

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Prediction of Groundwater Chemistry in Conjunction with
Underground Constructions
- Field Studies and Hydrochemical Modelling

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Constructions – Field Studies and Hydrochemical Modelling

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ABSTRACT

In almost all cases, tunnels are subjected to influx of groundwater. The influx varies depending on geological and hydrological conditions as well as the design and performance of the waterproofing system. The influx causes hydrological changes that are likely to have an impact on the hydrochemical conditions. As part of the planning process for underground constructions, it is important to propose a cost-effective design, including the selection of construction materials. According to regulatory documents issued by the authorities, the material selection in underground constructions should be based on hydrochemical conditions. This thesis presents a methodology for predicting the hydrochemical conditions that will exist during the construction and operation phase for constructions that are being built in crystalline bedrock in areas that have been subjected to recent glaciation and thereby provide a basis for material selection.

Four field studies were carried out: two as field experiments with extraction of groundwater from boreholes in the bedrock and two during the construction phase of two rail tunnels built in crystalline bedrock. The results from field studies emphasised the interaction between geological conditions and hydrochemistry. The heterogeneity of the bedrock was found to be of importance for the hydrochemical conditions. In one of the tunnels studied it was found that the groundwater hydrochemistry in a fracture zone resembled that of the surrounding bedrock. In more homogeneous and less fractured rock nearby, the groundwater hydrochemistry was affected by sealing grout. This observation is of importance for the tunnel drainage system.

In the overburden, aeration of wetlands may occur, including the release of S and H⁺ (acidification) through oxidation, resulting in the depletion of alkalinity and release of base cations Ca²⁺, Mg²⁺ and K⁺. The influence of shallow waters on the bedrock groundwater is likely to increase. In groundwater recharge areas, the main impact is the possibility that oxidised water could influence the bedrock groundwater. In crystalline bedrock and under pristine conditions, slow processes with silicate weathering are of importance for the buffering capacity against acidification. However, during construction, minerals with more rapid reactions, such as FeS₂ (pyrite) oxidation or CaCO₃ dissolution, may be of greater importance (if available) as shorter groundwater retention times disable the slow processes. Particularly in locations with wetlands that have a hydraulic connection with the bedrock and with the presence of FeS₂, the hydrochemistry will most likely become aggressive towards construction materials. In three of the field studies, hydrochemical changes were observed that would require complementary protection against deterioration of construction materials. In two instances in approximately five years, hydrochemical and hydrological recovery was observed.

The proposed methodology in the thesis is based on 1) coupled hydrogeological-chemical assessments, 2) field investigations and 3) modelling of hydrochemical conditions. Important hydrochemical processes were identified under different geological conditions. The proposed methodology includes three steps: 1) a desk study to assess the potential for hydrochemical conditions that are aggressive towards cement or steel. If so, further studies, including field investigations, are proposed in step 2) with the aim of either forming a basis for the selection of construction materials or recommending hydrochemical prediction modelling in an additional step 3).

Keywords: Groundwater, Hydrochemistry, Tunnelling, Modelling, PHREEQC

LIST OF PAPERS

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

- I. Mossmark, F., Annertz, K.K., Ericsson, L.O., Norin, M., 2014. Impact on Hydrochemistry from the Construction of the Western Tube of the Hallandsås Railroad Tunnel, Sweden. Submitted to 'Tunnelling and Underground Space Technology'.
- II. Mossmark, F., Ericsson, L.O., Norin, M., Dahlström, L.-O., 2013. Hydrochemical Changes Caused by Underground Constructions – a Case Study of the Kattleberg Rail Tunnel. Submitted to 'Engineering Geology'.
- III. Mossmark, F., Hultberg, H., Ericsson, L. O., 2007. Effects on water chemistry of groundwater extraction from crystalline hard rock in an acid forested catchment at Gårdsjön, Sweden. *Applied Geochemistry* (vol. 22, 1157-1156).
- IV. 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), 253-261).
- V. Mossmark, F., Ericsson, L.O., Norin, M., Dahlström, L.-O., 2010. Field study: aggressive groundwater caused by underground constructions and water extraction. IAEG Conference, Geologically Active, Auckland 2010.
- VI. Mossmark, F., Ericsson, L. O., 2014. Predictive simulations of hydrochemistry affected by groundwater extraction from crystalline bedrock in the context of tunnelling. Submitted to 'Applied Geochemistry'.
- VII. Mossmark, F., 2010. Groundwater chemistry affected by underground construction activities. Publ. lic. 2010:2. Chalmers University of Technology. Gothenburg. (Abstract).

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Mossmark, F., Norin, M. Dahlström, L.-O., Ericsson, L.O., 2008. Vattenkemins påverkan på undermarksanläggningar (in Swedish). Swedish Rock Engineering Research Foundation (SveBeFo) report K29. Stockholm, Sweden.

Mossmark, F., Ericsson, L. O., Norin M., Annertz K. K., Dahlström, L.-O., 2010. Groundwater and hydrochemical interaction with underground constructions – experience from Hallandsåsen. NBM 2010, Kongsberg, Norway.

Ericsson, L.O., Mossmark, F., 2010. The chemistry of groundwater is a wildcard in construction. Sustainability. Stockholm, Sweden.

Mossmark, F., Ericsson, L. O., 2011. Modeling Approach for Groundwater Chemistry Related to Underground Constructions. Modflow and More, 2011 – Integrated Hydrological Modeling, Colorado School of Mines, USA, 2011.

Mossmark, F., 2014. Hydrogeological Conditions at the F3 Catchment Area, Lake Gårdsjön. Publ. 2014:9. Division of GeoEngineering, Chalmers University of Technology. Gothenburg, Sweden.

Mossmark, F, Ericsson, L. O., Norin M., 2013. Grundvattenkemisk interaktion med undermarksanläggningar (in Swedish). Rock Engineering Research Foundation (BeFo), report 126. Stockholm, Sweden.

Ericsson L. O., Hultberg H., Hultengren S., Mossmark F., 2005. Impact from groundwater level decrease and groundwater abstraction on groundwater recharge and water quality development in crystalline bedrock – Final report Phase 1, Field tests in Äspö and Gårdsjön, 1997-2005 (in Swedish). Report 2005:17, Dep. of Civil and Environmental Engineering, Div. of GeoEngineering, Chalmers University of Technology.

Division of work between the authors

Paper I: All the authors formulated the scope of work and objectives. Annertz and Mossmark wrote the description of the study area, the tunnelling techniques and the progress of the tunnelling and evaluated its hydrogeological influence. Mossmark evaluated the hydrochemical conditions and their implications for construction materials with support from Annertz, Ericsson and Norin. Mossmark was the main author of the paper.

Paper II: All the authors formulated the aim and scope of work. Mossmark wrote the paper with support from Ericsson. Norin provided expert knowledge that supported evaluation of the hydrochemistry. Dahlström provided expert knowledge of underground constructions. Mossmark was the main author of the paper.

Paper III: All the authors formulated the hypothesis. Mossmark wrote the paper with support from Hultberg. Ericsson provided expert knowledge of hydrogeology. Mossmark was the main author of the paper.

Paper IV: All the authors formulated the scope of work and objectives. Mossmark wrote the paper with support from Ericsson and Hultberg. Mossmark was the main author of the paper.

Paper V: Mossmark, Ericsson and Norin formulated the scope of work and objectives. Mossmark wrote the paper with support from Ericsson. Norin provided expert knowledge that supported evaluation of the hydrochemistry. Dahlström provided expert knowledge of underground constructions. Mossmark was the main author of the paper.

Paper VI: All the authors formulated the aim of this paper. Mossmark carried out the hydrochemical modelling and wrote the paper with support from Ericsson. Mossmark was the main author of the paper.

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Fredrik Mossmark

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1 INTRODUCTION

Compared to the large number of underground constructions that are being built, there are relatively few related systematic studies of hydrochemistry and even fewer attempts to predict hydrochemical conditions. In Scandinavia, examples of observational studies of hydrochemical changes in conjunction with underground constructions include the Bolmen water supply tunnel (Olofsson, 1991), the construction phases of the Hallandsåsen (Mossmark, 2010b) and Romeriksporten rail tunnels (Brettum and Løvik, 2005; Kitterød et al., 2000; Kværner and Snilsberg, 2013) as well as SFR, the final repository for low and intermediate level radioactive operational waste (Laaksoharju and Gurban, 2003; Nilsson et al., 2010). Two predictions of hydrochemical changes caused by the Hallandsås rail tunnels have been carried out (Laaksoharju et al., 2000; Mossmark, 2010b).

From an international perspective, there are also some relevant published observational studies related to hydrochemistry and underground constructions. Studies have been carried out for the planning of storage of spent nuclear fuel in Japan (e.g. Mizuno et al., 2013), in South Korea (e.g. Ryu et al., 2012), in Sweden (e.g. Laaksoharju et al., 1999; Mathurin et al., 2012) and in the United States (e.g. Al-Qudah et al., 2011). In addition, several studies have been carried out on the impact of hydrochemistry on the planned storage systems of nuclear fuel, including the corrosion of copper canisters (e.g. Ha et al. (2011) and Wang et al. (2013)). Among studies of road and rail tunnels, a few published studies also exist, including the Tsukuba Tunnel in Japan (Shimada and Ishii, 1986), the subway system in Seoul (Chae et al., 2008) and the New Colle Di Tenda road tunnel between France and Italy (Banzato et al., 2011).

One aspect of hydrochemistry is its importance for the degradation of construction materials used to waterproof and support underground constructions. This matter has only been monitored in a few previous studies, e.g. groundwater investigations in relation to the durability of waterproofing grout in the construction of a repository for spent nuclear fuel in Finland (Soler et al., 2011). There has been one study involving an evaluation of the hydrochemistry in a road tunnel and a utility tunnel in relation to the degradation of cementitious grout (SBUF, 2012). Furthermore, a study of hydrochemical influence on occlusions of drainage systems in tunnels has also been carried out (Ekliden, 2008).

Most previous investigations described in the international literature have been case studies of individual sites and the aim has not been to obtain a general understanding of the topic of underground constructions and hydrochemistry. So far, the topic has also been absent in the prominent standard references for rock engineering, such as the

suggested investigation methods published by the International Society for Rock Mechanics (2007) or in Hudson et al. (1993).

The hydrochemistry is difficult to predict since it is dependent on geological and hydrological conditions as well as the design of the tunnel (Mossmark, 2010a). Hydrological and hydrochemical changes may have an adverse effect on the environment and could affect the lifespan of construction materials, such as rock support, drainage systems and waterproofing systems (Mossmark, 2010a). Because this area of expertise as a whole has been neglected, it has been difficult to assess the extent to which problems may arise.

This thesis summarises studies of hydrochemistry in conjunction with underground constructions that have been carried out at Chalmers since the 1990s and in which the author of this thesis has been involved since 2001. It highlights and proposes methods for the prediction of hydrochemical conditions and changes in conjunction with such activities.

2 AIM AND OBJECTIVES

The research presented in this thesis is aimed at increasing the understanding of hydrochemistry and its potential changes related to underground constructions. The general objective is to obtain significant information for proposing cost-effective methodologies to predict the hydrochemical conditions. Detailed objectives are as follows:

1. Conducting a literature review of hydrochemistry related to underground constructions with the aim of acquiring knowledge of previous research.
2. Using systematic field studies to further develop the understanding of coupled hydrochemical processes in crystalline bedrock overlain by Quaternary deposits in the context of tunnelling or groundwater abstraction.
3. Providing robust input data for hydrochemical evaluations with conceptual models.
4. Evaluation of hydrochemical modelling as a tool for the prediction of hydrochemical conditions in conjunction with tunnelling.
5. Proposing methodology to predict the hydrochemical conditions that are likely to occur during the construction and operation phases of underground constructions. The prediction will be used for the selection of construction materials and measures required to prevent degradation of steel and cement and to prevent malfunctioning drainage systems.

3 LIMITATIONS

The field investigations and evaluations included are limited with regard to geological settings for commonly found conditions in Northern Europe and exclude sedimentary rocks and conditions in the Caledonides. The sites that are included have been subjected to recent glaciation (during the last 20,000 years), two had also been subjected to recent marine transgressions following glaciation. Furthermore, the sites within the studied areas have predominantly crystalline bedrock. The aspect of contaminant transport, which could be an important factor of hydrochemical impact from tunnelling in an urban environment, has not been included in this study. The methodology is aimed at the prediction of hydrochemical parameters that are of importance for the degradation of construction materials and maintenance of underground constructions. The work is not aimed at parameters that are only of environmental concern.

Use of stable or radioactive isotopes is often made in groundwater recharge investigations. The present field studies exclude such isotopes in the analysis and evaluation.

4 SCOPE OF WORK

The work included in this thesis is based on literature (desk) studies, field studies and hydrochemical modelling. Desk studies comprising a literature review were made of relevant research of groundwater and tunnelling as well as numerical codes for the modelling of water chemistry. The research presented in this thesis also includes four field studies. These comprise two tunnelling projects and two field investigations of the impact from groundwater extraction. The field investigations were carried out for periods of 2-12 years.

Based on the combined knowledge gained from the literature review and the field investigations, a stepwise methodology for the prediction of hydrochemistry in conjunction with underground constructions is presented. Generic conceptual models were established as part of this. The models present probable hydrochemical processes in different geological settings that are common in areas that have been subjected to recent glaciation and have crystalline bedrock. The generic models are used in the methodology to assess the need for further investigations and to determine whether numerical modelling should be recommended. Numerical modelling was also carried out for one of the field studies to confirm the applicability of the proposed methodology.

The work is summarised in this thesis and presented in the chapters listed below. Concluding remarks are presented in each section in Chapters 9-11 and conclusions are also synthesised in Chapter 12.

- Chapters 5-7 are aimed at presenting the reader with an introduction to the related subjects: 1) Introduction to geology, hydrogeology and hydrochemistry, 2) Introduction to underground constructions, 3) Degradation of construction materials.
- Chapter 8: Hydrochemistry in tunnelling in Sweden. This chapter describes related regulatory documents and their implementation in underground constructions.
- Chapter 9: Field studies. This chapter summarises the field studies described in Papers I-V. An evaluation and conclusions based on all field studies are presented.
- Chapter 10: Hydrochemical modelling. This chapter summarises the hydrochemical modelling that was conducted using data from one of the field studies. (see also Paper VI).
- Chapter 11: Predicting hydrochemistry. A methodology is proposed for the prediction of hydrochemistry in conjunction with underground constructions.
- Chapter 12: Conclusions and recommendations.

5 INTRODUCTION TO GEOLOGY, HYDROGEOLOGY AND HYDROCHEMISTRY

This chapter offers an introduction to hydrology, geology and hydrogeology. Its function in this thesis is to guide readers who are unfamiliar with these subjects.

5.1 Geological conditions in Scandinavia

The bedrock in Scandinavia, with the exception of the mountain ridge, comprises mainly Precambrian (formed >570 Ma B.P.) igneous rock. In some parts, particularly in the south-west, it is covered by Cambrian-Tertiary sedimentary rocks. The igneous rock belongs to the Baltic Shield, which extends from the Kola Peninsula to south-west Norway (Lindström et al., 2000).

The bedrock was formed during several orogenic periods and the rock types are both felsic and mafic. In the south-west part of the Baltic Shield, including the Blekinge region, the Southwest Scandinavian Province and the Transscandinavian Granite-Porphyry belt (see Figure 5.1), it is mainly felsic rock types that dominate although intermediate rock types are also present. The Svecofennian bedrock includes metamorphosed sedimentary (often greywacke and argillite) and volcanic rocks (commonly felsic). The classification of the rock types, including the mineralogy, is presented in Table 5.1 (National Atlas of Sweden, 1994).

Table 5.1. Classification of igneous rock types based on chemical and mineral composition and texture. Felsic and intermediate rock types dominate in most parts of the Baltic Shield (modified from Tarbuck and Lutgens (2005)).

Chemical composition		Granitic (Felsic)	Andesitic (Intermediate)	Basaltic (Mafic)	Ultramafic
Dominant minerals		Quartz, K-feldspar, Na-rich plagioclase	Amphibole, Na- and Ca-rich plagioclase	Pyroxene, Ca-rich plagioclase	Olivine, pyroxene
Accessory minerals		Amphibole, muscovite, biotite	Pyroxene, biotite	Amphibole, olivine	Ca-rich plagioclase
Texture	Coarse-grained	Granite	Diorite	Gabbro	Peridotite
	Fine-grained	Rhyolite	Andesite	Basalt	Komatiite
	Porphyritic	Porphyritic precedes any of the above names			

The Caledonides (the Scandinavian mountain ridge) were formed between 510 and 400 Ma BP. The Caledonides include sedimentary rocks that have been subjected to various

degrees of metamorphism as well as intruded crystalline rock types. Figure 5.1 shows the bedrock types that are present in Northern Europe (National Atlas of Sweden, 1994).

In contrast to the mainly Precambrian bedrock, most of the overburden was formed during the recent Quaternary period. Glacial deposits from the Weichselian ice age dominate, primarily glacial till that covers approximately 75% of the land surface in Sweden. This type of formation was deposited directly by a glacier on top of the bedrock, often as thin layers, and it comprises all grain sizes, from clay to boulders.

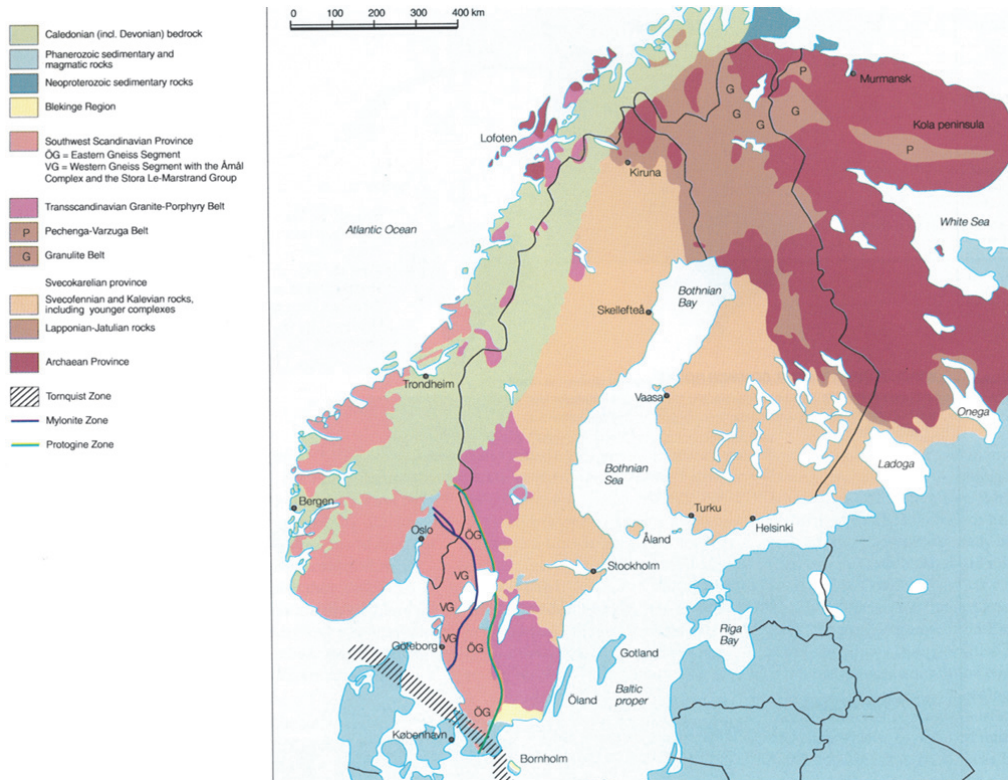


Figure 5.1. The bedrock in Scandinavia was formed during several orogenic periods. In the south-west and around Oslo, Precambrian rocks are overlain by sedimentary rocks comprising limestone, sandstone and shale (National Atlas of Sweden: Geology, 1994).

Further deposits related to the glaciation are glacial deposits such as eskers and deltas. Those are sediments that may be tens of meters thick and comprises particles deposited in flowing melt water from the glacier including sand, gravel, pebbles, cobbles and boulders. During deglaciation, marine and lacustrine transgressions occurred in many areas. The largest deposits of glacial material are found in valleys in areas that were subjected to transgressions. Glacial and postglacial clay was deposited in calm waters, usually in deep valleys. During regression of the coastline (the

land is rising in comparison to the sea level), the glacialfluvial and clay sediments rose above the sea.

5.2 Introduction to hydrology and hydrogeology

The hydrological cycle describes how water changes from one type to another. Water evaporates from the oceans (where it leaves most of its salinity behind), lakes and land surfaces to the atmosphere. Biota contributes to the water in the atmosphere through transpiration. From the atmosphere, the water is redeposited on the earth, mainly as rain or snow. Some of the water that is deposited remains in what is termed interception storage in the vegetation before, as is most often the case, it evaporates directly back into the atmosphere (see e.g. Bengtsson, 1997).

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 in liquid form is either absorbed by the vegetation, runs off as surface water or infiltrates into the groundwater. The water that was absorbed by the vegetation can be transpired back into the atmosphere. The surface water is transported to larger streams and lakes before it reaches the ocean (or, less likely, it evaporates on the way to the ocean). In most unaffected conditions only a small fraction of the deposited water infiltrates to become groundwater (see e.g. Bengtsson, 1997).

In climates with fairly high precipitation, such as in Northern Europe, the locations of groundwater recharge and discharge areas are mainly influenced by topography. The groundwater flows along paths from higher elevations (recharge areas) towards lower elevations (discharge areas) before once again becoming surface water in wetlands, streams, lakes and oceans, see Figure 5.2. The retention period as groundwater in unaffected conditions varies considerably, from a few days to thousands of years (Fetter, 1994). Due to seepage of water, underground constructions are likely to influence and shorten the retention times of groundwater in their vicinity (see e.g. Mossmark, 2010a).

Following deglaciation, areas of groundwater recharge and discharge were formed in the landscape. Recharge areas comprise topologically higher altitude areas than the discharge areas. Commonly, the recharge areas have simple quaternary strata comprising glacial till that has been deposited on the bedrock. The discharge areas are located in a topological depression in the landscape. In areas such as these, the quaternary strata is often more complex. In locations that are inundated, there are the prerequisites for the formation of wetlands (National Atlas of Sweden, 1994).

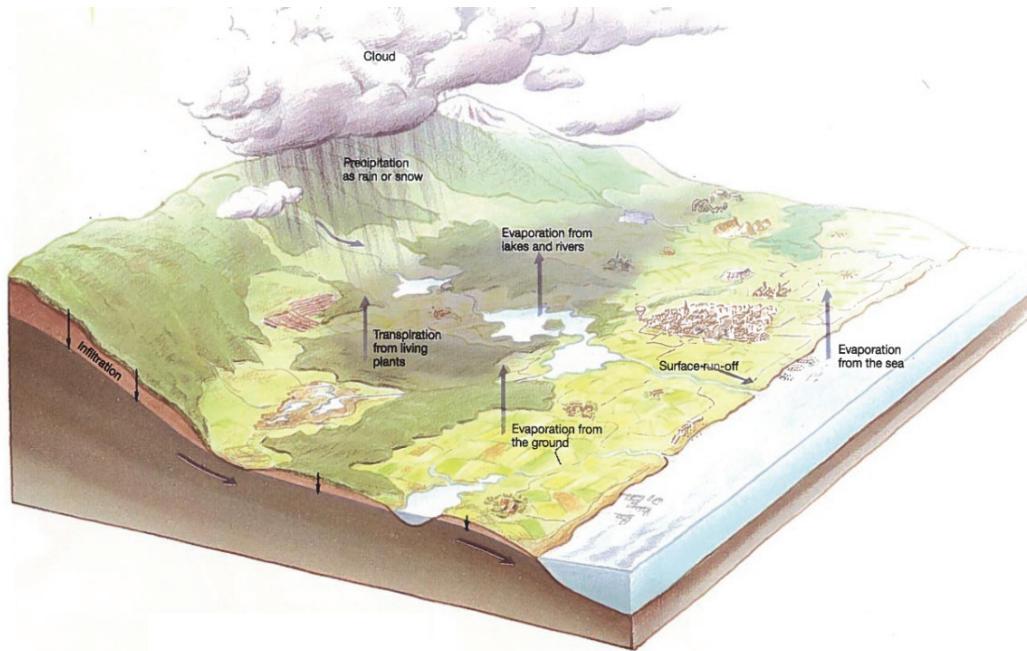


Figure 5.2 The hydrological cycle presented schematically. Drawing by Hans Sjögren. From the National Atlas of Sweden/Geology (1994).

5.2.1 Introduction to hydrochemistry

The hydrochemical conditions in deeply located groundwater (more than 20-30 m) are often stable compared to more shallow waters 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 relatively 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 (Appelo and Postma, 2005). Figure 5.3 describes common changes to the water chemistry as the water flows from a recharge to a discharge area. The processes that occur and their rate depend on the local conditions.

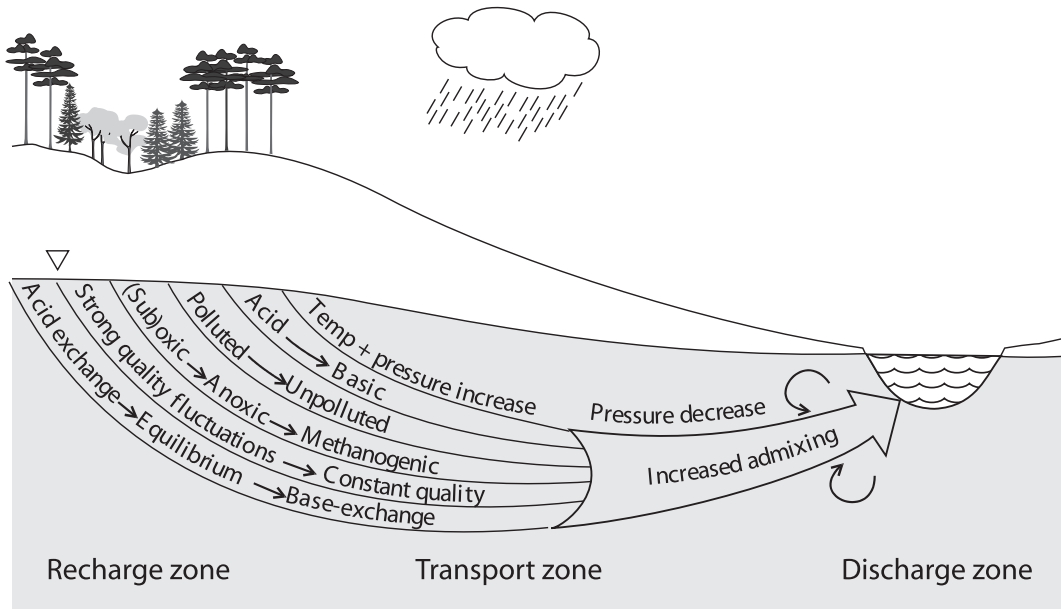


Figure 5.3 Changes in the hydrochemistry as the water flows from a recharge area to a discharge area. Modified from Knape (2001).

This introductory chapter deals with the following processes:

- The carbonate system
- Ion exchange processes
- Redox-related processes
- Microbial processes
- Weathering processes

5.2.2 Carbonates and carbon dioxide

Carbonates occur as limestone and dolomites as well as fracture minerals. They mainly comprise Ca- and Mg-carbonates and are related to dissolution and precipitation processes that may occur during short time frames. Carbonates occur both in pure phase minerals, such as calcite (CaCO_3), dolomite ($\text{CaMg}(\text{CO}_3)_2$) and aragonite (CaCO_3), but also as solid solutions with a more random structure and varying composition (Appelo and Postma, 2005).

On a global scale, the carbonate system is the most important acid-base system that gives natural water its character. Other acid-base systems involve sulphide, phosphate and silicic acid. The carbonate 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, two of the possible compounds in an acid-base system dominate. 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 due to the fact that the base can neutralise with the addition of hydrogen ions (acidification) (Deutsch, 1997). The partial pressure of carbon dioxide has an effect on the carbonate system (Mattheß, 1994).

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



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 carbonate source/sink is calcite. Formula 5.2 describes the chemical reaction where calcium carbonate is either dissolved or precipitated. When water that contains calcium carbonate reaches the surface, the carbonate acid is released as a gas into the air and calcium carbonate is precipitated.



5.2.3 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 and on metal oxyhydroxides. 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 (Deutsch, 1997). From the nature of the mentioned surfaces where cation exchange occurs, this process commonly occurs in shallow groundwater. However, cation exchange also takes place in fracture zones, see e.g. Molinero and Samper (2006).

At a low pH the surfaces available on clay minerals and humus are occupied mainly by H^+ 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, including Mg^{2+} , K^+ and Ca^{2+}). The share of exchange sites that are occupied by base cations is referred to as base saturation. If steady-state hydrochemical conditions occur, the exchange surfaces will be in equilibrium with the surrounding groundwater. If water with a different composition enters such aquifer, some of the ions bond to the surfaces will be replaced and this process thereby functions as a buffer against hydrochemical changes including acidification (Appelo and Postma, 2005).

5.3 Redox-related processes

Oxidation and reduction involve the take-up or release of valence electrons in an element. The solubility of many elements in groundwater and surface water depends on the redox conditions and the prevailing pH. The different redox species, for Fe 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 (given as Eh(V) or pe (activity of electrons)) and pH conditions, an Eh/pe-pH graph can be drawn (Deutsch, 1997).

According to Drever (1988), all shallow 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 reverse photosynthesis during the degradation process. In some cases a sequence of more reductive environments is found along a groundwater flow path. After the dissolved oxygen has been consumed, a post-oxic environment with typically relatively high concentrations of dissolved Mn and Fe may occur. If further reduction occurs because of e.g. oxidation of organic matter, a sulphidic environment with reduction of SO_4^{2-} to H_2S is likely. Further down a flow path, fermentation of organic matter may cause a methanogenic environment (Appelo and Postma, 2005). Figure 5.4 illustrates oxidation and reduction reaction sequences.

An oxidising chemical environment can be created by dissolved oxygen being transported in water, e.g. during periods of groundwater recharge (Deutsch, 1997). For instance, the Fe species that dominates at a certain redox potential is largely dependent on the pH, where a change in pH can result in iron either dissolving or precipitating. As with the balances in the acid-base reactions, redox potential is temperature-dependent (Mattheß, 1994). The groundwater recharge may increase as a result of influence from underground constructions, particularly during the construction phase. Such influence is likely to cause changes in the redox conditions with increased availability of dissolved oxygen.

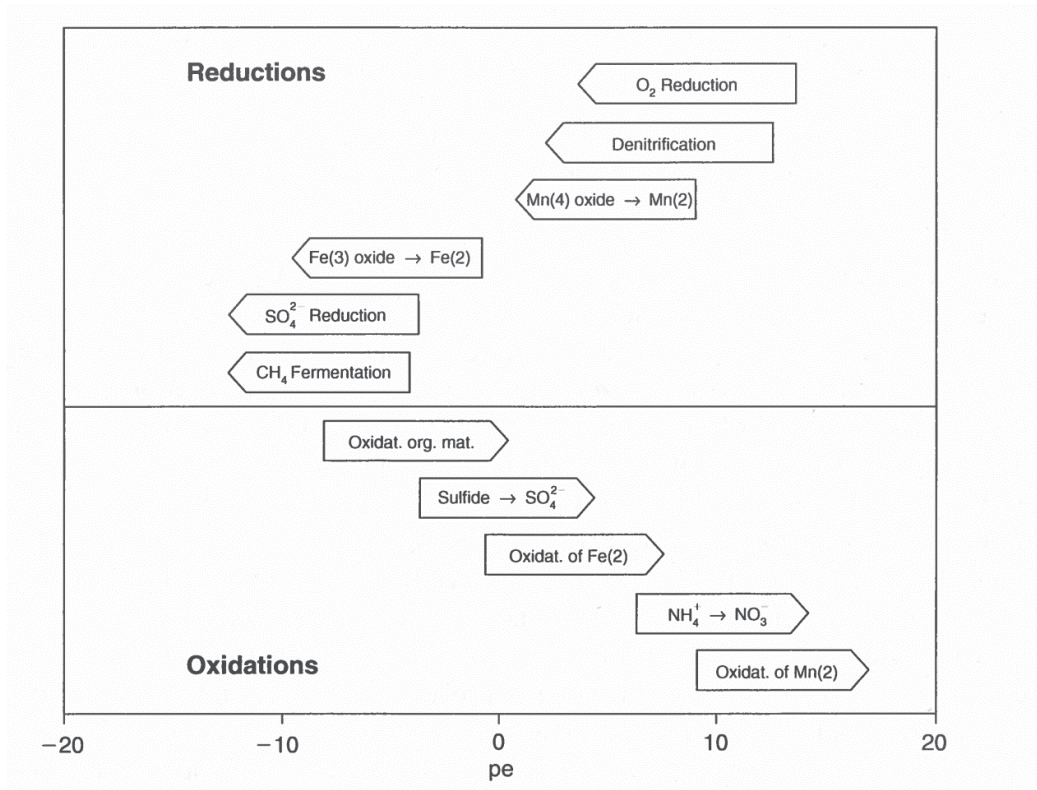


Figure 5.4. Sequence of redox processes at $pH = 7$ (Appelo and Postma (2005). Modified from Stumm and Morgan (1996)). The redox potential is presented as pe , which is $-\log[e^-]$ with $[e^-]$ being the “activity” of electrons, $pe = Eh/0.059$ at $25^\circ C$.

5.3.1 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, K., Gothenburg University, personal communication, 2007). 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 S, Fe and Mg in groundwater. Figure 5.5 shows how iron-oxidising bacteria form a reddish brown mass in the surface water. It has been noted that sulphur-oxidising bacteria could oxidise SO_2 to SO_4^{2-} in groundwater where pyrite (FeS_2) is present and thus accelerate the process significantly (Appelo and Postma, 2005).



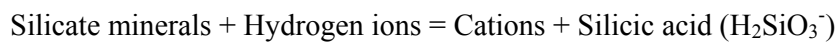
Figure 5.5 *Fe oxidising bacteria at Äspö HRL (Photo: SKB).*

5.3.2 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, and redox processes 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 silicates through hydrolysis:

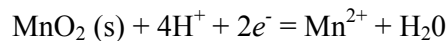
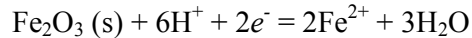


Aluminium silicate minerals (e.g. kaolin) + Hydrogen ions = Cations + Silicic acid (H_2SiO_3^-) + Secondary minerals (e.g. clay mineral)

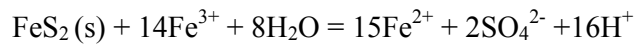
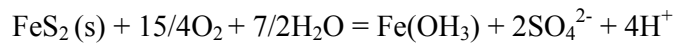
Soluble salts in the groundwater e.g.

Gypsum, halite, anhydrite etc.

Redox reactions e.g.



Pyrite oxidation



5.4 Hydrochemical character of bedrock groundwater

The chemical character of bedrock groundwater in Scandinavia is described in quite a large number of publications, e.g. in Eriksson (1970), Aastrup et al. (1995), Eklund (2002) and Frengstad (2002) and the Swedish geological survey (2013).

Eklund (2002) studied how the chemical composition of groundwater differed between typical defined hydrogeological environments. This characterisation has been modified by the Swedish Geological Survey (2013) to include ten different environments based on approximately 1,000 wells, see Figure 5.6.

The typical environments included in Eklund (2002) are defined environments in rock and soil, partly based on hydrogeological conditions such as whether a certain location constitutes a recharge or a discharge area for groundwater. One typical environment was defined for sedimentary rock whilst there are two different typical environments defined for crystalline rock: one for rock located above the highest coastline after the most recent glacial period (Weichselian) and one for rock located below the highest coastline. The wells that formed part of the study were affected to a limited extent by human activity.

The characterisation presented in the Swedish Geological Survey (2013) is based on bedrock geology and previous marine transgressions rather than local conditions reflected as recharge and discharge areas from groundwater, see Figure 5.6.

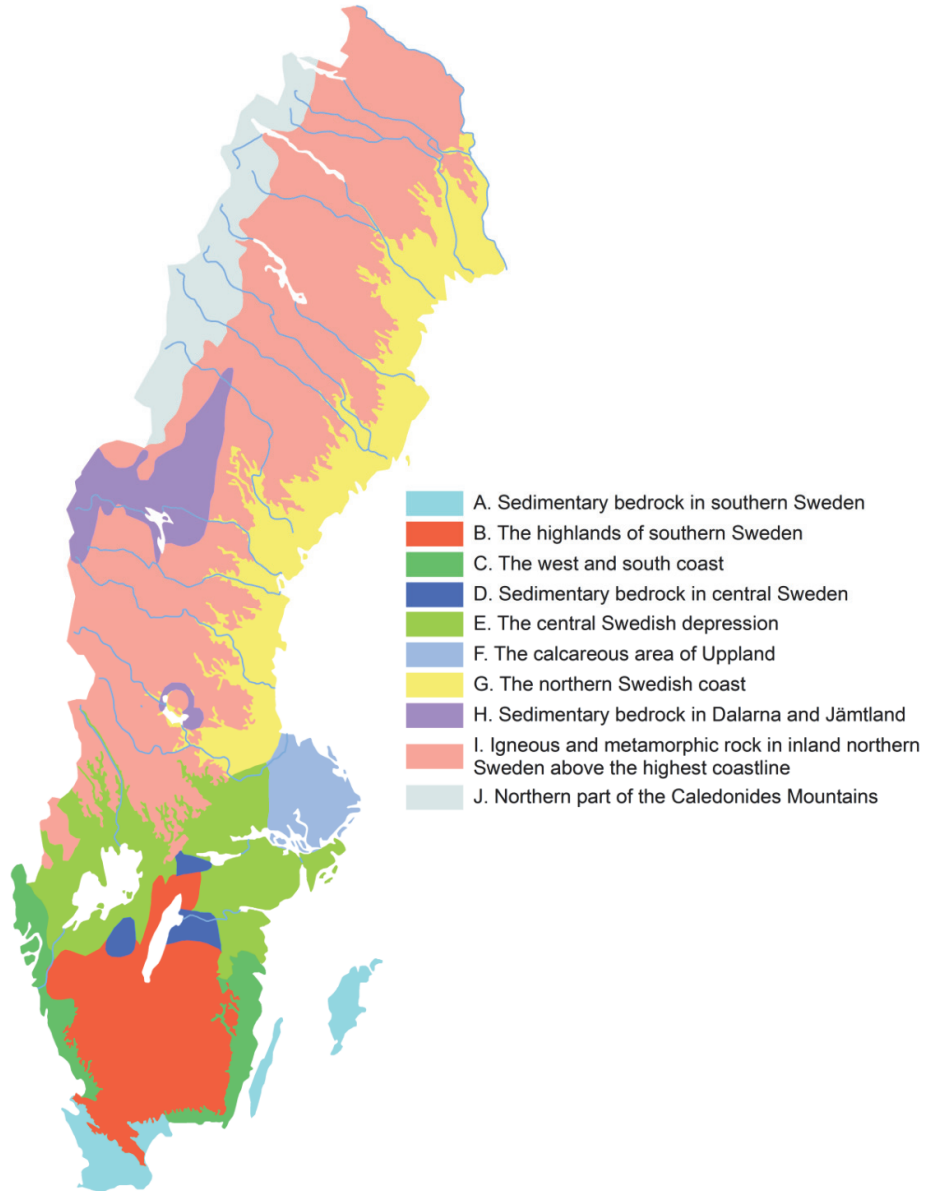


Figure 5.6 Division of hydrochemical units (regions) based on geological conditions and previous marine transgressions (Swedish Geological Survey, 2013).

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. These areas are presented as units A, D and H in Figure 5.6. 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 unit F in Figure 5.6. 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.

According to the Swedish Environmental Protection Agency (1999) the highest Cl^- concentrations for bedrock groundwater in crystalline rock are to be found below the highest coastline. Figure 5.7 shows that the highest Cl^- 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 (National Atlas of Sweden, 1994). According to Eklund (2002), 25% of the wells in crystalline rock below the highest coastline have Cl^- concentrations in excess of 40 mg/L. In a typical sedimentary rock environment there are Cl^- 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 was located below the highest coastline. For the 25% of the wells in crystalline rock above the highest coastline that have the highest Cl^- content, the level was slightly over 15 mg/L, which is considerably lower than for the rock wells below the highest coastline.

High SO_4^{2-} concentrations in the bedrock groundwater are often linked to the existence of rocks containing S, such as pyrite (FeS_2), 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 SO_4^{2-} content in the groundwater. Gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is also a source of high SO_4^{2-} concentrations although only to a very limited extent in Sweden. The groundwater below the highest coastline is commonly affected by marine S from seawater.

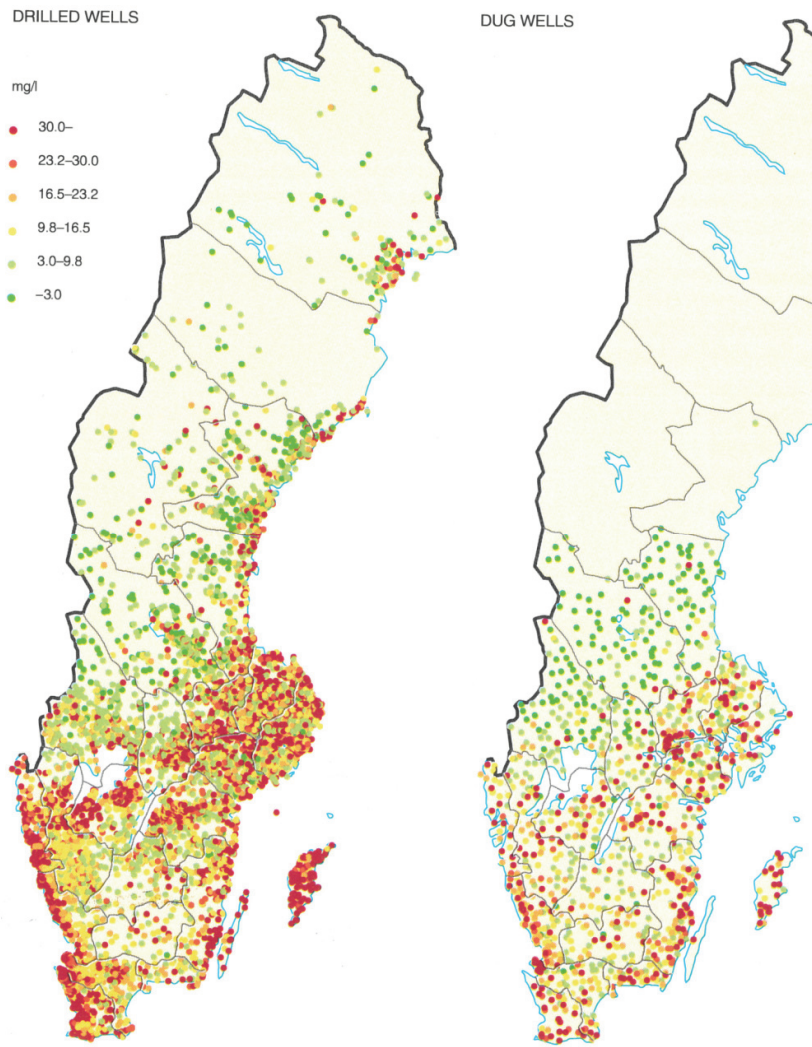


Figure 5.7. *Cl* concentration in wells in the bedrock (drilled) and in the overburden in Sweden (the National Atlas of Sweden, Geology (1994)).

6 INTRODUCTION TO UNDERGROUND CONSTRUCTIONS

This chapter is intended for readers who are relatively unfamiliar with the design of underground constructions and provides a brief introduction to the subject.

The design of underground constructions deals primarily with functions related to structural support and groundwater. Generally, the function design is partly adapted to the geological and hydrogeological conditions at the location of the underground construction in question. However, a uniform design for an entire section is commonly used and problems are addressed on an ad hoc basis (Jendeby, L., Swedish Transport Administration, personal communication, 2013). The main functions of an underground construction are listed below.

- Structural support to prevent a construction, i.e. a tunnel, from collapsing (mainly rock bolts and shotcrete).
- A waterproofing system (sealing grout).
- A system to collect water that seeps into the tunnel (drainage system).

The above functions are needed in all types of underground constructions.

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

The supporting system in tunnels comprises a construction designed to minimise seepage of water into the tunnel and to secure the tunnel to prevent rock fall or collapse. Deciding which parts of the construction to choose 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 (Norwegian Public Roads Administration, 2006).

In normally fractured 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 and 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 (Norwegian Public Roads Administration, 2006).

6.1 Grouting

In Sweden, pre-grouting is used generally for sealing tunnels with supplementary post-grouting as necessary (Swedish Road Administration, 2000). Pre-grouting is carried out by means of 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 (Swedish Road Administration, 2000).

Figure 6.1 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 (Norwegian Public Roads Administration, 2006).

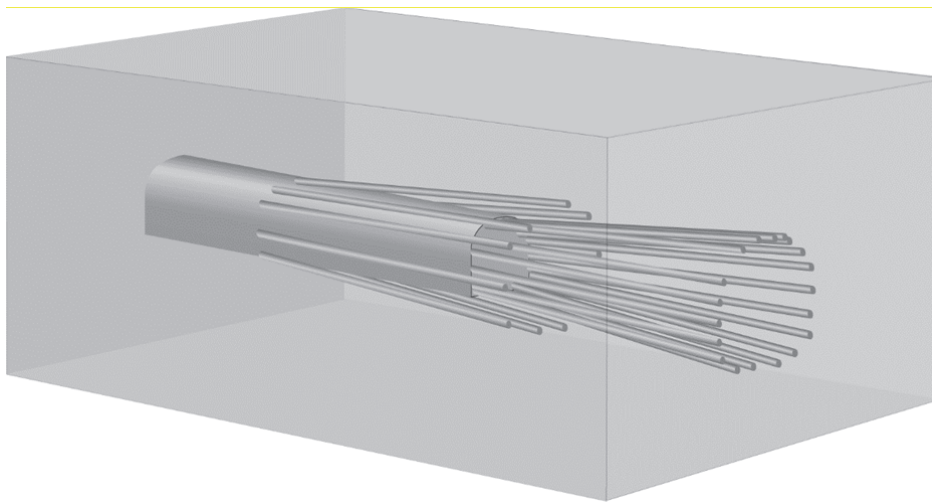


Figure 6.1. *Pre-grouting sketch; the left-hand part of the figure shows the tunnel front with a grouting fan.*

For grouting, a cement-based grout is commonly used although different types of grout are being developed. The so-called chemical grout types that are most commonly used are sodium silicate (a silicate-based material and a cement accelerator) and the water-soluble silica sol (Palmström and Stille, 2010). Non-water-soluble substances include polyurethane (Andersson, 1999) and acrylamide (Palmström and Stille, 2010).

6.2 Reinforcement bolts

For reinforcement, three main types of bolt are used: fully grouted rock bolts, 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 6.2a. 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 6.2 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 with cement paste.

A common end-secured, pre-tensioned bolt is the expansion bolt, see Figure 6.2 c. 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 rock bolt (see Figure 6.2 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 using water under high pressure (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 in completed tunnels are temporary and are subsequently replaced with other, permanent reinforcements although a method where the bolts are made permanent in conjunction with pre-bolting is also 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).

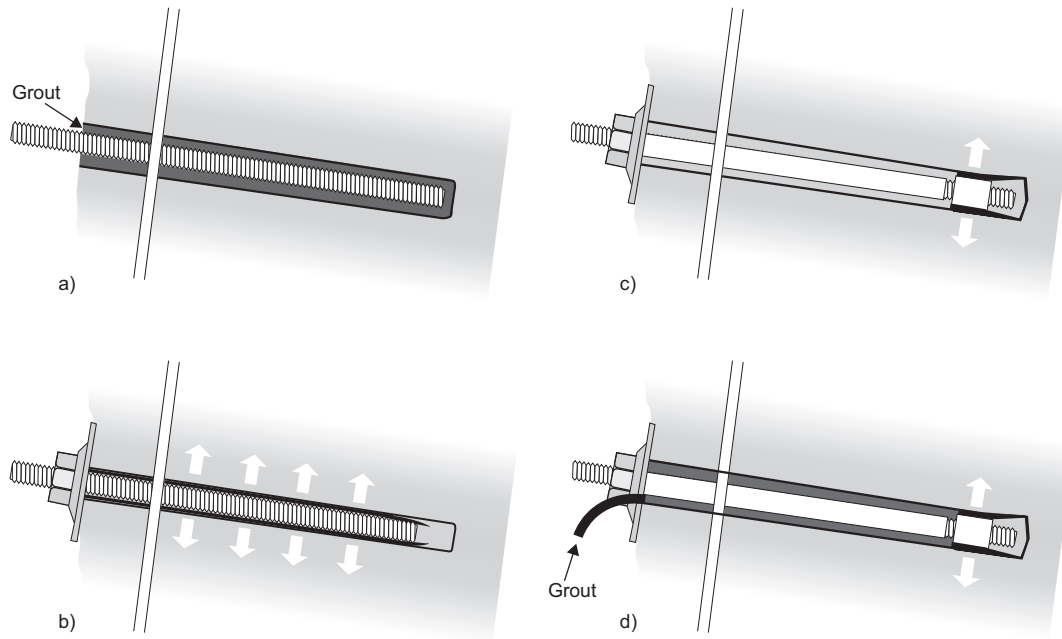


Figure 6.2 Common types of bolt for rock reinforcement: a) Fully grouted rockbolt b) Split set rockbolt c) Combi-bolt (temporary or initial use) d) Combi-bolt (permanent installation (grouted)).

6.3 Shotcrete

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

6.4 Cement lining

For tunnel sections through low-strength rock, cement lining can be used as permanent reinforcement (Norwegian Public Roads Administration, 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 (Norwegian Public Roads Administration, 2006). Mobile moulds are used for continuous cement lining in longer tunnel sections (Lindblom, 2001).

6.5 Drainage system for leaking water

In infrastructure tunnels 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 the Norwegian Public Roads Administration (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 6.3 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.

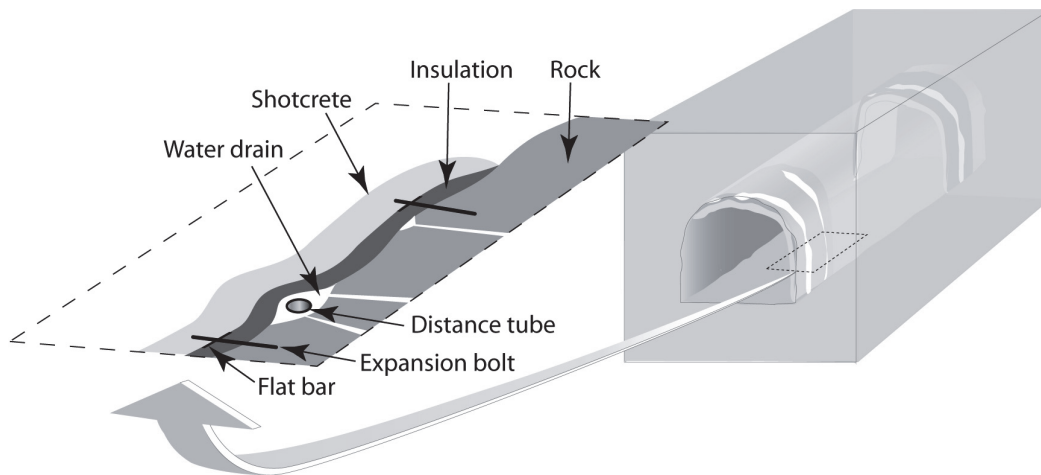


Figure 6.3 Water drain designed to deal with leaking water in a tunnel. The design comprises both insulation to avoid freezing and shotcrete.

7 DEGRADATION OF CONSTRUCTION MATERIALS

This section provides a brief discussion of observed degradation processes for cement and steel materials in underground constructions.

7.1 Degradation of steel materials

The degradation of steel-based materials is commonly counteracted by covering them with cement or epoxy. Selecting alloys for the bolt as well as zinc coating could also be used to minimise degradation.

There is an increased risk of corrosion when a bolt is not covered completely when adding a protective layer such as cement grout or zinc coating (Windelhed and Lagerblad, 2002). The results from an investigation of bolts in the Kvarntorp sandstone mine (Helfrich and Finkel, 1989), the Muskö Tunnel (Andersson et al., 2001) and the Vardø Tunnel (Pedersen, 1993) where unsuccessfully grouted or zinc-coated bolts were subjected to corrosion, could be explained by the hydrochemically heterogeneous setting created near the bolt. Such conditions for a steel construction part have in earlier studies been 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.

According to Windelhed and Lagerblad (2002), bolts embedded in cement, if done 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 (Deutsches Institut für Normung (DIN) 50929). When cement with a low water-cement ratio is used, 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). In a study of fully grouted bolts (Sederholm and Reutersvärd, 2013), the pH and alkalinity near fully grouted bolts were initially high after being installed. However, these parameters were observed to have decreased two years after the installation and the conditions gradually became more corrosive.

The risk of corrosion in steel materials is due largely to hydrochemical conditions, which mainly 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. Rock bolts can also be exposed as a result of rock movements. This can cause a heterogenic hydrochemical environment near a bolt. According to SBUF (2012), rock bolts near a fracture zone may need replacing as frequently as once every ten years.

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).

Nordström (2005) presents results from field and laboratory studies 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. On inspection of fractured shotcrete, a low level of corrosion was noted even in hydrochemical environments that were assessed to be aggressive and with high chloride concentrations. Nordström (2005) also found that 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%.

7.2 Construction elements made of cement-based materials

There are several processes that may have an impact on the durability of cement-based materials. The main processes are:

- Ettringite formation (sulphate attack)
- Thaumasite formation (due to low ionic strength)
- Carbonation
- Leaching
- Alkali-silica reaction
- Acidic attack

The use of cement that is resistant to sulphate has increased gradually since the 1960s. Cement that is not resistant to sulphate can, following the addition of sulphate after the cement paste has hardened, acquire the ettringite formation ($\text{Ca}_6\text{Al}_2[(\text{OH})_{12}(\text{SO}_4)_3] \cdot 26 \text{H}_2\text{O}$). This leads to swelling and fracturing of the cement, which means that the groundwater can come into contact with the bolts and by 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.

Shotcrete has proved to have more sensitive properties than normal concrete through abnormal fracturing at drains (Lagerblad et al., 2006). In the Södra Länken tunnels in Stockholm, and in other places, the shotcrete revealed shrinkage fractures. According to Lagerblad et al. (2006), shotcrete containing alkali accelerators is sensitive to sulphate attack.

An examination of tunnels in the Swiss Alps revealed sulphate attacks on cement (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). Romer et al. (2003) also found that 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. In 1995, it was noted that 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.

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 a number of places, including Äspö HRL (Laaksoharju, M., Geopoint AB, personal communication, 2008), the SKB facility for medium-active nuclear waste (Andersson et al., 2001), the Hitra Tunnel (Hem, 2002) and the Göta Tunnel (Albino, B., Tyréns AB, personal communication, 2008). 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, thereby decreasing the leakage into a tunnel.

Even if experience largely indicates that the flow of groundwater into tunnels during operation gradually decreases, there are also processes that degrade cement-based grouting agents. 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).

7.3 Construction parts made of other material

There are alternative methods to cementitious grout for sealing tunnels, one of them being the use of polyurethane and silica sol (Funehag, 2007). 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. Furthermore, Jakubowicz (1992) found major differences between different types of polyurethane grouting agent. According to Axelsson's (2006) summary, the durability of silica sol decreases in conjunction with a high pH. Using silica sol in combination with a cement-based grouting agent could lead to durability problems for silica sol as the cement-based grouting agent creates a basic environment.

7.4 Durability of drainage systems

Durability problems in drains can be attributed in part to the issues addressed 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 (Gothenburg University, personal communication, 2007), microbial oxidation of iron means that a slimy mass is formed, comprising 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 Hargelius (2006), the greatest risk of microbial oxidation of iron in drains occurs when the pH is between 5.5 and 7.0. If the pH falls below 5.5, precipitation of dissolved Fe and Mn will not occur and if the pH is above 7.0, the concentrations of dissolved species are too low (Hargelius, 2006).

8 HYDROCHEMISTRY IN TUNNELLING IN SWEDEN

This chapter summarises common practice in tunnelling projects and the regulatory documents issued by authorities that are related to hydrochemical monitoring and selection of construction materials in tunnelling projects.

8.1 Regulatory documents in Sweden

The Swedish authority responsible for the development of the road and rail infrastructure, the Swedish Transport Administration, has issued regulations and recommendations for the planning, construction and operation phases of tunnels. The regulations (referred to as TrvK) and the recommendations (referred to as TrvR) are set out in two documents that came into effect in early 2012 (Swedish Transport Administration, 2011a and 2011b). Prior to 2012, separate documents concerning road tunnels (Swedish Road Administration, 2004) and rail tunnels (Swedish Rail Administration, 2005) were provided.

As mentioned in Section 0, the construction materials used in underground constructions mainly comprise steel and concrete. The regulations concerning material selection therefore concern these two material groups.

Until the release of TrVK in 2011, regulations for the selection of steel materials in underground constructions were based on four criteria for groundwater chemistry. The Swedish Rail Administration (2005) required complementary protection (it assessed the water to be aggressive) for rock bolts if any one of the following hydrochemical criteria was satisfied:

- 1) pH < 6.5
- 2) Total hardness < 20 mg/L (1 meq/L) Ca
- 3) Alkalinity < 1 mEq/L (equivalent to approximately 61 mg/L HCO₃⁻)
- 4) Electrical conductivity > 100 mS/m

In current regulatory documents (Swedish Transport Administration, 2011a), the above criteria have not been included. Instead, the selection of corrosion protection in steel materials is based on the assessment of the groundwater being fresh, brackish or salty. Furthermore, the selection for a particular part of the construction is based on whether 1) it is located above or below the groundwater level, 2) if it is in direct contact with the water, 3) the procedure of pre-grouting and 4) the rock quality. For steel materials,

there are three corrosion classes – Im1, Im2 and Im3 – where Im3 is the one that requires the highest protection against corrosion (used in the most corrosive environment). In current and previous regulations a guideline has been issued for the selection of cementitious construction materials in accordance with the international standard SS-EN206. The three classes listed in Table 8.1 are intended to address different degrees of aggressive conditions, with XA3 representing the most aggressive conditions.

Table 8.1. Exposure classes for concrete according to SS-EN206-1 and included in current and previous regulatory documents for tunnelling (Swedish Transport Administration, 2011; Swedish Rail Administration, 2005).

Parameter	XA1	XA2	XA3
SO₄²⁻ mg/L	≥ 200 and ≤ 600	> 600 and ≤ 3000	> 3000 and ≤ 6000
pH	≤ 6.5 and ≥ 5.5	< 5.5 and ≥ 4.5	< 4.5 and ≥ 4.0
CO₂ mg/L	≥ 15 and ≤ 40	> 40 and ≤ 100	> 100 up to saturation
aggressive			
NH₄⁺ mg/L	≥ 15 and ≤ 30	> 30 and ≤ 60	> 60 and ≤ 100
Mg²⁺ mg/L	≥ 300 and ≤ 1000	> 1000 and ≤ 3000	> 3000 up to saturation

For water supply systems, assessment of hydrochemistry is carried out from both perspectives, taking into account drinking water quality as well as technical aspects. Finland (Ministry of Social Affairs and Health, 2001), Norway (Ministry of Health and Care Services, 2001) and Sweden (Swedish National Food Agency, 2011) have presented guidelines for assessing whether drinking water is aggressive towards technical installations such as pipes or if, for example, precipitation of Fe or Mn is likely, see Table 8.2. The guidelines state similar limits for pH as the Swedish Transport Administration (Table 8.1). However, lower limits are stipulated for SO₄²⁻ and higher limits are stipulated for electrical conductivity.

Table 8.2 Guidelines for the assessment of the aggressivity and proneness to precipitation of drinking water in Finland, Norway and Sweden.

Parameter	Finland	Norway	Sweden
SO₄²⁻ (mg/L)	>250 (>150 ¹)	>100	>100
pH	<6.5	<6.5	<7.5
Cl⁻ (mg/L)	>100 (25 ¹)	>200	>100
Fe (mg/L)	>0.20	>0.20	>0.10
Mn (mg/L)	>0.05	>0.05	>0.05
Electrical conductivity (mS/m)	>250	>250	>250

¹Recommended limits to avoid corrosion.

8.2 Implementation of regulatory documents

The use and implementation of the regulations in tunnelling projects have been studied by Lidén and Saglamoglu (2012). The study included four recent tunnelling projects and reveals that hydrochemistry and the selection of construction materials is of low priority in the planning process for underground constructions. Sampling of groundwater and material selection were commonly carried out in the planning phase and were performed by consultants under the supervision of the client (commonly the Swedish Transport Administration) and subject to its approval. The contractors were rarely involved in classification of exposure and corrosivity classes for construction materials in tunnelling projects.

The selection of construction materials was carried out in at an early stage to avoid disruptions in material supply during the construction phase. Such shortages have been assessed to be more likely if the selection was carried out at a later stage and could cause costly delays (Lidén and Saglamoglu, 2012).

The implementation of the regulations varied between the four objects studied. One of the objects comprised a road tunnel where the contractor was stipulated to be responsible for maintenance for the first fifteen years of operations. It was concluded that the analysis of hydrochemistry for the selection of construction materials was well documented and was carried out in accordance with the regulations issued by the authorities. In another object studied, where the contract for the construction stipulated that responsibility for the maintenance lay with the client rather than the contractor, significantly less documentation was found regarding the selection of construction materials in relation to hydrochemistry (Lidén and Saglamoglu, 2012). The two above-mentioned projects were contracted for less than SEK 1,000 m each (Bjerneling and Åberg, 2011; www.veidekke.se, 2013).

Two larger tunnelling projects (>SEK 15,000 m (Regeringskansliet, 2009)) were also studied – the Stockholm City Line and the Stockholm Bypass. These two larger projects included more data collection compared to the smaller projects. However, the water sampling and selection of construction materials based on hydrochemical parameters were less structured and documented compared to the smaller project where the contractor was responsible for maintenance (Lidén and Saglamoglu, 2012).

9 FIELD STUDIES

This chapter summarises and synthesises the findings in the field studies, which are presented in more detail in the appendices.

Four field studies were conducted within the framework of this research project. Two of the field studies dealt with the impact of groundwater abstraction and are presented in detail in Appendices III, IV and V. Two field studies of tunnelling projects were also conducted, see Appendices I and II. The geographical locations where the field studies were carried out are presented in Figure 9.1.



Figure 9.1. Location of the four field studies: The two studies of the impact from the construction of tunnels (Kattleberg and Hallandsås) and from the studies of groundwater abstraction (Lake Gårdsjön and the island of Äspö).

The four field studies were carried out in areas with igneous rock in southern Sweden. As can be seen in Table 9.1, all locations have predominantly felsic rock types with a granitic composition. There are also, to a less extent, dioritic (intermediate) components at three of the locations. There was a varying degree of geological mapping at the

different locations, resulting in inconsistent detail for the description of fracture minerals. Among the fracture minerals, calcite has been observed at all locations. In Hallandsås, pyrite (FeS₂) was observed in some of the boreholes.

Two of the locations had been subjected to transgressions since the most recent, Weichselian, glaciation. According to Table 9.1, these two locations (the island of Äspö and Kattleberg) reveal a more complex layering of quaternary deposits. On Äspö, wave-washing processes have occurred forming bedrock outcroppings and the presence of wave-washed deposits. In both Kattleberg and on Äspö, clay is present in topologically low-lying areas. At Lake Gårdsjön and on the Hallandsås Ridge, where transgressions have not occurred, the strata are less complex. Generally, the bedrock is covered by glacial till and the wetlands and streams are located in low-lying groundwater discharge areas.

The four locations have a similar climate, classified as maritime temperate, which according to the Köppen-Geiger system is a mild, humid climate without dry seasons. There are, however, minor climatic differences between the locations, primarily Äspö, which receives less annual precipitation than the other three locations, see Table 9.1.

Table 9.1. Description of the geological and climatological conditions at the filed study locations.

Location	Lake Gårdsjön	Island of Äspö	Kattleberg Rail tunnel	Hallandsås
Bedrock	Granite and granodiorite	Granites, granodiorite and quartz monzodiorite	Mainly gneiss, granitic or dioritic. Metabasite is present, as well as veins of pegmatite	Granitic gneiss, dolerite and amphibolite dykes
Fracture minerals	Calcite, kaolinite, chalcedony, chlorite	Calcite, chlorite, hematite	calcite, chlorite and iron hydroxide	Chlorite, calcite, pyrite
Quaternary geology	Glacial till, wetlands (little impact from transgressions)	Complex, recent transgressions: bedrock outcroppings, wave-washed deposits, clay	Complex, recent transgressions: glacial till, clay in topologically low-lying areas and wetlands	Glacial till, wetlands (no transgressions)
Climate	951 mm/year precipitation (1961-1990)	644.4 mm/year precipitation (1991-2010)	807 mm/year precipitation (1961-1990)	872 mm/year (2000-2012)

9.1 Field study at the Hallandsås rail tunnels

Two parallel rail tunnels have been built through a horst in north-west Scania in southern Sweden. The horst is approximately 80 km long, 5-10 km wide and its highest point is 226 m above sea level (Ringberg, 2000). Most of the construction has been

carried out with a tunnel boring machine (TBM). Tunnelling through the Hallandsås Ridge has had a notable impact on the groundwater levels and the hydrochemistry (Borca, 2007; Mossmark et al., 2010a). In most areas, the impact has been limited in terms of drawdown and time period. However, in certain areas along the two tunnels, tunnelling has had a persistent hydrological impact for more than a decade (Mossmark et al., 2010).

9.1.1 Study arrangement

A surface water catchment area and the underlying bedrock on the Hallandsås Ridge were studied during construction of the western tunnel in 2011-2012. The study included monitoring and evaluation of hydrology, hydrogeology and hydrochemistry in streams, groundwater in the overburden and in the bedrock. Data from the construction of the eastern tunnel, which was carried out in the area in 2007-2008 were also evaluated and discussed.

Three bedrock boreholes had previously been drilled within the study area and transducers had been installed by the Swedish Transport Administration to measure groundwater levels. The boreholes were drilled from ground surface down to tunnel level. Two of the boreholes were drilled vertically, MK56 (123 m deep) and MK60 (160 m deep), while one (BP08) was graded in a north-easterly direction parallel to the tunnel, see Figure 9.2.

The sampling frequency for the three bedrock boreholes in the monitoring area was twice monthly during the period April 2011-December 2011. During spring 2012, sampling of bedrock groundwater took place on a monthly basis. The sampling frequency for surface water was twice a month. In addition, one shallow filter well in the overburden was sampled on two occasions. On the third occasion, the filter well was dry and the sampling series was discontinued (Paper I).

The bedrock groundwater was sampled using a submersible pump and purging was used to collect samples that were representative of the entire length of the open borehole. Measurements of pH, temperature, dissolved O₂ (oxygen) and electrical conductivity were made *in situ*. Laboratory analysis was carried out of, among others, the concentrations of main anions and cations (Paper I).

9.1.2 Geological, hydrological and hydrogeological conditions

The bedrock of the study area is geologically heterogeneous, consisting mainly of gneiss, with several small fault zones, amphibolite dykes (not shown) and dolerite

dykes. In some parts, water-bearing structures provided relatively high hydraulic conductivity (Paper I).

The study area has a hydrogeological boundary towards the south marked by a wide and highly weathered weakness zone running along the southern slopes of the ridge, followed by a 150 m wide amphibolite dyke. A dolerite dyke cuts through the study area and divides it hydrogeologically into two more or less separate aquifers: the Skeadal-Flintalycke aquifer (to the south) and the Flintalycke Norr aquifer (to the north), as seen in Figure 9.2.

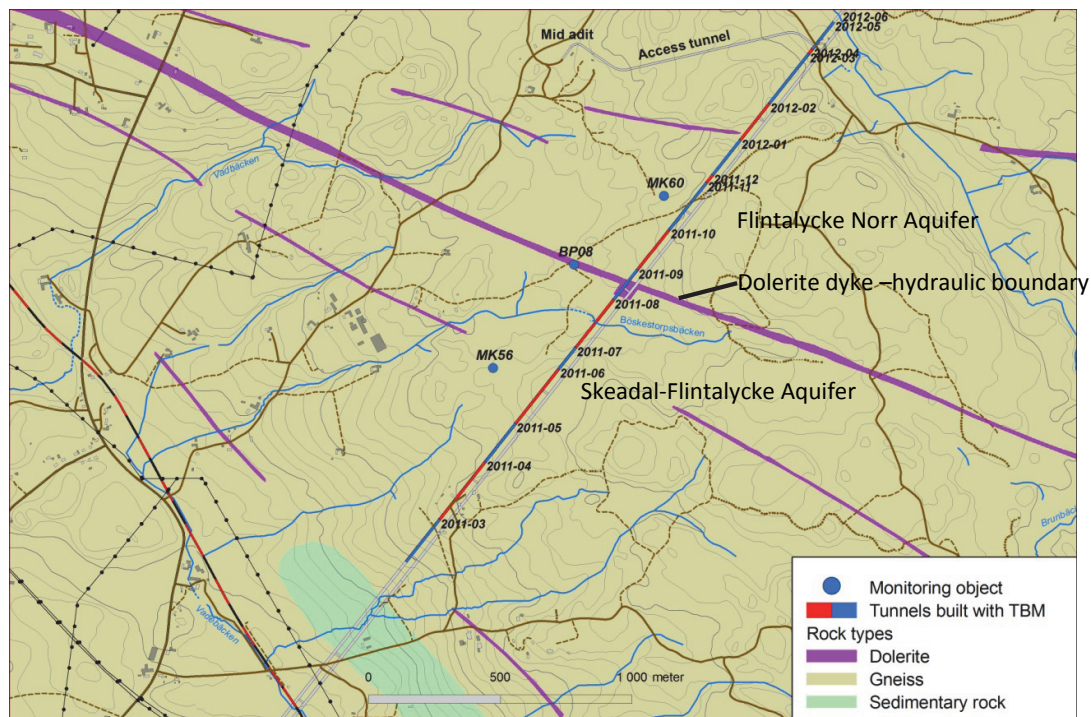


Figure 9.2. Location of the monitored boreholes and streams as well as bedrock geology in the vicinity of the study area. The progress of construction of the western tunnel is mentioned in the format yyyy-mm starting with March 2011 (2011-03) and ending with June 2012 (2012-06) to the north.

Both aquifers consist mainly of relatively competent rock with moderate hydraulic conductivity. Some areas of open fractures and zones of contact between the gneiss and minor dolerite entities comprise water-bearing structures. The dolerite dyke that separates the two aquifers is almost impermeable at tunnel level and acts as a negative hydraulic boundary. Closer to the surface, however, the dolerite is more fractured, permitting some contact between the aquifers. The contact zones between the dolerite dyke and the gneiss form a water-bearing zone that is located mainly within the gneiss. The hydrogeological conditions and the tunnelling activities define the area of

influence. The different waterproofing methods also had an impact on the area of influence in other parts of the tunnelling project (Paper I).

The overburden in the study area is dominated by thin layers of glacial till and some areas have been mapped as bedrock outcrops. In the topographical depressions in the study area, around the ponds, there are organic soils comprising bogs and peat. The groundwater in the soil in these areas was noted to be well connected to the rock aquifer. In unaffected conditions, the water level of the rock groundwater was higher than that of the aquifer in the bogs and peat, which would therefore normally pose as groundwater discharge areas.

9.1.3 Impact on hydrology and hydrogeology

The groundwater level in a borehole decreased as the TBM head approached, starting as construction-created hydraulic contact with water-bearing fractures connected to the borehole. Provided the tunnel was sealed successfully with the concrete lining, the level would start to recover once the TBM had passed. In fractured rock volumes with high hydraulic conductivity and effective contact with the tunnel through water-bearing fractures, the area of influence was larger compared to more competent rock volumes. The geological conditions varied significantly through the study area, as mentioned in the geological description section.

The drawdown and recovery processes were also affected by the variation in production methods. Groundwater levels were affected by construction through the (negative) hydraulic boundary that separates the different aquifers. Because of the absence of confining soil layers, there was interaction between rock and soil on the Hallandsås Ridge. Some groundwater discharge areas, where permeable soils are well connected to the rock aquifer, temporarily became groundwater recharge areas. Figure 9.3 shows the fluctuation of the groundwater levels in the monitored boreholes during the study and the impact from tunnelling activities was significant. Table 9.2 describes events that caused observable changes in the groundwater levels with reference to Figure 9.3. The TBM commenced construction of the western tunnel from the south and the description presents events in chronological order.

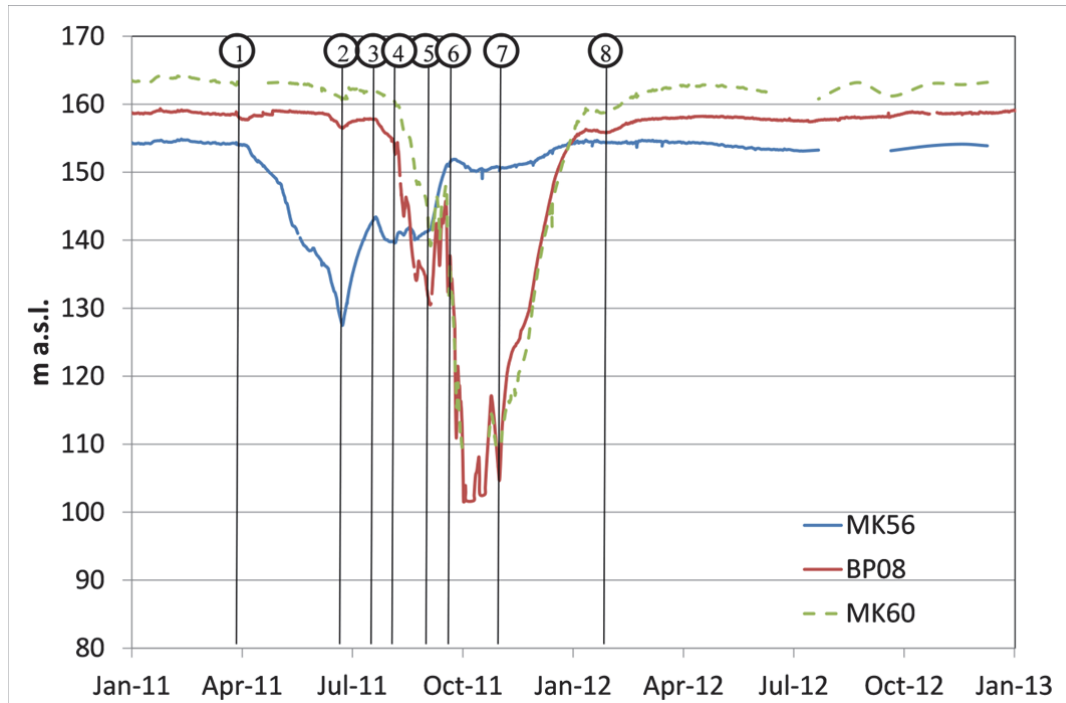


Figure 9.3. Groundwater levels in the investigated boreholes on the Hallandsås Ridge.

Table 9.2 Construction activities and related observations that had a significant impact on the groundwater levels.

Event	Construction activity/observation	Hydrogeological impact
1	Tunnelling through the southern hydraulic boundary.	Falling groundwater levels in MK56.
2	Maintenance stoppage, construction of backfilling barrier.	Recovering groundwater levels in all boreholes.
3	Resumption of tunnelling.	Falling groundwater levels in all boreholes.
4	Tunnelling through the hydraulic boundary (dolorite dyke) located in the centre of the study area.	Falling groundwater levels in MK60 and BP08.
5	Construction of a backfilling barrier.	Groundwater levels recover in all monitored boreholes.
6	Probe drilling, tunnelling north of the hydraulic boundary.	Significantly falling groundwater levels in MK60 and BP08, minor decrease in levels in MK56.
7	A backfilling barrier was constructed, which reduced water influx.	Recovering groundwater levels, primarily in MK60 and BP08. Gradual recovery until almost unaffected levels in MK56.
8	Tunnelling through competent gneiss north of the monitored boreholes.	Continuous recovery of groundwater levels to almost unaffected levels in BP08 and MK60.

9.1.4 Impact on water chemistry

The hydrological changes had an impact on hydrochemistry in both shallow systems and in the bedrock within the study area (Paper I). For the surface waters, the main cause of hydrochemical changes was related to a temporary absence of (or decrease in) groundwater discharge. The hydrochemical changes were observed as a generally lower ionic strength (diminished discharge), SO_4^{2-} surges (due to oxidation of S) from the wetlands, and absence of or lower alkalinity were also observed. For the shallow waters, the magnitude of the hydrochemical changes varied between the sampling points and was affected by the proportion of the relative decrease in groundwater discharge.

The hydrochemical changes in deep groundwater in the bedrock also differed between the three monitored boreholes. The geological conditions were the most important factor behind the differences. However, some results were universal for all monitored boreholes. Increasing redox potential was observed in all three monitored boreholes during drawdown of the groundwater level and the solubility of Fe and Mn thus decreased temporarily. There was an increased presence of organic matter although degradation (oxidation) of organic matter did not reduce Fe or Mn significantly into soluble species. The redox potential recovered (decreased) after the waterproofing system of the tunnel was installed.

Two of the three boreholes (BP08 and MK60) revealed significant hydrochemical changes for some of the major anions and cations. The two boreholes had been drilled in relatively fractured bedrock with the presence of pyrite. The hydrochemical changes were caused primarily by hydraulic connections to shallow water and by the oxidation of pyrite. Increased SO_4^{2-} concentrations to levels more than fivefold the unaffected concentrations and a lowering of pH were observed, see Figure 9.4. The changes primarily occurred at times when the groundwater levels recovered, both in 2007-2008 and again in 2011-2012. Furthermore, alkalinity decreased and the concentrations of the base cations fluctuated.

The third borehole (MK56) revealed fewer changes to the major anions, cations and pH. The concentrations of SO_4^{2-} increased by approximately 50%. This borehole penetrates gneissic rock with few fractures, hence the absence of contact zones and less hydraulic contact with shallow water. Pyrite was not observed during the drilling of this borehole. Figure 9.5 shows pH measurements from borehole logging in MK60. The results show a general alkaline environment in the upper parts of the borehole. The two initial logging occasions revealed a pH of approximately 6.5 at levels below 80 m above sea level. As shown in Figure 9.5, the three subsequent measurements revealed a lower pH, approximately 6.0 at levels below 80 m above sea level. The most significant depth

variations in MK60 were measured on 06.12.2011 (Figure 9.5) during a period of recovery of the groundwater levels in the bedrock, see Figure 9.3.



Figure 9.4. Concentrations of SO_4^{2-} , pH and groundwater levels in BP08. There was an increase in SO_4^{2-} concentrations and subsequent decrease in pH during time periods with groundwater recovery, such as after the construction of the eastern (2007/2008) and western (2011/2012) tunnel tubes through the study area.

The borehole loggings showed significant hydrochemical depth variations, highlighting the difficulties encountered when collecting groundwater samples that are representative of the entity of interest. Furthermore, the results confirm the conclusions from previous studies that recovery from hydrochemical changes caused by underground constructions takes longer compared to the recovery of groundwater levels, see e.g. Mossmark (2010a). As seen in Figure 9.4, the groundwater quickly reached near-unaffected levels after the construction of the eastern tunnel tube through the area in 2007/2008. However, pH and SO_4^{2-} did not fully recover to pre-construction levels before the construction of the western tunnel tube in 2011.

Slow processes, such as silicate weathering, became less significant because of a shorter residence time for the groundwater compared to unaffected conditions. Silicate weathering is an important contributor to alkalinity in crystalline bedrock and short retention times thus decrease buffer capacity against acidification. The absence of influence from silicate weathering probably contributed to the temporary decrease in alkalinity in the bedrock groundwater during the period with affected groundwater levels.

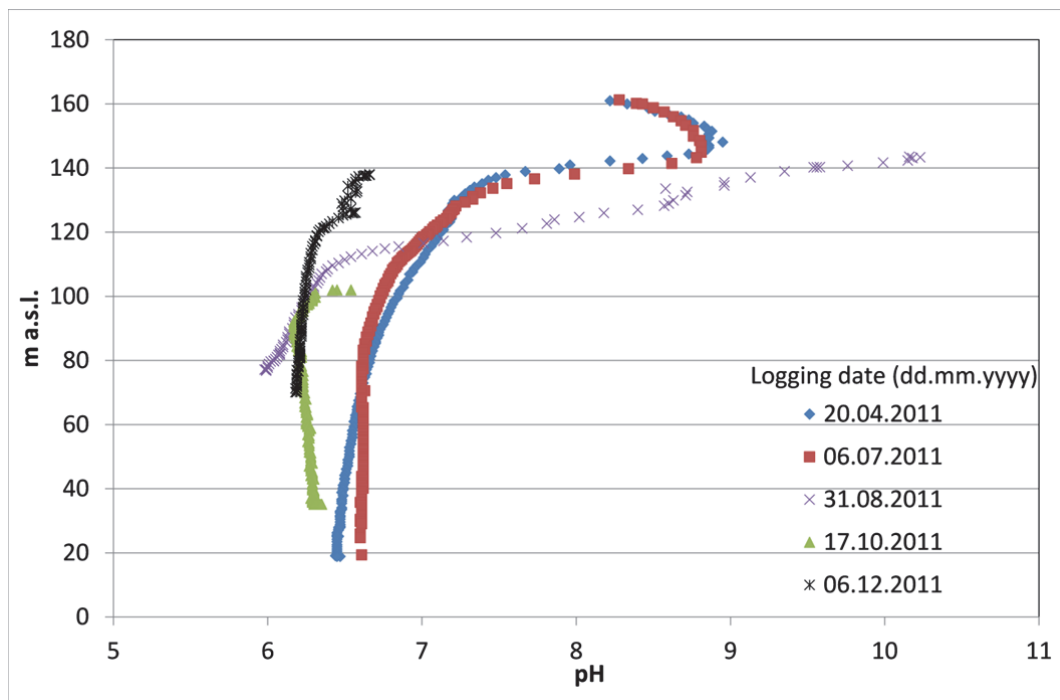


Figure 9.5. Logging of pH in the MK60 borehole. The pH decreased during construction in the vicinity of the borehole and remained low until the end of 2011. The most significant depth dependent variations were measured on 06.12.2011 during the recovery of the groundwater levels in the bedrock.

9.1.5 Implications for construction materials

The redox potential increased in the groundwater in each of the three boreholes although the changes in other parameters that are of importance for the durability of construction materials differed significantly. As regards the most significant parameters related to durability of construction materials, the MK56 borehole exhibited less significant changes compared to boreholes MK60 and BP08.

According to the regulations valid during the period 2005-2012 (Swedish Rail Administration, 2005), the pH values decreasing to below 6.5 in two of the boreholes (MK60 and BP08) and alkalinity decreasing below 61 mg/L HCO_3^- in one of the boreholes (MK60) in the study area should be grounds for using complementary protection against corrosion for e.g. steel bolts. Corrosion index calculations were also carried out, revealing that the groundwater in the two boreholes with the most significant hydrochemical changes (BP08 and MK60) also became corrosive to steel construction materials. The corrosivity decreased gradually alongside recovery of the hydrochemistry, see Figure 9.6.

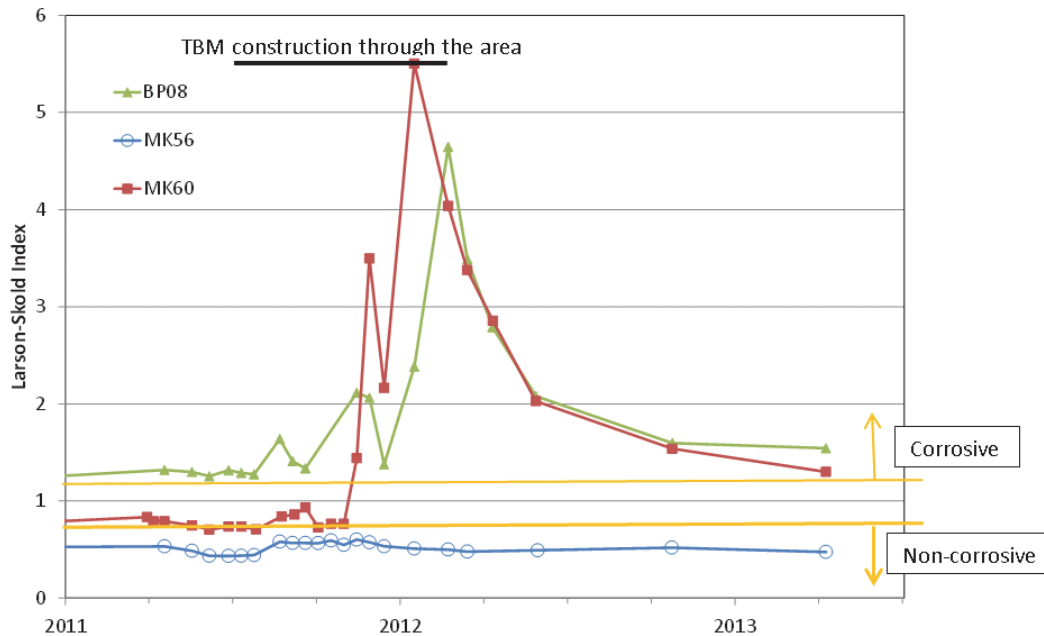


Figure 9.6. Larson-Skold Index for groundwater in the three monitored boreholes. The groundwater in two of the boreholes was assessed to have become more corrosive to steel.

Interpretations similar to steel were also valid for cement-based materials based on exposure class standards as described in Section 8.1. According to industry standard EN206-1, high concentrations of SO_4^{2-} , Mg^{2+} and aggressive CO_2 as well as low pH are detrimental to the durability of concrete. The standard has established three exposure classes for groundwater, XA1, XA2 and XA3, with XA3 being the most aggressive environment, see Section 8.1.

Before construction with the TBM began, the groundwater in the three monitored boreholes would have been considered non-aggressive according to EN206-1. However, during construction of both the eastern (2007/2008) and western tunnels (2011/2012), the hydrochemistry in BP08 and MK60 reached the lowest exposure class, XA1, on several occasions. For MK60, a low pH (below 6.5) caused the water to be characterised as XA1 for several consecutive sampling occasions during a period of six months in late 2011 and early 2012. For BP08, a pH below 6.5 and SO_4^{2-} concentrations above 200 mg/L caused the water to be considered aggressive on two occasions. During construction of the western tunnel, the groundwater in BP08 would have been considered to be exposure class XA2 on one sampling occasion. MK56 remained within the non-aggressive range (below XA1) throughout the monitoring period. The hydrochemistry in BP08 and MK60 recovered to return to a non-aggressive state after tunnelling activities with the TBM were completed within the study area.

The Hallandsås tunnels are lined through the study area and are virtually waterproof. Drainage systems are therefore not used to handle seepage water through the walls along this section. However, there is a discussion of drainage systems with regard to the observed hydrochemical changes that would have been relevant if conventional construction methods had been used. The results from the monitoring showed decreasing concentrations of dissolved Fe and Mn during the construction phase of the western tunnel. This indicates that the increased redox potential caused Fe and Mn to precipitate in the bedrock. However, the concentrations recovered (increased) within a few months of the tunnel being sealed through the area, implying that dissolved Fe and Mn may reach the tunnel.

The tunnelling activities increased the concentrations of dissolved Ca^{2+} in the bedrock groundwater with CaCO_3 being dissolved to neutralise H^+ (observed as decreasing pH). With degassing of CO_2 at the tunnel wall and inside the drainage system, Ca would be likely to once again precipitate as CaCO_3 . This may cause the clogging of a drainage system. If conventional construction methods had been used, higher water influx would probably have remained during the operational phase of the tunnel. This could also have resulted in prolonged periods of elevated concentrations of Ca^{2+} in the bedrock groundwater and a greater likelihood of clogging of a drainage system.

9.1.6 Conclusions for the Hallandsås study

The main conclusions regarding the impact from tunnelling through the study area are listed below:

- The geological differences observed in the three monitored boreholes were reflected in the changes to the hydrochemical conditions:
 - In two of the boreholes that had been installed in heterogeneous conditions (MK60 and BP08), including the presence of pyrite, significant changes in the major ions and pH was observed.
 - In one of the boreholes that had been drilled through relatively homogeneous gneiss, only primary changes in redox-sensitive parameters (solubility of Fe and Mn) were observed.
- In the two boreholes with significant changes in the hydrochemistry, the water became aggressive towards steel and cement according to official regulations. In the third borehole, the groundwater was assessed to be non-aggressive.
- In all three boreholes, the concentrations of dissolved Fe and Mn decreased and would be less prone to cause clogging of drains (if used).
- Gradual recovery of the hydrochemistry was observed after the eastern tube was completed through the area in 2008. However, full recovery was still not

achieved before the impact from the construction of the western tube in 2011. According to the regulations, the hydrochemistry recovered from being aggressive to steel and cement-based materials within six months.

- It is probable that dissolved Fe and Mn could reach the tunnel, which could have led to precipitation and clogging if drains had been used.

9.2 Field study at the Kattleberg rail tunnel

A study was made of the hydrology and hydrochemistry during the construction phase of a rail tunnel at Kattleberg, approximately 40 km north of Gothenburg in Sweden. The 1.8 km rail tunnel is part of an infrastructure project involving the construction of a four-lane, limited-access highway and a double-track railway linking the city of Gothenburg and the town of Trollhättan. The distance between the two urban centres is approximately 75 km. The study area comprised a surface watershed along a section of the rail tunnel, which was built using regular drilling and blasting techniques. The tunnel was pre-grouted along its entire length to limit the influx of seepage water (Paper II).

9.2.1 Study arrangement

A monitoring area comprising a watershed and related rock volume was selected for the study. Hydrochemical conditions and groundwater levels were monitored from October 2010 to June 2012. Five filter wells (GW1001-1005) were installed in the overburden along with two boreholes that were drilled in the tunnel (BH3/896 and BH3/999) in order to collect water samples for chemical analysis within the framework of this research project. A percussion-drilled, 30 m borehole in the bedrock was monitored and sampled (BH1001). The surface runoff from the wetland water was also sampled. The locations of the boreholes and filter wells are shown in Figure 9.7.

Two of the filter wells were installed in shallow peat (GW1002 and GW1005), two were installed in a glacial till layer beneath a clay layer (GW1001 and GW1004) and one was installed in a shallow layer of glacial till on a slope (GW1003).

The boreholes inside the tunnel were drilled slightly north of the surface watershed. The borehole BH3/999 was drilled in a fracture zone, the inference being that it intersects both the tunnel and the superficial aquifers beneath the wetland. The other borehole, BH3/896, was drilled in more homogeneous rock with fewer fractures. The two boreholes in the tunnel were drilled horizontally from the tunnel wall to an approximate length of 5 m. Packers equipped with vent valves for sampling were used to seal the

boreholes. The packers were installed at a distance of approximately 0.5 m from the tunnel wall.

Samples from the filter wells and the percussion borehole were collected regularly (approximately once a month) using a sampling bailer. The water in the filter wells was purged before each sample was collected. The groundwater levels were measured on each sampling occasion. Runoff water samples were collected manually from the stream. Water from the boreholes in the tunnel was collected from the vent valves in the packers. The samples were analysed in a laboratory for pH, electrical conductivity, major cations and anions, Fe, Mn, dissolved organic carbon (DOC), nitrogen species and Si.

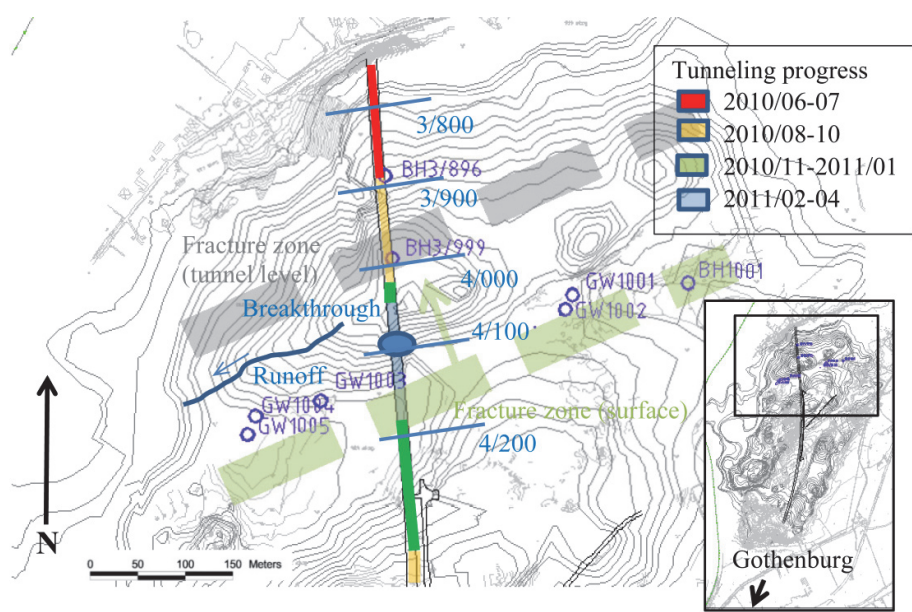


Figure 9.7. The location of the runoff sampling location, the five filter wells (GW1001 – GW1005), the percussion-drilled borehole from the surface (BH1001) and the boreholes from inside the tunnel (BH3/896 and BH3/999). Within the study area, the depth from the ground surface to the tunnel varies between 30 m and 35 m.

9.2.2 Geological, hydrological and hydrogeological conditions

The study area is located east of major fault zone (the Göta Älv river) in an area dominated by plutonic rock types of granitic to tonalitic composition, formed approximately 1,650Ma BP. The Göta Älv river fault zone stretches from the town of Kungsbacka in the south to Lake Vänern in the north and the bedrock within the zone is largely fragmented (Samuelsson, 1978). According to the structural geology map, the

hill is surrounded by fractured rock on the northwest, southwest and southeast sides, represented topologically by valleys. The northern slopes of the hill are located along a distinct fracture zone that extends in a north-easterly direction from the Göta Älv river fault zone (Samuelsson, 1985).

According to information gathered from the mapping of rock drill cores collected near the study area, as well as mapping of bedrock outcrops, the bedrock is dominated locally by gneiss of granitic or dioritic origin. The mapping of collected drill cores revealed the presence of calcite, chlorite and iron hydroxide in the fractures (Tyrens, 2009). Veins of pegmatite are present in the study area. Metabasite and amphibolite are also present but have not been observed in the tunnel. There is a fracture zone (approximately 70 m wide) at the surface and it can be seen between sections 3/910 and 4/040 on the tunnel level (Lindström, on-site geologist, Swedish Transport Administration, personal communication, 2011).

The overburden was formed during the current Quaternary geological period, primarily during glaciation and deglaciation. The glacier deposited till in thin layers directly on top of the bedrock. The maximum sea level for the period after the last glaciation was 110-120 m a.s.l. and consequently the whole of the Kattleberg Hill has been subjected to transgression. During the transgressions, fine-grained sediments, such as silt and clay, were deposited in calm or stagnant waters in the area. These clays are commonly found in areas located below 20 m a.s.l. Clays containing sulphide are common at shallow depths, both in glacial clays and in post-glacial clays (Fredén, 1986). The study area has become covered with glacial clay in the low-lying areas, which under unaffected conditions act as groundwater discharge areas. A wetland with sphagnum peat has also developed in some parts of the study area overlying the clay.

9.2.3 Impact on hydrology and hydrogeology

The groundwater level fluctuations differed between the monitored boreholes in the study area (Paper II). For one of the boreholes, KBH1, the levels fell by almost 10 m during construction but recovered when construction was completed through the area. In another borehole (BH1001), located in the study area, the groundwater levels were approximately 2 m lower in the post-tunnelling phase compared with unaffected conditions.

While the groundwater in the glacial till interacted with the water in the bedrock, the groundwater in the wetland seemed to be separate from the other entities. Groundwater levels in the wetland in the study area were therefore reasonably stable throughout the monitoring period and there was little flow from the wetland towards the tunnel.

9.2.4 Impact on water chemistry

The observation that groundwater in the wetland did not interact with the groundwater in the bedrock or the water in the glacial till beneath the wetland had significant implications for the potential changes in hydrochemistry. The presence of glacial clay thus prevented the wetland from changing from a groundwater discharge area into a recharge area (flow from the wetland to the bedrock). Consequently, the observed hydrogeological conditions prevented important hydrochemical changes that could have caused the water in the bedrock to become more acidic (through aeration of the wetland and oxidation of S and release of H^+) (Paper II).

The shallow waters had relatively little influence on the bedrock groundwater hydrochemistry. In the boreholes in the tunnel and in BH1001, the impact was observed through increased DOC concentrations. For BH1001, a slightly decreasing pH was observed due to influx of the shallow waters that had been acidified due to clearance/filling activities in the wetland. However, for other parameters, the influence from shallow water was deemed to be insignificant. Meanwhile, hydrochemical changes were observed in the wetland, particularly as increasing Cl^- , SO_4^{2-} and decreasing pH. These were not assumed to be caused by the tunnelling activities but rather by clear-cutting of trees and the deposition of rockfill from blasting within the study area (Paper II).

The geological and hydrogeological conditions in the bedrock were seen to be of significance to the hydrochemical changes that were observed in the two boreholes that had been drilled inside the tunnel. In one of the two boreholes in the tunnel (BH3/896), which was drilled in relatively homogeneous rock with few fractures, the grout had a significant impact on the hydrochemistry, see Figure 9.8. In contrast, the other borehole (BH3/999), which had been drilled in a fracture zone, had hydrochemical conditions that resemble those of the surrounding bedrock (in unaffected conditions). For the groundwater in borehole BH3/896, the most significant temporal change is the varying concentrations of Ca^{2+} . In November 2010, the concentration in the groundwater was 110 mg/L and in September 2011, the Ca^{2+} concentration had decreased to 2.2 mg/L, see Figure 9.8.

The Na^+ concentration was high compared with the Cl^- concentration ($Na^+/Cl^- \gg 1.0$) throughout the entire monitoring period, similar to the background concentration before the construction phase (Paper II). This may be part of a long-term process where fresh water flushes out marine water. Under such conditions, Na^+ is released in exchange for Ca^{2+} due to ion exchange (Appelo and Postma, 2005).

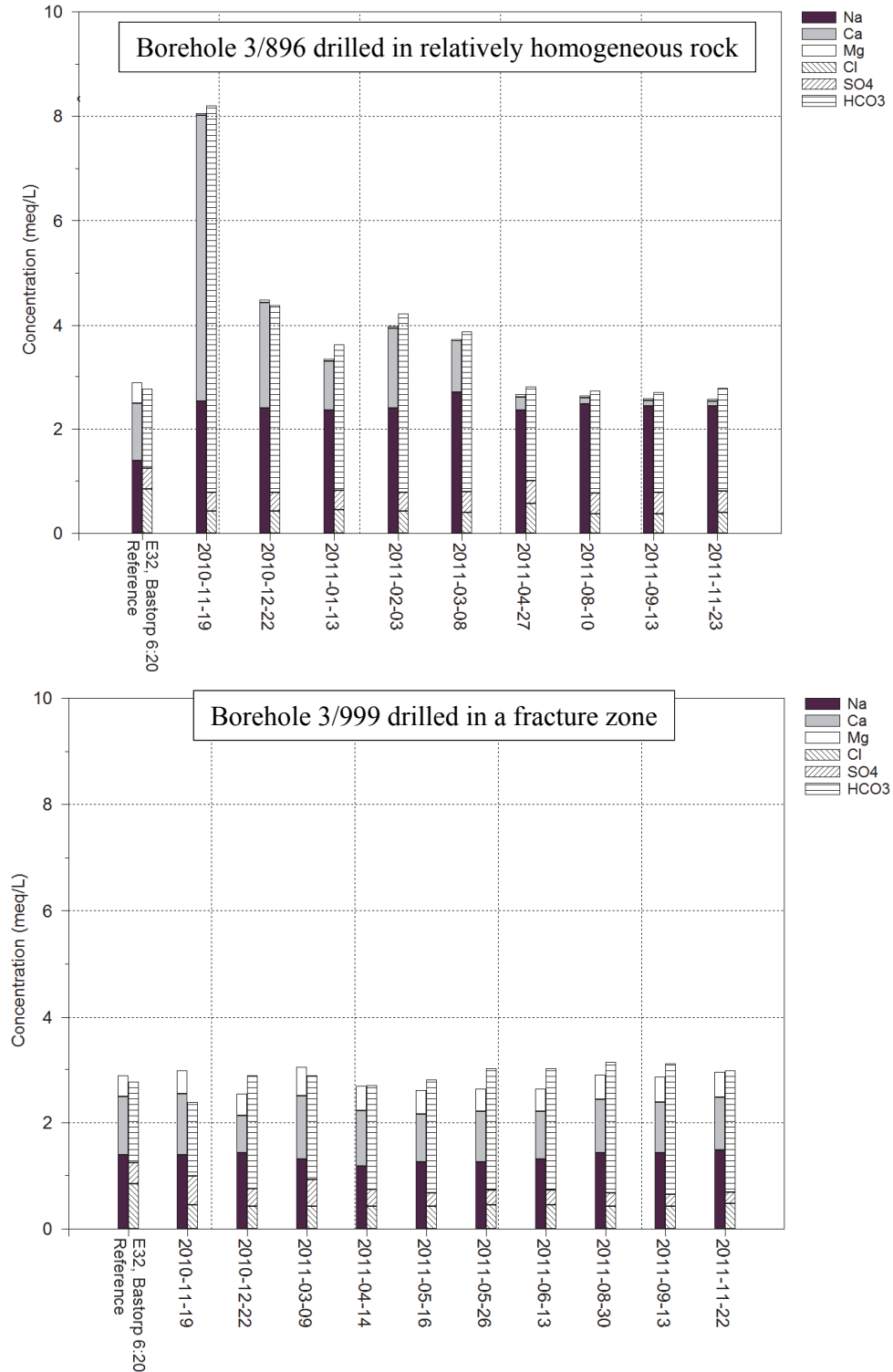


Figure 9.8. Major anions and cations in the bedrock groundwater in the boreholes that had been drilled from inside the tunnel. Significant impact from sealing grout was observed in one of the boreholes (3/896 above) while the other (3/999 below) was unaffected.

9.2.5 Implications for construction materials

Reinforcement bolts with complementary protection against corrosion would be required according to the requirements laid down by the Swedish authorities that were in force during construction of the tunnel (Swedish Rail Administration, 2005). This assertion could be made based on the hydrochemical analysis of water from nearby water supply wells as well as water from one of the boreholes in the tunnel (because of low Ca^{2+} and Mg^{2+} concentrations and/or low alkalinity).

In borehole BH3/896, the changes in Ca^{2+} and Mg^{2+} (mentioned in Section 9.2.4) were also reflected in the calculated Langelier saturation index and the water gradually became less prone to scaling, see Figure 9.9. The other borehole (BH3/999) had a Langelier saturation index that varied between scaling and corrosive. In the 30 m percussion-drilled borehole in the bedrock in the vicinity of the tunnel (BH1001), properties that became slightly more corrosive were observed according to the calculated Langelier saturation index.

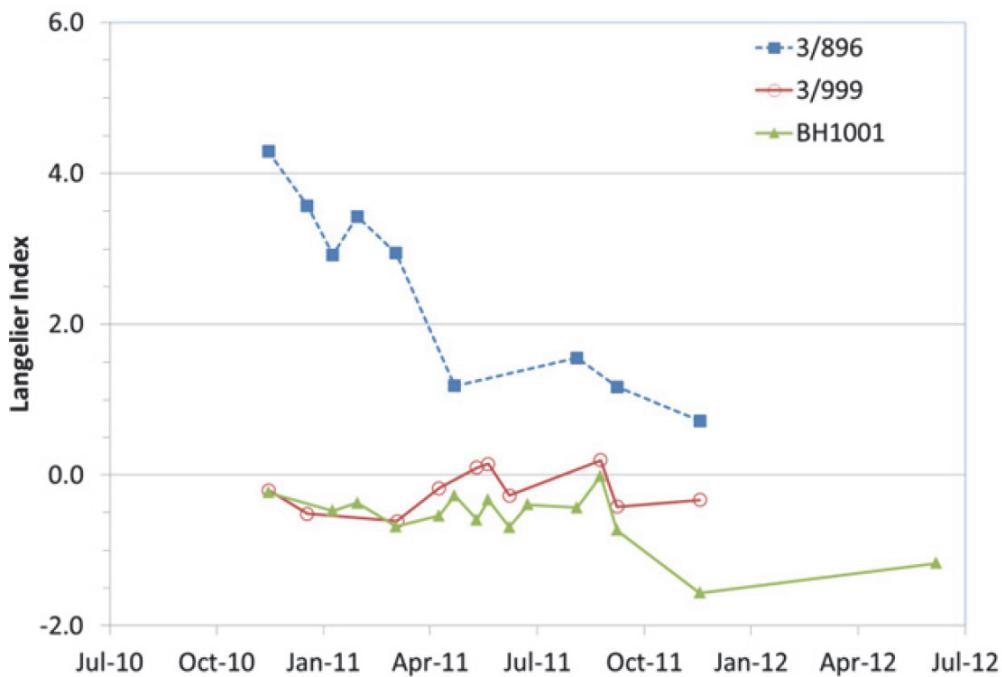


Figure 9.9. Langelier saturation index calculated for groundwater in the bedrock. If the index is below 0, calcite dissolution may occur. Scaling (calcite precipitation) may occur if the index is above 0.

The concentrations of dissolved Fe and Mn were also affected by the alkaline environment created by the grout. In the borehole drilled from inside the tunnel

(BH3/896), which had been subjected to significant hydrochemical influence from sealing grout, Fe and Mn were below the detection limit throughout the monitoring period. In the well that had water with a hydrochemical composition that resembled the groundwater in the surrounding bedrock (BH3/999), dissolved Fe and Mn were detected. The solubility and precipitation of Fe and Mn are of importance for the potential clogging of the drainage systems in the tunnel.

9.2.6 Conclusions from the Kattleberg study

The following main conclusions were made from the Kattleberg study:

- The quaternary geological conditions, particularly the presence of clay beneath the centrally located wetland, limited hydraulic communication as well as hydrochemical changes. The groundwater levels in the wetland were relatively unaffected by the tunnelling activities and flow from the wetland to the bedrock was prevented.
- The hydrochemistry in the bedrock groundwater near the tunnel differed depending on the geological conditions. In a fracture zone, the groundwater hydrochemistry resembled that of surrounding bedrock. Meanwhile in more homogeneous rock, the groundwater hydrochemistry was strongly affected by sealing grout.
- According to the regulations from the authorities, (Swedish Rail Administration, 2005), complementary protection should be used for steel materials based on data collected before the construction started. Apart from one of the boreholes in the tunnel (BH3/896), only minor changes were observed in the bedrock groundwater during tunnelling.

9.1 Field study on the island of Äspö (abstraction)

The field study on the island of Äspö was carried out between 1997 and 2002. Two small watersheds were studied in an unaffected state for two years followed by a period of groundwater abstraction from mid-1999 through to the end of 2001. Previously, the results and analysis from the study of hydrochemical variations prior to the initiation of abstraction had been presented in Knape (2001) and data from the study had been presented in Knape Hansén (2002) and in Graffner (2005). The Äspö study is discussed further in Paper V.

9.1.1 Study arrangement

Two similar watersheds on the island of Äspö (A1 and A2) were monitored for two years, from mid-1997 to mid-1999, in unaffected conditions. Groundwater abstraction was carried out from a borehole in the bedrock in watershed A2 (HAS23) from mid-1999 to the end of 2001. The installations in the area included five boreholes in the bedrock and 11 filter wells in the overburden.

Monitoring in the area included frequent (monthly) sampling of groundwater and surface water and measurements of groundwater levels. Major anions and cations, pH, nitrogen species and DOC were measured in a laboratory. In addition, pH and electrical conductivity were measured *in situ*. Runoff volumes from the two watersheds were monitored through the installation of Thomson weirs. The location of the instrumentation and the outline of the two watersheds are presented in Figure 9.10.

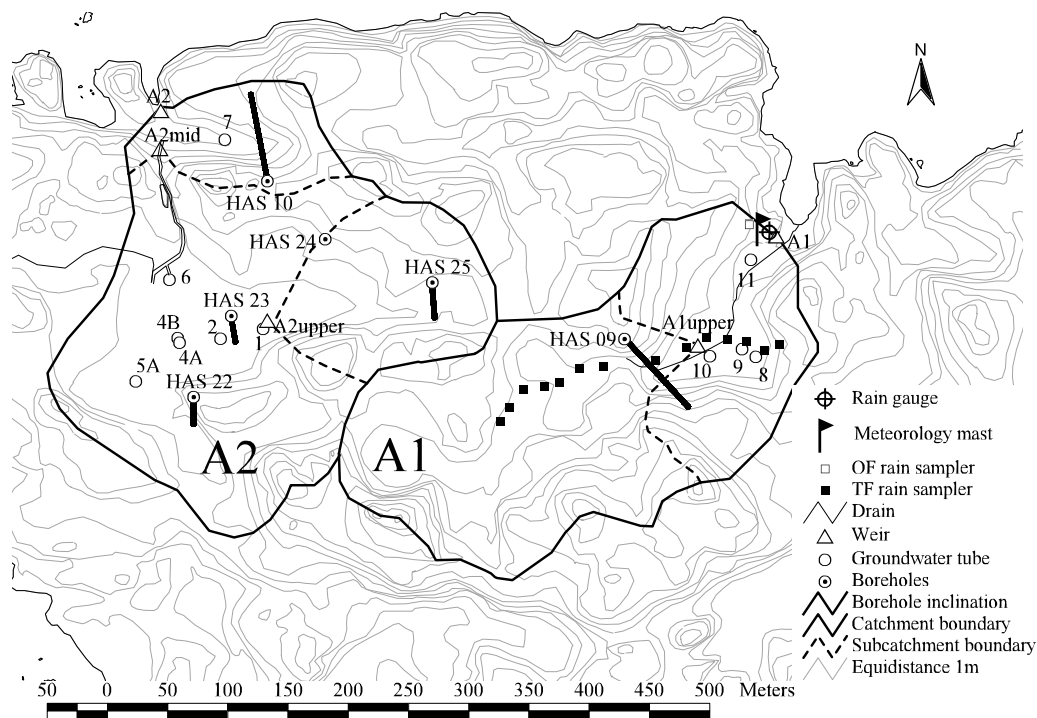


Figure 9.10 Topographical map revealing the instrumentation at the location of the groundwater abstraction on the island of Äspö (Knappe Hansén, 2002).

9.1.2 Geological, hydrological and hydrogeological conditions

Groundwater abstraction was carried out in the vicinity of the Äspö Hard Rock Laboratory (HRL). The area has similar geological conditions to the HRL but the

abstraction affected a smaller area than the laboratory. The bedrock in the area is made up of Småland-Värmland granitoids, which include quartzsyenite, granite and granodiorite (Lundegårdh et al., 1985). The most recent glaciation ended in 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 ice sheet that had mainly 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 currently located a few metres above sea level. After the regression, it was largely organic soils such as sphagnum peat that formed in the groundwater discharge areas.

About two-thirds of the surface area of the two watersheds that were studied consisted of uncovered bedrock. Glacial till makes up the land surface of 10-15% in the two areas, and clay makes up about 5%. Organic wetlands constitute the most common soil type on the surface – 10-20% (Knape, 2001). Clay can in some cases be found as a sublayer beneath the organic soils. In some locations, glacial till can be found as a sublayer below both clay and organic soils.

9.1.3 Impact on hydrology and hydrogeology

According to data presented in Graffner (2005), groundwater abstraction had a low impact on the annual runoff volume. As shown in Figure 9.11, the runoff from the area with groundwater abstraction was smaller than from the reference area during the two years with the largest abstraction volume. The impact on groundwater levels in the overburden was also small. However, one of the boreholes in the bedrock located near the borehole used for groundwater abstraction was affected (Paper V).

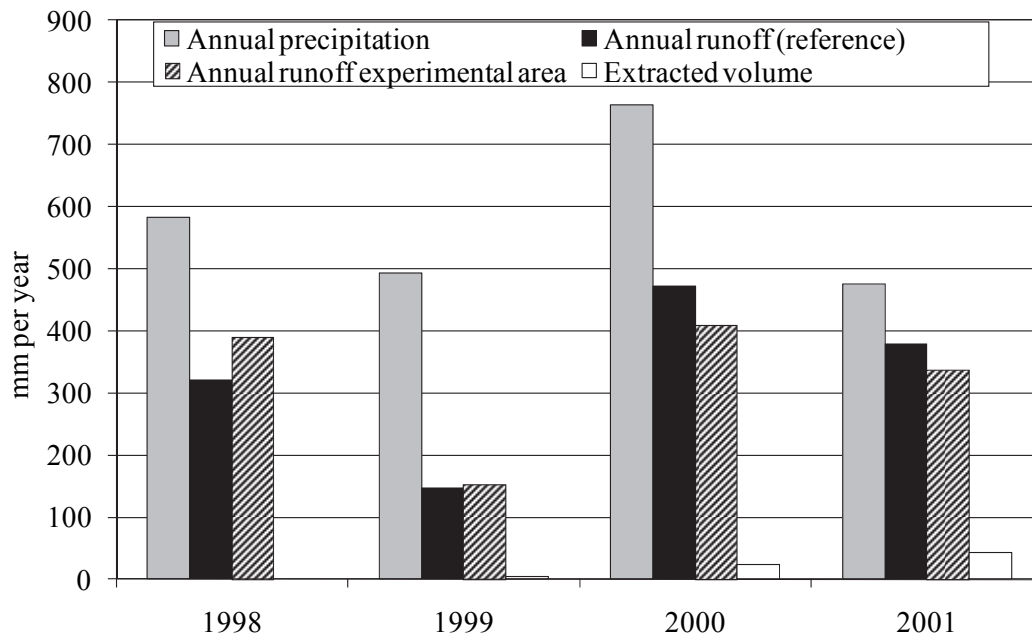


Figure 9.11. Water budget for the two monitored watersheds located on the island of Åspö. Data according to Graffner (2005). Groundwater abstraction was carried out from mid-1999 to the end of 2001.

9.1.4 Impact on water chemistry

The abstraction caused evident hydrochemical changes. The groundwater chemistry of the abstraction borehole came to resemble the chemistry of the shallow waters. Figure 9.12 displays a surge of SO_4^{2-} concentrations during the initiation of the abstraction. However, the surge is followed by a recovery. Meanwhile, pH decreased gradually throughout the abstraction period and was more than one unit lower towards the end of 2001 compared to the unaffected conditions. The time-based variations of the SO_4^{2-} concentrations of the borehole mimic those of the shallow filter well GV5. The increased influx of shallow waters is also evident for Cl^- , which decreased by more than 50% during the abstraction period (Paper V). This implies increased recharge whereas there was no upconing or induced infiltration of saline waters.

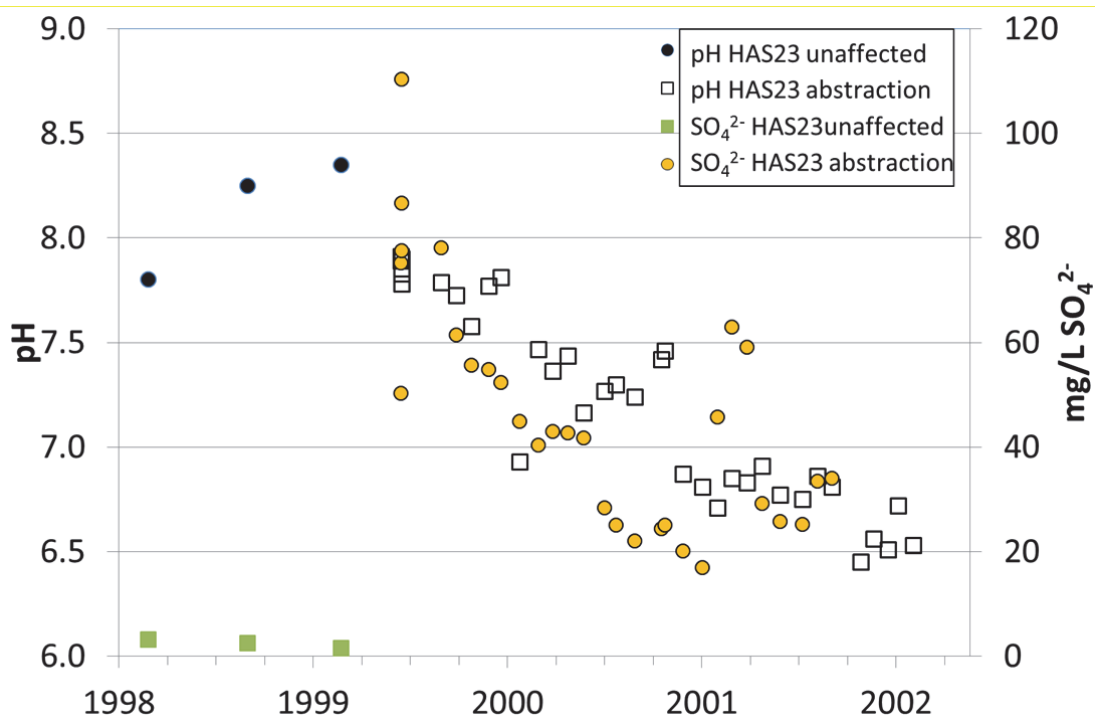


Figure 9.12. The concentrations of SO_4^{2-} and pH under unaffected conditions and during the abstraction of groundwater. A decreasing trend for pH was observed during abstraction. Meanwhile, the concentrations of SO_4^{2-} spiked at the time of initiation of the abstraction and this was followed by a gradual decrease (Knappe Hansén, 2002).

9.1.5 Implications for construction materials

As seen in Figure 9.12, the pH decreased throughout the abstraction period and fell to approximately 6.5. According to SS-EN 206-1 (Swedish Standards Institute, 2012), the groundwater was considered to be aggressive if the pH falls below 6.5 and it stipulates a maximum water-cement ratio. The previous regulations (Swedish Rail Administration, 2005; Swedish Road Administration, 2004) stipulated that complementary protection was also necessary for steel bolts if the pH is below 6.5.

According to Knappe Hansén (2002), the concentrations of dissolved Fe and Mn increased significantly during the abstraction period. This is probably related to increased solubility of Fe and Mn caused by decreasing pH, see e.g. Stumm and Morgan (1996). The increased concentrations of Fe and Mn may have implications for a drainage system in a tunnel through the increased potential for precipitation and thus clogging.

The total hardness and alkalinity were affected by the abstraction and their concentrations decreased temporarily (Knape Hansén, 2002). However, the changes were significantly below the level at which increased protection against degradation of cementitious material or steel would be required. The electrical conductivity increased during the initial period of abstraction (Knape Hansén, 2002) and temporarily surpassed the limit for the requirement of complementary protection against corrosion of steel materials according to the previous regulations issued by the Swedish Rail Administration (2005).

9.1.6 Conclusions from the Äspö Island study

The following main conclusions were made from the Äspö study:

- The abstraction volumes were small because the fracture system in the bedrock had low transmissivities. The hydrological impact related to runoff volumes and groundwater levels in the overburden was limited.
- Despite the limited hydrological impact, the hydrochemical changes in the bedrock were significant: Cl⁻ concentrations fell to less than 50% of the original concentrations and SO₄²⁻ concentrations increased substantially.
- pH concentrations fell below 6.5 in the bedrock groundwater, which meant it was necessary to limit the water-cement ratio according to the regulations in order to prevent degradation in cementitious materials.
- Fe and Mn concentrations increased significantly in the bedrock groundwater and this may be of importance for a drainage system in a tunnel with regard to potential clogging.

9.2 Field study at Lake Gårdsjön (abstraction)

One of the field studies of groundwater abstraction was carried out at Lake Gårdsjön in western Sweden. In this study, two similar surface water catchments areas and related rock mass were monitored. One of the catchment areas (experimental) was studied under pristine conditions for three years and for four and a half years during groundwater abstraction. The recovery from the impact of groundwater abstraction 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 III and in Paper IV. Findings from the initial three years of monitoring under pristine conditions have also been published in Knape (2001) and data from the abstraction period have been published in Graffner et al. (2005) and Knape Hansén (2002). Results

from the recovery period have also been published in Ericsson et al. (2005) and in Mossmark (2010a).

9.2.1 Study arrangement

In the experimental (designated F3) and reference catchment areas (designated F1), several physical parameters were measured. Groundwater levels in both boreholes in the bedrock as well as in filter wells in the overburden were measured. In the experimental catchment area, the runoff volume was monitored in three weirs and in the reference catchment area, one weir was used. Air temperature, precipitation, air moisture, wind speed and wind direction were measured using two climate stations. The abstracted groundwater volume was also measured continuously. In the bedrock boreholes, samples were collected at a depth of approximately 30 m. The sampled water was analysed in the laboratory for pH, electrical conductivity (EC), DOC, major anions and cations. In the abstracted groundwater, pH, EC as well as redox potential were measured and logged continuously. In addition, pH and EC were measured *in situ* (Paper III)

Groundwater abstraction was carried out from two different drilled boreholes (HGF31 and HGF33) in the bedrock. The boreholes were approximately 50 m deep.

Groundwater abstraction took place from borehole HGF33 during the period December 2000 to April 2005. During the last year of groundwater abstraction, from April 2004 to April 2005, borehole HGF31 was also used for abstraction. From February to April 2004, there was an intermission in the groundwater abstraction. Borehole HGF33 had a sealed-off section through the use of an inflatable packer for most of the abstraction period, HGF31 was used as an open borehole.

9.2.2 Geological and hydrological conditions

The area is characterised 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 during the study period). 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 bedrock in the study area mainly comprises granite and gneissic granodiorite (Samuelsson, 1985) covered by thin layers of regolith (mainly glacial till) and podzol and organic soils. According to Fridh and 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. Glacial 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, marine transgressions took place. The Gårdsjön area is located at a height of between 110 to 130 m a.s.l. and, according to Fredén (1986), the highest shoreline following the most recent glaciation is 125 m a.s.l. 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 as well as in the experimental area F1 (Nilsson, 1985). The wetlands in the two catchment areas consist mainly of sphagnum peat.

Several mineralogical investigations have been carried out on samples from the Lake Gårdsjön area. The results from these studies have mainly been presented in Samuelsson (1985) and in Melkerud (1983). The dominating minerals in the granodiorite and in the granite are quartz, K-feldspar and plagioclase (Melkerud, 1983). This composition is also reflected in the glacial till.

Table 9.3. *Mineralogical composition of the bedrock and soil in the Lake Gårdsjön area (Melkerud, 1983)*

Mineral	Bedrock		Soil
	Granodiorite	Granite	Glacial till
Quartz	27	40	28
K-feldspar	20	46	15
Plagioclase	33	12	14
Hornblende	2.6		0.5
Epidote	4.2		0.1
Biotite	13	0.1	1.2
Garnet	0.3		0.1
Chlorite	0.4		0.4
Vermiculite	0		5.0
Apatite	0.1		0.1

The climate in the area has been classified as maritime temperate, which according to the Köppen-Geiger system is a mild, humid climate without dry seasons. The annual precipitation during the period 1961-1990 was 951 mm, slightly lower than during the study period (Alexandersson and Eggertsson, 2001).

9.2.3 Hydrological and hydrogeological effects

The abstraction caused a lowering of the groundwater levels by 5-20 m in the bedrock and by up to 5 m in the soil cover compared to unaffected levels. Furthermore, the runoff volume decreased by nearly 50%. The abstracted volume corresponded to the decrease in runoff volume in the experimental area. This indicates that the abstracted 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 (see Paper IV).

The hydrological conditions of the Lake Gårdsjön experimental area have been evaluated based on measurements of drawdown and abstraction volume. The evaluation shows that different conditions exist in different parts of the area. Generally, all the boreholes in the bedrock within the study area (See Figure 9.13) were affected during groundwater abstraction.

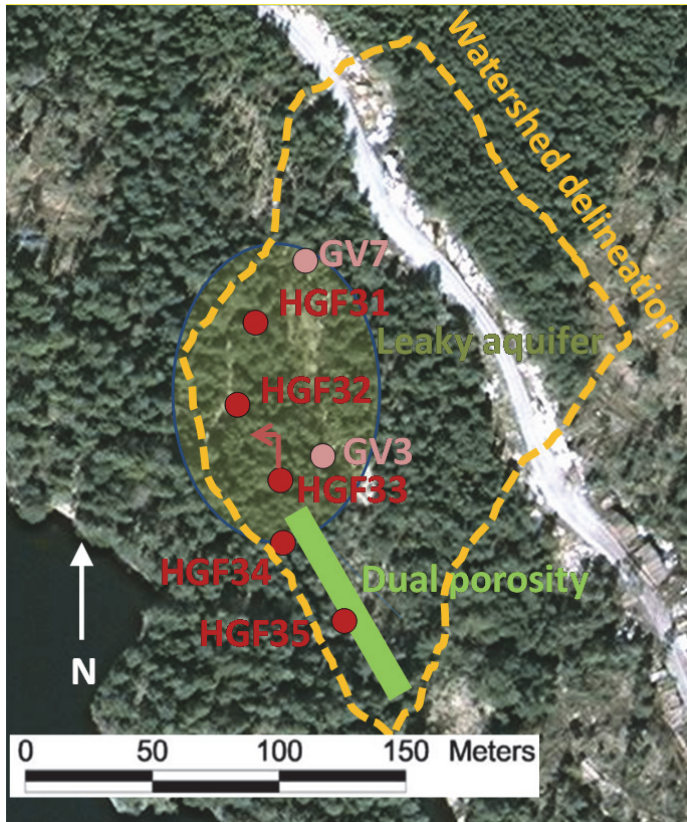


Figure 9.13 Aerial photo of the study area. Different groundwater flow regimes were seen within the watershed. In the south, a dual porosity system was observed while the overburden in the north is made up of a leaky aquifer system. Abstraction of groundwater took place from HGF33 during the periods that were modelled.

The HGF31, HGF33 and HGF35 boreholes were drilled at an inclination of approximately 30 degrees to intersect the fracture zone beneath the wetland. The evaluation confirmed flow along the fracture zone as well as secondary porosity, which contributes water to the zone (Mossmark, 2014). In the northern parts, near HGF31, there was consistently saturated flow from the overburden to the bedrock during the

period when groundwater abstraction was solely from borehole HGF33. The drawdown was limited by increased recharge from the shallow systems. However, these conditions changed and became unsaturated during the period when abstraction also took place from HGF31 (Mossmark, 2014).

In the southern part of the study area, the flow from the wetland to the bedrock became unsaturated after a brief period of abstraction during 2000 and 2001. The drawdown gradually increased and revealed a system of dual porosity. According to Mossmark (2014), this is represented by 2D flow in the fracture zone during the initial stage of the abstraction. However, the 2D flow pattern later changed to a system where a 3D component with lower conductivity feeds the fracture zone.

After abstraction was stopped, a quick recovery of the groundwater levels was seen. However, the recovery of the runoff volumes was slow. During the first two years after the groundwater abstraction was terminated, the runoff volumes from the experimental catchment were 35% lower than from the reference catchment area. During 2009, the runoff volumes from the experimental catchment area F3 had increased further to near pre-experimental volumes, see Figure 9.14. Approximately five years after abstraction was discontinued, the studied catchment area had achieved hydrological balance.

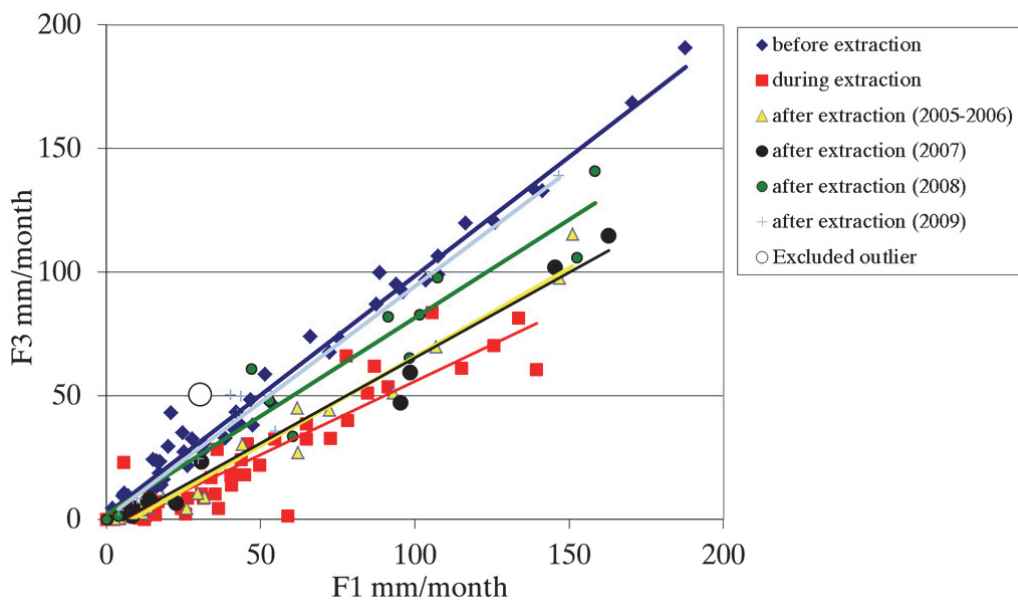


Figure 9.14. Relationship between runoff volumes from the two monitored catchment areas, F3 being the catchment area where groundwater abstraction occurred. In unaffected conditions, the runoff volumes were similar from the two catchment areas. During abstraction, the runoff from F3 decreased by nearly 50%. This was followed by recovery after abstraction stopped.

It should be observed that the groundwater levels in the bedrock were measured in open boreholes and interpretation of the results is therefore difficult. According to Offerdinger et al. (2014), unsaturated conditions may also occur in conjunction with tunnelling. Furthermore, the gas pressure in the unsaturated zone in the bedrock may increase during the recovery period as observed by Philips (1994). The unsaturated conditions are likely to decrease the portion of the porosity that is available for flow (see e.g. Engesgaard et al., 1996) and thus decrease the amount of water that may be discharged to the wetland and become runoff.

9.2.4 Water chemistry

During the period of groundwater abstraction, the hydrological changes had an impact on the hydrochemical composition. This affected processes, including increased oxidation (redox), ion exchange and the composition through mixing of water with different compositions. For redox, increased seasonal fluctuation in the groundwater level led to aeration of the shallow organic soil layers of the wetland in the experimental catchment area F3. This caused the S bond in the wetland to oxidise, releasing H^+ and SO_4^{2-} , see Figure 9.15. The effect of the experiment was gradual acidification of the wetland. H^+ was buffered through cation exchange and Mg^{2+} and Ca^{2+} were released due to being replaced by H^+ (Paper III).

The chemistry of surface runoff water and the groundwater in the bedrock were affected by the processes in the wetland. The increase in SO_4^{2-} (see Figure 9.15) and base cation (Mg^{2+} , K^+ , Ca^{2+}) concentrations during abstraction was lower compared to the shallow groundwater. There are no other processes present in addition to oxidation of S in the wetland that would contribute to sharp increases in concentrations of SO_4^{2-} . The increase in the runoff water and in the bedrock is thus assessed to originate from the wetland and the lesser magnitude is due to dilution. The increased recharge during abstraction from shallow water also caused induced acidification of more than 0.5 pH units in boreholes where low buffer capacity (e.g. HGF31) was measured. The hydrochemistry of shallow groundwater in the glacial till surrounding the wetland was, however, unaffected by the experiment (Paper III).

The chemical changes in runoff observed during the abstraction period were partly reversed during the period of monitoring of recovery, see e.g. for SO_4^{2-} in Figure 9.15. However, the concentrations of SO_4^{2-} in the wetland persisted at slightly higher levels after the experiment compared to pre-experiment levels. In the reference catchment area F1, the concentrations of sulphate decreased during the same period (see Paper IV).

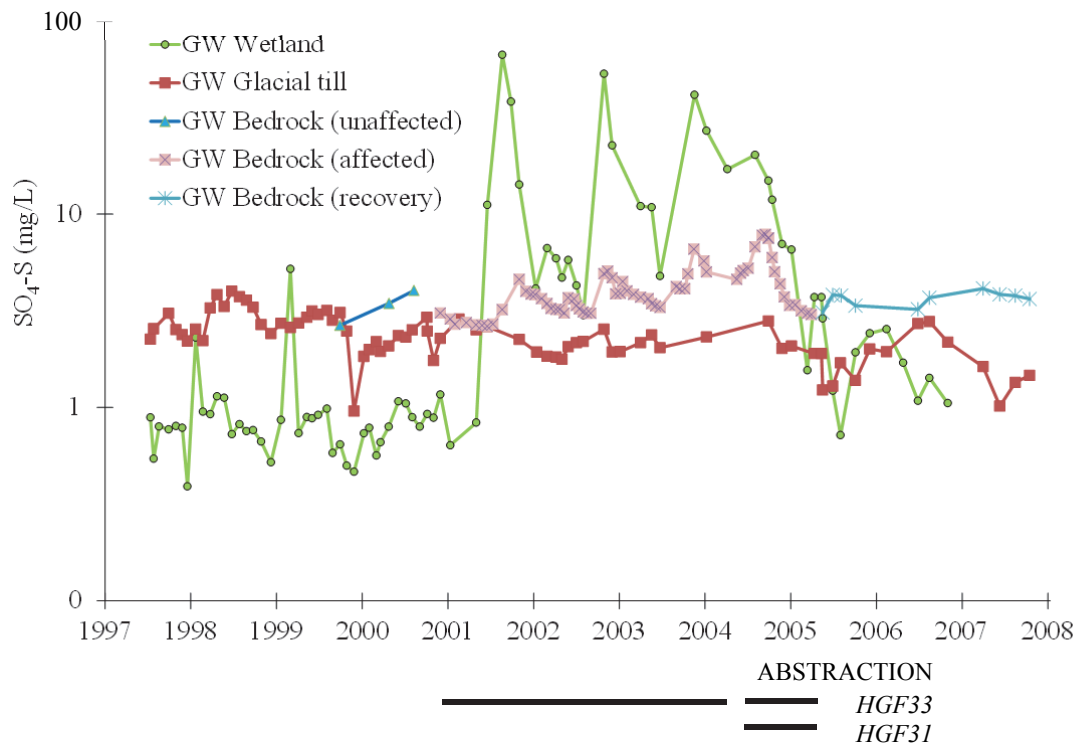


Figure 9.15 Concentrations of $\text{SO}_4^{2-}\text{-S}$ in the groundwater from the bedrock, in the glacial till and in a wetland. The periods with active abstraction from boreholes HGF31 and HGF33 are presented as lines below the graph.

9.2.5 Implications for construction material

One important change to the hydrochemistry of the bedrock that may have implications for construction materials is that the redox potential of the extracted groundwater from HGF33 increased throughout the abstraction period, while Cl^- concentrations remained relatively unchanged (Paper IV). There was an increase in SO_4^{2-} concentrations although at a low level and where increased protection to avoid what is termed 'sulphate attack' would not be required.

Among the cations, the concentrations of total hardness (Ca^{2+} and Mg^{2+}) are beneficial for protection against steel corrosion. However, high concentrations of Mg^{2+} are detrimental to the durability of cementitious materials, see section 8.1. The hardness and alkalinity decreased below the limit in the previous regulations, which stipulated a need for complementary protection of bolts on a few occasions during abstraction. However, this situation was quickly reversed after abstraction terminated. During a brief period, the pH decreased below 6.5 in one of the boreholes (HGF31), which would require both complementary corrosion protection (in previous legislation, see Section 8.1) as well as protection against acid attack on concrete.

9.2.6 Conclusions for the Lake Gårdsjön study

The abstraction of the groundwater from the bedrock affected both hydrology and water chemistry within the experimental catchment area, see main findings summarised below:

- The resulting hydrochemistry was affected considerably by the geological and hydrogeological setting. The varying hydrogeological flow regimes in different parts of the study area created spatially different hydrochemical conditions in the bedrock.
- The wetland communicated hydraulically with the bedrock groundwater. The abstraction from the bedrock caused aeration of the wetland, oxidation and release of S and H⁺.
- During abstraction, the groundwater in the bedrock became aggressive towards steel (low alkalinity, total hardness and pH) and cementitious (low pH) materials according to regulations issued by the authorities.
- Recovery of the hydrological system, particularly runoff volumes, occurred after approximately five years. However, recovery of the hydrochemistry was not achieved within the three years of monitoring after abstraction was stopped. After abstraction was stopped, the parameters relevant for degradation of steel and cementitious materials recovered to indicate non-aggressive conditions on most sampling occasions.

9.3 Conclusions from the field studies

The geological conditions as well as the presence of marine waters determined the hydrochemical changes. The most important hydrochemical changes were observed in conjunction with oxidation of S in either wetlands or fracture zones.

According to the division of hydrogeological conditions issued by the Swedish Geological Survey (2013), the four locations for field studies with groundwater abstraction belong to three different sub-groups: the west and south coast (Äspö), the highlands of southern Sweden (Gårdsjön, Hallandsås) and the central Swedish depression (Kattleberg), see Figure 9.16. Due to the low resolution of the division in the map, it may appear as if Gårdsjön belongs to a different sub-group. Table 9.4 summarises the findings in the field studies.

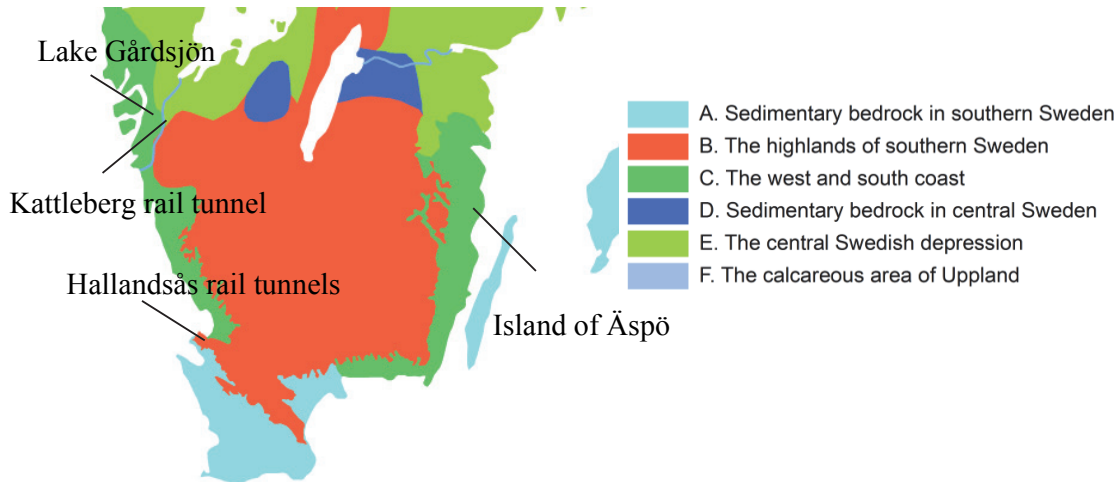


Figure 9.16. The hydrogeological environment at the sites for the field studies according to the division set issued by the Swedish Geological Survey (2013).

The following main conclusions can be drawn from the studies:

- Importance of hydrogeological properties of the bedrock: In both field studies (island of Äspö and Lake Gårdsjön), S was being oxidised in wetlands. However, the magnitude of changes to the bedrock groundwater was more significant at Äspö, despite a lower hydrological impact compared to Lake Gårdsjön. This difference was likely because of low fracture transmissivity in the bedrock on Äspö compared to Lake Gårdsjön, see e.g. Graffner, 2002.
- Variations in hydrochemistry may occur near a tunnel depending on the geological conditions, as observed in the Kattleberg rail tunnel. In a fracture zone, the groundwater hydrochemistry may resemble that of surrounding bedrock. Meanwhile, in more homogeneous and less fractured rock, the groundwater hydrochemistry may be more affected by sealing grout.
- Importance of Quaternary geology. The Kattleberg tail tunnel was the field study with the least significant hydrochemical changes for the bedrock groundwater due to excavation. The main reason was the existence of a clay layer underlying the wetland of the study area. This clay layer prevented hydrological interaction between the wetland and the bedrock groundwater. Furthermore, it prevented increased aeration and chemical oxidation of the wetland.
- Influence of fracture minerals. In two of the boreholes that had been installed in heterogeneous conditions on Hallandsås (MK60 and BP08), including the presence of pyrite, significant changes to the major ions and pH were observed.
- In three of the field studies (Lake Gårdsjön, Äspö and Hallandsås), the hydrochemical conditions in the bedrock changed sufficiently to become assessed as aggressive towards steel or cement according to regulations.

- Observations of recovery at Lake Gårdsjön and Hallandsås. The results indicate that it takes more than five years before hydrochemical recovery is achieved. However, the assessment of bedrock groundwater being aggressive towards cement or steel recovered to non-aggressive within six months.

Table 9.4. Geological and hydrological conditions as well as hydrochemical changes observed during the four field studies.

Location	Lake Gårdsjön	Island of Äspö	Kattleberg rail tunnel	Hallandsås rail tunnels.
Bedrock	Granite and granodiorite	Granites, granodiorite and quartz monzodiorite	Mainly gneiss, granitic or dioritic. Metabasite is present, as well as veins of pegmatite	Granitic gneiss, dolerite and amphibolite dykes
Fracture minerals	Calcite, kaolinite, chalcedony, chlorite	Calcite, chlorite, hematite	Calcite, chlorite and iron hydroxide	Chlorite, calcite, pyrite
Quaternary geology	Glacial till, wetlands (little impact from transgressions).	Complex, recent transgressions: bedrock outcroppings, wave-washed deposits, till, clay.	Complex, recent transgressions: glacial till, clay in topologically low-lying areas and wetlands.	Glacial till, wetlands (no transgressions).
Hydrochemical changes in discharge areas and streams	S surge, acidification, cation release		None observed	
Hydrochemical changes in the bedrock	Decreasing alkalinity and pH. Small increase in S.	Decreasing Cl concentrations, significantly increased S concentrations	Presence of DOC	Increasing DOC, decreasing Mn, Fe. Where pyrite was present, also high SO_4^{2-} (>200 mg/L) and pH below 6.5 was observed.

10 HYDROCHEMICAL MODELLING

This chapter summarizes Paper VI and exemplifies how hydrochemical modelling can be used as a tool to understand chemical processes and to predict hydrochemistry.

The aim of the hydrochemical modelling was to create numerical models that represent the hydrochemical changes observed during the field study of groundwater abstraction at Lake Gårdsjön, see Section 0. The results were evaluated in the context of predicting hydrochemical changes caused by tunnelling.

The modelling examined the significance of mineralogy, hydrolysis, cation exchange capacity (CEC), redox processes and CO₂ (g) partial pressure in relation to the measured hydrochemical conditions in the groundwater. Mixing various amounts of groundwater of different origins was also studied in the context of the prevailing hydrogeological conditions. The influence of the present mineralogy on the hydrochemistry was also studied through inverse modelling.

10.1 Input data

The modelling was based on hydrogeological, geological and hydrochemical data. The geological and hydrogeological data are described in more detail in Section 9.2. The hydrochemical input data for the models consisted of three end-member types: groundwater in the recharge areas (glacial till), groundwater in the wetland and groundwater in the bedrock.

Data from the period before abstraction started were used as input data. Measurement data from the groundwater abstraction period were used to calibrate the models. This is described further in Section 9.2. The abstracted groundwater from the bedrock is termed seepage water to highlight that it exemplifies the impact from tunnelling.

The sources of the end-members, their functions and detailed hydrochemical data are also presented in Paper VI. Below is a list of the input data used for the modelling.

End-members:

- Unaffected GW hydrochemistry (E1), wetland
- Unaffected GW hydrochemistry (E2), glacial till
- Unaffected GW hydrochemistry (E3.1 and E3.2), bedrock
- Atmospheric chemistry

Geochemical data:

- Cation exchange capacity
- Geological data
- Hydrogeological data

10.2 Modelling approach

Two different models were created using PHREEQC, which is modelling software with the capability to handle transport calculations with reversible and irreversible reactions, such as aqueous, mineral, gas, solid-solution and ion-exchange, as well as mixing of solutions (Parkhurst and Appelo, 2013). One of the models was a backward (inverse) model to study the influence of the mineralogical composition of the bedrock on the hydrochemistry. The forward (reactive transport) model included the results from the inverse model. The forward model was prepared by fitting to measured *in situ* data. The two different types of modelling are:

- 1) Inverse modelling to determine which minerals influence the hydrochemistry of the groundwater.
- 2) Reactive transport modelling, which includes reaction models of the wetland mixing with groundwater in the glacial till and a 1D-flow model for the abstraction point in the bedrock. These models were calibrated against measured data and gathered under three different hydrogeological conditions.

10.2.1 Inverse modelling

This model was applied to undisturbed conditions that existed prior to initiation of abstraction. The geochemistry of the bedrock and the fracture minerals had not been studied in any detail during the field studies at Lake Gårdsjön. Based on mapping by the Swedish Geological Survey (Samuelsson, 1985) and the studies presented in Olsson (1985) and Melkerud (1983), the following minerals were assumed to be present in this type of bedrock.

- Calcite (fracture mineral)
- Quartz (matrix rock)
- Biotite (matrix rock)
- Plagioclase (representing both sodic (albite) and calcic (anorthite) plagioclase) (matrix rock)
- K-feldspar (matrix rock)
- Pyrite (fracture mineral)
- Cryptocrystalline quartz (fracture mineral)

- Gypsum (fracture mineral)
- Halite (fracture mineral)
- Chlorite (fracture mineral)
- Kaolinite (fracture mineral)

CO₂ gas was also assumed to be present in the groundwater and has implications for the hydrochemical processes (affecting pH).

The modelling assumed long residence periods for the groundwater in the bedrock (>25 years based on Bockgård et al., 2004). The inverse modelling used laboratory results from the shallow (2 m) filter well GV7 (glacial till) and percussion-drilled borehole HGF33 (70 m), see Figure 9.13 for the geographical locations. Hydrogeologically, the inverse modelling is represented by a flow pattern with groundwater recharge in more highly elevated areas (covered with glacial till) (GV7) and discharge in the wetland area or in Lake Gårdsjön. Along this flow path, the groundwater passes through the bedrock (HGF33). The results from the inverse modelling were used to select processes and detect the presence of minerals (if any) in the reactive transport and mixing model.

10.2.2 Reactive transport and mixing modelling

This model was applied to disturbed conditions with abstraction of groundwater to simulate the impact from water seepage into a tunnel. The reactive transport models describe the hydrochemical processes and the mixing of water from different origins along the flow path towards the abstraction point (HGF33), see Figure 10.1. This abstracted water is assumed to represent seepage water into a tunnel. The modelling is presented schematically in Figure 10.2.

Two different hydrochemical models for the wetland were created to replicate the observed changes during the experiment with abstraction (R1 and R2). The models were included the assumed hydrochemical processes as presented in Paper IV. Three different models for the entire system of shallow and bedrock groundwater were calibrated: two models representing different occasions for the HGF33 borehole (HGF33 Autumn Model a) and HGF33 Spring Time Model b), where abstraction occurred) and c) one representing the HGF31 borehole (which functioned as a monitoring borehole for hydrochemical changes), see Figure 10.2. The models were calibrated against measured hydrochemical composition in samples that had been collected in the spring and autumn of 2003.

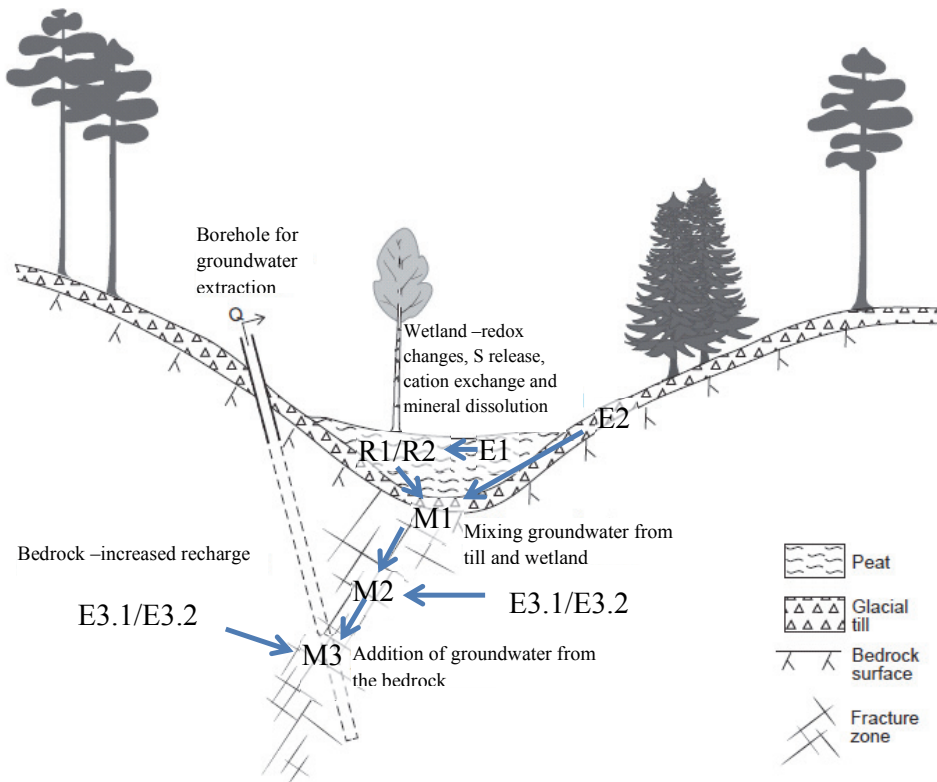


Figure 10.1. Hydrochemical processes and mixing of groundwater differing in origin (end-members), including groundwater from the wetland (E1), glacial till (E2) and bedrock (E3.1/E3.2). The reactions are designated R1/R and the mixing M1-M3.

The calibration of the wetland models was then carried by adjusting three parameters:

- Adjustment of the oxidation of S to calibrate towards measured concentrations of SO_4^{2-} in the groundwater. This was done by varying the gas availability (including O_2) in the wetland models.
- Adjustment of ion exchange surfaces to obtain a better fit with the measured concentrations of cations and alkalinity. The calibration results for the ion exchange surfaces are compared with previously measured ion exchange capacities in the glacial till in the study area (see Melkerud, 1983).
- The presence of calcite was also adjusted.

In the calibrations of the bedrock model, the following parameters were adjusted:

- Proportions between the water types (unaffected bedrock groundwater (E3.1 and E3.2), groundwater from the glacial till (E2) and modelled affected groundwater in the wetland (R1 and R2) in a mixing model.
- The composition of the gas that represented the air at the abstraction point.

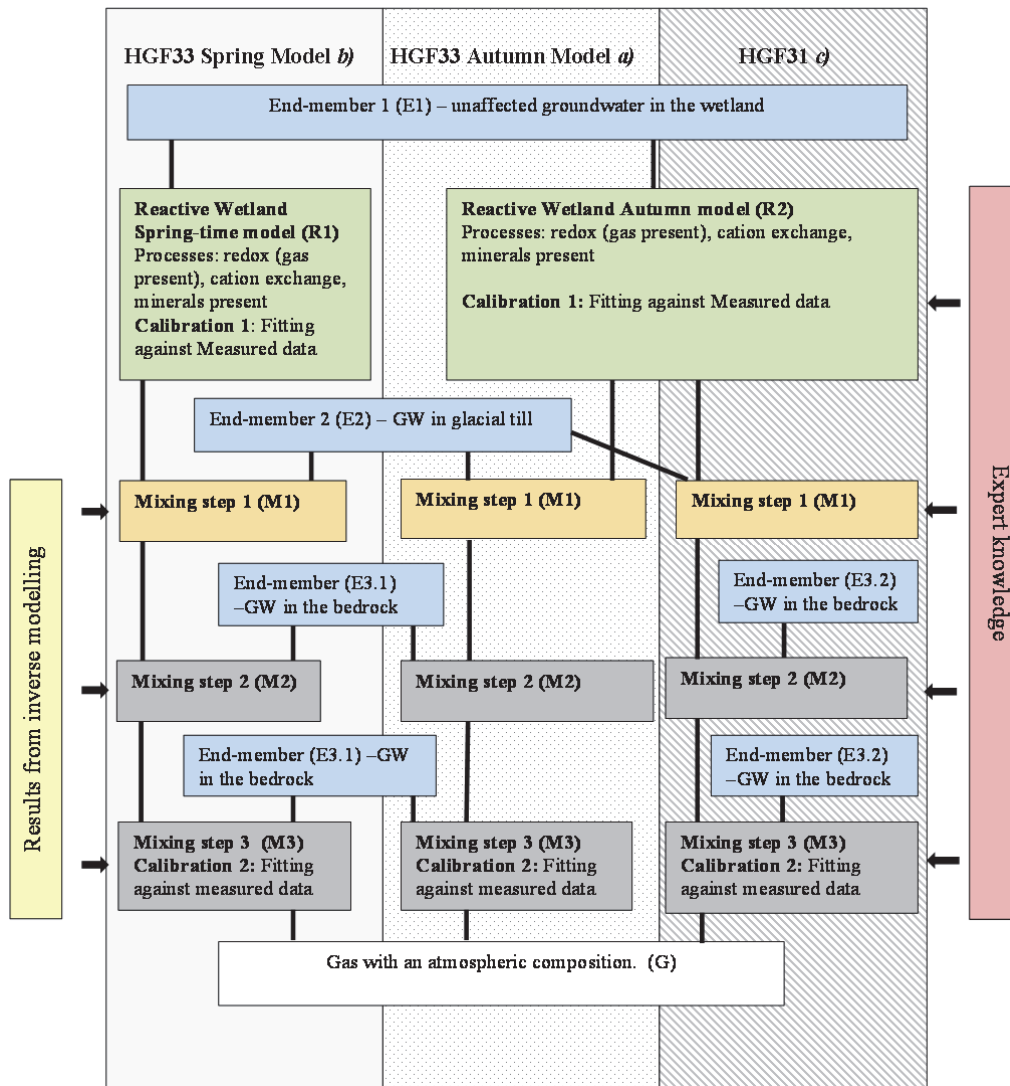


Figure 10.2. Reactive transport and mixing modelling. Schematic description of the modelling steps including reactive and mixing modelling. Three different models were built and calibration was carried out in two steps.

The modelled and calibrated hydrochemistry of the wetland was used as input data for this model. The mixing model was set up in three mixing steps and was subjected to gas varying in composition after the final mixing step. In the first step, the modelled water from the wetland was mixed with an end-member representing the groundwater from the glacial till. In the two following steps, groundwater representing the unaffected chemistry in the bedrock was added, see Figure 10.2. For the calibration of the bedrock model, the parameters, including the fractions in the mixing, were adjusted for optimisation. The primary hydrochemical parameters (concentrations) used for calibration were K^+ and SO_4^{2-} . However, other major ions (Ca^{2+} , Mg^{2+} , Na^+ , Cl^- and

HCO₃⁻) were also used. For the wetland calibration all the mentioned hydrochemical parameters were used. The calibration process is discussed further in Paper VI.

10.3 Results from inverse modelling

The results from inverse modelling indicate that hydrolysis of K-feldspar, plagioclase and biotite occurs to form kaolinite and cryptocrystalline quartz (chalcedony). Regular quartz is also present in the bedrock in the study area (Melkerud, 1983). However, according to Stumm and Morgan (1996), quartz is significantly less prone to hydrolysis compared with other silicate minerals that are present in the bedrock (at neutral pH) and has been excluded from the model. Chalcedony has the same chemical composition as quartz (SiO₂) although it is more prone to dissolution as well as precipitation in the presence of silicic acid (H₄SiO₄) in the groundwater (Appelo and Postma, 2005). The results from inverse modelling are presented in Table 10.1 and are discussed further in Paper VI.

Table 10.1. *Dissolution and precipitation of minerals seen to be present in the study area. The table shows the results from one viable modelled numerical solution using inverse modelling*

Mineral	Dissolution (mole/L)	Precipitation (mole/L)
Biotite	4.6•10 ⁻⁶	0
Halite	0	0
Gypsum	0	0
Calcite	6.4•10 ⁻⁴	0
Cryptocrystalline quartz	0	3.5•10 ⁻⁴
Plagioclase	2.4•10 ⁻⁴	0
K-feldspar	3.3•10 ⁻⁵	0
Pyrite	0	0
Chlorite	0	0
Kaolinite	0	2.0•10 ⁻⁴

10.4 Results from reactive transport and mixing modelling

In Paper VI the results from three different models are presented: HGF33 Autumn, HGF33 Spring and HGF31. In this section, it is mainly the results from the HGF33 Autumn model that are presented.

10.4.1 Wetland model – initial calibration for the autumn (R2)

This modelling step is referred to as R2 in Figure 10.2. Modelling results indicate that the degree of oxidation (availability of oxygen) in the wetland was the limiting factor for S oxidation (assumed to originate from pyrite) and thus the increase in SO_4^{2-} and H^+ concentrations. The calibration of S concentrations was carried out through variation in the aeration of the wetland. Based on the geological description in Samuelsson (1985) and the results from the inverse model, the presence of small amounts of calcite was also assumed.

The simultaneously observed changes of the cations (caused by the mobilisation of H^+) were modelled on the assumption of exchange surfaces. The calibration of the wetland model indicated that the distribution of the exchanger sites differed slightly from those in the nearby glacial till, as presented in Melkerud (1983). According to modelling using PHREEQC, this was mainly evident for K^+ , which was higher in the measured CEC in the glacial till than in calibrated CEC in the wetland. However, according to Melkerud (1983) the total CEC in the calibrated model (0.756 meq/100 g) was similar to the measured CEC in the uppermost podzol profile of the glacial till in the study area (approximately 0.9 meq/100 g). The calibrated parameter values are presented in Table 10.2, 'Run 10' being considered a satisfactory replication of the hydrochemistry in the wetland (lowest MPE).

Table 10.2. Calibrated parameters for the reactive wetland model, including the presence of minerals, ion exchangers and gas (air) in the wetland. The table shows examples of three different runs of the model, including 'Run 10', which was assessed to be satisfactory (minimising MPE).

	Minerals		Ion exchangers				Gas (aeration)			RMSE ¹	MPE ²
	CaCO ₃	FeS ₂	CaX2	MgX2	KX	NaX	CO ₂	O ₂	Gas share		
	Availability (moles)		meq/100g				Partial pressure				
Run 8	10 ⁻⁴	10 ⁰	0.6	0.15	0.005	0.001	0.035	0.2	0.3	549	0.54
Run 9	10 ⁻⁴	10 ⁰	0.6	0.15	0.005	0.005	0.035	0.2	0.3	467	0.42
Run 10 (selected)	10 ⁻⁴	10 ⁰	0.6	0.15	0.001	0.005	0.035	0.2	0.3	472	0.21

¹Root mean square error RMSE

²Mean percentage error (MPE)

10.4.2 HGF33 Autumn Model (M1-M3)

The hydrochemistry in the bedrock was modelled through the mixing of (modelled) groundwater in the wetland (R2) with (unaffected) groundwater in the glacial till (end-member 3, E3) and (unaffected) groundwater in the bedrock (end-member 2, E2). The end-members were selected based on the evaluation of hydrogeology (Mossmark, 2014) and hydrochemistry (Paper IV). The resulting composition was compared with

measured (affected) hydrochemical composition in the bedrock as described in Paper VI. The input data for the model, the modelling results and the data used for calibrating the model are presented in Figure 10.3.

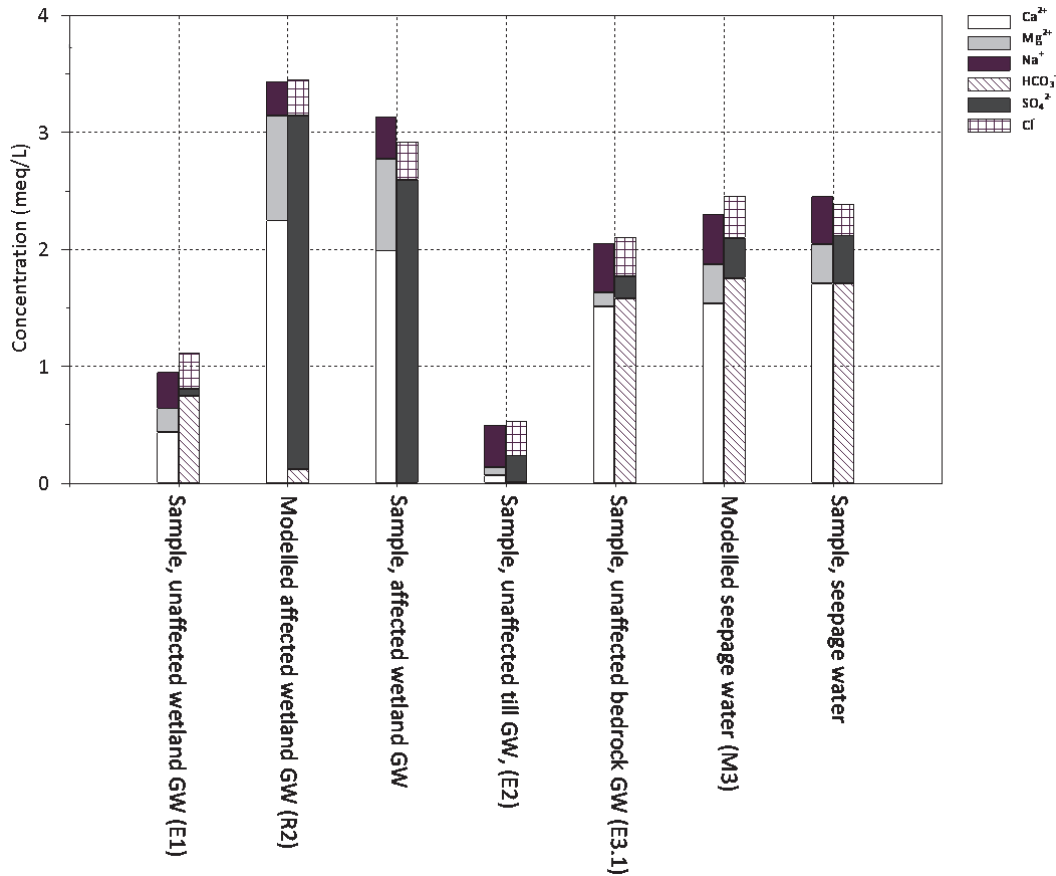


Figure 10.3. Concentration of major ions in the input data end-members and calibrated modelling results as well as the measured affected composition of the groundwater. The results and affected compositions are from the two parts of the modelling (wetland and seepage water in the bedrock (HGF33)).

The results describing the mixing proportions of water of different origins are summarised in Table 10.3. The calibrated model showed that 5% of the extracted water from HGF33 originated from the wetland (R2), whereas 20% originated from areas with glacial till (E2). Furthermore, it is shown that 75% of the water extracted (seepage water) originated from bedrock groundwater with long retention times (E3.1, unaffected groundwater from the bedrock), see Table 10.3. Modelling results for other occasions

Additional reactive and mixing models were calibrated, as mentioned in Section 0. The Spring Model (R1) indicated a significantly lower degree of aeration (0.025 gas share)

and thus aeration compared with the autumn (R2) situation (0.3 gas share). The mean percentage error was similar to the Autumn Model, (25.9% compared with 21.3%), thus supporting the possible distribution of the present cation exchangers in the wetland as presented in Paper IV.

Similar to the HGF33 Autumn Model, the HGF33 Spring Model and the HGF31 were calibrated to measurement data. Table 10.3 describes the proportions of groundwater with different origins in the calibrated models. The calibrated model indicates a higher proportion of groundwater originating from the bedrock during autumn compared to spring. The HGF31 model indicated little influence from the wetland compared to the HGF33 models.

Hydrochemically, the calibrated models showed implications for construction materials according to previous regulatory documents (e.g. Swedish Rail Administration, 2005). The models indicated low alkalinity and total hardness in the HGF31 model that would have required complementary protection against corrosion for steel bolts.

Table 10.3. Mixing proportions of groundwater differing in origin (end-members), including affected groundwater from the wetland (R), glacial till (E2) and bedrock (E3). The table presents the mixing proportions in the calibrated models.

	Groundwater from the glacial till (E2)	Affected groundwater in the wetland (R1, R2)	Groundwater from the bedrock (E3)
HGF33 Autumn	20%	5%	75%
HGF33 Spring	34%	8%	58%
HGF31 (Autumn)	40%	2%	58%

10.5 Conclusions –hydrochemical modelling

Based on field studies of mineralogy, hydrology, and geochemistry, as well as robust hydrogeological field studies, evaluation and conceptual models, the hydrochemical modelling successfully replicated measured field data, thereby exemplifying the impact from tunnelling.

The following main conclusions were drawn from the hydrochemical modelling:

- The SO_4^{2-} surge in the wetland and related acidification were mainly dependent on redox changes simulated in the model.
- The calibrated models revealed a distribution between the respective elements of released cations and total cation exchange capacity, which coincided with expectations based on previous field studies.
- The magnitude of the release of cations was related to the release of H^+ in conjunction with the oxidation of S in the wetland.
- The groundwater in the soil layers beneath the wetland and in the bedrock was modelled using mixing models. This model was based on the results of previous hydrogeological studies of the area. The calibrated model was consistent with the findings in the field studies.

The modelling results showed that the groundwater in the bedrock could become aggressive towards steel-based materials and was prone to precipitation of Fe and Mn.

11 PREDICTING HYDROCHEMISTRY

This chapter proposes a methodology to predict hydrochemical conditions that will exist during the construction and operation phases of underground constructions. The prediction is aimed at providing a basis for the selection of construction materials.

It is suggested that predictions of potential hydrochemical changes are carried out in three steps. The primary objective is to identify locations where the groundwater hydrochemistry will probably have negative implications for construction materials. Using a stepwise procedure, cost-effective methodology to assess hydrochemical conditions is proposed and necessary measures can be recommended.

Although in most cases the hydrochemical changes are not likely to have a significant adverse effect on the assessed durability of the construction material, there are certain areas that require careful assessment. The method described in this thesis focuses on finding the locations where more detailed studies are recommended. The methodology is thus cost-effective and offers guidelines for a minimum number of investigations and evaluations. In order to assess whether a detailed study is necessary, a three-step procedure is suggested:

1. A **desk study**, including assessments based on geological maps, conceptual models and geographical location. The models are based on hydrogeological conditions as well as the geology of the bedrock and the Quaternary history. If the assessments of risks associated with existing or potential changes in hydrochemistry indicate an aggressive environment (according to standards, see Section 8.1), further investigations (see step 2.) are necessary.
2. **Field investigations** that are adapted to requirements that are specific to a certain project and conditions. This could include the collection of rock core samples of fracture zones, samples of surface and groundwater or geochemical investigations of soil. The results should either lead to recommendations for the design of underground constructions or the conclusion that hydrochemical modelling is necessary (see step 3.).
3. **Predictive hydrochemical modelling**. The modelling approach and the selection of modelling tools should be based on the results from steps 1 and 2 above. The modelling results should be used for design recommendations and the selection of construction materials based on criteria for assessment of aggressivity or proneness to precipitation of Fe, Mn or CaCO₃.

The methodology does not focus on the complex issues that are related to hydrogeology and hydrochemistry in urban environments. However, many of the recent and future underground constructions, primarily for transportation, are located in urban areas. The complex hydrogeological and hydrochemical conditions in urban environments have been described previously in e.g. Mossmark (2003), Norin (2004) and Persson (2007). In addition to the factors mentioned for pristine conditions, the following should be considered:

- The overburden, hydrologically, hydrogeologically and hydrochemically, is commonly affected by historical and current land use.
- For the hydrogeology in the bedrock in the case of pre-existing tunnels, artificial groundwater infiltration may exist.
- The hydrochemistry in the bedrock may therefore be affected by anthropogenic activities before the pre-investigation phase.

11.1 Desk study: assessment using conceptual models

The chemical composition of the groundwater is mainly dependent on geological and hydrological conditions as well as biota and climate. Both local and regional conditions are therefore of importance in the assessment of hydrochemistry. During the construction and operation phases of a tunnel, the design of waterproofing systems is also of importance.

The use of conceptual models includes utilisation of regional maps, geological maps and generic hydrochemical models. In Sweden, the hydrochemistry in the bedrock has been classified by the Swedish Geological Survey (2013), as presented in Figure 5.6. The division is based on previous marine transgressions, the geochemistry of the bedrock and the presence of Quaternary sediments. The following general observations are relevant to the use of Figure 5.6:

- Areas C, E, F and G have been subjected to marine transgressions. High concentrations of (primarily) Na^+ and Cl^- may therefore occur as well as relict groundwater. Low concentrations or near depletion of Ca^{2+} may exist during the flushing of saline waters with freshwater (unlikely in F).
- In area F, a relatively high level of hardness should be anticipated in the groundwater.
- In areas C, E, F and G primarily, wetlands may be oxidised to cause the release of S and acidification.

- In areas B and I, the availability of S is less compared to in areas C, E, F, and G. However, the wetlands are more likely to become aerated by groundwater fluctuations in the bedrock..
- The shallow groundwater in areas I and J are often reduced in wetlands, resulting in high Fe and Mn concentrations.
- The areas with sedimentary bedrock (A, D and H) generally have groundwater with high alkalinity and a high pH. However, in area H, alum shale presents a source of S that could be oxidised and result in acidification.

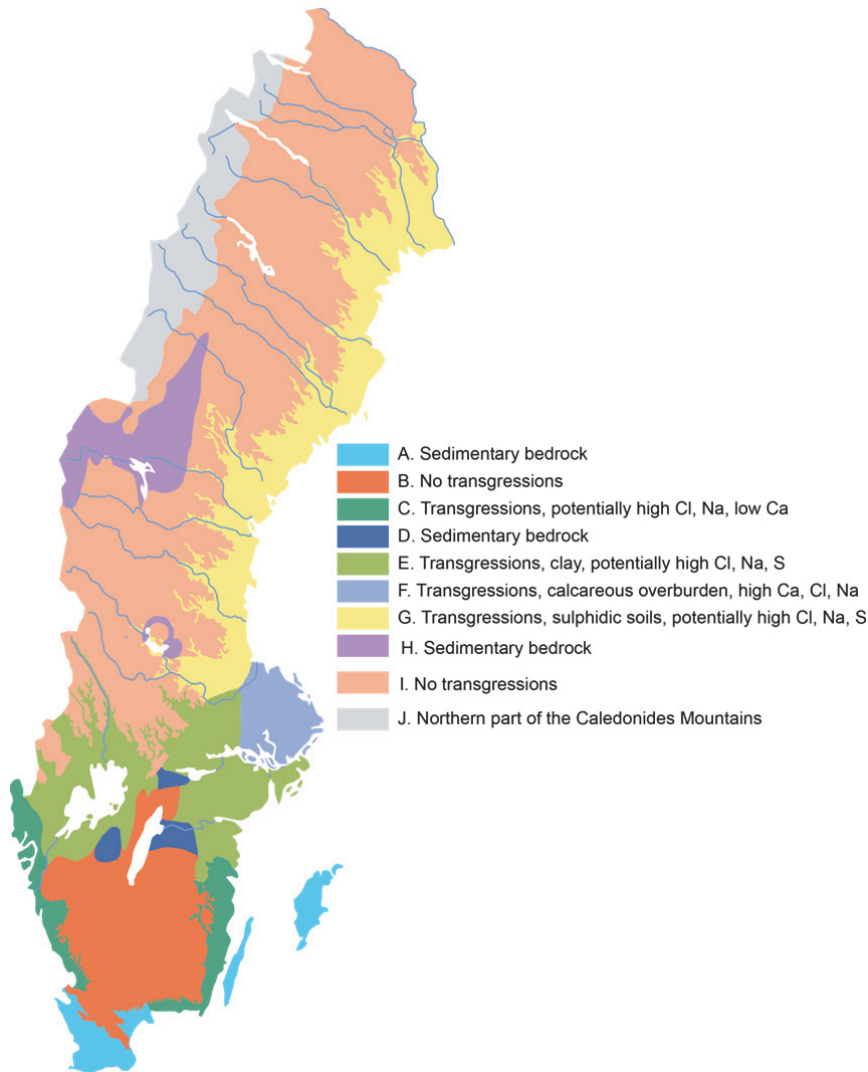


Figure 11.1. Possible hydrochemical situations in each division of the hydrochemical regions in Sweden (based on the Swedish Geological Survey, 2013).

A similar division of groundwater in the bedrock could be made for other areas with similar geological conditions as being covered in this thesis (e.g. parts of Norway and

Finland). However, this has yet to result in divisions similar to the one presented by the Swedish Geological Survey (2013). Such a division could be based on e.g., Karro and Lehermo (1999) or Väisänen (2004) for Finland and Frengstad (2002) for Norway.

Conceptual models were first presented in Mossmark (2010a) and include typical geological settings that have been subjected to recent (Weichselian) glaciations. In the conceptual models, similar to the geographical division of hydrochemical areas produced by the Swedish Geological Survey (2013), transgressions following the most recent glaciations are important factors. In addition to the regional scale included in Figure 11.1, the conceptual models also cover local differences such as recharge and discharge areas for groundwater. The highest shoreline following the Weichselian glaciations is defined by the largest transgression and the subjected areas are defined as C, E, F and G in the Swedish Geological Survey (2013). In this section, a revised version of the conceptual models is presented.

11.1.1 **Groundwater recharge areas in regions B, I**

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, see Figure 11.2. Such areas were represented in the field study by e.g. borehole MK56 on the Hallandsås Ridge, see Paper I.

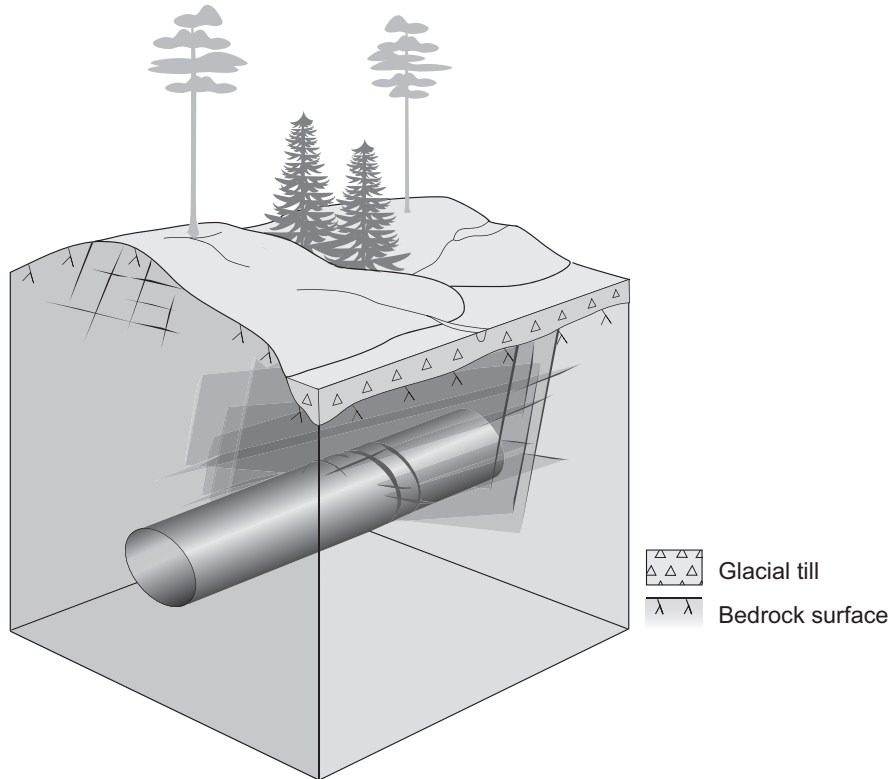


Figure 11.2 Geological model in a groundwater recharge area that has not been subjected to marine transgressions. The bedrock is overlain immediately by glacial till.

The following hydrological and hydrochemical aspects relevant to underground constructions have been identified and verified in the Hallandsås field study. Figure 11.2 shows conditions for groundwater recharge areas at this location:

- There are no shallow S pools available that may be oxidised to and be released together with H^+ .
- Leakage into the tunnel may cause changes in the redox potential and this has been shown to cause the precipitation of Mn and Fe.
- Shorter retention time of the bedrock groundwater – lower degree of silicate weathering etc. may lead to decreased alkalinity and pH and lower concentrations of base cations.

This impact from tunnelling through locations that act as recharge areas for groundwater should not require complementary field investigations unless there is little rock cover or if saline waters or sulphide minerals are present.

11.1.2 Groundwater discharge areas in regions B, I

The results from the field studies identified the groundwater discharge areas with wetlands that have not been subjected to transgressions as being vulnerable to hydrochemical changes caused by underground constructions. Geological conditions with a lack of fine-grained sediments are important. It is common to find organic wetlands (e.g. sphagnum peat) immediately overlaying glacial till and thereby providing direct hydraulic communication with the bedrock groundwater, see Figure 11.3.

According to the Swedish Geological Survey (2013), the Lake Gårdsjön area has been classified as division C (the west and south coast of Sweden). However, the local Quaternary geology resembles that of division B (the highlands of southern Sweden).

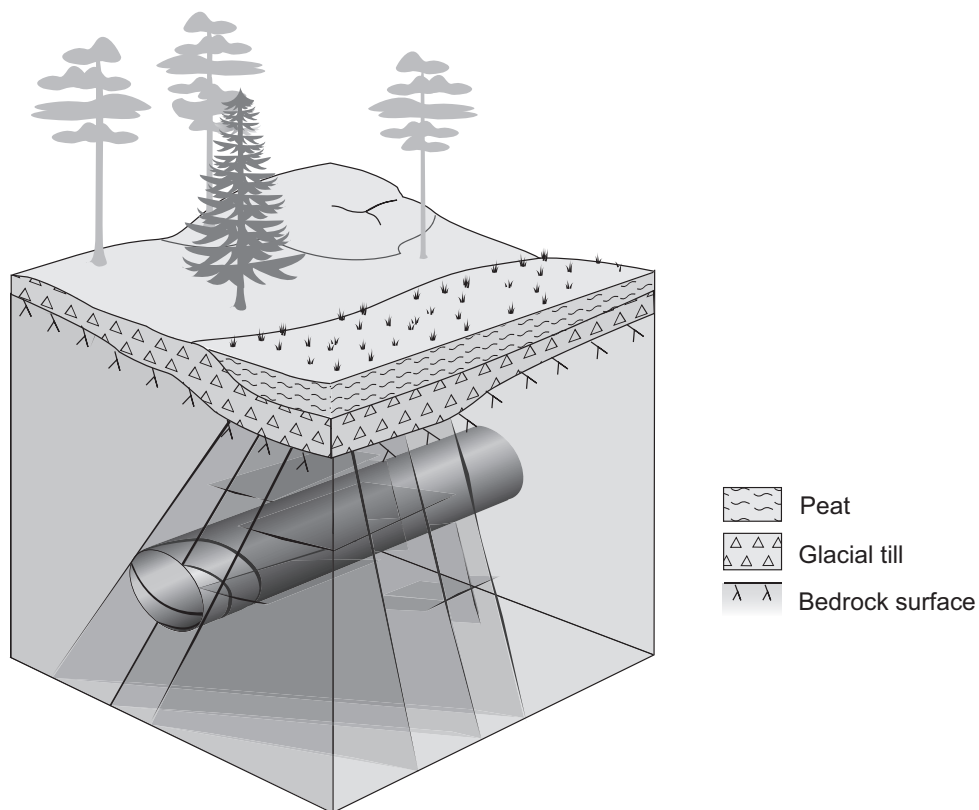


Figure 11.3 A groundwater discharge area that has not been subject to marine transgressions. The glacial till is immediately overlain by peat. In the figure, a fracture zone intersects the tunnel and the wetland (indicated by a dark grey geometrical shape).

The depressions commonly represent weakness zones in the bedrock, such as fracture zones. The fracture zone could (if open) constitute a hydraulic connection and the following changes would be likely:

- Tunnelling may lead to aeration of the wetland (peat) in Figure 11.3, mobilising S and H⁺ and subsequently the release of base cations through cation exchange.
- The hydrochemistry in the vicinity of the tunnel is likely to become affected by the shallow groundwater in the wetland. The magnitude is partly dependent on the depth of the tunnel and the transmissivity of the aquifer.
- The buffer capacity in the bedrock in division B and division I (igneous and metamorphic rock) is often dependent on slow processes of silicate weathering. However, if calcite is present as a fracture mineral, the impact from shallow waters may be counteracted.
- 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 (may lead to precipitation of Fe and Mn), decomposition of the organic matter may counteract this process through the consumption of oxygen as seen at the Äspö Hard Rock Laboratory (Laaksoharju, 2008). However, observations at Hallandsås (Paper I) and at Lake Gårdsjön (Mossmark, 2010a) show gradually more oxidised groundwater during abstraction/seepage into the tunnel.

If underground constructions are being built through groundwater discharge areas in locations that have not been subjected to recent marine transgressions, there is a probable need for a field investigation. The hydrogeological conditions, rock cover and the radius of influence should be used to assess the potential influence from a wetland.

11.1.3 Areas that have been subjected to recent marine transgressions (regions C, E, F, G)

For groundwater discharge areas that have been subject to transgressions, it is common to observe marine/post-glacial clays overlaying the glacial till. In the field studies, such conditions were observed at Kattleberg. However, the conditions on the island of Äspö provided discontinuities in the clay layer. The formation depends on whether the prerequisites for deposition of fine-grained sediments (calm, deep waters) were obtained. As seen in Figure 11.4, peat may also have been formed, overlaying the clay layer. This conceptual model may also represent a groundwater recharge area that has been subject to marine transgressions. During regression, wave-washing may have occurred, causing redeposition of the overburden.

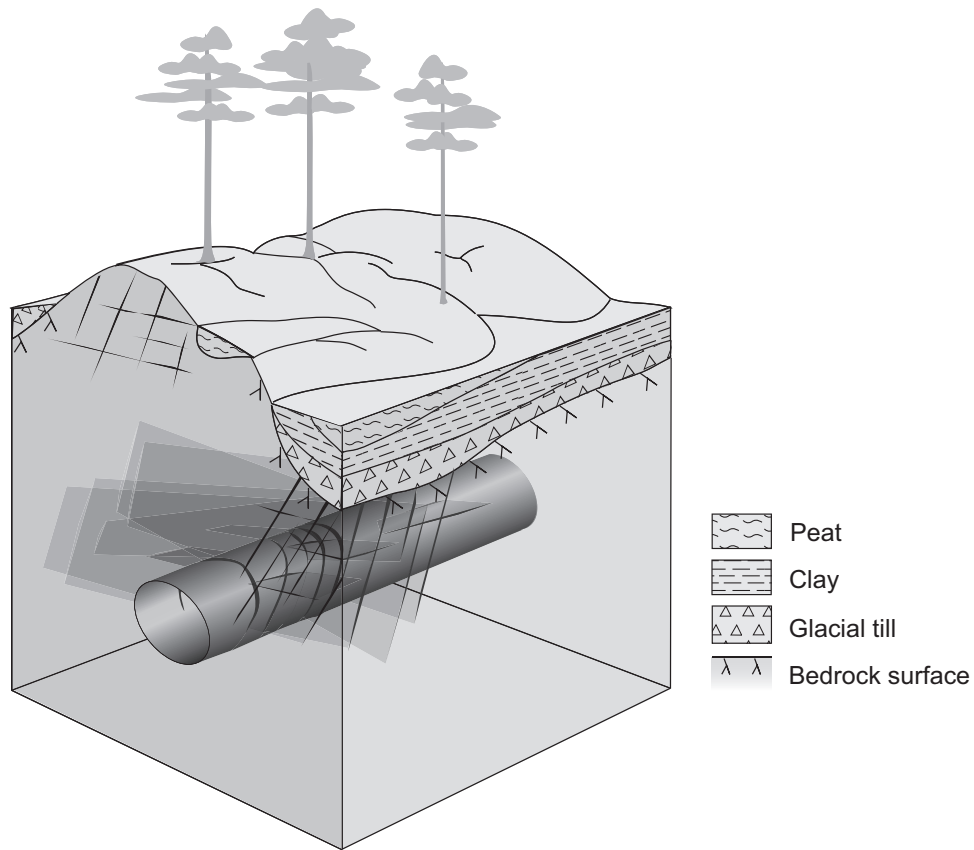


Figure 11.4 Typical geological conditions at an area that has been previously subject to marine transgressions. In the figure, a fracture zone intersects the tunnel and the wetland (indicated by a dark grey geometrical shape).

The following aspects should be considered in addition to the aspects presented in Section 11.1.2:

- A clay layer may limit the hydraulic interaction between the groundwater of the bedrock and the groundwater in discharge areas.
- A clay layer such as this, especially if it is of marine origin, is likely to contain a substantial pool of Cl^- and S in addition to pools in a tentative wetland. The S may be subject to oxidation and the release of SO_4^{2-} and H^+ (leading to acidification). Consequently, alkalinity (if present) may be depleted and the release of base cations (increasing concentrations of Mg^{2+} , Ca^{2+} , K^+) through cation exchange with H^+ may occur.
- Cl^- is likely to be present in the groundwater at higher concentrations compared to the areas that have not been subjected to marine transgressions.
- Flushing of previous saline groundwater may lead to the depletion Ca^{2+} and a high Na^+/Cl^- ratio as seen at e.g. Kattleberg.

From the perspective of underground constructions, the potential hydrochemical changes are more uncertain compared to the other conceptual models. This is primarily because the hydraulic connection between a wetland and the groundwater in the bedrock may differ between sites. At locations where such a hydraulic connection can be established, the hydrochemical changes with high SO_4^{2-} concentrations, low pH and low alkalinity are likely and may be of importance for the selection of materials. If such a connection is assessed to be negligible, the influence of groundwater from a wetland on the bedrock is likely to be irrelevant to construction materials.

The Cl^- and Na^+ are sometimes high in areas that have been subjected to marine transgressions. In locations where the saline waters are being flushed out, cation exchange may cause the concentrations of Na^+ to be high compared to Cl^- and at the same time Ca^{2+} may become depleted.

In the planning of underground constructions in areas that have been subjected to marine transgressions, several hydrochemical considerations are necessary. If wetlands are present, the potential hydrological contact with the bedrock needs to be assessed and, if deemed likely, investigated.

11.1.4 Influence of fracture minerals on hydrochemistry

The presence of fracture minerals has been identified as being an important factor in vulnerability to hydrochemical changes caused by underground constructions. The field study at Hallandsås (see Paper I) exemplifies the importance of sulphide minerals, primarily FeS_2 (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, leading to the release of Fe, S and H^+ with resulting high SO_4^{2-} concentrations, low alkalinity and low pH, contributing to groundwater that is more aggressive towards steel and cementitious materials. Furthermore, the released Fe may immediately precipitate, although if the pH is sufficiently low, Fe may stay dissolved in the groundwater and later precipitate inside the tunnel and thus contribute to clogging of drainage systems. Similar effects are expected in the presence of pyrrhotite (Fe_{1-x}S).

CaCO_3 is one of the most common types of fracture minerals. The solubility of CaCO_3 is highly dependent on $\text{CO}_2(\text{g})$ pressure and the dissolution may also be enhanced by the introduction of more acidic groundwater. Leakage into an underground facility may cause the hydrochemical conditions of the groundwater to change with aerobic decay of organic matter during the production of $\text{CO}_2(\text{g})$, see e.g. Appelo and Postma (2005). This could cause CaCO_3 fracture minerals to become dissolved (Drever, 1988). Dissolved Ca^{2+} ions may later precipitate to once again form CaCO_3 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). Precipitation of CaCO_3 could cause clogging of drainage systems in underground constructions. However, the dissolution of CaCO_3 would contribute to a buffer against acidification (by countering the lowering of the pH), increase alkalinity and Ca^{2+} concentrations and thus make the groundwater less aggressive towards both steel and cementitious materials. (avoiding a low pH).

The observed presence of Fe_2S should be studied further through field investigations. CaCO_3 may have implications due to precipitation inside underground constructions and should be taken into consideration when designing the drainage system.

11.1.5 Conclusions from desk studies

The desk study should identify areas that offer increased potential for hydrochemical changes that are of importance. The following aspects should be considered:

- The existence of groundwater discharge areas with wetlands or clay in the case of a hydrogeological connection between the groundwater in the bedrock and the shallow systems.
- In groundwater recharge areas, if the rock cover is less than 10 m.
- The presence of sulphidic minerals.
- Hydrochemical conditions that indicate the need for complementary protection of steel or cementitious materials according to standards issued by the authorities (e.g. SS-EN 206-1, Swedish Rail Administration (2005)).

If any of these risk factors exist, further evaluations should be carried out. If it is found likely that the hydrochemistry will be assessed as aggressive (according to standards, see Section 8.1) or if substantial problems with Fe precipitation inside underground constructions are likely, a field study should be carried out.

11.2 Field studies

A complementary field study should be carried out in conjunction with other relevant studies for the planning of an underground construction. Such studies need adaption to the local conditions. The field study should focus on locations that have been identified in the desk studies (Section 11.1) to present conditions that are associated with aggressive hydrochemical conditions during the construction or operation phase of underground constructions (based on standards presented in Section 8.1)

Field studies of geochemical, hydrogeological and hydrochemical conditions in locations that act as groundwater recharge areas (divisions B, I, see Figure 11.1) should, in most cases, focus on locations where underground constructions with little rock cover are planned. Hydrogeological conditions should be studied (e.g. through test pumping) to assess the influence of shallow waters. The hydrochemistry of groundwater, both in the bedrock and in shallow systems should be studied.

In the case of groundwater discharge areas in locations that have not been subjected to transgressions (divisions B, I, see Figure 11.1), the hydrochemistry of wetlands and the hydrogeological conditions of the bedrock are often of significant importance. For a wetland, analysis of hydrochemistry and geochemistry, including mineralogy and cation exchange capacity, should be investigated. The hydrogeological conditions should be either investigated through test pumping or assessed based on e.g. mapping of core samples or outcroppings.

In the case of areas that have been subjected to recent transgressions, the hydrochemical conditions may be more complex. If a wetland area is being investigated, it is important to study hydrogeological communication between the wetland and the bedrock groundwater. If such communication is negligible, further studies of the wetland or the hydrogeological conditions may not be necessary. If such communication is observed, similar studies as in divisions B and I above should be conducted. Hydrogeological investigations using field methods such as test pumping from bedrock boreholes to study interference with the wetland may be necessary.

In the case of the presence of sulphidic minerals, mineralogical investigations should be carried out. Rock core samples should be collected and mineralogical mapping should also be performed. Furthermore, mapping of outcroppings and rock core samples (should be collected as a part of the pre-investigation), groundwater sampling of boreholes and, if possible, water supply boreholes, should be carried out. The mineralogical composition of the bedrock should be evaluated from a hydrochemical perspective.

11.2.1 Evaluation of the field studies

The results from the field studies are evaluated to assess the hydrochemical conditions and their potential changes, based on the standards that stipulate the need for complementary protection of steel and cementitious materials, see Section 8.1. The evaluation of the hydrochemical conditions needs to be made by hydrochemistry and hydrogeology experts. The evaluation should result in a recommendation for the selection of construction materials and the design (including the design of the drainage

system). For further assistance in the prediction of hydrochemical conditions, numerical modelling could be used as described in Section 11.3

11.3 Hydrochemical modelling

If deemed necessary, hydrochemical modelling should be carried out. The need for modelling should be assessed based on field studies dealing with the geology, hydrogeology and hydrochemistry that have been carried at the pre-investigation stage, including the recommendations in Section 11.2. The process of establishing a hydrochemical model could require complementary field studies to provide sufficient input data.

There are several numerical modelling computer programs (codes) available that could be useful in predictive modelling. In order to select the optimal computer program with sufficient capabilities, it is important to determine the aims of the modelling. The different features in the computer programs include models that:

1. Are reactive or describe equilibria (e.g. Minteq, see VanBriesen et al., 2010).
2. Mix water of different origins and composition as well as handling mass balance (e.g. M3, see Laaksoharju et al., 1999).
3. Handle several types of chemical reactions, flow and mixing as well as batch reactions. Such models include e.g. PHREEQC (Parkhurst and Appelo, 2013), PHT3D (Prommer et al., 2003).

The code types that handle reactions and equilibria, but exclude flow (1.), could be suitable for the modelling of e.g. hydrochemical reactions in a wetland or the oxidation of pyrite in conjunction with underground constructions. However, it is not suitable for studying a complex system where flow and mixing are also modelled.

The code types that handle mixing and mass balances (2.) could be suitable for the modelling of e.g. saline upconing during tunnelling. However, such a modelling tool would not be suitable for the simulation of e.g. pyrite oxidation.

For the modelling of a complex system with different hydrochemical end-members, groundwater flow and various chemical reactions, modelling tools with sufficient capabilities (3.) would be suitable. It should be noted that such complex models need more data compared to the simpler modelling tool types in order to achieve a robust model.

In Paper VI and in Section 10, hydrochemical modelling in conjunction with tunnelling is presented. In the presented case, detailed hydrochemical field studies of groundwater

abstraction have already been carried out, providing data sets for calibration. However, in most underground construction projects, such data will be unavailable. Instead, predictive modelling should be carried out based on hydrochemical data from unaffected conditions as well as geochemical, hydrological, and hydrogeological data that have been collected in the pre-investigation phase.

The results from the hydrochemical predictive modelling should provide scenarios. These will be assessed by hydrochemistry experts according to their probability. The results should be used to provide a recommendation for the selection of construction materials and the design of an underground construction, including its drainage system.

11.3.1 **Conclusions from hydrochemical modelling**

The modelling tool (computer program) should be selected carefully to provide sufficient capabilities to meet the requirements of the hydrochemical modelling. Sufficient input data from field investigations must be provided. The results from the hydrochemical modelling will provide different scenarios. Recommendations for material selection should be based on results that are deemed probable by hydrochemistry experts.

12 CONCLUSIONS AND RECOMMENDATIONS

The literature review showed that only a few systematic studies of hydrochemical conditions in relation to underground constructions had been carried out. In the previous tunnelling studies and from an international perspective, general methods for the prediction of hydrochemistry were absent (Mossmark, 2010a).

The four field studies (Papers I-V) revealed hydrochemical aspects of importance to underground constructions in different geological environments. The main conclusions from the field studies are:

- Importance of hydrogeological properties of the bedrock.
 - Increased S was observed in overlying wetlands and was reflected in the bedrock groundwater. The magnitude of S increase in the bedrock groundwater is affected by the advective flow capacity (mainly fracture transmissivities) in the bedrock aquifer. A lower magnitude of SO_4^{2-} is therefore found if the conditions provide for a higher degree of dilution with bedrock groundwater.
 - The interaction between the hydrochemistry and the tunnel environment may vary depending on the geological conditions and the relative sealing effects from e.g. cement grouting. In a fracture zone, the groundwater hydrochemistry may resemble that of the surrounding bedrock. Meanwhile, in more homogeneous and less fractured rock, the groundwater hydrochemistry may be more affected by sealing grout.
 - As regards the influence from fracture minerals, the presence of pyrite (FeS_2) may cause significant changes to the major ions and pH due to oxidation of the bedrock groundwater. If calcite (CaCO_3) is present as a fracture mineral in the bedrock, dissolution (and contribution to alkalinity and dissolved Ca^{2+}) is probable due to the influx of shallow waters (with a low pH). Hematite (Fe_2O_3) and iron hydroxides ($\text{Fe}(\text{OH})_2/\text{Fe}(\text{OH})_3$) in fractures may be dissolved if exposed to water with decreasing pH.
 - A shorter retention time of bedrock groundwater results in less influence from silicate weathering compared to undisturbed recharge conditions. This contributes in turn to decreased alkalinity and pH and lower concentrations of base cations.
- Influence of Quaternary geology. The likely existence of a clay layer underlying wetlands in areas with previous transgressions may prevent a hydrological interaction between a wetland and the bedrock groundwater. Furthermore, it may also prevent induced aeration and chemical oxidation of the wetland.

- In three of the field studies (Lake Gårdsjön, the island of Äspö and Hallandsås), the hydrochemical conditions in the bedrock changed sufficiently during abstraction/tunnelling to be assessed as aggressive towards steel or cement according to regulatory documents.
- Results from two of the field studies indicate a period of more than five years before hydrological and hydrochemical recovery is achieved if groundwater abstraction is terminated/sealing is successful. However, the assessment according to regulatory documents of bedrock groundwater being aggressive towards cement or steel returned to non-aggressive within six months.

Generic and schematic conceptual models were established based on the results from the literature review and the field studies. The generic conceptual models present likely hydrochemical conditions based on geological and hydrological conditions. For evaluations in Sweden, these should be used in combination with an established (Figure 11.1) hydrochemical regional map.

Hydrochemical (numerical) modelling successfully replicated measured field data, thus exemplifying the impact from tunnelling:

- The calibrated models revealed a distribution between the elements of released cations and total cation exchange capacity that coincided with expectations based on previous field studies.
- The magnitude of the release of cations was related to the release of H^+ in conjunction with the oxidation of S in a wetland.
- The groundwater in the soil layers beneath the wetland and in the bedrock was modelled using mixing models. This model was based on the results of previous hydrogeological studies of the area. The calibrated model was consistent with the findings in the field studies.
- The modelling results showed that the groundwater in the bedrock could become aggressive towards steel-based materials and was prone to precipitation of Fe and Mn. Measured data was thereby replicated.

The modelling presented in the thesis suggests that non-coupled hydrochemical predictions can be made based on mineralogy, hydrology, geochemistry and additional robust hydrogeological field studies. The results from the field studies, the conceptual models and the hydrochemical numerical modelling created a foundation for the recommendation of a methodology to predict hydrochemistry. The methodology can be stipulated in three steps as listed below:

1. Desk studies, including the use of generic conceptual models. The conclusions from a desk study in the planning process for tunnelling may either reveal the need for further studies or indicate a non-aggressive hydrochemical environment.

2. Further studies may include field investigations. These should be planned and carried out based on the results from the desk study. The conclusions from such studies should comprise recommendations for design and material selection or stipulate the need for hydrochemical predictive modelling.
3. Hydrochemical modelling. Selection of modelling tools to achieve the objectives set for the modelling at a specific location. The modelling outcome should, together with assessments in steps 1 and 2, result in recommendations for the selection of construction materials.

Many of the recent and future underground constructions, primarily for transportation, are located in urban areas. The presented methodology highlights important urban related factors for the prediction of hydrochemistry. However, it does not focus on the complex hydrological, hydrogeological and hydrochemical conditions of such environments. Further research on hydrochemistry related to tunnelling in urban areas is therefore recommended.

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