately 5% of the area of the experimental catchment area F3 (Nilsson, 1985). The F1 reference catchment area also includes a wetland (Andersson et al., 1998) similar in extent to the F3 wetland. The wetlands in the two catchment areas consist primarily of sphagnum peat.

The total annual net precipitation is around 1100 mm/year and approximately 50% is lost through evapotranspiration. Using the Köppen–Geiger system the climate has been classified as maritime temperate, which is a mild, humid climate without dry seasons. Vegetation mainly consists of a mixture of Norway spruce and Scots pine (Olsson et al., 1985).

2.2. *Experiment and monitoring approach*

The experiment in catchment area F3 involves the constant withdrawal of groundwater in a percussion-drilled borehole (HGF33) at a depth of 50 m, from December 2000 to April 2005. A brief interruption in groundwater extraction occurred during February and March 2004. From April 2004 until April 2005, the percussion-drilled borehole HGF31 was used for complementary groundwater withdrawal (from a depth of 50 m) in order to increase the impact. Three additional percussion boreholes in catchment area F3 (HGF32, HGF34 and HGF35) and one in the reference catchment area F1 (HGF1) were used for monitoring only. The six percussion boreholes were drilled to an approximate depth of 70 m, and HGF31, HGF33 and HGF35 were inclined at an angle of 20° from the vertical. As mentioned above, the extracted groundwater was pumped to the nearby Lake Gårdsjön, which is outside the monitored catchment areas.

A logging system regularly recorded data on extracted water volumes, surface runoff (Thomson weirs), weather conditions (climate station), and groundwater levels in the bedrock in the five percussion boreholes (transducers). Three shallow groundwater wells in F3 (GGF31, GGF32 and GGF33) and one in F1 (GGF1) in the soil/regolith were measured with transducers. Seven of the shallow wells in F3 (F3GV1-7) as well as four wells in F1 were only measured manually. The pH and electrical conductivity (EC) of the extracted groundwater and surface runoff were measured continuously in the F3 experimental catchment area. The location of the equipment and its arrangement in catchment area F3 is presented in Fig. 1.

The monitoring included a regular sampling program for chemical analysis. Shallow groundwater (at an approximate depth of 2 m) from the two catchment areas was collected six to ten times per year, while extracted groundwater and runoff water were sampled every fortnight. The groundwater in the bedrock was sampled four to eight times per year from a depth of 30 m. The groundwater samples from the observation boreholes were collected using a small submersible electric pump designed for water sampling. The extracted groundwater was sampled directly in the water outflow from the permanently installed pumps in HGF31 and HGF33. The sampled water was analyzed for pH, EC, and major constituents. The shallow groundwater samples were filtered in the field using a 0.45 μm filter. The deep groundwater samples and the surface water samples were transported to the laboratory unfiltered. EC and pH were measured in the laboratory before filtration using a 0.45 μm filter. Chloride, sulfate and base cations were analyzed using ion chromatography and alkalinity was analyzed by means of titration with hydrochloric acid.

3. Results and discussion

During the period of groundwater extraction a significant alteration in the hydrological system of the F3 experimental area was observed, which in turn affected the hydrochemical situation of the ground and surface waters (Mossmark et al., 2007). Since the experiment, a gradual recovery of the hydrochemistry and hydrological system has occurred. Most

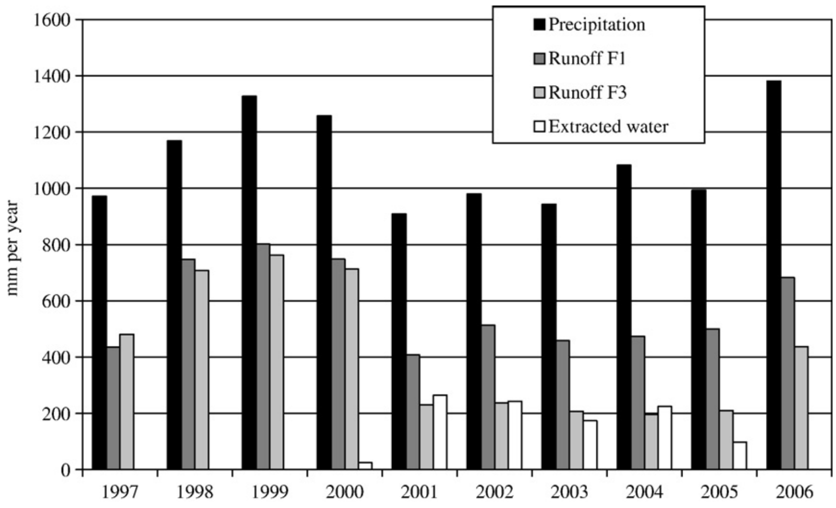

Fig. 2 – Precipitation for the Lake Gårdsjön area, runoff water volume from the reference catchment area F1 and runoff and extracted water volumes from the experiment catchment area F3 during the period 1997–2006.

important, a number of more persistent effects of the experiment have been observed.

3.1. *Hydrological changes*

Prior to the experiment, the two catchment areas exhibited similar hydrological properties regarding runoff volumes. During groundwater extraction an approximate decrease of 50% in runoff volume in the F3 experimental area was observed (Fig. 2) compared to the reference catchment area F1. The decrease in runoff from F3 compared to the reference area F1 corresponded well with the extracted water volume. This indicates that the extracted water mainly consisted of water recharged within the F3 catchment area and consequently that the boundaries of the groundwater aquifer would not exceed the water divide of the catchment area. Since the extraction of groundwater was terminated in April 2005, the runoff volumes from the F3 catchment area have gradually increased. During the last full year (2004) of groundwater extraction, the runoff from the F3 catchment area was only 41% compared to runoff from F1. After extraction was terminated it gradually increased to 61% in 2006.

The level of shallow groundwater in the wetland and the drilled boreholes was subject to greater seasonal fluctuations during extraction. Fig. 3 reveals that seasonal fluctuation in shallow groundwater is up to 2.5 m (GGF32). The groundwater levels in the wetland have fluctuated less since the experiment. For the groundwater in the bedrock, seasonal fluctuation (Fig. 4) became evident in some of the boreholes (HGF31 and HGF32) during extraction. The pattern of fluctuation was a lowering of the groundwater level during the summers of 2001, 2002 and 2003. Other boreholes showed a more permanent decrease in the groundwater level (HGF34 and HGF35) throughout the period of groundwater extraction.

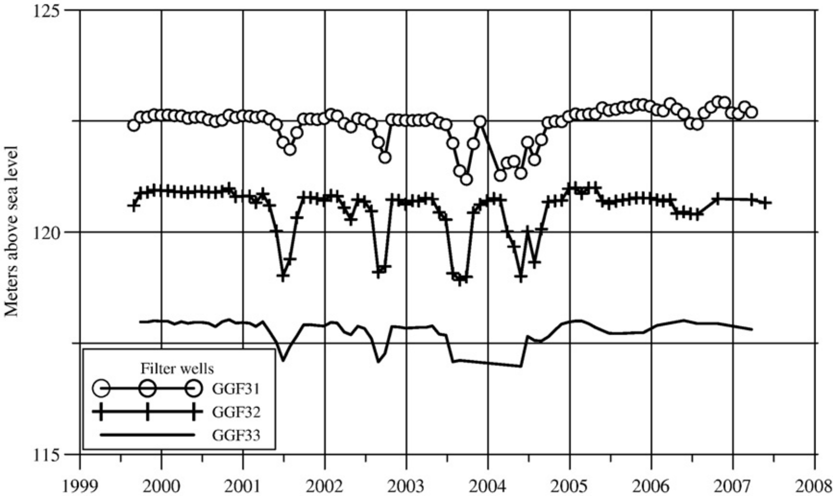

Fig. 3 – Shallow groundwater levels in the wetland of the F3 catchment area from August 1999 to July 2007. The experiment caused an increase in seasonal fluctuation in groundwater levels. Since termination of the experiment the levels have stabilized.

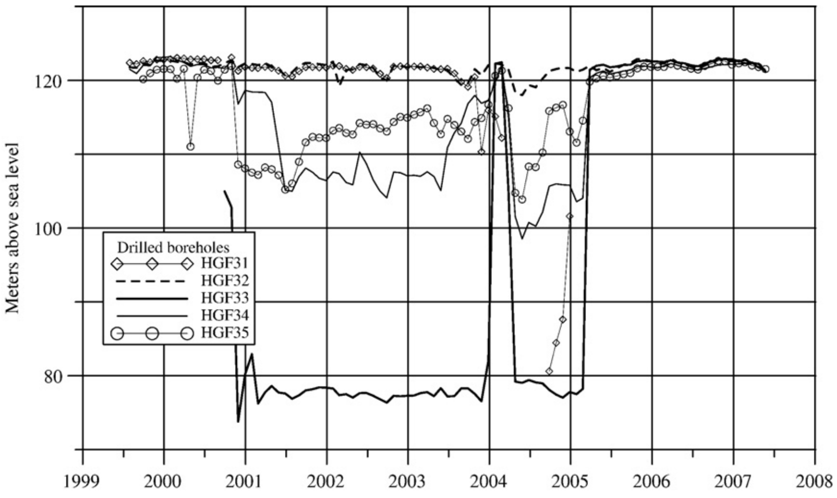

Fig. 4 – Groundwater levels in the five boreholes in the bedrock in the F3 catchment area between 1999 and 2007. The groundwater levels stabilized after the experiment was terminated.

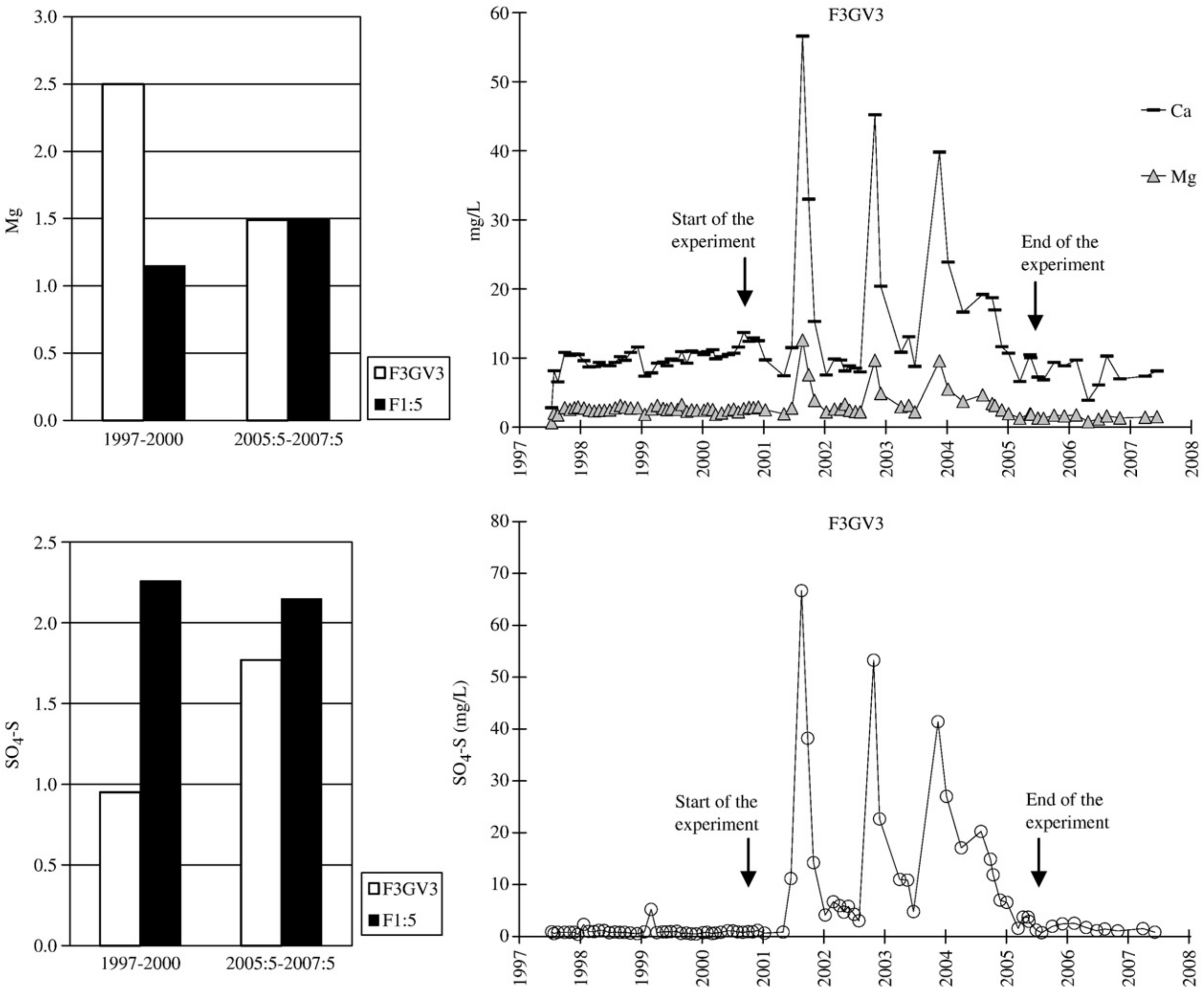

Fig. 5 – Changes in sulfate–sulfur, magnesium and calcium concentrations in shallow wetland groundwater. The bar charts show average concentrations of sulfate–sulfur and magnesium in the wetlands of the reference area F1 (F1:5) and the experimental area F3 (F3GV3) before and after the experiment. The scatter plots show the time series for before, during and after the experiment in F3.

Since the experiment was concluded all boreholes have exhibited stable groundwater levels (Fig. 4).

During extraction, the groundwater levels in the bedrock were lower than in the wetland. The groundwater situation in the bedrock during extraction can be characterized as a semi-confined aquifer with non-saturated flow in the shallowest parts of the rock mass. After termination of the groundwater extraction experiment, the groundwater levels in the boreholes in the bedrock recovered quickly. However, the groundwater level in a borehole represents the groundwater pressure in all the fractures that it communicates with. The groundwater pressure is likely to differ between different parts of the rock mass. The recovery with resaturation of the shallow fractures in the rock that was unsaturated during the experiment is likely to be delayed following termination of extraction (Bockgård, 2004). The rapid recovery in the groundwater levels in the boreholes does not necessarily represent the groundwater pressure levels in the shallow rock fractures. A slow and gradual recovery of the groundwater to resaturate the shallowest fractures could explain the gradual and delayed recovery of the runoff from the F3 catchment area.

3.2. Chemistry of the shallow groundwater and surface water

During the experiment, the increased seasonal fluctuation in the groundwater level led to aeration of the shallow organic soil layers of the wetland. The seasonal aeration caused the sulfide bond in the wetland to oxidize to sulfate causing a sulfate surge and resulted in a subsequent acid pulse when the groundwater levels rose in the autumn. The effect of the experiment was gradual acidification of the wetland. Effects similar to the oxidation of sulfide to sulfate that led to acidification in a tarn due to the lowering of the groundwater level were observed during the construction of the Romeriksporten tunnel in Norway (Brettum and Løvik, 2005). In the case of Romeriksporten, the decrease in pH from neutral levels (pH 6.7 according to data in Brettum et al., 1999) to below 4 in the affected tarn, occurred during the construction phase of the tunnel. However, a similar tarn located near the affected tarn but outside the hydrological influence area of the tunnel was noted to be unaffected and the pH in this tarn remained at neutral levels during the construction period (Brettum and Løvik, 2005).

During the first two years after the experiment at Lake Gårdsjön, a pH recovery has been noted and sulfate surges have been absent. However, the concentrations of sulfate–sulfur have persisted at slightly higher levels after the experiment compared to pre-experiment levels. In the reference catchment area F1, the concentrations of sulfate–sulfur decreased during the same period (Fig. 5). In the case of the tarn affected during the construction phase of the Romeriksporten tunnel, a gradual recovery indicated by increasing pH and decreasing sulfate concentrations was observed after the construction phase (Brettum and Løvik, 2005). However, the pH in the tarn still remained below the pH of the nearby unaffected tarn five years after completion of the tunnel (Brettum and Løvik, 2005).

The concentrations of the cations magnesium and calcium paralleled those of sulfate–sulfur with high concentrations in the autumn during the extraction period at Lake Gårdsjön. Afterwards, concentrations of magnesium in the groundwater of the wetland were lower than pre-experiment levels (Fig. 5). This could be explained by the higher mass fluxes of magnesium in runoff water from the experimental catchment compared to the reference catchment during the experiment period (Mossmark et al., 2007). Hultberg et al. (1995) showed that the mobility of magnesium was higher than for calcium after dolomitic limestone was added to another catchment area at Lake Gårdsjön. This could further explain the exhaustion of magnesium in the F3 catchment area. Acid deposition has been observed to cause depletion of calcium and other cations in soil (Hultberg and Johansson, 1981; Likens et al., 1996; Driscoll et al., 2003). A similar effect was observed from the acid pulses caused by oxidation of sulfur in F3 causing depletion of magnesium in the wetland.

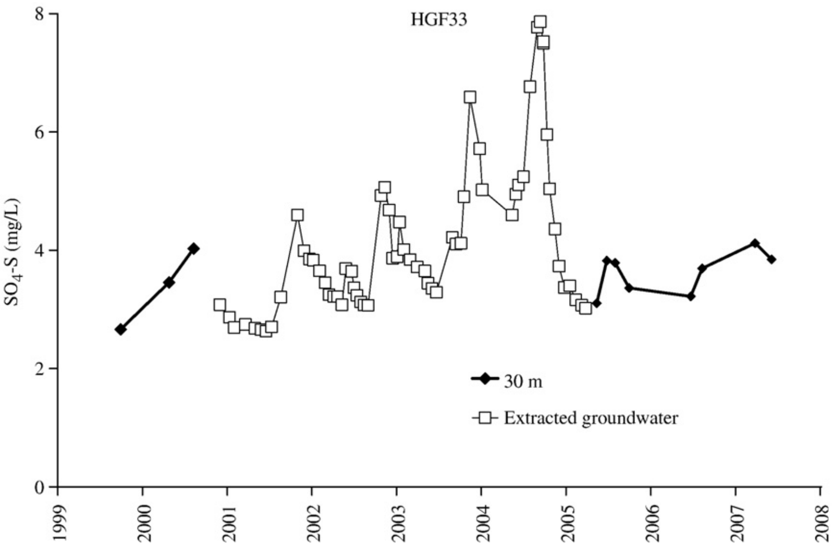

Fig. 6 – Groundwater in bedrock. Time series of sulfate–sulfur in HGF33 from 1999 to 2007. High concentrations of sulfate–sulfur occurred seasonally during the experiment and were followed by complete recovery after the experiment came to an end.

The chemistry of surface runoff water displayed a pattern similar to the shallow groundwater. The increase in sulfate–sulfur and base cation concentrations during the experiment was slightly lower in runoff compared to the shallow groundwater. The chemical changes for runoff observed during the experimental period have been reversed since extraction was terminated. The hydrochemistry of shallow groundwater in the glacial till surrounding the wetland was, however, unaffected by the experiment (Mossmark et al., 2007). According to Melkerud (1977) the glacial till is mainly of local origin and therefore reflects the composition of the bedrock in the Gårdsjön area (Olsson et al., 1985). Originating primarily from granodiorite and granite, the till does not contain high concentrations of sulfur. According to an investigation into sulfur in glacial till in southern Finland (Nikkarinen and Lestinen, 2003), the mobile sulfur in the glacial till mainly originates from sulfides in the till particles that have been exposed to weathering. There is consequently little mobile sulfur available in the glacial till that could cause effects similar to those that occurred in the wetland.

3.3. *Chemistry of the groundwater in the fractured bedrock*

During the experiment, the chemistry of the groundwater in the fractured bedrock became more similar to that of the wetland and surface water (Mossmark et al., 2007). Effects of changes in water chemistry in shallow groundwater in the wetlands were also reflected in the rock groundwater. The sulfur surges in the wetland groundwater were observed in boreholes that were quickly recharged by shallow wetland water (Fig. 6). The elevated concentrations of sulfate–sulfur in the bedrock groundwater during the experiment recovered quickly when the experiment was terminated. The increased recharge from shallow water also caused an induced acidification of more than 0.5 pH units in boreholes where low buffer capacity (e.g. HGF31) was measured. After extraction was intensified in 2004 through the use of two boreholes, a decrease in pH also occurred in borehole. HGF33 (Fig. 7). During this intensive final year of extraction, alkalinity also decreased

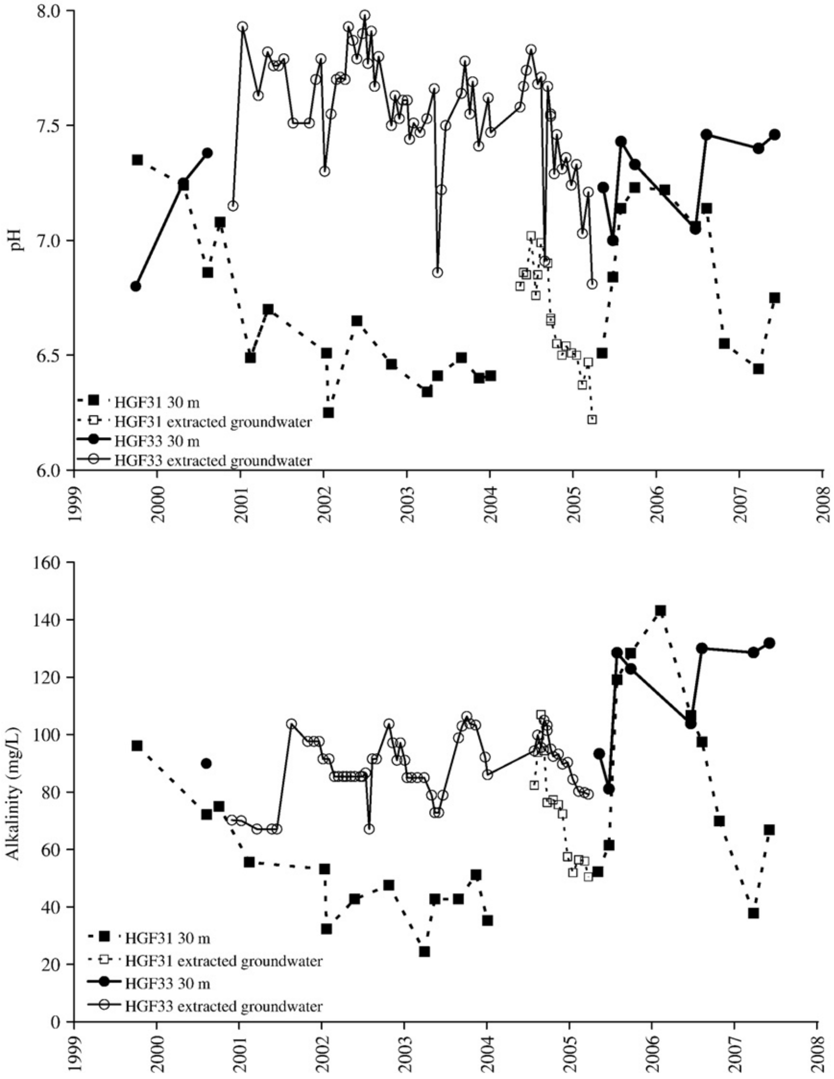

Fig. 7 – Groundwater in the bedrock. Time series of pH and alkalinity in the percussion boreholes HGF31 and HGF33 from 1999 to 2006. The decrease in pH and alkalinity during the experiment was reversed after extraction of groundwater was terminated.

in HGF33, whereas HGF31 exhibited a decreasing trend throughout the experiment (Fig. 7).

Tunneling projects and groundwater extraction have previously been noted to have an impact on the deep groundwater, similar to the changes observed at Lake Gårdsjön. It was noted that the impact was mainly caused by increased groundwater recharge from shallow waters. In the Romeriksporten tunnel, the increased sulfate concentrations in shallow waters (Brettum and Løvik, 2005) were reflected in increased sulfate concentrations in the water leaking into the tunnel during the construction phase (Traaen and Berge, 1999). Laaksoharju et al. (1999) described how the groundwater chemistry in the bedrock was affected by the construction of the tunnel system for the Äspö Hard Rock Laboratory in Sweden. According to Laaksoharju et al. (1999) the construction of the tunnel caused groundwater at depth to be replaced by shallower groundwater. In addition, a similar change in the deep groundwater composition was also observed during the construction of the Tsukuba Tunnel in Japan (Shimada and Ishii, 1986). The nature of the deep groundwater along the Tsukuba tunnel gradually came to mimic the nature of shallow waters (Shimada and Ishii, 1986). Olofsson and Ericsson (1985) noted the effects on groundwater chemistry caused by long-term water extraction at eighteen production wells. At four wells, a trend of increasing sulfate concentrations was observed and two wells revealed a trend of decreasing pH. The results from these wells were similar to those from the experiment at Lake Gårdsjön.

When the experiment at Lake Gårdsjön was terminated, the pH and alkalinity increased rapidly in both HGF31 and HGF33. For HGF33 the pH and alkalinity increased to levels similar to those observed before the experiment (Fig. 7). In HGF31 the initial increase in pH and alkalinity was followed by a decrease. The reason for the immediate increase in alkalinity and pH could be an effect of horizontal flow of old groundwater within the bedrock to the previous drawdown cone around HGF31 and HGF33, replacing the water affected by the wetland. The decrease in alkalinity and pH that occurred from the late summer of 2006 through to spring 2007 could be caused by shallow groundwater from the wetland resaturating the shallow fractures of the bedrock.

4. Conclusions

During the experiment, one obvious result of the extraction of groundwater was a 50% decrease in runoff. The water that would normally appear as surface runoff instead infiltrated and recharged the groundwater in the bedrock. Since the groundwater extraction experiment was terminated in April 2005, fluctuations in groundwater levels in the wetland caused by groundwater extraction have stabilized and groundwater levels in the bedrock boreholes have recovered. Moreover, runoff volumes from the experiment catchment area have gradually increased, but are persistently lower than from the reference catchment area. An explanation for the slow gradual increase in runoff is that a delayed recovery occurs with resaturation in the shallow rock that was unsaturated during the experiment. The boreholes in the bedrock are approximately 70 ym deep and their water levels do not necessarily represent the pressure levels in the shallowest parts of the bedrock.

Since the experiment was terminated, the sulfate surges that occurred during the experiment in the shallow groundwater in the wetland and in surface waters have ceased. However, the sulfate–sulfur concentrations are slightly higher in the wetland groundwater after the experiment compared to before. A decrease in magnesium in the wetland groundwater due to exhaustion of the magnesium pool is evident. For the runoff water chemistry, there were no noticeable persistent effects from the experiment despite chemical changes similar to those that occurred in the wetland during the experiment.

During the experiment, vertical flow of groundwater from the wetland to the bedrock caused increased sulfate–sulfur concentrations up to three times the pre-experimental concentrations in the deep groundwater. Its alkalinity decreased as well as the pH. After the experiment, the sulfate–sulfur concentrations and pH of the rock groundwater returned to their pre-experiment levels. The reason for this could be an effect of horizontal flow of old groundwater in the bedrock to the area of the previous drawdown cone around the extraction boreholes.

The observations regarding hydrologically induced hydrochemical changes caused by the extraction experiment presented in this paper can be attributed to the geological conditions at Lake Gårdsjön. Similar conditions are common in Finland, Norway, Sweden, Canada, the northern parts of the USA and more regions worldwide. The results from this study could be used to stress the importance of taking proper precautions to minimize negative hydrochemical impact from activities that affect the groundwater balance.

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