CHALMERS

Grundvattenkemisk interaktion med undermarksanläggningar

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Avd. Geologi och geoteknik

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CHALMERS TEKNISKA HÖGSKOLA
Göteborg, 2013
Rapport

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Chalmers reproservice
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SAMMANFATTNING

Grundvattenkemisk påverkan har observerats vid ett ganska stort antal tunnelprojekt. I förekommande fall har dessa förändringar inneburit att vattnet fått nya kemiska egenskaper som har större potential att bryta ner stål- och cementbaserade konstruktionsmaterial.

De grundvattenkemiska förändringarna drivs av att det sker inläckage i undermarksanläggningar. Dessa läckage innebär ökad grundvattenströmning, något som bl.a. orsakar att vatten med nya egenskaper strömmar mot platsen för anläggningen. Som regel innebär detta också att grundvattenbildningen ökar på bekostnad av vatten som finns tillgängligt för ytavrinning och för vegetationen. Dessa ändrade hydrogeologiska förhållanden möjliggör också för att vattenkemiska processer sker på ett annat sätt än tidigare.

I föreliggande rapport presenteras en sammanfattning av två fältstudier som genomförts vid järnvägstunnlar under genomförandeskede. Studierna har gjorts i syfte att förbättra förståelsen för påverkan från undermarksanläggningar på hydrologi, hydrogeologi och vattenkemi. Målet är att skapa ett underlag för att förutse vilka förändringar som kan förväntas vid ett undermarksprojekt och kvantifiera dessa.

Resultaten från de två studierna, vid Kattleberg och Hallandsås, bekräftar att de geologiska förhållandena är avgörande för vilka förändringar som sker. De två studieobjekten har sina markytor belägna över (Hallandsås) respektive under (Kattleberg) högsta kustlinjen efter senaste istiden. Denna skillnad har medfört att de jordartsgeologiska förhållandena skiljer sig åt. Vid Kattleberg begränsade ett (i havsvatten avsatt) lerlager den hydrauliska kontakten mellan en våtmark och berggrundvatten/tunnel. Detta begränsade också den vattenkemiska påverkan. Däremot konstaterades att heterogeniteten i berggrunden skapar olika vattenkemiska förhållanden i tunnelns närhet. I ett av borrhålen som gjorts från tunnelvägg hade vattnet stark påverkan från injekteringsmedel, medan ett annat borrhål från tunnelvägg uppvisade ursprunglig berggrundvattenkaraktär.

På Hallandsås observerades stora rumsliga skillnader i berggrundvattnet. I ett av bergborrhålen skedde enbart mindre förändringar, medan två andra borrhål fick en miljö som var tydligt mer aggressiv mot cement- och stålbaserade material. Oxidation av pyrit, både som sprickmineral och förekommande i våtmarker (direktkontakt spricksystem-våtmark då detta område inte legat under havsytan efter sista istiden och därigenom inga finsediment avsatts) bedöms vara en viktig orsak till höga sulfatkoncentrationer, pH-sänkning och minskad alkalinitet.

De redoxkänsliga parametrarna järn och mangan återhämtade sig snabbt i samband med att grundvattennivåerna steg efter påverkan från tunneldrivningen vid Hallandsås. De vattenkemiska förändringarna med sulfatpulser och pH-sänkning

återhämtade sig däremot långsammare. Vid ett återställande av grundvattennivåer bedöms denna process ske under några år.

Projektet har givit värdefulla insikter om processförståelse som i sin tur ger underlag till konceptuella utångspunkter för modellering. Avsikten är nu att genomföra kopplad hydrokemisk numerisk modellering i prediktivt syfte för att bättre förutse eventuella nedbrytningsmekanismer på förstärkningsmaterial och installationer i tunnlar.

Förord

Rapporten presenterar en sammanfattning av två fältstudier som bedrivits inom projektet ”Vattenkemins påverkan på undermarksanläggningar” (12373) med finansiering av Svenska Byggbranschens Utvecklingsfond (SBUF). Medverkande i projektet har varit Fredrik Mossmark (doktorand vid Chalmers/Vectura), Lars-Olof Dahlström (NCC), Lars O. Ericsson (Chalmers), Malin Norin (NCC) och Katinka Klingberg Annertz (Trafikverket). Genomförandet har skett med överinseende av en referensgrupp bestående av Ann Emmelin (Golder/SKB), Ola Landin (Trafikverket), Per Tengborg/Mikael Hellsten (BeFo), Bror Sederholm (Swerea KIMAB), Marcus Laaksoharju (SKB) och Ulf Håkansson (Skanska). Föreliggande projekt har under genomförandet samordnats med ett annat forskningsprojekt finansierat av BeFo (Stiftelsen Svensk Bergteknisk Forskning), vars syfte är att ta fram prognosmodeller för vattenkemiska förändringar vid undermarksbyggande.

INNEHÅLLSFÖRTECKNING

Bilaga 1	–Publikationslista.
Bilaga 2	–Mossmark, F, Ericsson, L O, Norin, M, Dahlström, L-O., to be submitted. Hydrochemical Changes Caused by Underground Constructions –a Case Study of the Kattleberg Rail Road Tunnel.
Bilaga 3	-Mossmark, F, Annertz, K K, to be submitted. Impact to Hydrochemistry from the Construction of the Western Tube of the Hallandsås Railroad Tunnel, Sweden.

1 INLEDNING

Det ändrade grundvattenflödet som orsakas av läckage i tunnlar och berganläggningar skapar förändringar av grundvattnets kemiska sammansättning. Dessa förändringar kan innebära att vattnet blir mer aggressivt mot stål- och cementbaserade material. På sikt kan detta medföra beständighetsproblem för bergförstärkning, tätande injektering och installationer. Vattenkemiska förändringar till följd av undermarksbyggande har observerats i ett ganska stort antal projekt. Däremot finns bara ett fåtal studier med högupplösta tidsserier.

1.1 MÅLSÄTTNING

Föreliggande rapport sammanfattar två genomförda fältstudier av järnvägstunnlar i Sverige; Hallandsås och Kattleberg. Syftet med studierna är att skapa ett underlag för att kunna förutse vattenkemiska förändringar vid tunnlars genomförande- och driftskeden baserat på information som insamlats under planeringsskedet. Dataserierna avses utgöra grund för att skapa konceptuella modeller likväl som indata till datorbaserade numeriska modelleringar. Projektet syftar till att skapa förutsättningar för att göra kostnadseffektivare materialval i undermarksanläggningar.

2 Bakgrund

Inom projektgruppen har ett flertal studier med syfte att förbättra förståelsen av vattenkemiska förändringar vid hydrogeologiska störningar genomförts. Nedan listas några av de studier som bedrivits:

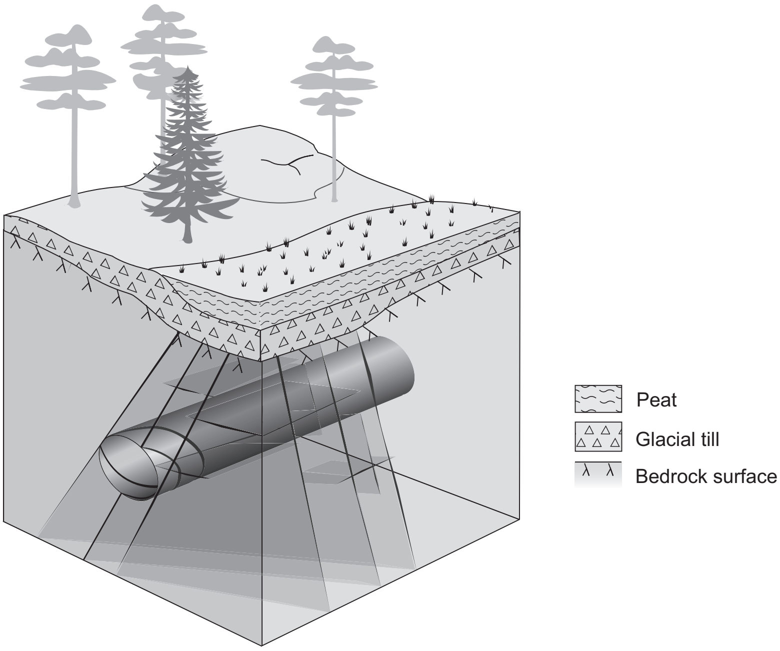
- En omfattande datasammanställning (Olofsson och Ericsson, 1985) av vattenkemiska förändringar vid grundvattenuttag.
- Två fleråriga försök med grundvattenuttag (bl.a. Mossmark m.fl., 2008b; Mossmark, 2010).
- En utvärdering av vattenkemiska förändringar vid genomförandet av det östra tunnelröret Hallandsås (Mossmark, 2010; Mossmark m.fl., 2010).
- En litteraturstudie av erfarenheter från vattenkemiska och hydrologiska förändringar vid tunnelbyggande (Mossmark m.fl., 2008a).
- En licentiatuppsats (Mossmark, 2010).

Ytterligare publiceringar finns i form av ett stort antal rapporter, konferensbidrag samt vetenskapliga artiklar (se bilagor).

2.1 Konceptuella modeller

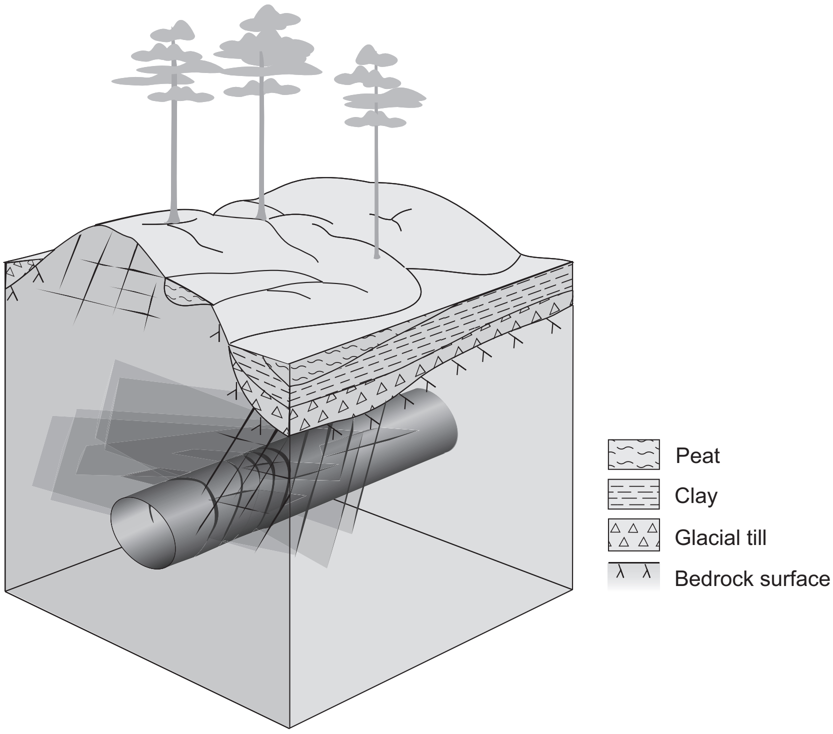
Eftersom projektgruppen genomfört studier under varierande geologiska förhållanden har resultaten från dessa kunnat användas för att utvärdera samband mellan geologi och vattenkemi. Erfarenheter från de tidigare forskningsprojekten sammanfattades därför i konceptuella modeller (Mossmark, 2010). Dessa modeller schematiserade vilka vattenkemiska processer som kan förväntas vara viktiga vid grundvattenpåverkan från undermarksbyggande beroende på geologiska förhållanden. Modellerna utgår bl.a. ifrån kvartärgeologiska förhållanden som uppstått under och efter den senaste istiden samt skillnader mellan ut- och inströmningsområden för grundvatten.

Förhållanden som vanligtvis råder i utströmningsområden för grundvatten över högsta kustlinjen presenteras i Figur 1. Vanligt förekommande är våtmarksområden med vitmossetorv som kan stå i god hydraulisk förbindelse med en underliggande svaghetszon i berggrunden. När en undermarksanläggning byggs i närheten kan vatten flöda från våtmarken och koncentrationen av organiskt material öka, redoxförändringar i både berg och jord kan ske. I våtmarken kan detta påverka svaveldynamik och kvävesystem. I observerade fall har sulfidmineral oxiderats och sulfatkoncentrationerna i yt- och grundvatten ökat med minskad alkalinitet och pH som följd. Detta är en typmiljö som bl.a. studerats under fältförsök vid Gårdsjön (Mossmark, 2008) och i föreliggande studie representeras av de hydrogeologiska förhållandena vid Hallandsås.



Figur 1. Vanliga geologiska förhållanden vid ett utströmningsområde för grundvatten beläget över högsta kustlinjen sedan den senaste glaciationen.

Vid förhållanden som vanligtvis råder i utströmningsområden under högsta kustlinjen förekommer sediment av finmaterial som silt och lera. Dessa kan fungera som en barriär mellan t.ex. en våtmark och spricksystem i berggrunden. Marint avsatta leror har normalt höga klorid- och svavelkoncentrationer. I tillägg har marint vatten genom sin högre densitet än sött grundvatten kunnat påverka berggrundvattnet. I tidigare studier inom projektgruppen har försök med grundvattenuttag i ett område som har förhållanden som liknar dessa genomförts på norra delen av Äspö (Knape, 2002; Mossmark, 2010). Inom förliggande projekt representerar Kattleberg nämnda geologiska förhållanden.



Figur 2. Vanligt förekommande geologiska förhållanden vid ett utströmningsområde för grundvatten under högsta kustlinjen.

2.2 Bedömning av vattenkemisk aggressivitet

Trafikverket och dess föregångare (Banverket/Vägverket) har beslutat om föreskrifter som bestämmer hur grundvattnets kemiska egenskaper ska bedömas för att göra materialval i tunnlar. Före år 2012 fanns vattenkemiska kriterier med haltangivelser för när kompletterande skydd av stålmaterial skulle vara obligatoriskt i Trafikverkets tunnlar. Dessa kriterier har dock avlägsnats i de nu gällande föreskrifterna Trafikverkets tekniska krav/råd Tunnel (TrVK/TrVR). Emellertid fanns vattenkemiska kriterier i de tidigare föreskrifterna BV Tunnel (ursprungligen utgiven av Banverket) och ATB Tunnel (Vägverket). De tidigare kriterierna bedömde vattnet som aggressivt om:

− *pH < 6,5.*

− *Totalhårdhet < 20 mg/L* (Ca^{2+}+Mg^{2+}).

− *Alkalinitet < 1 mEq/l (motsvarande 61 mg/l* $HC0_3^-$).

− *Elektrisk konduktivitet > 100 mS/m.*

I de nu gällande föreskrifterna från Trafikverket saknas kriterier med haltangivelser för att bedöma aggressivitet mot stålmaterial. Materialval efter korrosionsklass görs istället efter kvalitativa bedömningar om vattnet är aggressivt, utifrån bergkvalitet, genomförd förinjektering och om det är sött, salt eller bräckt vatten.

För att anpassa sammansättning på cementbaserade material hänvisar TrVK till standarden SS-EN 206-1. De delar av standarden som berör vattenkemiska förhållanden anger tre nivåer på förhöjd exponering, XA1-XA3, se tabell 1.

Tabell 1. Exponeringsklasser för cementbaserade material enligt SS EN 206-1

Parameter	**Ej förhöjd**	**XA1**	**XA2**	**XA3**
SO_4^{2-} mg/l	<200	200-600	600-3000	3000-6000
pH	>6.5	6.5-5.5	5.5-4.5	4.5-4.0
CO_2 mg/l aggressive	<15	15-40	40-100	> 100
NH_4^+ mg/l	<15	15-30	30-60	60-100
Mg^{2+} mg/l	<300	300-1000	1000-3000	> 3000

3 Avgränsingar

De två fältstudierna har genomförts i tydligt avgränsade delområden av de två undermarksanläggningarna. I Hallandsås har det ej funnits möjlighet att övervaka grundvattenkemi i tunnelvägg. Enbart begränsade okulära mätningar av avrinningsflöden från de två objekten har genomförts.

4 GENOMFÖRANDE

Fältstudierna har gjorts under genomförandefas av två järnvägstunnlar, Hallandsås och Kattleberg (Banaväg i Väst), studierna pågick mellan år 2010 och 2012. Inom ramen för fältstudierna övervakades yt- och grundvattenkemiska förhållanden samt grundvattennivåer. Hydrologiska och meteorologiska data inhämtades. Vid båda objekten fördes en nära dialog med Trafikverket. Vid Hallandsås genomfördes även undersökningar och utvärdering i aktivt samarbete med Trafikverket. I Kattleberg bedrevs undersökningarna även genom nära dialog med entreprenören Veidekke entreprenad.

4.1 FÄLTSTUDIER

4.1.1 Kattleberg

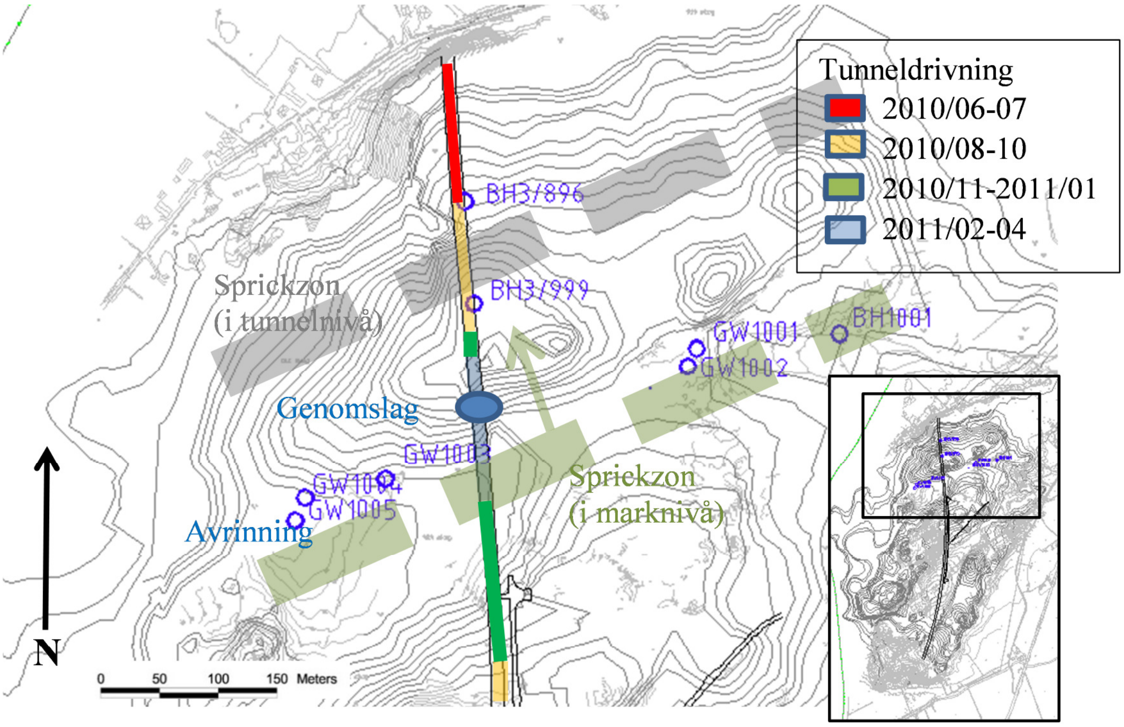
Den studerade järnvägstunneln i Kattleberg utgör en del av BanaVäg i Väst, ett kombinerat projekt för att bygga 75 km fyrfältsväg och dubbelspårig järnväg mellan Göteborg och Trollhättan. Tunneln, som är belägen mellan Älvängen och Alvhem i Ale kommun, är 1.8 km lång och är byggd för dubbelspårig trafik med en parallell servicetunnel längs en delsträcka. Inom föreliggande projekt har ett delområde på norra delen av Kattleberg studerats. Sprängningsarbeten påbörjades sommaren 2010 och avslutades under våren 2011.

Kattleberg är beläget någon kilometer öster om Göta Älv-zonen. Berggrunden i Kattleberg består i huvudsak av granodiorit som utsatts för varierande grad av metamorfos. Intrusioner av metabasit förekommer och representeras av gångar i granodioriten. Inom studieområdet dominerar gnejs av granistisk eller granodioritiskt ursprung, vid borrhålskartering har kalcit, klorit och järnhydroxid identifierats i spricksystem.

Området är beläget under högsta kustlinjen efter den senaste istiden med marina transgressioner som påverkat jordlagerföljd och grundvattenkemi. Glaciären avsatte morän i tunna lager direkt överlagrande berggrunden. Under påföljande marina transgressioner avsattes leror, både som glaciala och post-glaciala leror. I utströmningsområden förekommer våtmarker med vitmossetorv.

I studieområdet finns en svaghetszon i berggrunden som topografiskt representeras av ett låglänt långsträkt område. Detta delområde fungerar hydrogeologiskt som ett utströmningsområde, här förekommer marint avsatta leror som överlagras av vitmossetorv. Svaghetszonen stupar med en svag lutning och en nordlig strykning. Därigenom korsar den tunneln norr om våtmarksområdet, se Figur 3.

I Kattleberg installerade projektet fem filterbrunnar för att övervaka nivåförändringar och för att provta grundvatten för kemisk analys, se Figur 3. Filterbrunnarna förlades i anslutning till ett topografiskt lågt beläget våtmarksområde, men vatten i olika jordarter och inströmningsområde för grundvatten övervakades. Två bergborrhål installerades i tunnelväggen, varav det ena installerades norr om svaghetszonen medan det andra installerades i svaghetszonen, se Figur 3. Ett bergborrhål borrat från marknivå fanns sedan tidigare i området för Trafikverkets övervakning av berggrundvatten (BH1001).



Figur 3. Studieområdet på norra delen av Kattleberg, fem filterbrunnar installerades i anslutning till ett våtmarksområde, två borrhål installerades i tunneln, ett borrhål för övervakning av berggrundvatten fanns sedan tidigare (BH1001).

Under perioden oktober 2010 till december 2011 genomfördes provtagning och mätning av grundvattennivåer varannan vecka. I flera av punkterna har provtagning skett glesare till följd av tekniska svårigheter i fält.

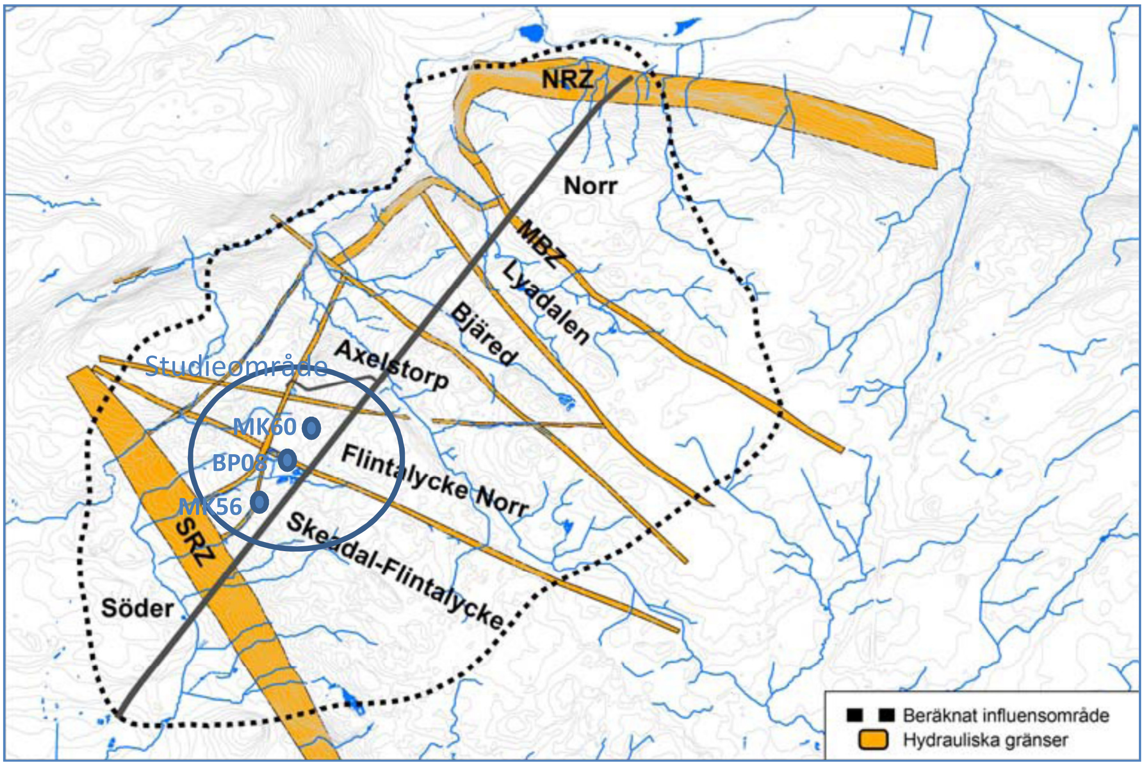
4.1.2 Hallandsås järnvägstunnel

Tunnlarna genom Hallandsås utgör en del av Västkustbanan som är en järnvägsförbindelse mellan Göteborg och Lund. Tunnlarna är 8.6 km långa och består av två parallella huvudtunnlar där varje tunnel är avsedd för enkelspårig järnväg. Byggskedet inleddes 1992 och har sedan dess avbrutits vid två tillfällen. Tunneldrivning inom ramen för den sista entreprenaden inleddes 2005 och bedrivs med tunnelborrmaskin. Tidigare entreprenader har i huvudsak använt konventionell borra-sprängteknik. Genomslag på den östra huvudtunneln erhölls 2010, medan genomslag på den västra huvudtunneln planeras att ske under 2013.

Hallandsås är en urbergshorst belägen i norra Skåne, c:a 80 km lång och 5-10 km bred och har en nordvästlig-sydostlig utbredning. Högsta punkten är belägen 226 m.ö.h.. Hallandsås avgränsas i nord respektive syd av sluttningar som utgörs av förkastningslinjer i vilka horsten förskjutits till att ligga topografiskt högre än omgivningen. I de låglandsområden som omger horsten i norr respektive söder överlagras urberget av sedimentära bergarter. Den dominerande bergarten i horsten är gnejs, men diabasgångar som intruderat har en viktig hydrogeologisk betydelse. Gångarna är i huvudsak orienterade längs horstens utbredningsriktning i en sydostlig-nordvästlig riktning. Gångarna har en nästan vertikal stupning och är mellan någon decimeter till några tiotals meter breda. Den bergmassa som omger gångarna, bestående av gnejs, är ofta ganska uppsprucken i närheten av bergartsövergången. Detta innebär att det ofta finns vattenförande vertikala zoner på var sin sida om en diabasgång. Diabasgångarna har, förutom ytnära, ganska få vattenförande sprickor och är därmed ganska vattentäta och fungerar genom sin vertikala utbredning som negativa hydrauliska gränser. Ytligt är berggrunden ganska uppsprucken med vattenförande sprickor (Annertz, 2010).

Morän finns avlagrat direkt ovanpå berggrunden över större delen av Hallandsåsen. Under isavsmältning har glacifluviala sediment sedimenterat i framförallt Sinarpsdalen, men även i Axeltorpsbäckens dalgång. Den högsta kustlinjen efter senaste istiden är i området c:a 60 m.ö.h.. Både norra och södra randzonerna (sluttningarna) har utsatts för svallningsprocesser under den gradvisa landhöjningen. Svämsediment finns i Vadebäckens, Axeltorpsbäckens och Lyabäckens dalgångar. Våtmarker är relativt vanligt förekommande på Hallandsås (Ringberg, 2000).

Studieområdet ligger i södra delen av Hallandsås och avvattnas av vattendraget Vadebäcken med biflöden som rinner från Hallandsåsens södra delar, nerför södra randzonen (åsens södra sluttning) och sedan genom tätorten Förslöv. Områdets utbredning och belägenhet visas i Figur 4. De västliga delarna av avrinningsområdet domineras av åkermark, medan barrskog och våtmarker dominerar i de östliga topografiskt högre belägna delarna vilka ingår i studieområdet. Ur ett grundvattenperspektiv utgör generellt våtmarkerna lokala utströmningsområden medan barrskogen utgör inströmningsområden. Dessa system med inströmnings- och utströmningsområden är känsliga för yttre påverkan, som exempelvis när hydrologiska förhållanden förändras genom att ett flöde skapas mot en uttagsbrunn för grundvatten eller, som i detta fall, mot en läckande tunnel.



Figur 4. Försöksområdets belägenhet, hydrauliska gränser och placering av undersökta bergborrhål på Hallandsås (Björkman, 2010).

Enligt Björkman (2010) är den svaghetszon som utgör Hallandsåsens södra slänter in-situvittrad och genom leromvandling hydrauliskt relativt tät. Studieområdet genomkorsas vid Flintalycke av en diabasgång som sträcker sig i Hallandsåsens längdriktning och är nästan vertikal. Gången, som på tunnelnivå är nästan tät, omges av vittrad gnejs som är relativt vattenförande (Gynnemo, personlig kommunikation). Från södra randzonen till våtmarkerna vid i studieområdet följer Vadebäcken en tektonisk zon. Denna zon har genom leromvandling av berg blivit relativt tät. Ytterligare en tektonisk zon finns mellan Vadebäcken och tunnelsträckningen. Berget överlagras i nästan hela studieområdet enbart av morän, men våtmarker förekommer i lågområden.

Dataövervakningen i studieområdet genomfördes som komplettering till Trafikverkets kontrollprogram. I kontrollprogrammet ingår främst övervakning av grundvattennivåer och provtagning av ytvatten. I tillägg till detta provtogs tre bergborrhål i samarbete med Trafikverket varannan vecka från april till december 2011 och därefter en gång per månad till juni 2012. Projektet genomförde också upprepade vattenkemiska borrhålsloggningar.

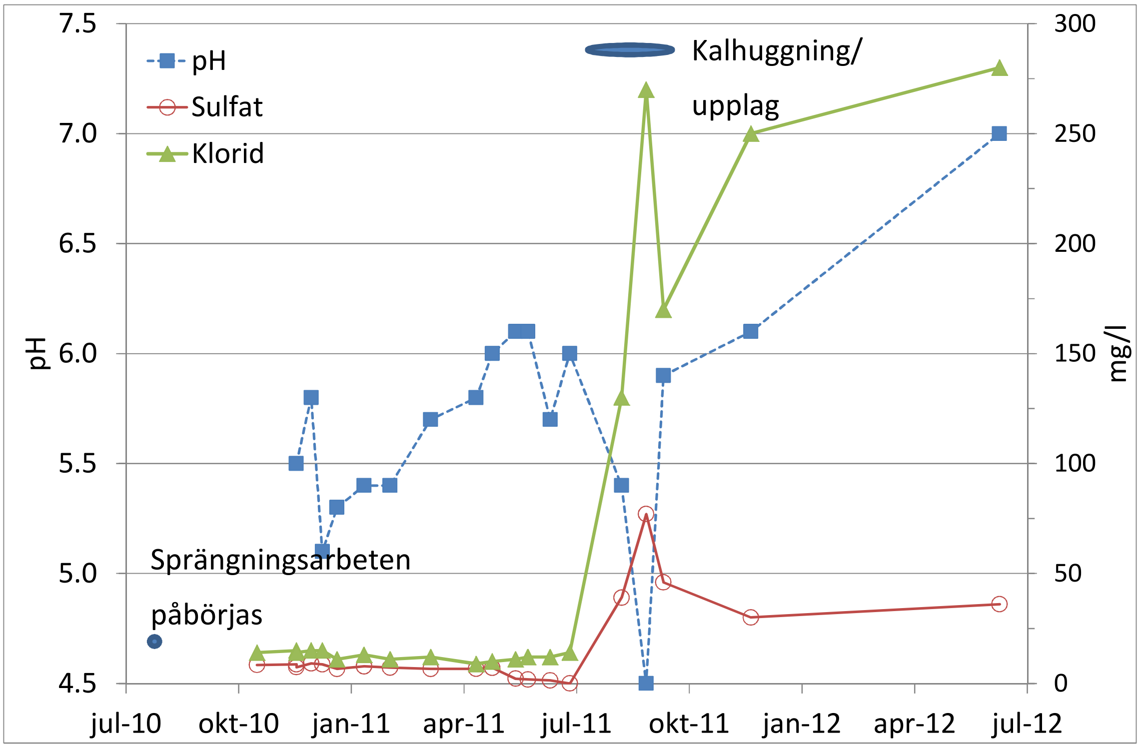
5 DISKUSSIONER OCH RESULTAT

Ett urval av observerade vattenkemiska förändringar vid de två studieobjekten presenteras i detta kapitel. För en mer utförlig beskrivning hänvisas till de två bifogade artikelmanuskripten (se bilagor 2 och 3).

5.1 Kattleberg

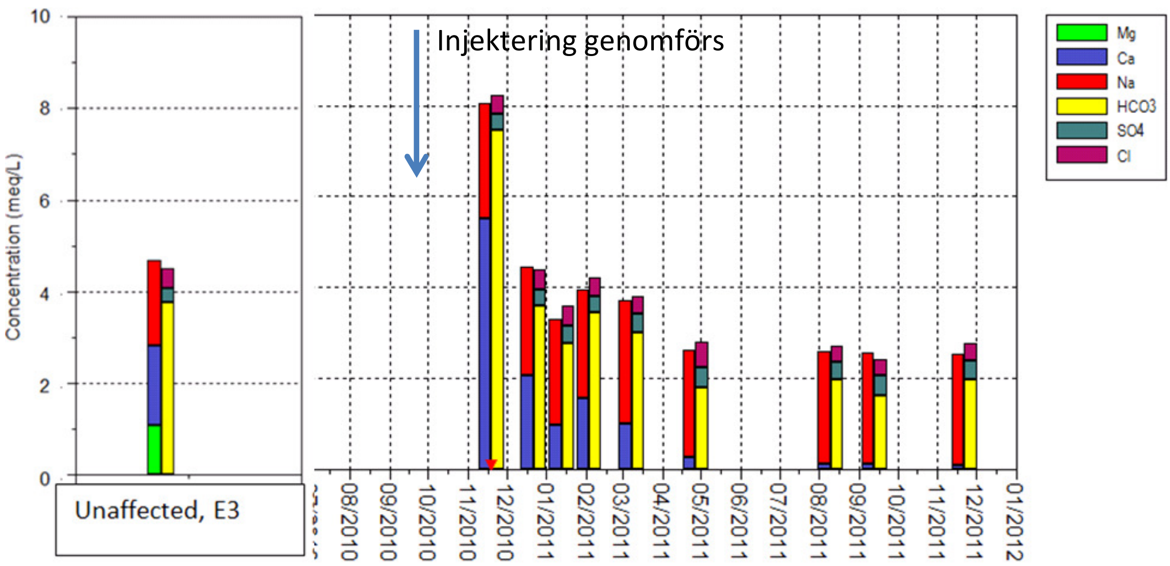
De vattenkemiska förhållandena vid Kattleberg påverkades under genomförandeskedet av järnvägstunneln. De viktigaste observationerna som var direkt kopplade till tunneldrivningen gjordes i tunnelns närhet, medan mätningar i ytliga system främst påverkades av entreprenadarbeten som utfördes i markytan.

Figur 5 visar alkalinitet, pH och sulfatkoncentrationer i avrinningsvatten från våtmarken. Den tydligaste påverkan skedde i samband med kalhuggning och fyllning av sprängmassor inom studieområdet under sommaren 2011. Förändringarna i ytliga system med en tillfällig pH-sänkning och en 10-faldig höjning av kloridkoncentrationer belyser dels omgivningspåverkan från skogsbruk, men dessa förändringar kan också användas för att bedöma hydraulisk kontakt mellan ytliga system och berggrundvatten.



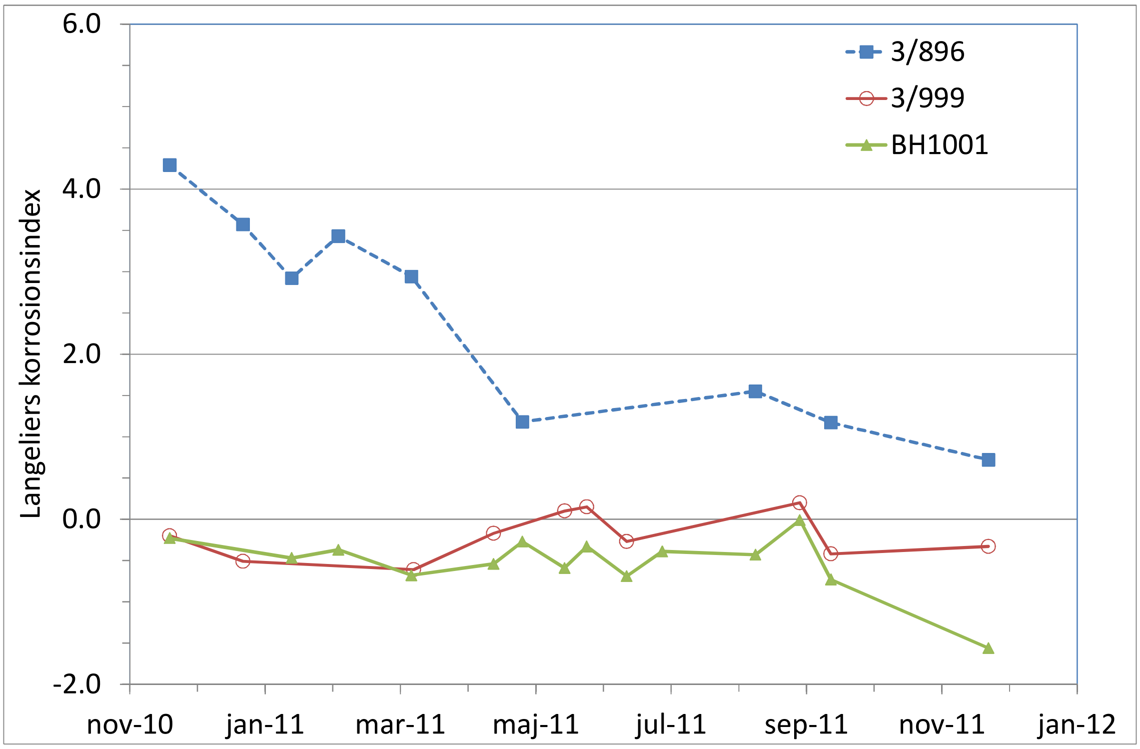
Figur 5. Alkalinitet, pH och sulfatkoncentrationer i Avrinningsvatten från våtmarken i studieområdet Kattleberg.

I Figur 6 visas jonbalans för bergborrhålet 3/896 vars vattenkemiska sammansättning bedöms som tydligt påverkad av hydratationsprocesser i vattentätande injektering. Enligt Dellming (personlig kommunikation) frigjordes kalcium under den initiella hydratationen. Senare under processen kom kalcium, kalium och magnesium att förbrukas. Under mätningsperioden sjönk pH från c:a 11.5 till 10.0, medan natriumkoncentrationerna var stabilt höga i förhållande till klorid. En studie av förhållanden i närheten av genomförd injekteringsskärm som presenterades av Soler m.fl. (2011) visar hur natrium frigörs och kalcium binds under hydratationsprocessen samtidigt som pH gradvis sjunker. I Kattleberg råder lokalt höga halter natrium i förhållande till klorid. Detta kan vara orsakat till följd av att grundvatten av marint ursprung ersätts med grundvatten av meteoriskt ursprung.



Figur 6. Jonbalans för grundvatten i borrhål 3/896. Initiellt höga i kalciumkoncentrationer som sedan minskar påtagligt, men med en relativt hög alkalinitet är beroende av hydratationsprocesser i injekteringsbruket.

Figur 7 visar beräknat korrosionsindex för berggrundvatten. Två av provpunkterna är borrade från tunnelväggen och ett är borrat från markytan (BH1001). Resultaten visar på hur geologisk heterogenitet skapar platsberoende viktiga skillnader. De två provpunkten 3/896 och 3/999, som båda borrats från tunnelväggen, skiljer sig tydligt åt. I borrhål 3/999 är Langeliers index runt eller strax under noll, medan grundvattnet i 3/896 indikeras ha en mindre aggressiv sammansättning. Sammansättningen i borrhål 3/999 har en vattenkemisk sammansättning som liknar den i borrhålet som borrats från marknivå, medan borrhål 3/896 är tydligt påverkat av injekteringmedel.



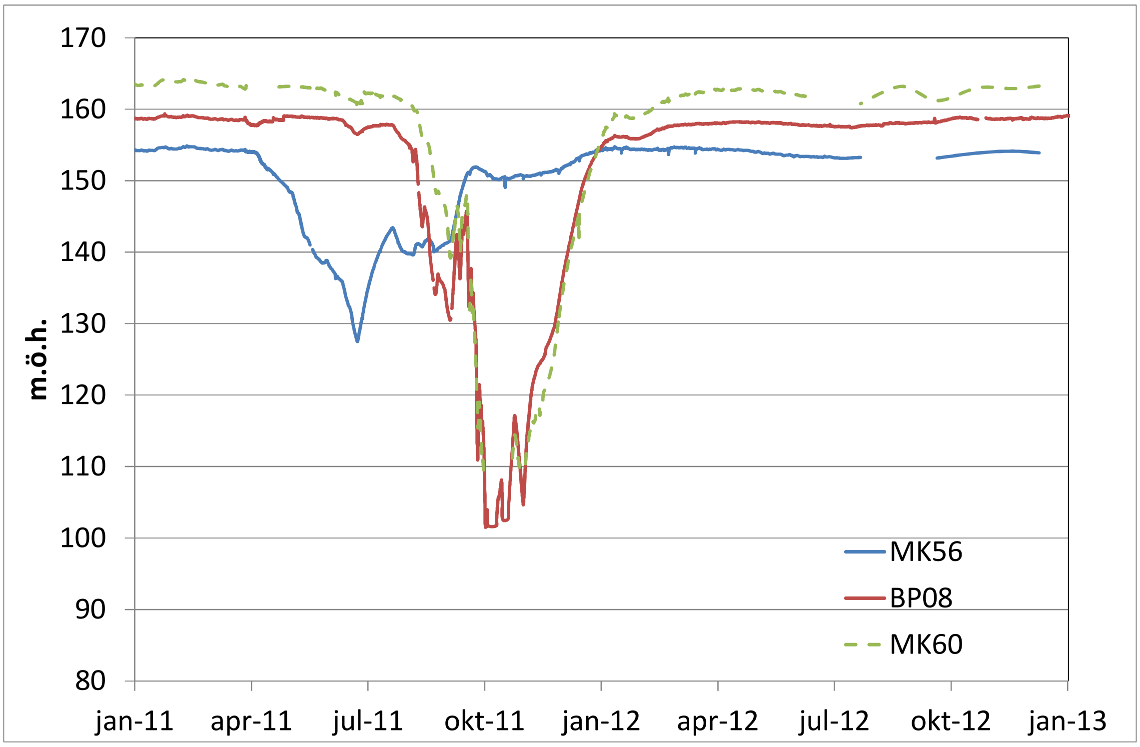
Figur 7. Langeliers korrosionsindex för berggrundvatten.

Även för de redoxkänsliga ämnena järn och mangan skiljde sig resultaten åt mellan de två borrhålen i tunneln. Generellt förekom löst järn och mangan i borrhål 3/999 meden koncentrationen var under detekteringsgränsen i borrhål 3/896. Troligen beror det på att cementinjekteringen orsakat en alkalisk miljö i 3/896 där järn och mangan bildade fällningar i berget i tunnelns närhet. I detta fall kan ett tätande lerlager i våtmarken genom att motverka en oxidation ha förhindrat att järn och mangan fällts ut i berget och istället kunnat flöda in i tunneln som vid 3/999. Dessa två parametrar är av betydelse då utfällningar som uppstår i dräneringssystem orsakar igensättning med stora underhållskostnader som följd.

5.2 Hallandsås

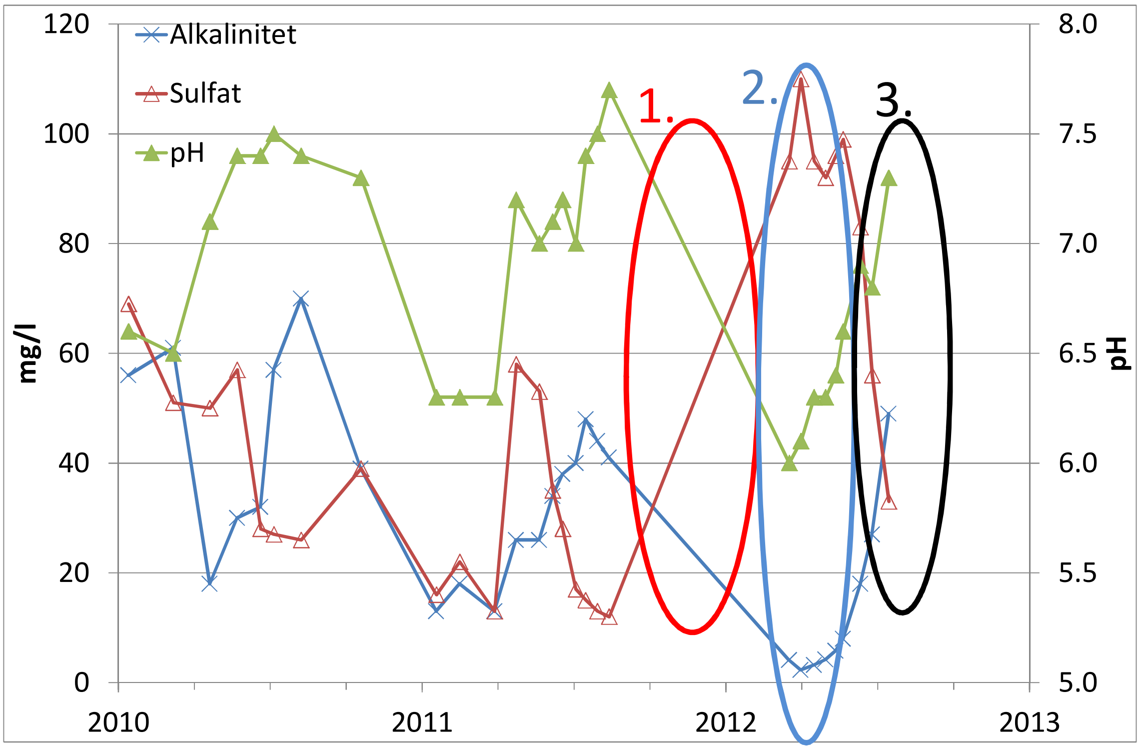
I studieområdet på Hallandsås påverkades både ytliga system och berggrundvatten av drivningen av den västra huvudtunneln. Eftersom området är beläget över högsta kustlinjen efter den senaste glaciationen avsaknas vattenavsatta finsediment som begränsar hydraulisk kontakt mellan berggrundvatten och ytliga system. I områden som påverkats av tunneldrivningen genom avsänkning av berggrundvattennivåer har detta inneburit att ytvattensystemen direkt påverkats. Detta har exempelvis utgjorts av att basflöde i bäckar har försvunnit och att våtmarker fått minskat tillflöde av utströmmande grundvatten. Ytliga vatten i områden som under opåverkade förhållanden utgör utströmningsområden har också fått ändrad flödesriktning och kunnat bilda berggrundvatten och flöda mot tunneln.

Figur 8 visar grundvattennivåer i de tre övervakade borrhålen inom studieområdet. MK56, som är belägen i den sydliga akviferen påverkades först när tunnelfromten närmade sig söderifrån. När tunnelnfronten passerat diabasgången som genomkorsar området (se Figur 4) skedde en återhämtning av nivåer i MK56 medan nivåerna i borrhålen belägna i den nordliga akviferen (BP08 och MK60) sjönk.



Figur 8. Berggrundvattennivåer, det sydliga borrhålet MK56 påverkas fore de mer nordliga borrhålen BP08 och MK60,

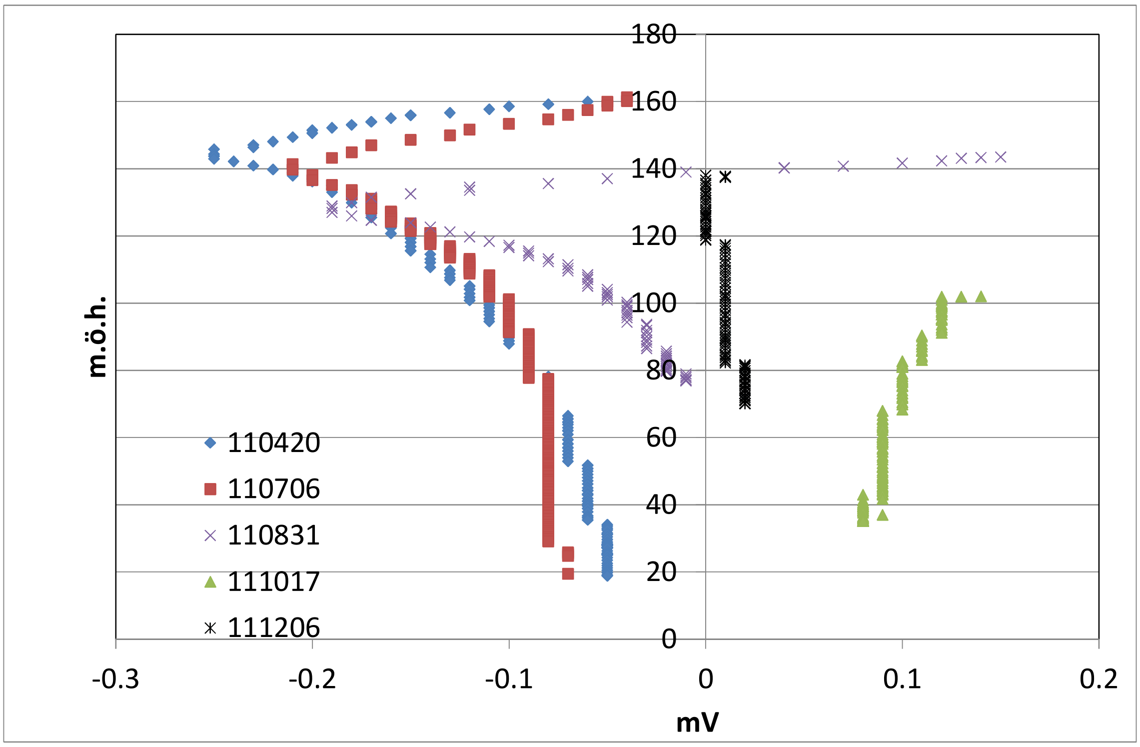
Figur 9 visar hur pH, alkalinitet och sulfatkoncentrationer varierar i en provtagningspunkt för ytvatten i studieområdet. Under hösten 2011, orsakade tunneldrivningen genom området att vattendraget torrlades, se händelse 1 i Figur 9. Återhämtning skedde under våren 2012, men sulfatpuls och påföljande alkalinitet- och pH-minskning. Under sommar 2012 återhämtades även de vattenkemiska parametrarna.



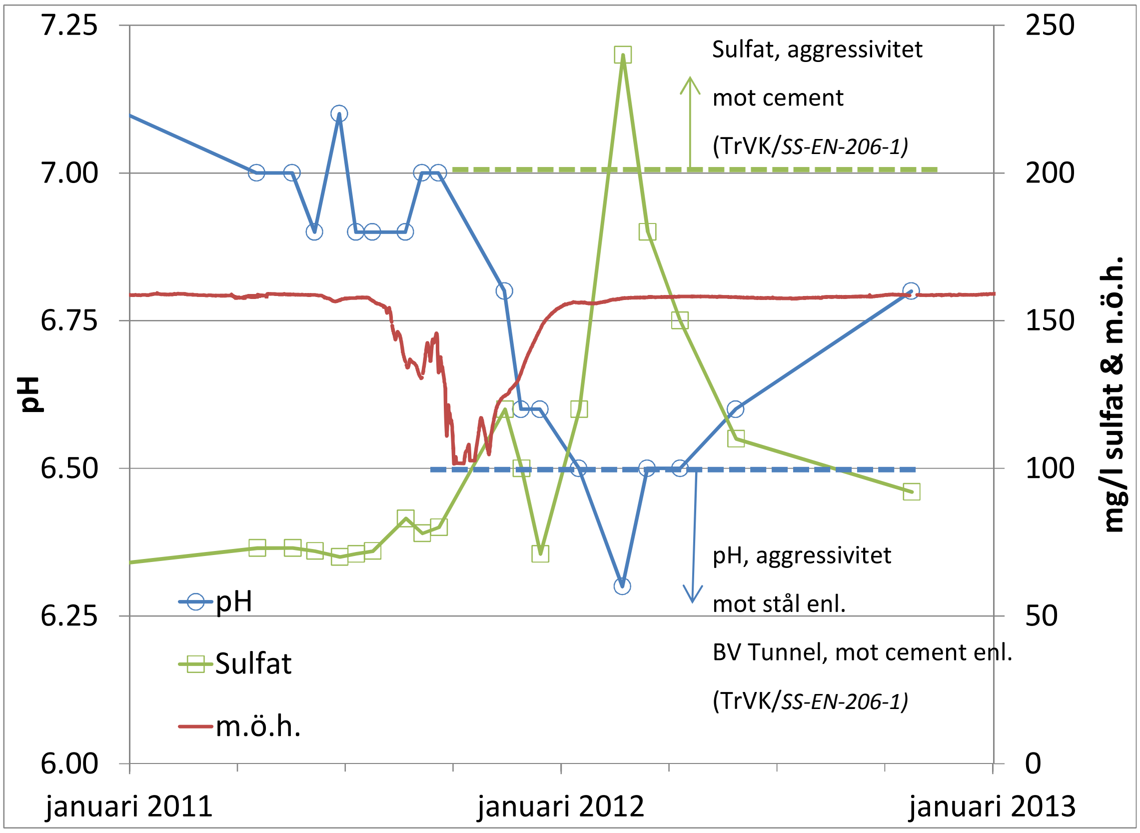
Figur 9. Alkalinitet, pH och sulfatkoncentrationer vid ytvattenprovtagningspunkten P03. Bäcken blev torr och provtagning var ej genomförbar (1). Återhämtning av flöden våren 2012, sulfatpuls, pH-sänkning och minskad alkalnitet (2). Vattenkemisk återhämtning sommaren 2012 (3).

Förändrade redoxförhållanden påverkar flera vattenkemiska parametrar och kan ge upphov till sulfidoxidation som i sin tur orsakar sulfatpulser och pH-sänkningar med minskning av alkalinitet som följd. Vidare är redoxförhållanden viktiga för lösligheten av järn och mangan, dessa parametrar är den vanligaste orsaken till problem med igensättning av dräneringssystem i tunnlar. Figur 10 visar resultat av borrhålsloggningar i MK60. Före det att tunnelfronten påverkade området rådde reducerande förhållanden (mätningarna 110420 och 110706). Under hösten 2012 påverkade tunnelfronten den norra akviferen i studieområdet, där MK60 är borrad, och en mer oxiderad grundvattenkemisk miljö orsakades.

Figur 11 exemplifierar vattenkemiska förändringar i bergborrhål BP08. Påverkan från tunneldrivning orsakade bl.a. att pyrit (svavelkis) oxiderade, vilket resulterade i förhöjda sulfatkoncentrationer och lägre pH. Påverkan är som mest påtaglig i samband med att grundvattennivåerna stiger efter att tunnelfronten passerat området. Förändringarna innebar att vattnet blev mer aggressivt mot både cement- och stålbaserade konstruktionsmaterial.



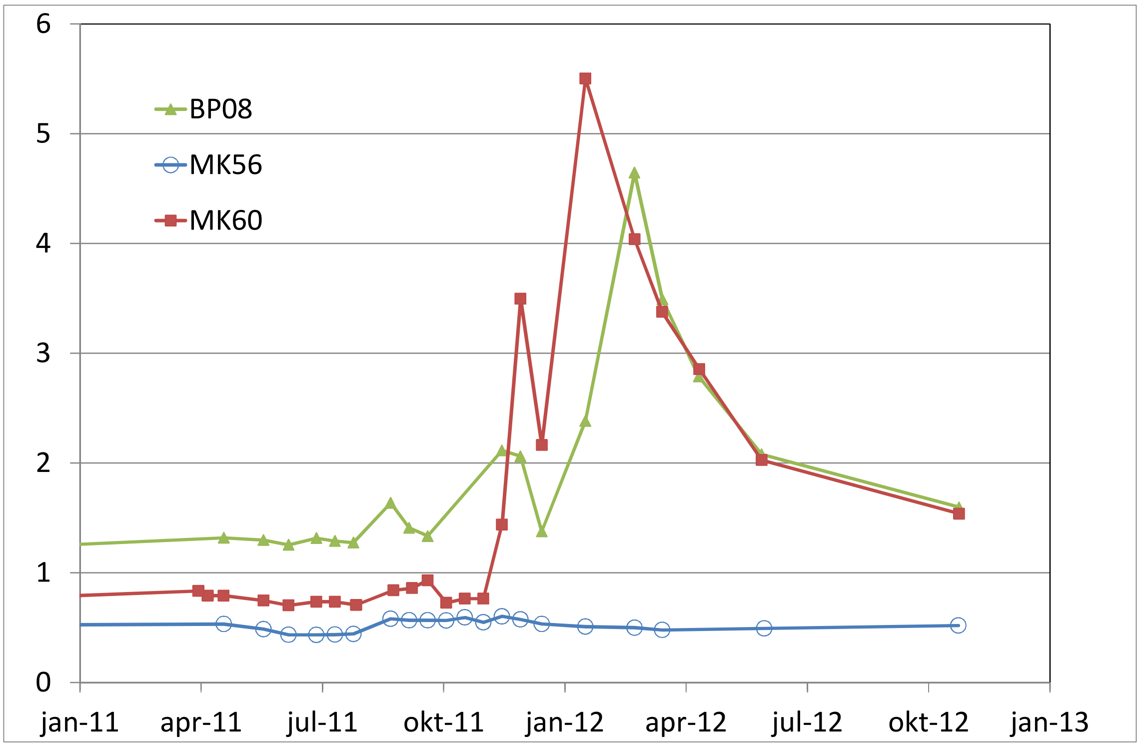
Figur 10. Redoxpotential på olika djup i bergborrhålet MK60 enligt loggningar som genomförts vid olika tillfällen.



Figur 11. Grundvattennivåer, pH och sulfatkoncentrationer i bergborrhål BP08.

Den ökade grundvattenbildningen och flödet mot den läckande tunneln bidrar till att omsättnings- och uppehållstider för grundvatten minskar. En viktig förändring är som nämnts att grundvattnet blir mer syresatt. Vid opåverkade förhållanden förekommer ofta långa omsättningstider för berggrundvatten, ibland 1000-tals år. Detta innebär att processer som är långsamma kan ha större betydelse vid opåverkade tillstånd, men bli irrelevanta till följd av påverkan av en undermarksanläggning. I svensk kristallin berggrund är ofta silikatvittring av betydelse för att ge grundvattnet ett relativt högt pH och buffringskapacitet mot försurning, alkalinitet. Genom att skapa korta uppehållstider får denna process en mindre viktig betydelse. Detta är troligtvis en bidragande orsak till de tydliga pH-sänkningar som observerats vid Hallandsås.

Korrosionsindex beräknades för berggrundvattnet för att bedöma aggressivitet mot stålbaserade konstruktionsmaterial. Figur 12 visar tidsserier för beräknat Larson-Skold Index och belyser platsspecifika skillnader. Detta index beräknar en kvot mellan sulfat- och kloridkoncentrationer respektive alkalinitet. Enligt Larson-Skold bedöms vatten vars beräknade index är <0.8 som ej aggressivt, medan vatten med index >1.2 bedöms som aggressivt. I borrhål MK56, som omges av relativt homogen gnejs skedde små förändringar under tunneldrivningen och grundvattnet kunde utifrån index bedömas som ej aggressivt (<0.8). De två borrhålen i den norra akviferen, BP08 och MK60 uppvisade större variation. Index i MK60 stiger från <1 till 5.5 och övergår således från att bedömas som ej aggressivt till att bedömas som aggressivt. För dessa borrhål förekommer pyrit som sprickmineral och i BP08 finns troligtvis hydraulisk kontakt med närliggande våtmarker.



Figur 12. Korrosionsindex Larson-Skold för grundvatten i de tre övervakade bergborrhålen. Vattnet i BP08 och MK60 blev mer aggressivt, en återhämtning med minskad aggressivitet pågår sedan våren 2012.

6 SLUTSATSER

Undersökningarna i föreliggande projekt bekräftar resultat från tidigare studier att platsspecifika geologiska förhållanden är avgörande för hur den vattenkemiska påverkan från ett undermarksprojekt blir.

- Vattenkemiska förhållanden i närheten av en tunnel kan variera betydligt lokalt beroende på heterogenitet i geologiska förhållanden.
    - I de två undersökta borrhålen i tunnelväggen i Kattleberg noterades skiljaktiga resultat där det ena uppvisade tydlig påverkan av injektering medan deta andra hade berggrundvattenkaraktär.´
    - Cementbaserad injektering kan bidra till ökad vattenkemisk heterogenitet.
- Finsediment under våtmarken i studieområdet på Kattleberg bidrog till att begränsa kommunikation mellan ytliga system och berggrundvatten.
    - Vattenkemiska förändringar motverkades, vilket också bidrog till att löst järn och mangan förekom i tunnelns närhet.
    - Resultat skiljer sig åt från tidigare studier på Äspö, belägen under högsta kustlinjen, där det finns kommunikation mellan ytliga system och berggrundvatten.
- Oxidation av mineralet pyrit (järnsulfid, både som sprickmineral och i våtmark) hade en avgörande påverkan då vattenkemiska förhållanden i ett par av borrhålen på Hallandsås. Vattnet blev mer aggressivt mot både cement- och stålbaserade material i två av borrhålen.
    - I ett av borrhålen på Hallandsås där mer homogena förhållanden råder erhölls enbart påverkan för löslighet av järn och mangan.
    - Eftersom studieområdet på Hallandsås är beläget över högsta kustlinjen förekommer ej finsediment i lågområden och direkt hydraulisk kontakt uppstår mellan spricksystem och våtmarker/ytvatten. Detta innebär större sårbarhet än i områden under högsta kustlinjen.
- Uppehållstiderna för grundvatten minskade. Detta har betydelse för under opåverkade förhållanden betydande men långsamma vattenkemiska processer. Silikatvittring är i kristallin berggrund ofta den viktigaste processen för att skapa ett välbuffrat vatten med relativt högt pH. Denna process får minskad betydelse vid korta uppehållstider, vilket bidrar till att berggrundvattnets buffrande egenskaper (mot försurning) försämras.

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Hydrochemical Changes Caused by Underground Constructions – a Case Study of the Kattleberg Rail Tunnel

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Abstract:

Changes in hydrogeology and hydrochemistry have been monitored during the construction phase of the Kattleberg rail tunnel in Sweden. The monitored area included a surface watershed with groundwater recharge and discharge areas. A centrally located discharge area coincided with a fracture zone in the crystalline bedrock. The fracture zone also intersected the tunnel. The quaternary deposits above the fracture zone included glacial till and marine clay sediments and the formation of sphagnum peat. In other areas, the bedrock was covered by glacial till only. Surface water discharged into a small stream.

The leakage of water into the tunnel during the construction phase caused changes in the hydrogeology with increased groundwater flow and a lowering of the groundwater level in the bedrock and in the overburden. These changes resulted in an alteration in the hydrochemistry in the glacial till and in the bedrock. A significant hydrochemical result was that the origin of the water sampled in the wells in glacial till changed depending on construction work, primarily blasting and grouting, and the progress of the tunnel front. During a construction standstill in early 2011, the groundwater levels recovered and rewetted the glacial till that had previously been dried during construction. During the rewetting episode, the chemical composition changed from being of bedrock origin to shallow origin. When construction was resumed, the water once again changed to bedrock type before the levels dropped below the glacial till.

The hydrochemistry of the runoff water was relatively unaffected by tunnel construction work. The stratigraphy at Kattleberg includes a layer of clay resulting from previous post-glacial marine transgressions and this has probably limited the hydrological and hydrochemical changes in the wetland resulting from the tunnel construction. The clay layer separates the bedrock aquifer from the wetland at Kattleberg hydrologically. However, infill of rock resulting from blasting on top of the marine clays within the study area caused increased concentrations of Cl, SO_4 and cations as well as a lowering of pH.

The results from two boreholes drilled from inside of the tunnel revealed contradictory results. For one of the boreholes, significant influence from the grouting was observed while for the other, hydrochemical conditions similar to those in the surrounding bedrock were observed. In the borehole that was affected by the grouting, hydration processes in the cementitious grout caused a very alkaline environment, while the other borehole displayed neutral or only slightly alkaline conditions. These results are of importance for the presence of dissolved Fe and Mn and the subsequent risk of the drainage system clogging. Dissolved Fe and Mn was detected in the borehole that revealed conditions similar to the surrounding bedrock. In the borehole that revealed significant impact from grouting, the concentrations of Fe and Mn were below the detection limit. The impact of shallow waters was evident in the two boreholes through the presence of DOC.

1 INTRODUCTION

Water leakage into underground constructions causes changes in the hydrology and hydrochemistry. Such changes have been observed whenever a monitoring programme was in place during the construction and operation phases of a number of infrastructure projects, including tunnelling. Notable examples from Scandinavia are observations from the construction phases of the Hallandsåsen (Laaksoharju et al., 2000; Mossmark, 2010) and Romeriksporten (Brettum and Løvik, 2005; Kitterød, 2000; Kværner and Snilsberg, 2008) rail tunnels as well as SFR, the final repository for low and intermediate level radioactive operational waste (Laaksoharju and Gurban, 2003; Nilsson et al., 2010).

The construction materials used to waterproof and support underground constructions could also have had an impact on the water chemistry. This impact has only been monitored in a few studies. However, studies have been carried out of the impact of grouting (Soler et al., 2011) on groundwater in relation to the durability of waterproofing grout in the construction of a repository for spent nuclear fuel in in Finland. In addition, there is an ongoing study involving an evaluation of the hydrochemistry in a road tunnel and a utility tunnel in relation to the degradation of cementitious grout (Abbas et al., 2012). A study of hydrochemical influence on occlusions of drainage systems in tunnels has also been carried out (Ekliden, 2008).

The hydrochemical changes are difficult to predict since they are dependent on geological and hydrological conditions as well as the design of the tunnel (Mossmark, 2010). The 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, 2010).

This paper presents a study of the hydrology and hydrochemistry during the construction phase of a rail tunnel. The subject is located in Kattleberg, about 40 km north of Gothenburg, Sweden, where a 1.8 km-long rail tunnel has been constructed. The tunnel is part of an infrastructure project comprising the construction of a four-lane, limited access highway and a double-track railway connecting the city of

Gothenburg to the city of Trollhättan. The distance between the two cities is approximately 75 km. A study area comprising a surface watershed was selected along a section of the rail tunnel. It was in this area that the hydrochemistry and hydrogeology were monitored.

2 OBJECTIVES AND SCOPE OF WORK

A field study was carried out during the construction phase of a tunnel to improve the understanding of related changes in hydrology, hydrogeology and hydrochemistry. These changes may be of importance for the durability of construction materials. This work is part of an ongoing research project aimed at improving the ability to predict hydrochemical changes caused by underground constructions.

The study included the monitoring of hydrochemistry in surface runoff water and groundwater as well as groundwater levels within a selected study area during the construction of a nearby rock tunnel.

3 MATERIALS AND METHODS

3.1 Description of the study area

The studied area is located at Kattleberg Hill in western Sweden (lat. 57.99 N, long. 12.14 E). From a land use perspective, the area consists of a mixture of suburban centres, agricultural areas and forests (deciduous and coniferous). The agricultural areas and deciduous forests are generally located in low-lying areas and the more hilly terrain is dominated by coniferous forests and local wetlands.

3.2 Geological conditions

The study area is located east of the Göta Älv river fault zone in an area dominated by plutonic rock types of granitic to tonalitic composition and formed approximately 1650 MA BP. To the west of the zone, younger augen granites have intruded these plutonic rocks. The Göta Älv river zone stretches from the City of Kungsbacka in the south to Lake Vänern in the north and the rock within the zone is largely fragmented (Samuelsson, 1978).

The bedrock at the Kattleberg Hill consists mainly of granodiorite that has been exposed to a varying degree of metamorphism. Metabasite is also present in the area in the form of dykes. These dykes were probably formed from previous mafic intrusions that have since been metamorphosed (Samuelsson, 1985).

According to information from the mapping of rock drill cores collected in the vicinity of the study area, as well as mapping of bedrock outcroppings, the bedrock is dominated locally by gneiss of granitic or granodiritic origin. The mapping of the drill cores revealed the presence of calcite, chlorite and iron hydroxide in the fractures (Tyrens, 2009). According to Lindström (personal communication), bands of pegmatite are present in the study area. Metabasite and amphibolite are also present, but have not been observed in the tunnel. The fracture zone is approximately 70 m wide at the surface and can be observed between sections 3/910 and 4/040 on the tunnel level (Lindström, personal communication).

According to the structural geology map, the hill is surrounded by fractured rock on the northwest, southwest and southeast sides. The northern slopes of the hill are located along a distinct fracture zone that stretches in a north-easterly direction from the Göta Älv river zone. East of the river, mylonite formed by deformations parallel to the Göta Älv river zone can be observed. These fracture zones are dipped at 30-60°, in a westerly or north-westerly direction (Samuelsson, 1985).

The area was glaciated several times during the current quaternary geological period and the last glacial retreat occurred 14,000 years BP. The glacier deposited till in thin layers directly on top of the crystalline rock. The glaciation was followed by marine transgressions and regressions. A map of the quaternary geology of the Kattleberg Hill and the study area is shown in Figure 1.

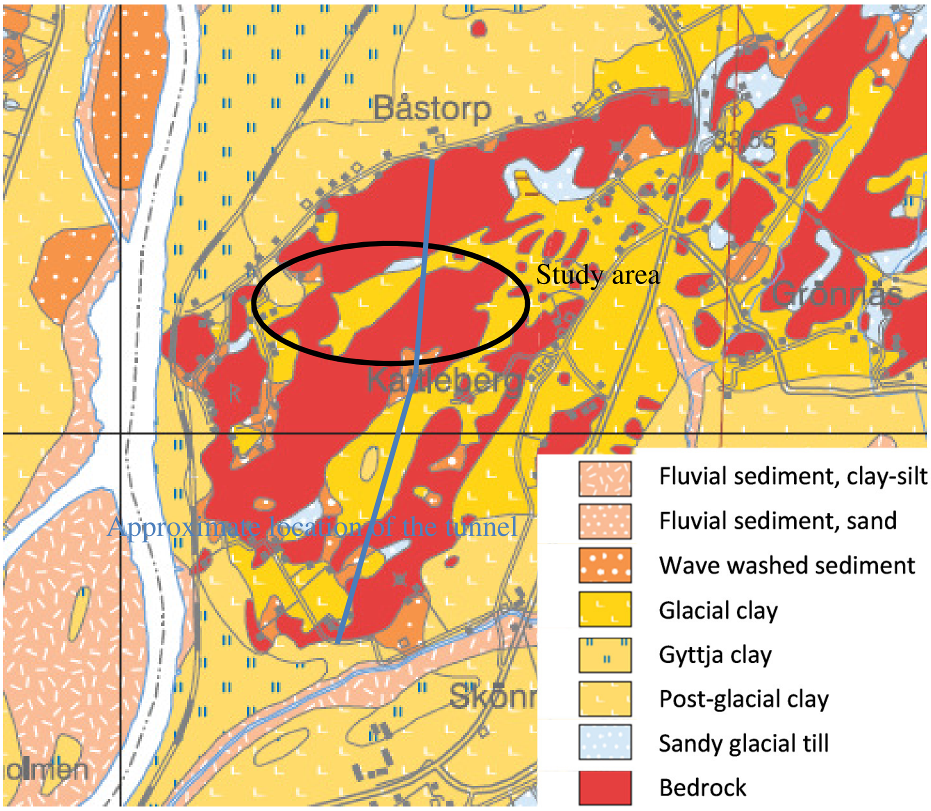

Figure 1. Quaternary deposits In the Kattleberg Hill area. The study area consists of a small watershed with a centrally located wetland (mapped as clay) surrounded by areas of higher elevation where the bedrock is covered by thin layers of glacial till. However, the till is mapped as bedrock outcrops as the depth of the deposit is commonly less than 1 m.

During the transgressions, fine-grained sediments such as silt and clay were deposited in calm or stagnant waters in the area. Coarser sediments of sand and gravel were deposited by flowing waters. During the transgressions, the Göta Älv river valley was a marine bay and glaciofluvial deposits and marine clays were formed. In the Kattleberg area, the glaciofluvial deposits were formed in the river valley. The glacial and post-glacial clays were deposited above the glaciofluvial deposits (Fredén, 1986).

The highest shoreline for the period after the last glaciation is 110-120 m a.s.l. The whole of the Kattleberg Hill has thus been subjected to transgression. On top of the Kattleberg Hill, marine glacial clays can be found and in more low-lying areas surrounding the hill, the glacial clays are covered by post-glacial clay sediments deposited later. These clays are commonly found in areas located below 20 m a.sl. Clays with a sulphide content are common at shallow depths, both in glacial clays and in post-glacial clays (Fredén, 1986).

Through sedimentation during marine transgressions, the till has become covered in glacial clay in low-lying areas comprising groundwater discharge areas. Wetlands with sphagnum peat have also developed in some parts of the groundwater discharge areas.

Figure 2 illustrates a conceptual model of the general geological conditions in the Kattleberg rail tunnel according to the description above. The conceptual model is one of three different conceptual models presented in Mossmark (2010), describing typical quaternary geological conditions in recently glaciated areas. The models were developed to describe likely chemical processes that may cause significant changes in the hydrochemistry during the construction and operation phases of a tunnel based on the geological conditions.

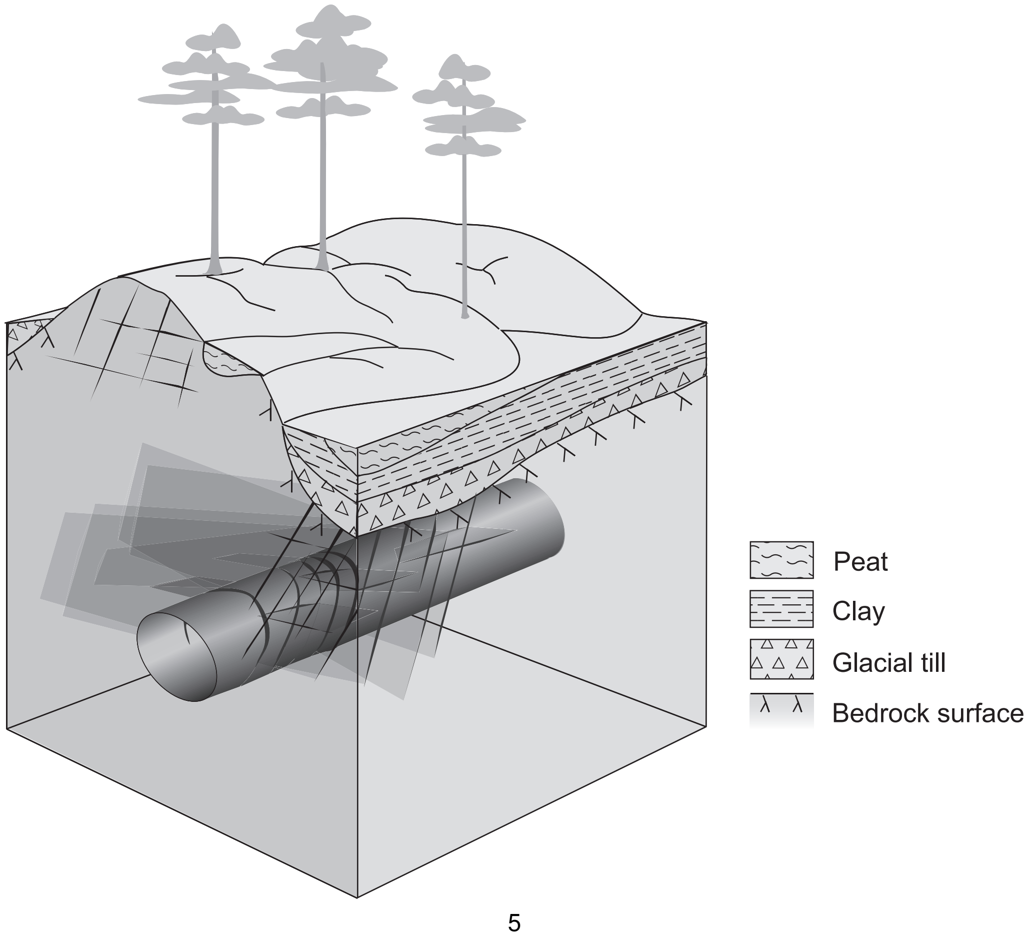

Figure 2. Conceptual model describing geological conditions similar to those in the study area (Eklund 2002, modified by Mossmark, 2010). The stratigraphy describes common conditions in recently glaciated areas that have been subjected to transgressions.

According to Mossmark (2010), the clay layer may limit the hydraulic interaction between the bedrock and the wetland. At Kattleberg, marine transgressions occurred after the most recent glaciation, resulting in the potential prevalence of high chloride concentrations in the groundwater and sediments as well as sulphides in marine clays. Unlike discharge areas that have not been exposed to transgressions, the discharge area within the study area is likely to comprise a significant S pool. However, in Mossmark (2010), it is concluded that the most significant hydrochemical changes arising from the aeration of wetlands during the construction of a tunnel with resulting oxidation of S, have occurred in areas that have not been subjected to transgressions.

3.3 Tunnel construction – techniques and progress

The tunnel was constructed using the drilling and blasting technique. The length of each blasting round was approximately 6 m. For waterproofing purposes, pre-grouting was used as the primary method. Waterproofing grout was injected for every third blasting round in 24 m boreholes, forming a grouting fan. The amount of grout injected varied depending on the rock quality. According to Lindström (personal communication), approximately 250 kg/m of cementitious pre-grout was used for sections 3/570 to 3/850. For sections 3/850 to 4/020, an average of 390 kg/m of cementitious pre-grout was used. For sections 4/020 to 4/100, an average of 250 kg/m was used.

Post-grouting with cement-based grout was carried out in sections 3/935 to 3/955 to address leakage of water (Lindström, personal communication). Degerhamn 30 grout was used for waterproofing grouting (Wilson, personal communication). From summer 2011 to spring 2012, complementary post-grouting with polyurethane was carried out to further address leakage of water into the tunnel (Wilson, personal communication).

The progress of the construction of the rail tunnel is presented in Figure 4. A mid-adit was established for the construction of a parallel service tunnel and to shorten the construction phase of the rail tunnel. The blasting for the tunnel construction commenced in June 2010 and the blasting and general waterproofing work related to the northern part of the tunnel (north of the mid-adit) was completed in April 2011. The progress of the blasting of the Kattleberg Tunnel is shown in Figure 4.

In July 2011, clear-cutting was carried out within the monitored watershed in order to deposit excess geological material from the blasting.

3.4 Groundwater chemistry of the bedrock before the construction phase

The Swedish Transport Administration collected samples for hydrochemical analysis from water supply wells in the bedrock and in the overburden in the pre-investigation phase of the project. The sampling was carried out to monitor possible changes in the water quality of the supply wells. According to Lidén and Saglamoglu (2012), the data from the water supply wells were used to select the quality of the steel bolts and cementitious grout in compliance with regulations laid down by the Swedish Transport Administration. In the study presented in this paper, 15 of the wells were selected to represent the groundwater in the bedrock in the vicinity of the monitored wetland and at the future tunnel location, below the wetland and before the construction phase.

The data show that the bedrock groundwater is slightly alkaline, with pH varying from 7.4 to 8.6. The water type can be described as Na-Ca-HCO_3 type for the majority of the wells. Alkalinity was generally high – 13 of the 15 wells had alkalinity above 100 mg/L HCO_3. SO_4 concentrations varied between 10 mg/L and 50 mg/L.For 10 of the 15 wells, the Na/Cl ratio was above 2.0. In the wells with a Na/Cl ratio of around 1.0, the Ca concentrations were significantly higher than in those with a Na/Cl ratio above 2.0. The two wells with the highest ionic strength had a Na/Cl ratio close to 1.0.

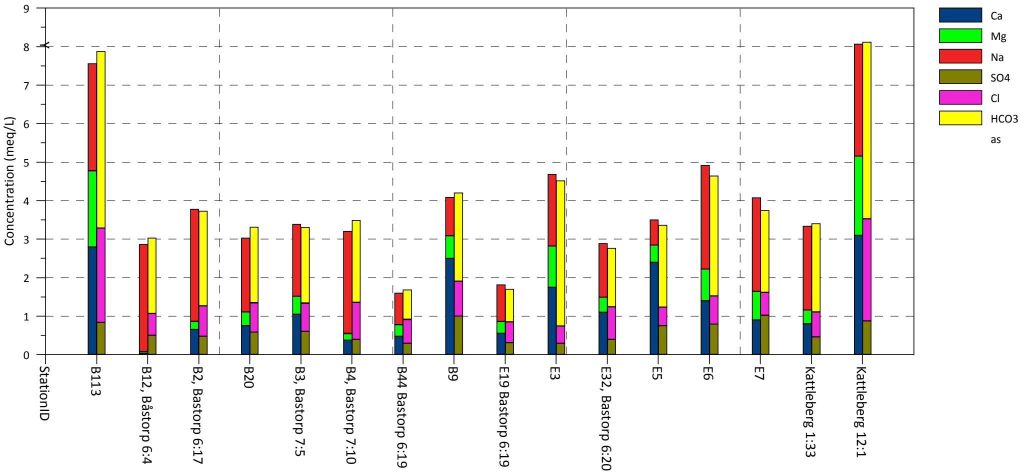

Figure 3. Major dissolved ions in groundwater in water supply wells in the bedrock in the vicinity of Kattleberg Hill. The water in the majority of the wells was of the Na-Ca-HCO_3 type. There was a generally high Na/Cl ratio.

In some of the wells in the bedrock at Kattleberg Hill, there are high Cl concentrations. Data reveals that concentrations between 500 mg/L and 1000 mg/L are common in some areas, primarily for wells located at the foot of the hill. The data from these wells were not presented in Figure 3, nor were they used to describe the water chemistry in the vicinity of the tunnel in the study area.

3.5 Monitoring

A study area comprising a watershed and adjacent areas was selected for the monitoring. Hydrochemical and groundwater levels were monitored from October 2010 to November 2011. Five filter wells (GW1001-1005) in the overburden were installed along with two boreholes in the tunnel (BH3/896 and BH3/999) in order to collect water samples for chemical analysis within the framework of this research project.

Two of the filter wells were installed in the 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 in a slope (GW1003). The boreholes in the tunnel were drilled slightly north of the surface watershed close to a fracture zone, which it is inferred intersects both the tunnel and the superficial aquifers beneath the wetland.

The two boreholes in the tunnel were drilled horizontally from the tunnel wall to an approximate extension 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.

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 4.

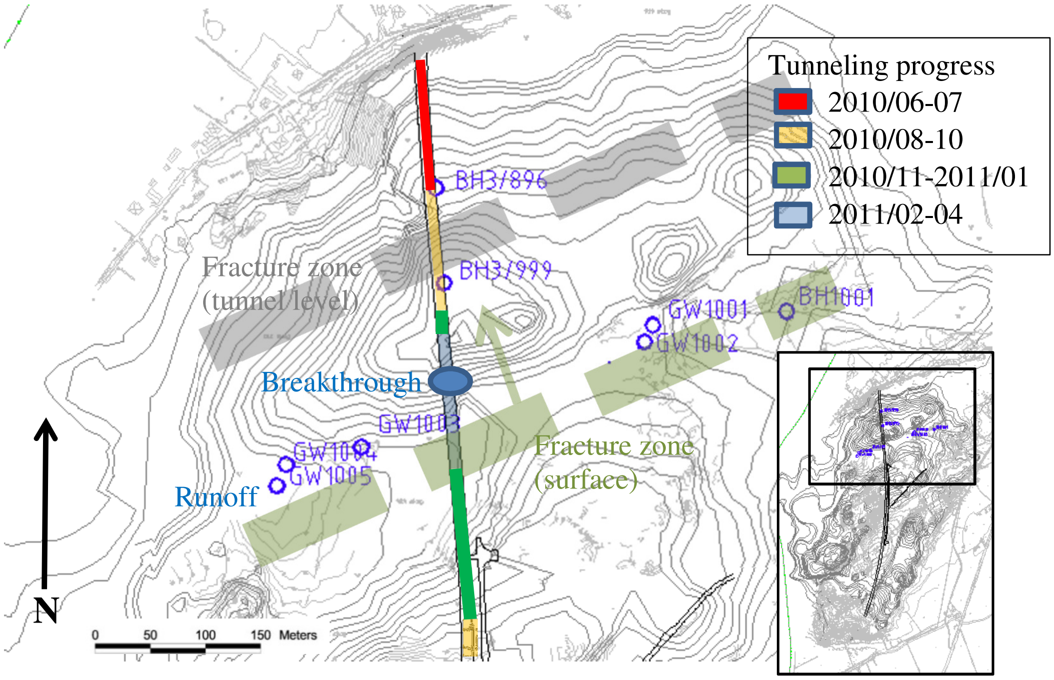

Figure 4. The location of the runoff sampling location, the five filter wells (GW1001 – GW1005), the percussion-drilled borehole from the surface (BH1001) and the boreholes from inside the tunnel (BH3/896 and BH3/999). Within the study area, the depth from the ground surface to the tunnel varies between 30 m and 35 m.

Samples from the filter wells and the percussion borehole were collected regularly using a sampling bailer. 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 (accredited according to ISO 17025) for pH, electrical conductivity, major cations and anions, Fe, Mn, dissolved organic carbon (DOC), nitrogen species and Si.

3.6 Metadata

Figure 5 shows temperature and precipitation data (Swedish Meteorological and Hydrological Institute (SMHI), smhi.se) from monitoring stations in the vicinity of the Kattleberg Hill. The precipitation data was collected at the Komperöd station (12 km from the study area) and the temperature data was collected at Säve Airport (27 km from the study area). Notable events include a period with temperatures below normal between November 2010 and February 2011 as well as monthly total precipitation above 140 mm for August and November 2010 and for August, September and December 2011. The monthly total precipitation for the period December 2010 to April 2011 was comparably low, between 30 mm and 80 mm per month.

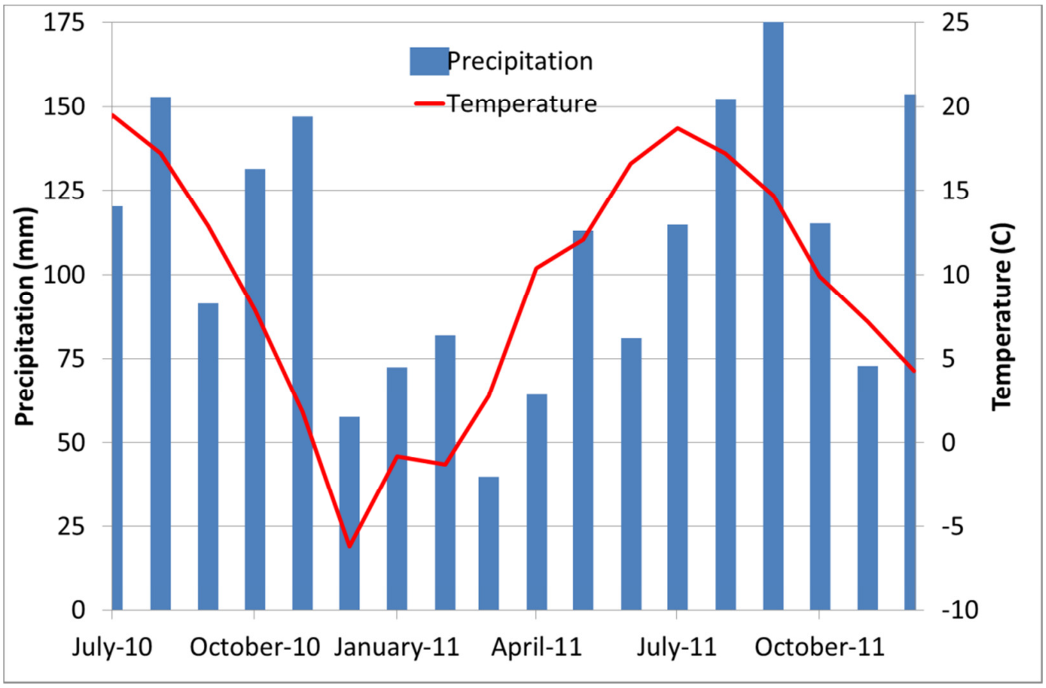

Figure 5. Temperature and precipitation at the Komperöd and Göteborg Säve (SMHI) monitoring stations. During the period November 2010 to February 2011, the average temperature was lower than normal compared to average temperatures calculated for the period 1961-1990.

Previously, SMHI operated a monitoring station for temperature and precipitation that was located in Alvhem, less than 2 km from the Kattleberg Hill. SMHI has compiled temperature and precipitation data at its monitoring stations for the period 1961-1990 and the data from that period from Alvhem can thus be compared to data from Komperöd and Säve. The mean temperature for the period 1961-1990 was 1.2°C lower at the Alvhem station compared to the Säve station. The most significant differences for the mean monthly temperature were observed for November, December and January (more than 1.5°C). For March and April, the difference between the two stations was less than 1.0°C. For precipitation, larger volumes were generally measured at the Komperöd station compared to the Alvhem station. For the period 1961-1990, the mean annual precipitation at Komperöd was 951.4 mm compared to 806.6 mm at the Alvhem station. The smallest difference in mean monthly precipitation for the period 1961-1990 was observed for April and May, when the mean monthly precipitation was only 7-8 mm higher at Komperöd compared to Alvhem.

4 RESULTS AND DISCUSSION

4.1 Groundwater levels

The groundwater level in the bedrock (BH1001) revealed smaller variations than in the glacial till (GW1003 and GW1004). However, it should be noted that the filter wells in the till are located closer to the tunnel than the borehole in the bedrock, see Figure 6.

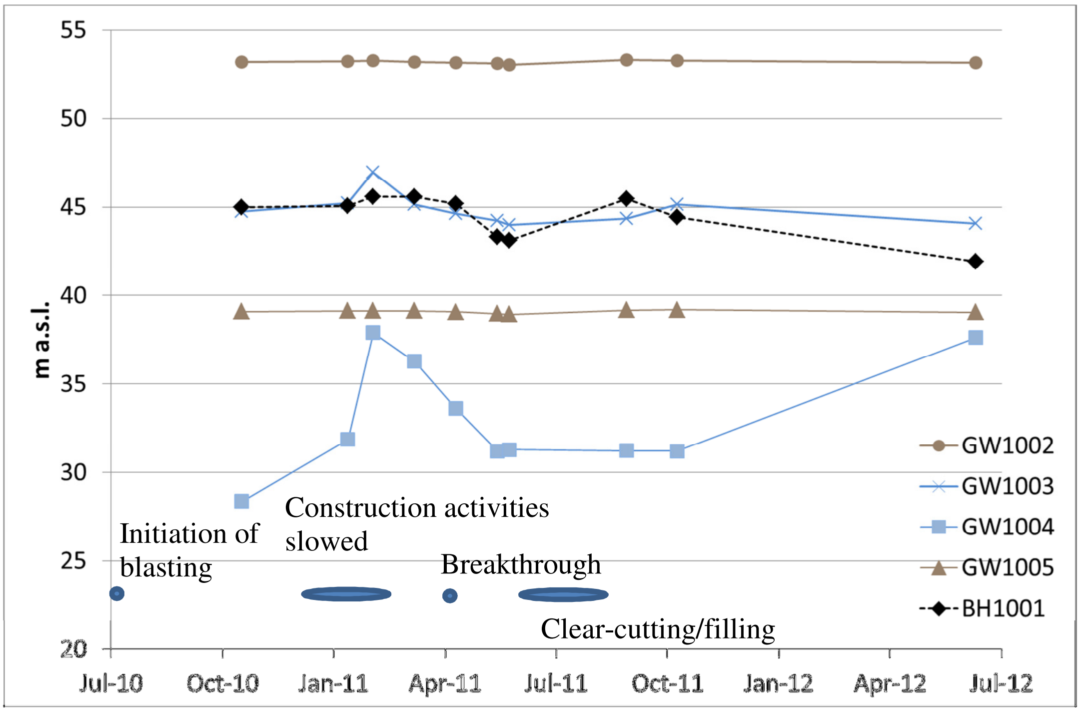

Figure 6. Groundwater levels in filter wells and in the groundwater in the bedrock. GW1001 was dry throughout the monitoring period. The filter wells in the wetland are marked in brown, the filter wells in the glacial till are marked in blue. The ceiling of the tunnel is located at approximately 5 m a.s.l.

Construction in the vicinity of the study area from the northern tunnel front came to a temporary halt in February 2011. At this stage, the tunnel sections that had already been constructed had been fully waterproofed. A recovery in the groundwater levels in the till and in the bedrock could be observed during this period (Figure 6). In March, however, activities commenced and tunnel blasting was completed in mid-April 2011. The groundwater levels in the glacial till (GW1004) remained low throughout 2011 although there was a recovery in spring 2012.

The groundwater levels in the wetland in the study area were reasonably stable throughout the monitoring period. While the groundwater in the glacial till interacts with the water in the bedrock, the groundwater in the wetland seems separated from the other entities. Although a seasonal lowering of the groundwater levels in the wetland filter wells (GW1002 and GW1005) was observed during the summer (July), the levels recovered during autumn 2011. Unfortunately, it was not possible to initiate measurements of groundwater levels before the construction phase of the tunnel although the Swedish Transport Administration carried out measurements in two boreholes in the vicinity of the monitoring area. For one of the boreholes, KBH1, the levels fell by almost 10 m during construction but have since recovered. In another borehole, located between the study area and the service tunnel, the groundwater levels are approximately 2 m lower at the current stage in the post-tunnelling phase.

4.1 Hydrochemistry of the surface water and the groundwater in the wetland

For the measured parameters in the runoff water, the most significant changes were observed in conjunction with clear-cutting within the monitored watershed. As shown in *Figure* 7, the SO_4 concentrations increased and pH decreased during August 2011 following the clear-cutting. During this episode, the concentrations of the cations Ca, K, Mg, Na as well as Cl increased with a pattern that paralleled the SO_4 concentrations while the alkalinity decreased in the runoff water. There are likely simultaneous processes involved in the changes in water chemistry. However, the more than 10-fold increase in Cl concentrations most likely originates from the marine clays in the monitoring area that had been affected by the clear-cutting and subsequent infill of rock from blasting. Cl is unlikely to be affected by hydrochemical processes that could have a significant impact on the flux of dissolved Cl (Appelo and Postma, 2005).

For the period before the episode caused by the clear-cutting/filling, a monitoring period was initiated with decreasing pH. However, during spring and summer 2011, a gradual increase in pH and alkalinity could be observed. These changes were probably caused by a shift between the dominance of base flow water in the stream originating from groundwater discharge to the dominance of meteoric water.

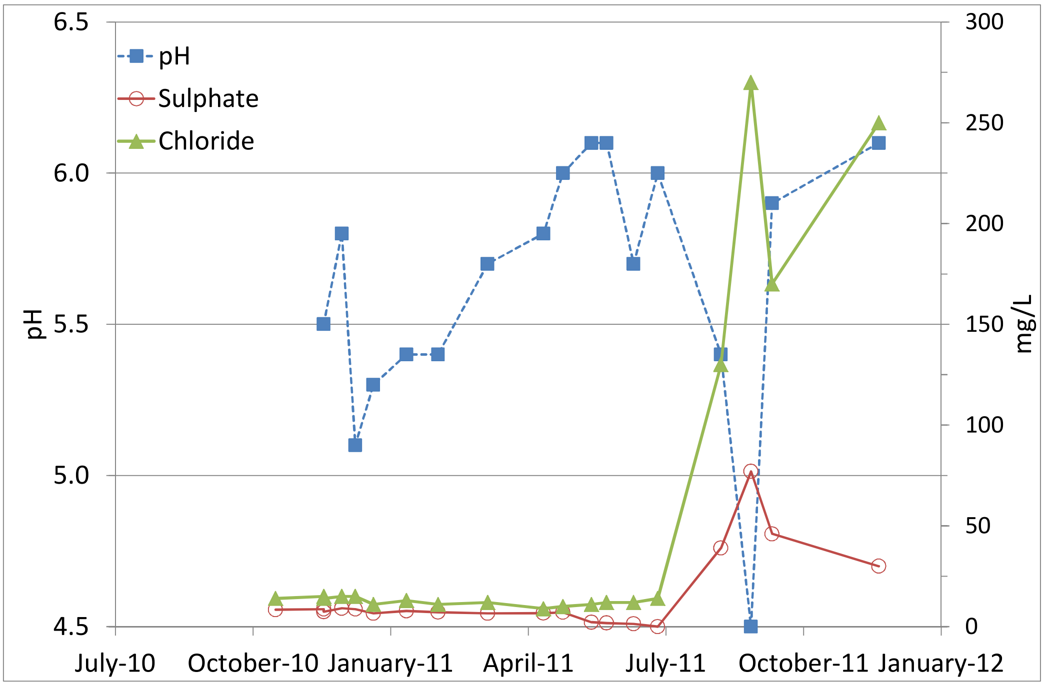

Figure 7. Concentrations of Cl and SO_4 as well as pH in the runoff water. The concentrations of SO_4 increased and pH decreased after the deposition of infill rock from blasting on top of marine clays in the study area.

The impact of the deposition of blasted excess material was also evident in the increased concentrations of nitrogen species in the runoff water. A surge of NH_4 and NO_3 was observed simultaneously with the SO_4 increase. The maximum concentrations for total N was about 0.5 mg/L in the runoff water. However, NO_3 concentrations peaked more sharply than NH_4. This may be an indication of changes in the redox state of the water during September 2011, which is also represented by the sharp increase in SO_4 concentrations with a simultaneous decrease in dissolved Fe concentrations. As for the runoff water, the shallow groundwater in the wetland displays significant variations in pH. For one of the two wells (GW1005), a decreasing trend can be observed during the monitoring period. The other filter well in the wetland (GW1002) mimics the pH in the runoff water with decreasing values during September 2011 followed by a recovery. However, there was no SO_4 surge in GW1002, unlike in the runoff water. A peak in high NH_4 (Figure 11) concentrations could be observed parallel to the lowering of the pH. Nitrification processes may have an impact on the changes in pH in GW1002 and the increased concentrations of the N species may be related to the infill of rock from blasting. GW1002 is likely to be sensitive to acidification due to low or non-existent alkalinity.

4.2 Hydrochemistry of the glacial till and in the bedrock

In the case of the groundwater in the glacial till, the hydrochemical composition differed for most of the time between the well in the slope (GW1003) and the well with a filter beneath the wetland (GW1004). The geological conditions as well as the groundwater level recovery in early 2011 in GW1004 are illustrated schematically in Figure 9.

The groundwater in the hill slope (GW1003) had a composition that could represent a mixture of water in the wetland and the water in the bedrock. The well in the slope was sampled on most scheduled occasions. It should be noted, however, that the groundwater in the glacial till beneath the wetland had only been sampled on four occasions during a recovery period in early 2011. On the other sampling occasions the well was dry.

The four successful sampling occasions in GW1004 occurred in January-March 2011. As revealed in Figure 8, the composition of the major cations and anions in the bedrock groundwater in the borehole that had been drilled from the surface (BH1001) was similar to the groundwater in the till beneath the wetland (GW1004) during the initial recovery phase when the groundwater level was below 35 m a.s.l. This is indicated as No. 2 in Figure 9. During this period, the glacial till in the hill slope was unsaturated with water. In February 2011, the water levels rose in the glacial till and in the bedrock and the glacial till probably became saturated, see the groundwater level indicated as No. 3 in Figure 9. On this occasion, GW1004 revealed a different composition compared to the other data points, which can be seen in Figure 8. This data point represents the composition of the groundwater sampled on February 3, 2011, on the occasion with the highest groundwater levels during a recovery period in early 2011 (Figure 6). The composition on this occasion is more similar to that of the water in the wetland and in the hill slope. On the subsequent sampling occasions, the groundwater levels fell due to increased construction activity and the composition in GW1004 once again became more similar to the water in the bedrock (Figure 8).

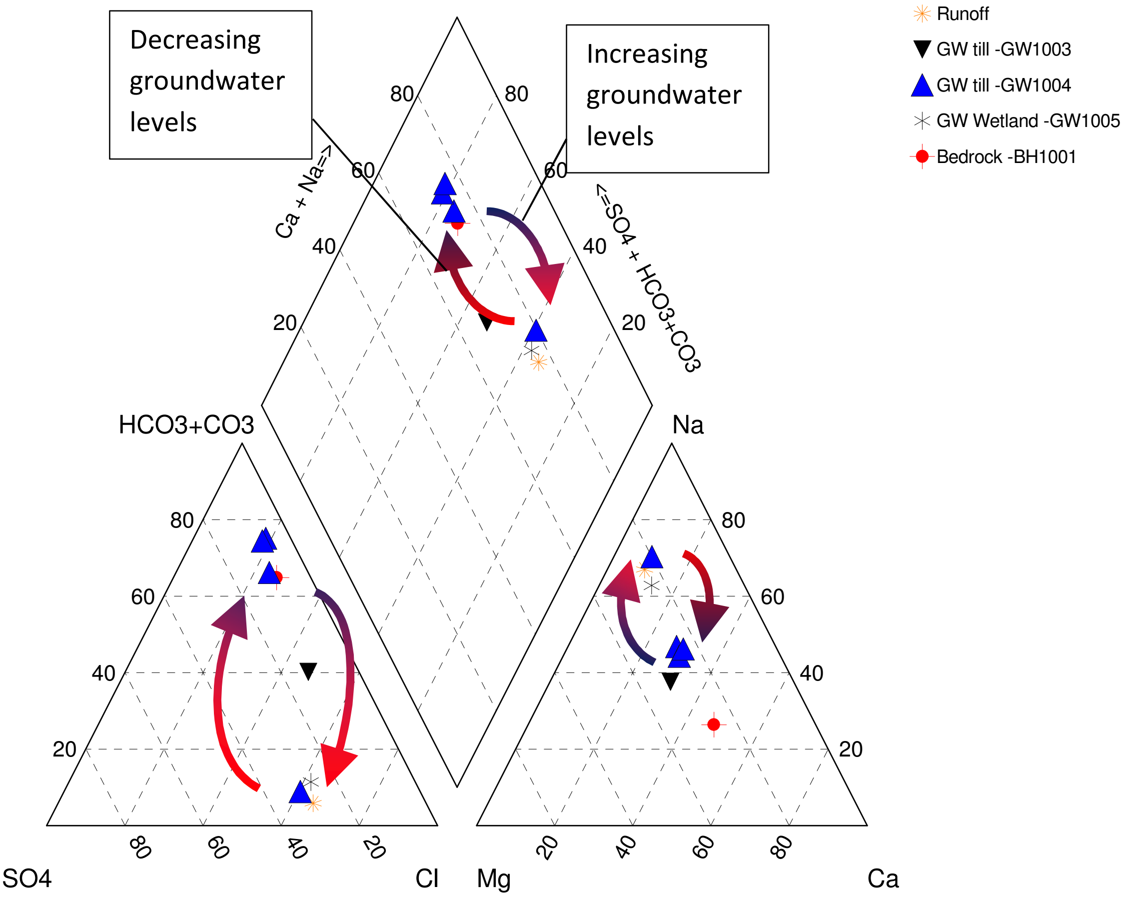

Figure 8. Piper plot describing the composition of the water the major anions and cations. Comparison between the glacial till beneath the wetland (GW1004, four data points) and single data points individually representing groundwater in the bedrock (BH1001), glacial till in the slope (GW1003) and in the wetland (GW1005). Of the four data points from GW1004, three resemble the hydrochemistry of the bedrock, while one resembles the hydrochemistry of wetland.

Figure 10 reveals the variation in pH and alkalinity of the groundwater in the glacial till on the hill slope (GW1003). A gradual decrease in alkalinity can be observed between November 2010 and September 2011. However, during autumn 2011 the alkalinity recovers slightly from a low level. The variations may be caused by processes that occur seasonally and under unaffected conditions. During the dry season, the shallow layers of overburden may be aerated. When the groundwater levels recover during the autumn, the S bound in shallow layers of overburden is released as S, resulting in lower pH. In late 2010, relatively low pH levels occurred on two occasions.

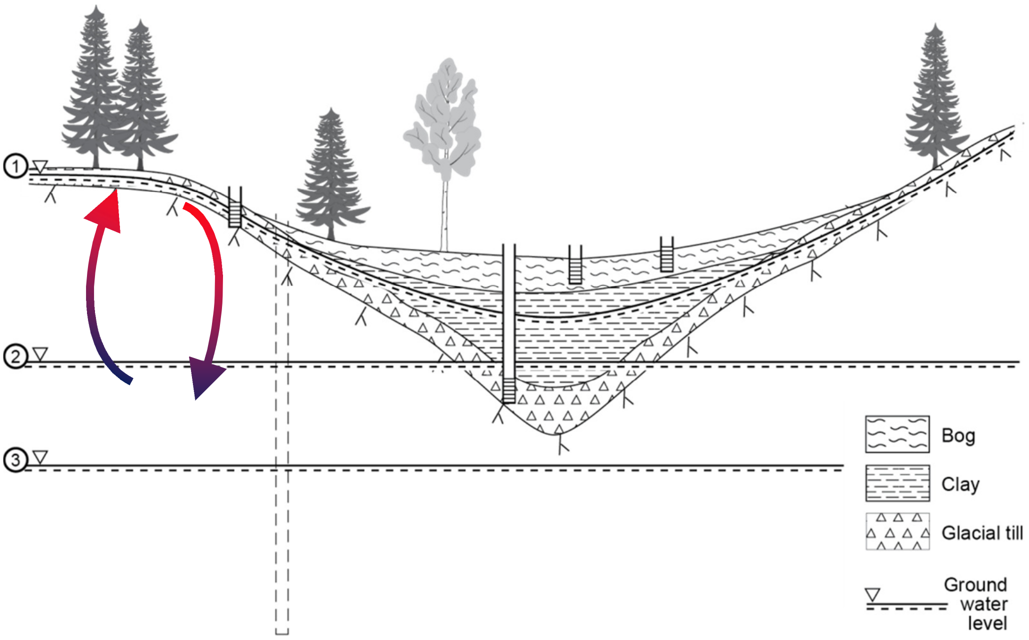

Figure 9. Cross-section of the wetland located within the study area. The groundwater level recovered gradually from the level marked 3 in the figure to the level marked 1.

At the same, there is a trend towards decreasing alkalinity and SO_4 concentrations in the beginning of the data series (Figure 10). The occasions with a low pH are also simultaneous with a temporary sharp decrease in dissolved iron concentrations. The hydrochemical changes during late 2010 may coincide with the rapid hydrological changes due to the progress of tunnelling operations.

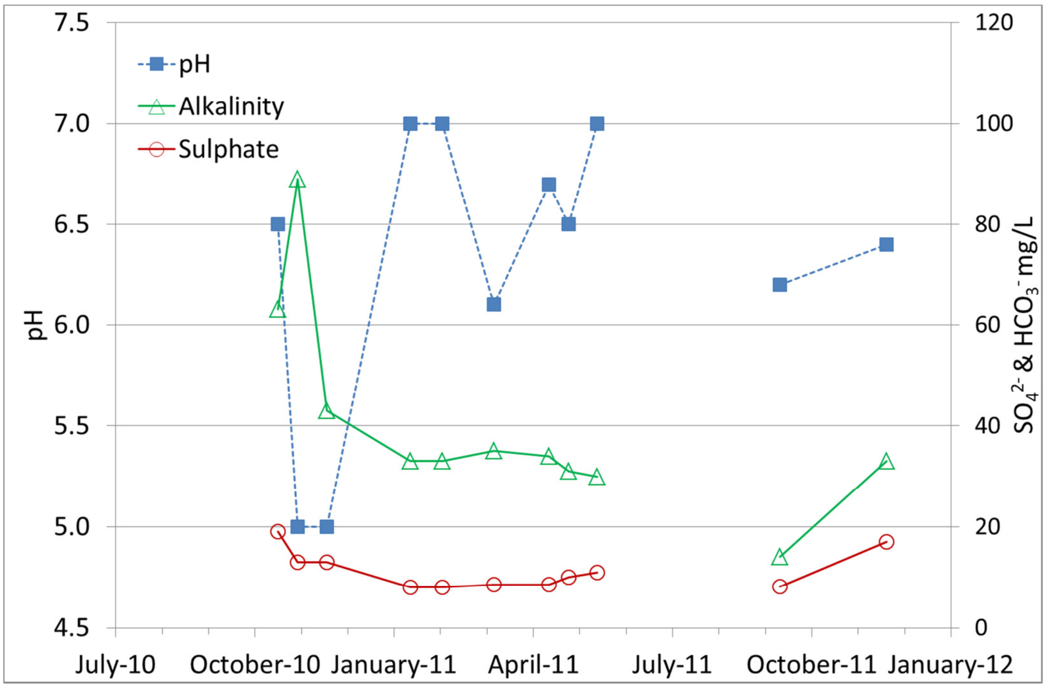

Figure 10. Alkalinity, pH and S for shallow groundwater in the glacial till (GW1003). The well was dry during summer 2011, indicated by the absence of a line connecting the data points representing May and September.

In the case of the groundwater in the bedrock, the hydrochemical changes are less significant than in the glacial till. However, a decreasing pH trend can be observed for the monitoring period. During summer and autumn 2011, a decrease in alkalinity and an increase in SO_4 could be observed. A decreasing trend for dissolved Fe can also be observed throughout the monitoring period and these changes may be related to redox changes with gradually higher redox potential. An increase in NH_4-N in shallow water coincides with a NO_3 and NH_4-N surge in BH1001. These changes may be a partial reason for the changes in pH and alkalinity.

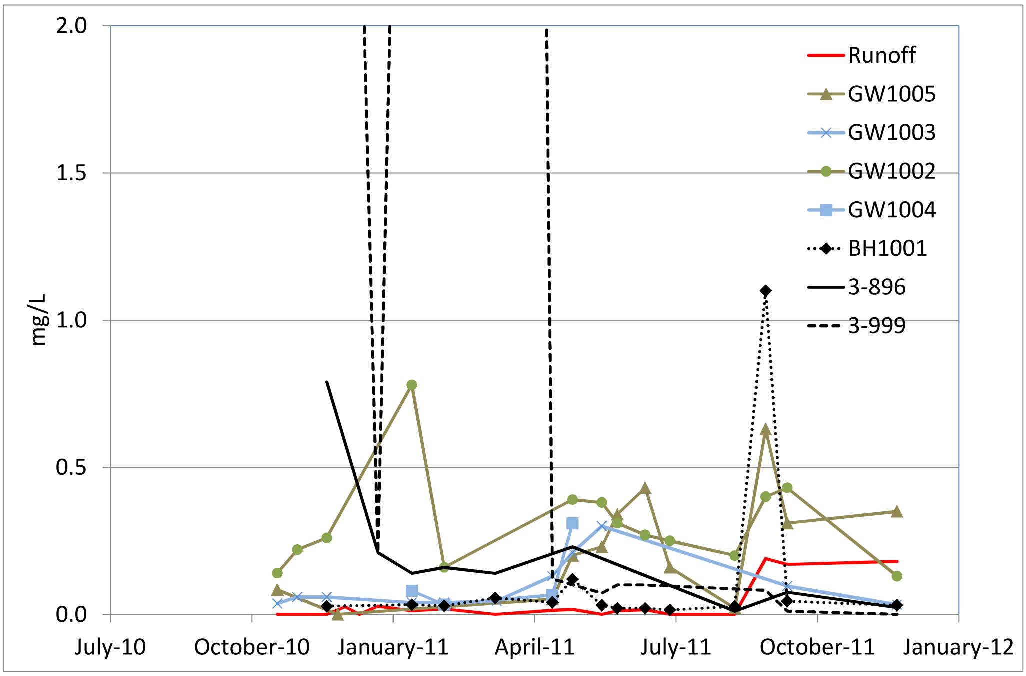

Figure 11. NH_4 concentrations in groundwater and runoff water. A sharp increase was observed in late summer 2011 following the deposition of infill rock in the study area. High but decreasing concentrations of NH_4 were measured in the boreholes that had been drilled from inside the tunnel in late 2010 and early 2011.

4.3 Hydrochemistry in the vicinity of the tunnel

Diverse results were revealed regarding the hydrochemistry of the groundwater in the two boreholes drilled from inside the tunnel. For one of the boreholes (BH3/896), the hydrochemistry was affected distinctly by the waterproofing system, comprising cement grout, while the other (BH3/999) displayed compositions similar to those of the surrounding bedrock. The locations of the two boreholes are presented in *Figure 4*. Figure 12 describes gradual changes for the cations in groundwater sampled in the boreholes (BH3/896), where the rock mass had been grouted for waterproofing purposes in July 2010. The water type gradually changed from Ca-Na-HCO_3 to Na-Ca-HCO_3 before becoming a Na-HCO_3 type from November 2010 to September 2011. The impact of grouting continued for more than one year after the pre-grouting. The most significant time-based change is the decreasing concentrations of Ca in the groundwater. In November 2010, the concentrations in the groundwater were 110 mg/L. In September 2011, the Ca concentrations had decreased to 2.2 mg/L. The sodium concentrations were high compared to the chloride concentrations throughout the entire monitoring period, similar to the background concentrations before the construction phase. This may be part of a long-term process where fresh water flushes out marine water. Under these conditions, Na is released in exchange for Ca due to ion exchange (Appelo and Postma, 2005).

Cementitious grout consists of various combinations of calcium oxide, silicon oxide, aluminium oxide, ferric oxide and magnesium oxide. Calcium oxides dominate and there is a content of S originating from gypsum comprising approximately 4% of the total mass (Dellming, personal communication).

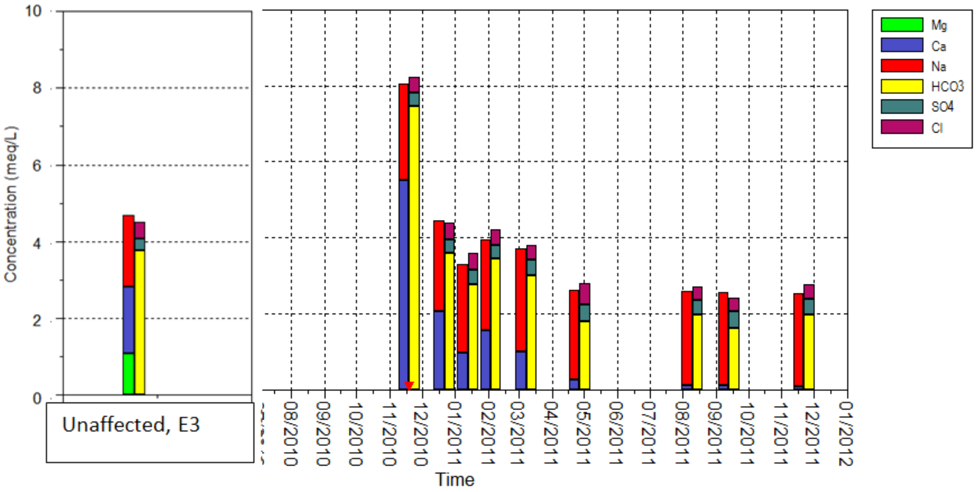

Figure 12. Major anions and cations in the bedrock. Unaffected groundwater (left) compared to a time series for groundwater adjacent to the tunnel (right, BH3/896). The section was grouted for waterproofing purposes in July 2010.

The use of cement grout primarily makes S and Ca more available. During hydration of cement, Ca is released. This is a likely explanation for the initially high concentrations of Ca in BH3/896. The concentrations in the groundwater in 3/896 were several times higher compared to those in the unaffected bedrock groundwater, see Figure 12. However, in early 2011 the Ca concentrations decreased to significantly lower concentrations than under unaffected conditions. The concentrations of Mg also decreased and slipped below the detection limit. The concentrations of K decreased from 8 mg/L to 4 mg/L and the background concentrations are approximately 7 mg/L. The concentrations of sodium remained at slightly higher concentrations than in the surrounding groundwater. The depletion of Ca and Mg and the decrease in K may be caused by the hydration processes of the cementitious grout. According to Soler et al. (2011), gradual changes in the water chemistry were observed adjacent to cementitious grout in gneissic rock during hydration in a field test. The groundwater revealed gradually decreasing pH during the observation period of 2.5 years. According to Soler et al. (2011), Na was released through dissolution of cement and the formation and dissolution of anhydrite had an impact on the Ca concentrations. In BH3/896, pH remained high during the monitoring period, although it decreased gradually from 11.6 in November 2010 to 10.2 one year later.

Figure 13 reveals the concentrations for the dominating anions and cations in the BH3/999 borehole. The composition of the major ions is more stable compared to that of BH3/896 and bears similarities to the unaffected groundwater in the bedrock compared to the results in Figure 3. However, the impact of shallow waters was observed through the presence of DOC in BH3/896 as well as BH3/999. According to Soler et al. (2011), grouting may cause diffusion of an alkaline plume. In BH3/999, the absence of increased alkalinity and the presence of DOC indicate leakage of water, consisting primarily of bedrock groundwater and shallow water, into the tunnel at this location. At the sampling location BH3/999, the pH was similar to the bedrock groundwater in the area, varying around 8.0. The mean pH value for the groundwater in the bedrock was 7.7 in wells used for water supply in Kattleberg and Båstorp. Grouting to waterproof the tunnel was carried out in conjunction with blasting in early November 2010.

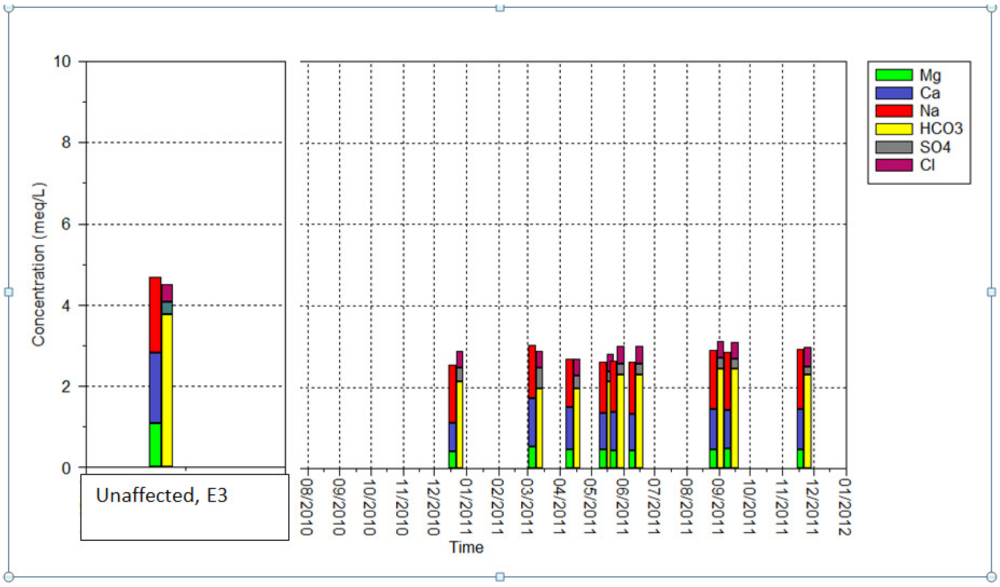

Figure 13. Major anions and cations in the bedrock. Unaffected groundwater (left) compared to a time series for groundwater adjacent to the tunnel (right, BH3/999). The section was grouted for waterproofing purposes in July 2010.

The concentrations of dissolved Fe and Mn also differed between the two boreholes in the tunnel. In the borehole that revealed significant impact of grouting on the hydrochemical composition (3/896), Fe and Mn concentrations were below the detection limit for analysis on all sampling occasions. The solubility of Fe and Mn is highly dependent on pH and redox conditions (Appelo and Postma, 2005). In borehole 3/896, the pH is consistently above the levels where high solubility should occur. In the borehole where the composition revealed hydrochemical conditions more similar to those in the surrounding bedrock (3/999), dissolved Mn was detected throughout the monitoring period. For Fe, a decreasing trend was seen during the initial part of the monitoring period, although the concentrations were below the detection limit after April 2011. The detectability of Fe and Mn in 3/999 is linked primarily to its lower pH in relation to 3/896.

The results indicate that dissolved Fe and Mn is prevented from reaching the tunnel if the waterproofing grout causes the water to become alkaline, thus causing the precipitation of the two elements. These results are of importance to the tunnel drainage systems, which frequently malfunction due to the precipitation and subsequent clogging by Fe and Mn (Ekliden, 2008).

The varying impact of cementitious grout on the hydrochemistry in the two boreholes highlights the heterogeneity of the hydrogeological properties in the vicinity of a tunnel. The occurrence of water-bearing structures and the design and success of the construction of the waterproofing system are of importance to the hydrochemical properties of the water leaking into a tunnel.

The concentrations of NH_4-N were elevated in the boreholes drilled from inside of the tunnel during the initial part of the monitoring period, shortly after the blasting of the tunnel. The highest concentrations of NH_4 were detected in the borehole with generally less impact from the waterproofing grout (3/999). According to SS-EN 206-1, NH_4 concentrations are considered to determine the selection of cementitious construction materials. The threshold value for the selection of construction materials with a higher durability is 30 mg/L NH_4. The highest concentration detected in the Kattleberg tunnel was 23 mg/L.

A Langelier saturation index for groundwater in the bedrock is presented in Figure 14. Conditions that may cause the dissolution of calcite are found in 3/999 and BH1001, whereas 3/896 has conditions that may cause scaling. A gradually falling trend can be observed in BH3/896 and BH1001, whereas BH3/999 has more stable conditions. The falling trend may lead to a more aggressive environment, especially considering that the groundwater in BH1001 has an index below 0. The Langelier saturation index for the unaffected reference E3 was 0.55, indicating slightly scaling, non-aggressive properties.

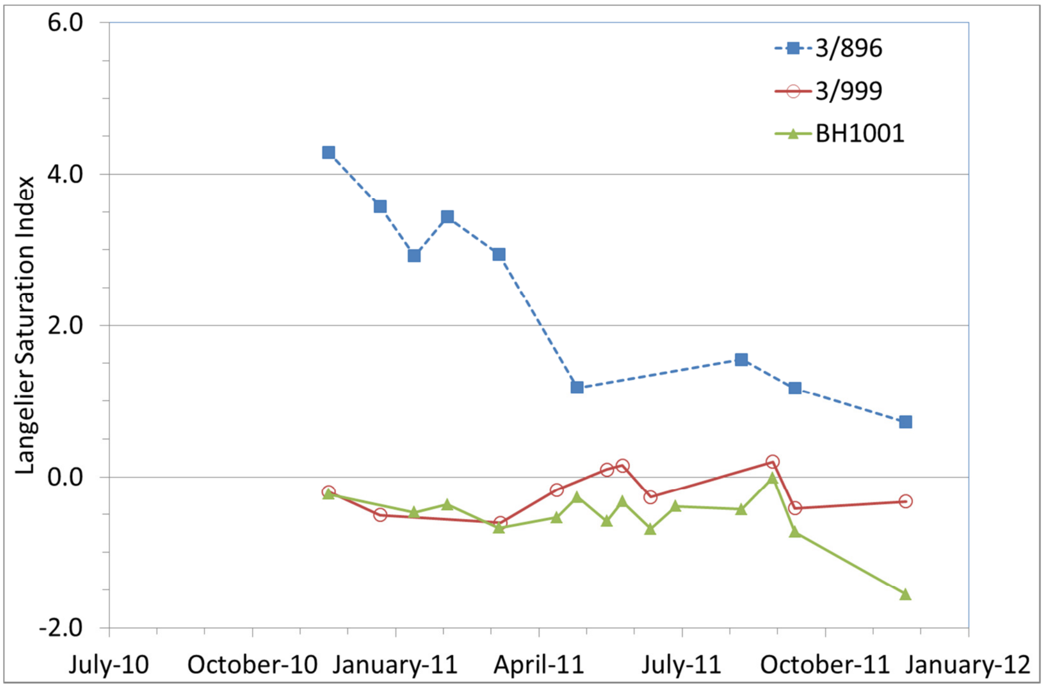

Figure 14. Langelier saturation index calculated for groundwater in the bedrock. If the index is below 0, calcite dissolution may occur. Scaling (calcite precipitation) may occur if the index is above 0.

5 CONCLUSIONS

The leakage of water into the Kattleberg Tunnel had an impact on the groundwater levels, water flow and water chemistry. Hydrochemical changes that were observed in the Kattleberg Tunnel were considered to be of importance for the selection of construction materials to be used in the tunnel. The most important conclusions are as follows:

- **One of the most important findings was that the groundwater in the wetland did not interact with the groundwater in the bedrock or the water in the glacial till beneath the wetland.** The presence of glacial clay prevented the wetland from transforming from a groundwater discharge area to a recharge area.
    - **The observed hydrogeological conditions prevented important hydrochemical changes** that could have caused the water in the bedrock to become more acidic and have higher concentrations of organic carbon.
- **The heterogeneity of the geological conditions in the bedrock was seen to be of significant importance** 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 (3/896), the grout had a significant impact on the hydrochemistry in the vicinity of the tunnel. Ca was released from waterproofing cement grout, causing initially increased Ca concentrations. However, the Ca concentrations gradually decreased to almost depletion. The concentrations of Mg and K were also lower than in unaffected conditions. In the other borehole (3/999), impact of this nature was negligible.
    - An impact of shallow waters on the groundwater in the bedrock was also noted through the increased presence of DOC in two out of three boreholes.
- According to the requirements laid down by the Swedish authorities that were in effect during the construction of the tunnel, **reinforcement bolts with complementary protection against corrosion would be required at this location**.
    - In borehole 3/896, the changes in Ca and Mg were reflected in the calculated Langelier saturation index and the water became gradually less prone to scaling. The other borehole 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), gradually more corrosive properties were observed according to a Langelier saturation index.

- The concentrations of dissolved Fe and Mn were affected by the alkaline environment created by the grout. In one of the wells drilled from inside the tunnel (3/896), 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, dissolved Fe and Mn were detected.

- Changes in the borehole drilled from the surface of the Kattleberg Hill, BH1001, could be caused by the combination of increased groundwater recharge and acidification of the shallow waters caused by clear-cutting/filling activities in the wetland.

- The hydrochemistry of the bedrock at Kattleberg implies previous marine environments through high Na/Cl ratios and low Ca concentrations in combination with high alkalinity.

The results from the two boreholes drilled from the tunnel wall (3/896 and 3/999) emphasise the difficulty predicting the hydrochemistry in the vicinity of the tunnel and may thus affect the durability of the construction materials.

ACKNOWLEDGEMENT

Financial support for the research presented in this paper has been granted by the Development Fund of the Swedish Construction Industry, SBUF.

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BILAGA 3

Manuskript Mossmark, F, Annertz, K K, to be submitted. Impact to Hydrochemistry from the Construction of the Western Tube of the Hallandsås Railroad Tunnel, Sweden.

Impact to Hydrochemistry from the Construction of the Western Tube of the Hallandsås Railroad Tunnel, Sweden

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Abstract

Changes to hydrochemistry occur during the constructional phase of tunnels whenever the groundwater flow is affected. The significance of these changes are determined by the geological and hydrological conditions, these may vary locally along the stretch of a tunnel. The hydrochemical changes may have implications for the ecosystems as well as for the durability of the construction materials in the tunnel.

This paper presents a study of the hydrochemical changes during the construction of a segment of the Hallandsås railroad tunnels in southwestern Sweden. A surface watershed and related rock mass was monitored from the spring of 2011 to the summer of 2012 through frequent groundwater sampling and hydrochemical borehole loggings in addition to the regular monitoring program set forth by the authorities that primarily included measurements of groundwater levels and sampling of surface waters.

The leakage to the tunnel caused a lowering of the groundwater level that in turn resulted in a decrease or the disapppearence of baseflow in the streams. Hydrochemical data indicate that the water in the streams became dominated by metheoric water during the periods of drawdown. Meanwhile, wetlands became aerated and oxygen could penetrate to oxidize reduced S in the wetlands releasing acids and SO_4.

For the groundwater in the bedrock, different results were observed depending on local geological conditions. However, all monitored boreholes were subjected to hydrochemical changes caused by leakage of groundwater into the tunnel during the constructional phase with resulting increased recharge. In the three boreholes that were monitored for hydrochemistry, higher redox potentials, conctrations of organic matter and lower concentrations of dissolved Mn and Fe were observed. In two of the boreholes, oxidation of pyrite, FeS_2, present as fracture minerals caused the formation of SO_4 and acids with subsequent drops of pH and alkalinity. Increased contrations of NO3 was also observed. The increased concentrations of organic matter, that were observed in all three boreholes, is a possible contributor to the depletion of oxygen and the reduction of, among others, Fe, Mn and SO_4. However, the groundwater travels through partially unsaturated conditions with free access to oxygen at shallow depth. Under such conditions organic matter is generally degraded without causing the depletion of oxygen, production of CO_2 or reduction of other dissolved elements or compounds.

For the durability of the tunnel, the hydrochemical changes that were observed in two of the three boreholes indicate a more aggressive environment according to the Larson-Skold Index. However, calculation of this index does not reflect the protecting impact from the increased presence of $NO_{3.}$

Engineering Geology

Introduction

Underground constructions are generally subjected to leakage of groundwater (Gustafson, 2012), its implications have been studied at several underground constructions. Besides the Hallandsås tunnels, Romeriksporten in Norway (Kitterød et al., 2000), the Hsueh-Shan tunnel in China (Chiu and Chia, 2012), as well as the Bolmen tunnel in Sweden (Olofsson, 1991) have (among others) been particularly well documented for groundwater related aspects. The constructional phase of the Hallandsås rail road tunnels started in 1992, however, progress has since been interrupted on two occasions (Jones, 2010). Since 2005, construction of the main tunnels has been carried out by the use of a tunnel boring machine (TBM). Before the initiation of tunneling with TBM in 2005, construction of the main tunnels had been carried out through regular drilling and blasting. There are two main tunnels, breakthrough in the eastern tunnel was achieved in August 2010. The western tunnel has been under construction through the use of the TBM since 2011 and breakthrough is scheduled for in 2013.

The tunneling activities has caused notable impact to the groundwater levels and hydrochemistry (Borca, 2007; Mossmark et al., 2010; Kvartsberg,in prep.). In most areas, the impact has been limited in terms of drawdown and time period.However, in particular areas along the tunnel stretch, the impact from tunneling has been persistent for over more than a decade (Mossmark, 2010).

Scope of work and objectives

A surface water catchment and the underlying bedrock on the Hallandsås ridge was studied during the construction of the western rail road tunnel. Water levels and water chemistry were monitored in the groundwater in deep drilled boreholes in the bedrock, as well as water chemistry and flow in streams. The results were evaluated for the purpose of understanding hydrogeological and hydrochemical influence from the tunneling. In the evaluation, mixing of water and hydrochemical processes were discussed. In the monitoring and evaluation, parameters that were assessed to be of importance to the degradation of the construction materials in a tunnel were paramount.

Limitations

This paper presents the results from a study of hydrochemical changes in one of the surface watersheds on Hallandsås during the construction of the western main tunnel during the years 2011 and 2012. The study used previously installed boreholes in the bedrock, filter wells in the overburden as well as existing sampling locations for surface waters. Additional installations were not carried out, hence the limited data on shallow groundwaters. The study did not include the sampling of seeping water into the tunnels, monitoring of the unsaturated zone or biological parameters. Furthermore, the study excludes organic contaminants of the groundwater

Hydrological conditions

Precipitation and temperatures have been monitored in a number of stations since the initiation of the project. Until the year of 2010, the monitoring was carried out by the Swedish Meteorological and Hydrological Institute (SMHI). The SMHI operated four stations on the Hallandsås ridge. However, because of unsatisfactory maintenance of the stations, the measurements have been carried out by the Swedish Transport Administration since January 2011. The measurements continued with equipment installed by the Transport Administrations at two of the locations where SMHI previosly monitored precipitation and temperature. One of the stations is located at Severtorp, in the vicinity of the area monitored for hydrological and hydrochemical changes in this study.

During the years 2000 to 2012, the annual precipitation at Severtorp varied between 763 mm (2001) and 1122 mm (2007) with an arithmetic average of 872 mm. The years of 2011 and 2012 had normal amounts of total annual precipitation of 863 mm and 868 mm respectively. The initial months of 2011 had less than normal precipitation as presented in Figure 1. During January to April of 2011, 102 mm was measured compared to the average for the months January to April for the years 2000 to 2012 of 180 mm. However, more than usual precipitation fell during July to September of 2011 with 419 mm compared to the average precipitation of 311 mm. Temperatures were near to normal for most of the two years of monitoring compared to the calcualted monthly averages for the period 2000 to 2010 as presented in Mossmark (2010). However, the coldest month of 2011 (February) as well as 2012 (February) were colder than the average for the corresponding month for the period 2000 to 2009.

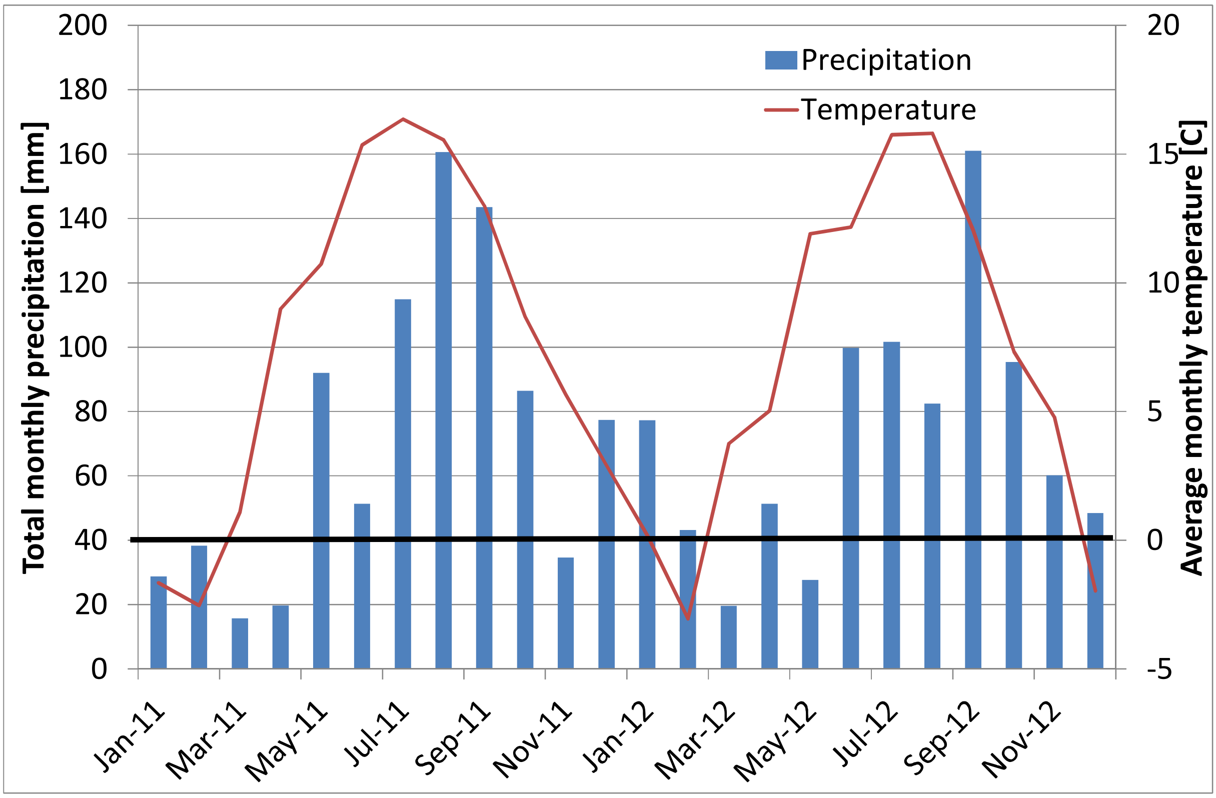

Figure 1. Monthly average temperatures and total precipitation for the period 2011-2012 in the study area.

The runoff volumes in the streams were measured manually every fortnight in weirs. The volume can be estimated based on these measuremnts, however, in this study they are primarily used as field observations for hydrological changes. The weirs at P03 and P36 became dry during the late autumn of 2011, after having had perennial since the year of 2007 when the eastern main tunnel was being constructed through the area. The other observational locations for surface water in the study area exhibited perennial flow during the years of 2011 and 2012..

Geological and Hydrogeological conditions

The two tunnels are being built through a horst in the north western parts of the Scania Province in the south of Sweden. The horst is approximately 80 km long, 5 to 10 km wide and its maximum altitude is 226 m a.s.l. (Ringberg, 2000).

The bedrock in the Hallandsås horst comprise rocks that were originally formed during the Gothian orogeny, 1.7 Ga (Åhäll and Gower, 1997). Several major geological events have shaped the current geological conditions. The Hallandsås is defined to be a part of the Sveconorwegian orogeny, that occurred between 1.15 and 0.9 Ga. At that time, the previous formed bedrock was mehamorphized (Lindström et al., 2000). During the most recent period of the Sveconorwegian orogeny, the bedrock was subjected to tectonic uplift, and the maindeformation processes changed from previously being ductile to be dominated by brittle conditions.

The northern and southern slopes of the horst as well as the dykes are parallel to deformations along the Tornquist zone which includes the Hallandsås ridge (Norling and Bergström, 1987). The Tornquist zone is approximately 100 km wide and stretches from the North Sea to the Black sea (Lindström et al., 2000). According to Norling and Bergström (1987) the Tornquist zone became active at least 300 Ma. Since the formation of the Tornquist zone, repeated events of tectonic activity have shaped the fractured bedrock of Hallandsås. The brittle deformation regimes have further contributed to the fracturing.

Superficial rock mass was subjected to denudation 205-100 Ma, warm and humid climatic conditions during the same time period contributed to conditions favorable for weathering. The weathered surface has generally eroded during the latest 100 Ma (Wikman and Bergström, 1987), however , strike-lift faulting has caused previously superficially located rock mass to be present at the level of the tunnel (Annertz, 2009).

The horst consists of crystalline rock, primarily granitic gneiss withdykes of dolerite. Amphibolite is also present within the gneiss. The dykes are generally oriented along the longitudinal direction of the horst (Annertz, 2009). The dolerite dykes have almost vertical dip. The host rock, the granitic gneiss, is generally fractured in the vicinity of the dolerite intrusions with fracture zones on both sides of the nearly vertical sheets of dolerite. The dolerite as well as the granitic gneiss have weathered surfaces and are fairly water-bearing at shallow depth. However, at larger depth the dolerite dykes have generally few water bearing fractures (Gynnemo, personal communication).

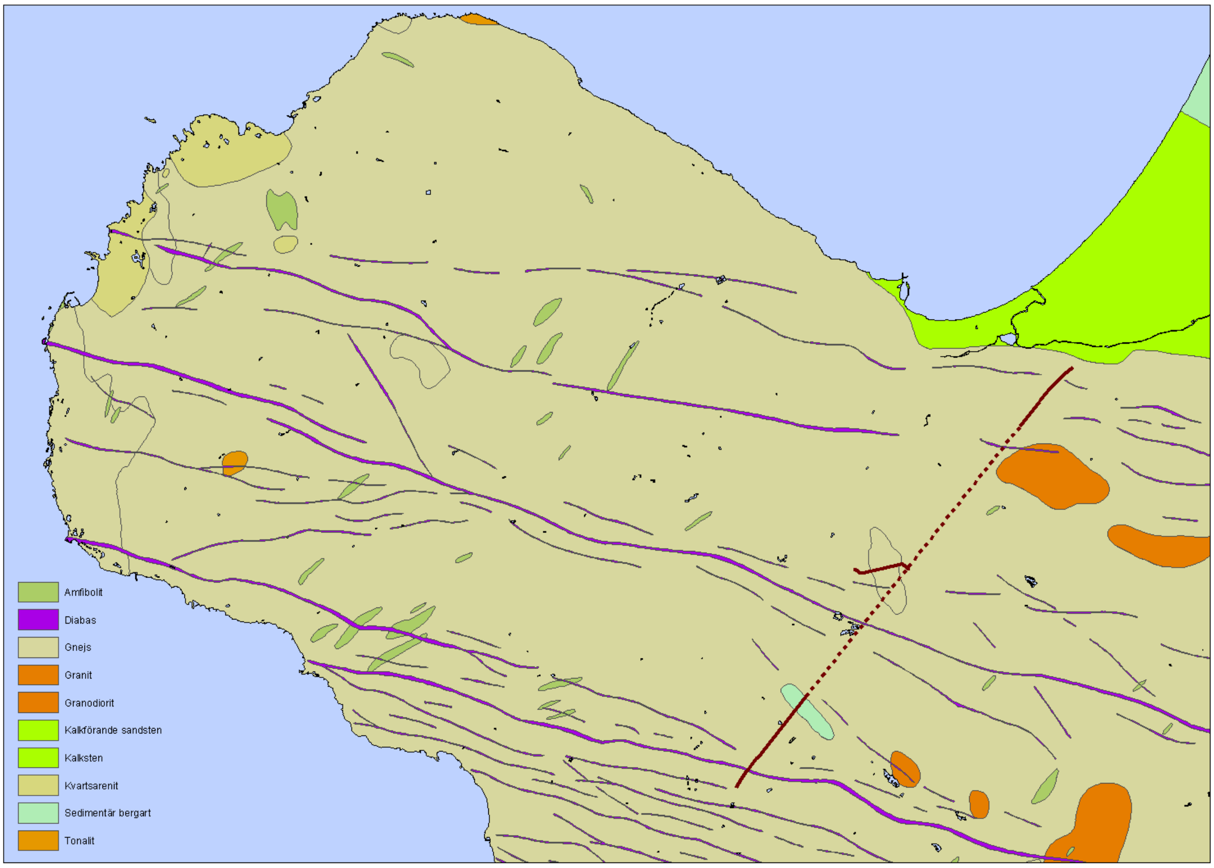

Figure 2. The bedrock of the Hallandsås horst is dominated by granitic gneiss that has been intruded by dolorite dykes. Amphibolite intrusions are present. On the southern and northern flanks of the horst more recent sedimentary rocks are overlying the igneous bedrock (Annertz, 2009) .

Alike many recently glaciated areas, the horst has an overburden that mainly constitutes of a thin layer of glacial till as displayed in Figure 3. Among other glacial deposits, glacifluvial sediments are also present, primarily along the Sinarpsdalen Valley to the west (Ringberg, 2000).

Along the slopes of the horst, wave washed sediments are present. However, areas with higher elevation have not been subjected to marine transgressions following the most recent glaciation (Ringberg, 2000). According to the National Atlas of Sweden (1994), the most extensive transgression following the most recent glaciations period submerged areas situated below 50- 60 m a.s.l. in the area of Hallandsås. Wetlands consisting of fens and bogs are present in hollows that constitute local groundwater discharge areas, these are common also within highland areas of the ridge. Hollows are commonly located above fracture zones since the fractured areas exhibit less resistance towards superficial weathering than the surrounding bedrock.

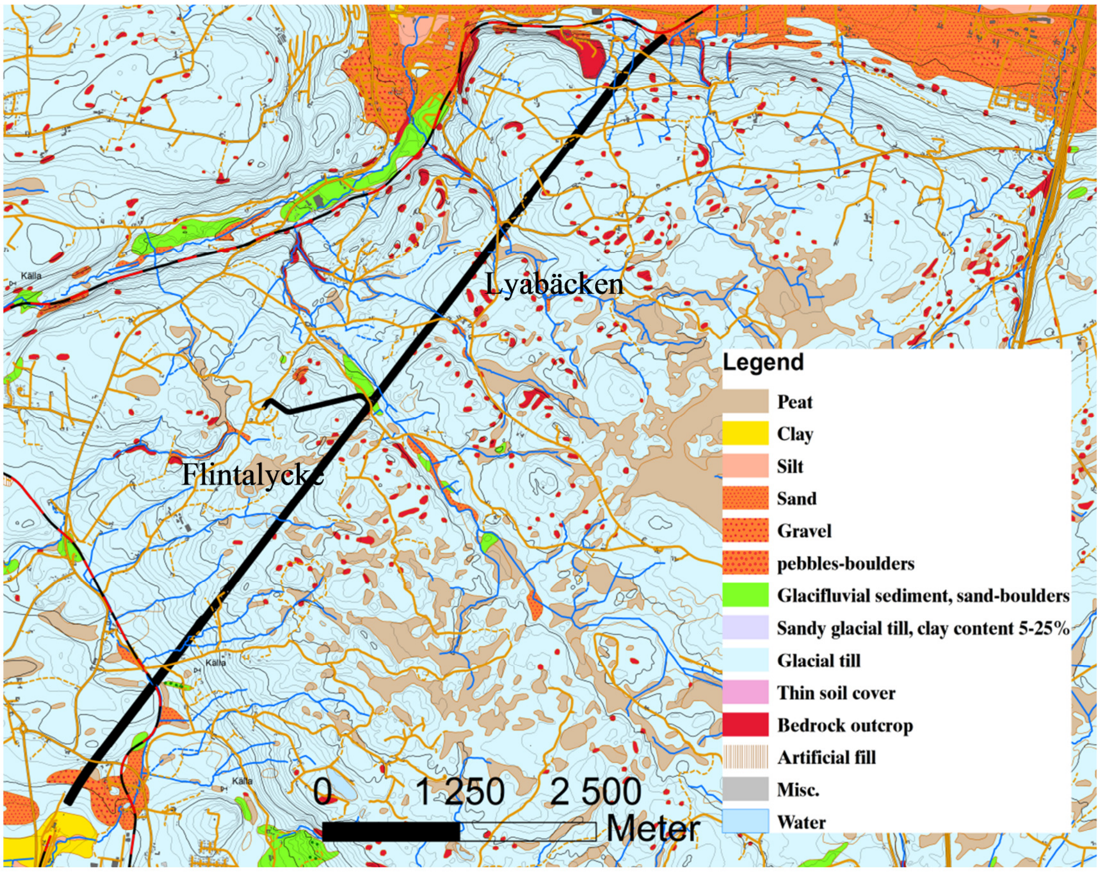

Figure 3. Quaternary deposits at the Hallandsås horst. Glacial till and peat dominate with the presence of glacifluvial deposits in the Sinarps Valley to the northeast and wave-washed sediments on the southern and northern slopes. © Swedish Geological Survey.

As a consequence of the geological history, the rock mass of Hallandsås in general is more fractured than the average igneous rock in Scandinavia. The fractures comprise water bearing structures, the high presence of fractures compared to normal Scandinavian conditions causes a higher storativity (Annertz, 2012). According to Kvartsberg et. al (in press), the median capacity of wells registered in the Wells archive of the Swedish Geological Survey is 6000 l/hour and the median depth is 78 m. The median for all registered wells drilled in Swedish Precambrian bedrock is 650 l/hour and the median depth is 70 m (Anderberg, 2000).

Tunnel construction and time line

Tunnel

The railway tunnel through the Hallandsås ridge is composed of two tunnel tubes, each 8.6 km long and mainly built with tunnel boring machine (TBM). The tunnel tubes are to be connected by a set of drill and blast built cross passages intended as emergency exits and for technical purposes. There are three adits, the TBM running from the south adit to the north. On its way, it passes the mid adit, that was constructed during a previous contract. After finishing the east tunnel tube in August 2010, the TBM was dismantled and transported back to the south adit were the building of the west tube started in February 2011.

Tunnel Boring Machine

To build the tunnel through the Hallandsås ridge, the contractor Skanska-Vinci uses a customized tunnel boring machine (TBM), designed to handle the complex geological conditions of the Hallandsås ridge.

The 10.6 m-diametre head of the TBM rotates and presses its 66 cutters forward to break the rock. After mucking a few meters, the TBM lines the most recent tunnel section by mounting a ring of precast concrete segments, forming a water sealed tube as the TBM constructs the tunnel. The lining work is performed inside a shield constructed to withstand the high water pressures that occur within the ridge (up to 15 bars).

The TBM can also, in extreme situations, continue the production in a closed, pressurized mode to limit the inleaking water. This has, however, proved very harsh/causing heavy wear on the equipment and has therefore rarely been used.

For the production to be able to quickly adjust for the varying geological and hydrogeological conditions, the TBM is equipped with an advanced system for probe drilling or grouting through the shield or the head.

Production sequences

If the probe drillings ahead of the machine indicate high water leakage, pregrouting is carried out as shown in Figure 4 (a). The TBM uses jacks to press against the lining behind and push forward (Figure 4b). After having mucked a few meters, the TBM is stopped and the concrete segments are placed and another ring of lining completed inside the TBM shield (Figure 4c). The thickness of the shield is left as a void between the lining and the rock. To achieve mechanical stability, this void is filled with fine gravel up to a certain height and with mortar to complete the perimeter (Figure 4d). The gravel is then grouted (Figure 4 e, f) to achieve a mechanical and hydrological stability.

To minimize the increased flow between different groundwater reservoirs that may be caused by the tunnel construction, hydrological barriers were installed at certain intervals. The barriers were commonly constructed by cement grouted fine gravel or by an concrete filled inflatable bag attached to the outer surface of the segments. The efficiency of a barrier to minimize the flow along the tunnel construction is largely dependent on the geological conditions. If the barrier is placed in competent rock free from water bearing structures, the drainage along the tunnel can be significantly reduced. If, however, it is placed in fractured and permeable rock, the result can be limited.

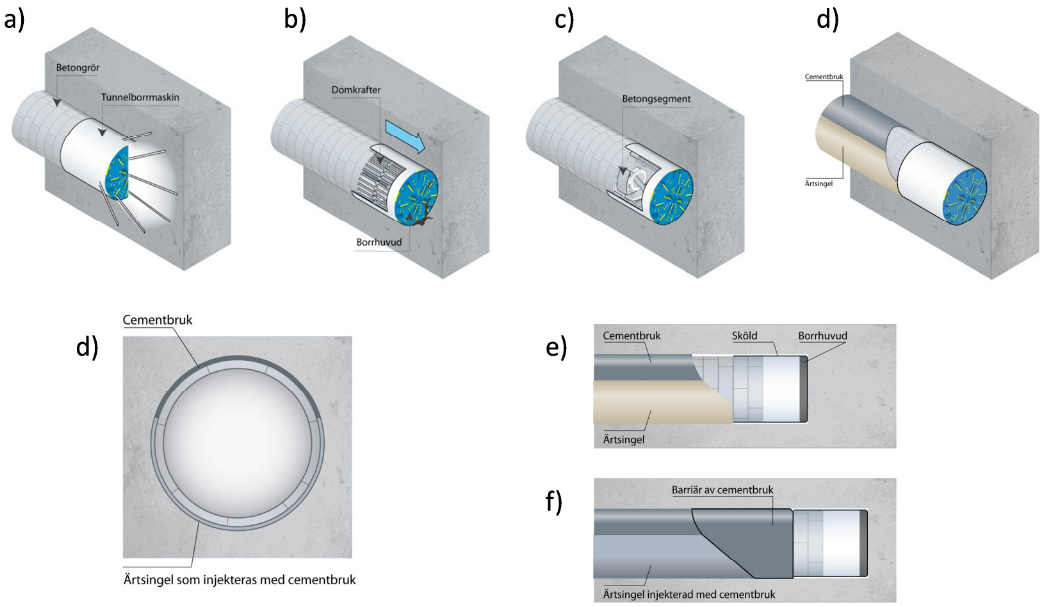

Figure 4. TBM production cycle. a) pre-grouting, b) progress, c) addition of new segment d) adding of gravel e) and f) grouting,

Production –Chronology

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

During the period when the drill and blasting method was used, tunnels were built from both the northern and southern sides of the ridge. An additional adit halfway between the southern and northern slopes of the ridge was also opened to shorten the construction period. The construction came to a halt in 1997 after two groundwater related obstacles occurred. The obstacles included the leakage to the tunnel in excess of regulations as well as toxic problems with the grout for water proofing.

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

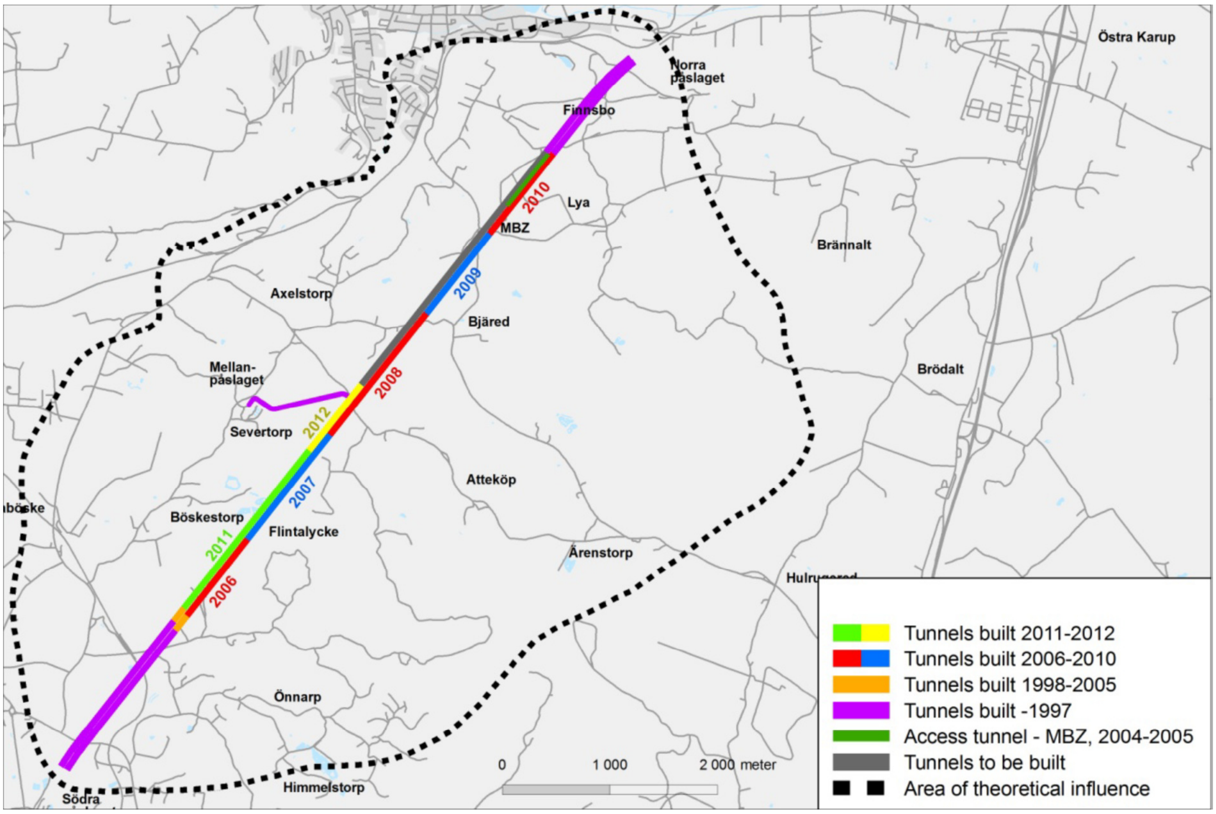

Figure 5. Sequence of tunnel construction. The northern and southern adits were initiated during the 1990's, primarily through drilling and blasting technique. Construction of the eastern tunnel tube through TBM technology was carried out during 2005 to 2010. Construction of the western tube with TBM commenced in 2011.

Study area

The investigated area covers 2 km^2 of pastureland, wetlands and woods on top of the tunnel stretch. The area belongs to the Vadebäcken catchment area, and is dewatered through two smaller streams going in a southwesterly direction; Böskestorpsbäcken and, to some extent, Krogstorpsbäcken.

Basically the area is composed by two enclosed pastures divided by a dirt road going in a north-easterly/south-westerly direction. Two small streams, one from each pasture, confluence in a point south of the road to form the stream Böskestorpsbäcken.

Vegetation, hydrology and streams

Part of the northern pastureland is covered by a continuous bog, watered by small, scattered bogs outside enclosures for cattle (UJ296, MK60). In the low-laying part of the study area a ring-shaped pond has been constructed that separates the bog from the higher and drier pasture to the south-west, where the stream Krogstorpsbäcken originates from a spring (UJ345, Y46). Another stream is running from the ring-shaped pond (P03) towards the south, exiting the pasture in a covered drain leading to the confluence with the stream from the southern pasture, finally forming Böskestorpsbäcken (P36).

The larger area of the southern pasture is dry. The north-eastern part, however, is connected to a vast wetland (mainly marsh, with or without tree vegetation) extending towards the border of the calculated influence area for the tunnel. A small stream has its source here (Y44). Further down in the catchment, it enters a covered drain passing four ponds in a flat area close to one of the monitored deep drilled boreholes in the bedrock (BP08). In the south-west the ground slopes from a hill (MK56) into a marshy wood where the stream exits the pasture and meets the stream from north (P36), to form Böskestorpsbäcken (P37).

Monitoring and instrumentation

A large number of transducers have been installed by Trafikverket to measure groundwater levels in boreholes in the bedrock. For most locations, Schlumberger brand Divers have been used in combination with Geawelltech brand Checkpoint communication systems. Levels have also been measured manually through the use of water level meter tapes, these measurements have been carried out at a monthly interval primarily to monitor the function of the transducers (Björkman, personal communication).

Trafikverket has set forth a monitoring program for hydrological conditions as well as water chemistry during the construction phase in order to comply with regulations. The collected data has been stored in a database. The extent of monitoring has varied depending on assessed impact from tunneling (Banverket, 2008).

According to the monitoring program, sampling of bedrock groundwater for chemical analysis was carried out before the construction with TBM affected a certain area with the purpose of collecting reference data. The groundwater was sampled during the construction phase at locations that were assessed to be affected by the construction activities based on changes in groundwater level. During construction of the western tunnel tube, the sampling frequency generally is two times per year. Within the framework of this study, the sampling frequency of the monitoring area was increased to twice per month during the period April 2011 to December 2011, during the spring of 2012 sampling of bedrock groundwater has been carried out on a monthly basis. The sampling frequency for surface waters was increased from once to twice per month. It was assessed by the research group that the monitoring within this monitoring program was sufficient for the project presented in this paper. In addition, one shallow filter well in the overburden was sampled on two occasions. On the third occasion, the filter well was observed to be dry, and the sampling series was discontinued.

The bedrock groundwater was sampled through the use of a submersible pump, purging was used to collect samples that are representative for the entire open borehole length. Measurements of pH and electrical conductivity were carried out in the field. Samples were collected in plastic bottles, the samples were kept refrigerated and were delivered to the laboratory for appropriate handling on the day of sampling.

The hydrochemistry of the groundwater in the bedrock was also monitored through iterated borehole loggings within the framework of this study. The device used for the logging included a Troll 9500 Water Quality Instrument that was equipped with sensors for pressure, temperature, pH, electrical conductivity, oxygen, Eh and chloride. During the loggings, the instrument measured and registered the values for the parameters with two seconds intervals.The loggings were carried out through manually and cautiously lowering of the probe to the bottom of each borehole. Measurements were carried out on five occasions during the period April to December 2011.

Geological and Hydrogeological conditions in the study area

The bedrock of the study area is geologically heterogeneous, mainly consisting of gneiss, with several small fault zones, amphibolite and dolerite dikes. In some parts it is highly hydraulically conductive.

The studied area is hydrogeologically confined towards the south by a wide and highly weathered weakness zone followed by a 150 m wide amphibolite, mentioned as SRZ in Figure 8. Towards the north, a dolerite dike constitutes hydraulic boundary. The dolerite dyke cuts through the investigated area and divides it hydrogeologically into two more or less separate aquifers: the Skeadal-Flintalycke aquifer and the Flintalycke Norr aquifer.

Both aquifers consists mainly of relatively competent rock with moderate groundwater flow. Some areas of open fractures and contact zones towards minor dolerites carry more water. The dolerite dyke in between is almost completely impermeable at tunnel level, where it acts as a hydraulic boundary. Closer to the surface, however, the dolerite is more fractured, allowing certain contact between the aquifers. All hydraulic boundaries are negative.

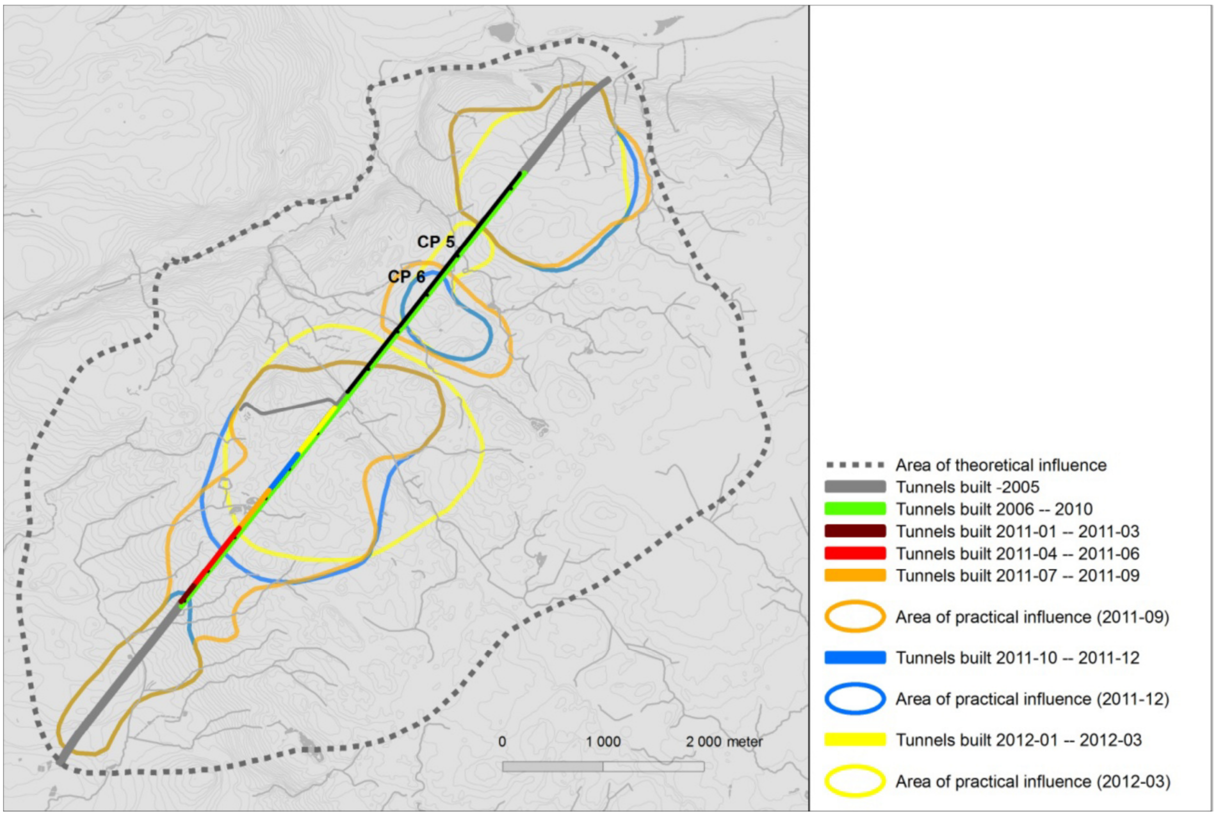

Figure 6. Influence areas to the tunnel from during the period when construction was carried out in the vicinity of the study area.

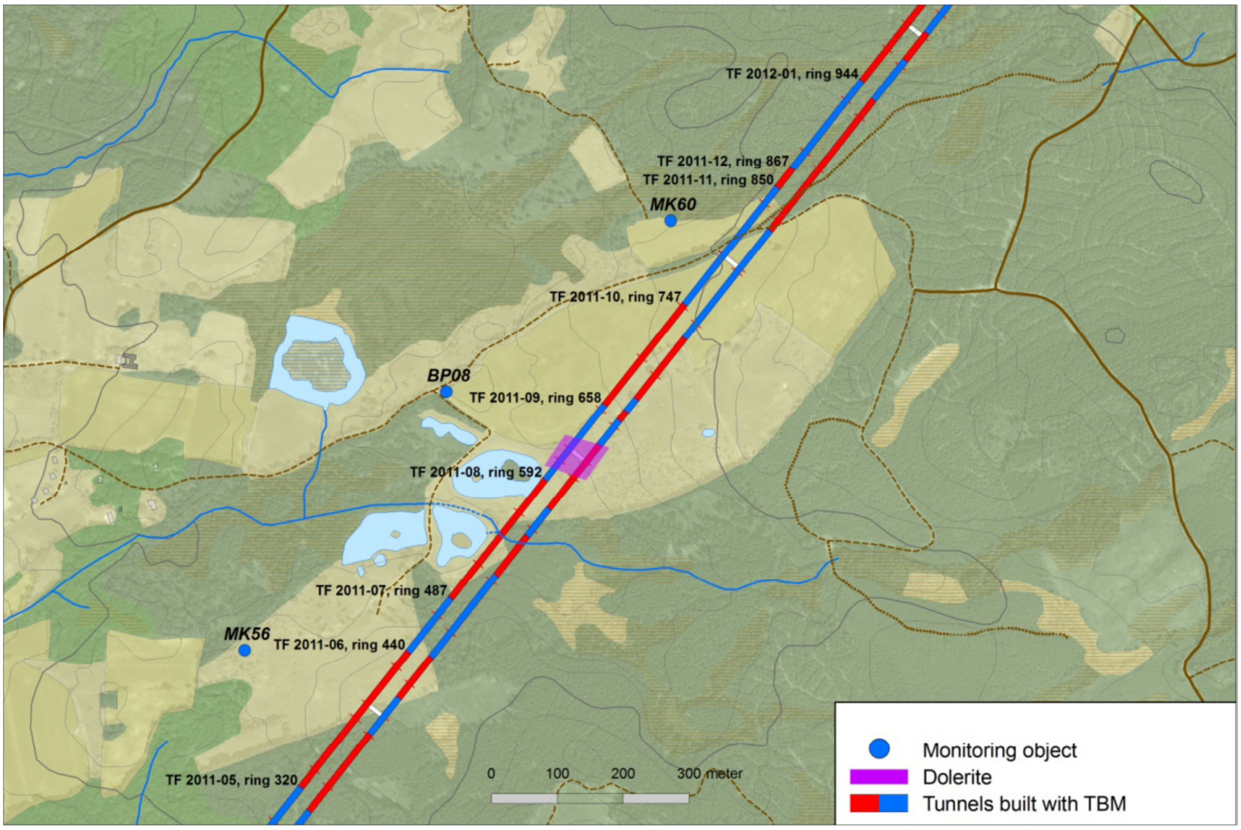

Figure 7. Chronology of tunneling in the vicinity of the study area. The two tunnels were constructed in a northeasterly direction.

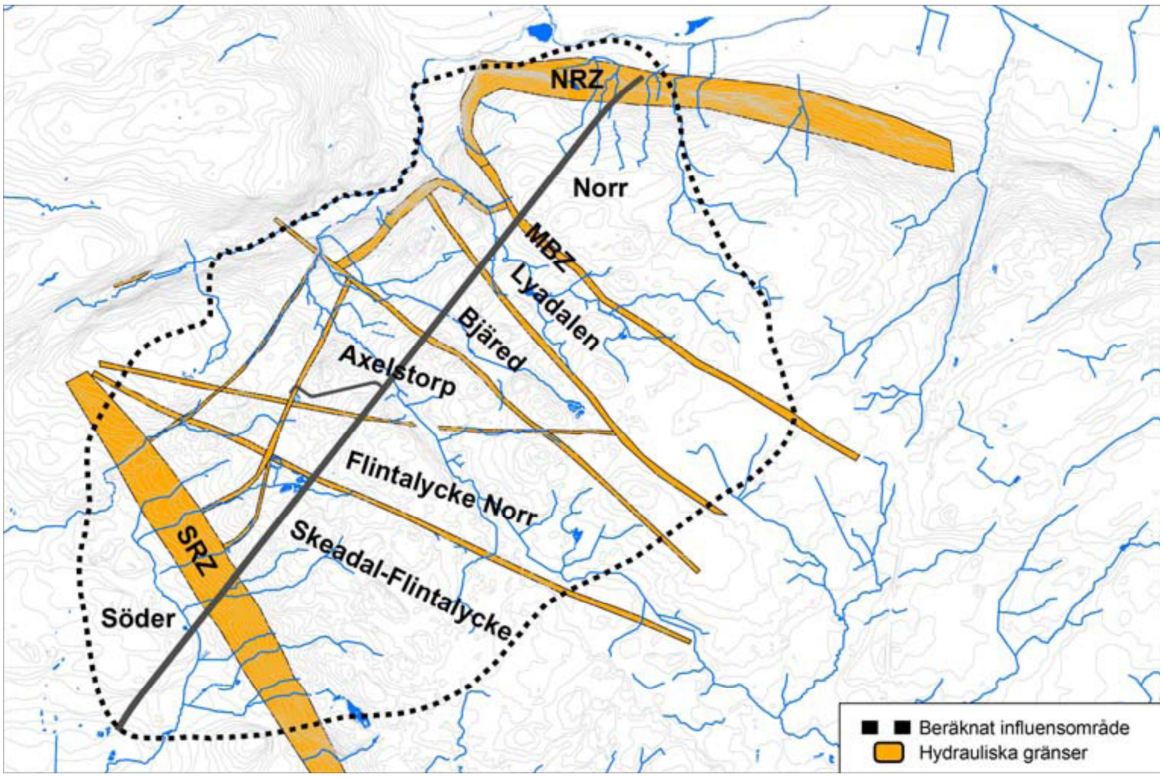

Figure 8. Hydraulic boundaries on the hallandsås ridge. All boundaries are negative comprising dolerite dikes or fracture zones with clay-altered core.

In the topographically lower part of the studied area, around the ponds, the permeable soil are well connected to the rock aquifer and the water pressure level of rock groundwater higher than that of the soil groundwater in unaffected conditions, hence posing as a groundwater discharge area. The response to drainage by the tunnel is rapid and appeearent.

Hydrological impact from the production on the studied area

Leakage into a tunnel may lead to a drawdown of the groundwater levels in the vicinity. The extent of the drawdown, in terms of area and depth, is governed by the influx of water to the tunnels, the hydraulic properties of the rock, the rate of the groundwater recharge and the leakage into the aquifers over boundaries (Olofsson, 1991).

If the influx to the tunnel is kept relatively constant, it is balanced by the recharge and leakage to and from surrounding aquifers. In this case, the drawdown keeps a constant extension; the ground water levels in adjacent wells stabilize at equilibrium and stationary conditions are reached.

The impact of production of the Hallandsås main tunnels on groundwater levels of the bedrock followed a general pattern. The groundwater level in a borehole would decrease as the TBM head approacheed, starting as the TBM made contact with connected waterbearing fractures. At the point where the TBM is at its closest to a certain borehole, the groundwater levels would generally be at their minimum levels. Provided the tunnel is successfully sealed by the concrete lining, the level would start to recover once the TBM has passed. The registered groundwater levels in the boreholes provide a measure of the drawdown in the rock aquifer during the passing of the TBM. In Hallandsås, theory coincides with practice so a well closer located to the tunnel line generally shows larger drawdown than a well at a further distance. In higly fractured rock volumes with high hydraulic conductivity and effective contact with the tunnel through water bearing fractures, the impact area is larger than in rock volumes with reverse conditions.

The drawdown and recovery processes were also being affected by the variation of production methods. Closing/pressurizing running mode of the TBM, pregrouting, backfilling and barrier construction resulted in decreasing the influx of water to the tunnel front, this resulted in rapidly recovering groundwater levels in the surrounding aquifer. Particularly the pressurizing/depressurizing of the TBM cause anobservable response on the surrounding aquifer. Groundwater levels are also strongly affected by the TBM passing hydraulic boundaries between aquifers.

If the conductivity between rock and soil is sufficient, a drawdown of rock groundwater can cause a local drawdown in soil, by draining the soil groundwater into the rock aquifer. The degree of leakage is determined by the hydrostatic pressure level difference between the rock groundwater and the soil groundwater. In areas with permeable soils that are well connected to the rock aquifer and where the water pressure level of rock groundwater is higher than that of the soil groundwater, the impact of a drainage from a tunnel is much stronger. Such is the case for part of the studied area.

MK56
Percussion drilled.
Location:
At tunnel length 814 m (ring 370w).
⊥ **Distance from tunnel:** 190 m.
Strike/dip: Vertical.
Overburden:
Till, 7 m (12 m grouted casing).
Rock type: 123 m gneiss
Fracture minerals:
Not mapped. In gneiss at a distance from basic intrusions, commonly clay and calcite.

Below is a description of the course of production events and their impact on the studied area. As the TBM starts in the south, excavating towards north, this is the order in which they are described. The lengths refer to the start point of the concrete lining (ref till figur).

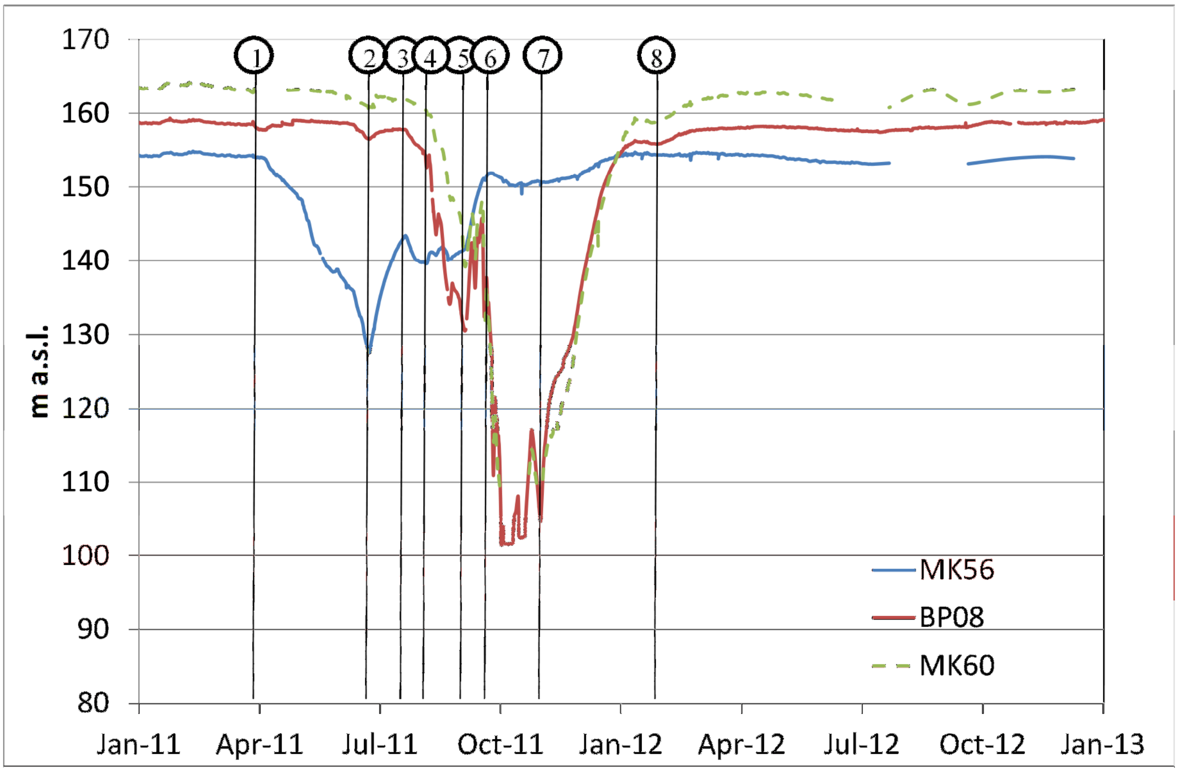

Figure 9. Groundwater levels in three monitored boreholes in the bedrock within the study area. One of the boreholes (MK56) is located to the south of the dolerite dyke

Impact of TBM production through the southern aquifer

April 2011 ①

Following the construction of the main tunnel through the southern hydraulic boundary of the studied area, the rock comprise relatively competent gneiss. The southernmost of the monitored boreholes, MK56, is located in this area. Hydraulic conductivity in this geological setting is expected to be high in all directions, despite the relatively competent rock quality. However, this borehole is located in rock that has less hydraulic contact with the tunnel compared to the other two boreholes.

As the TBM entered the southern aquifer, the groundwater level in MK56 were affected. There was a minor but visible impact on the northern aquifer as well (1), since the otherwise negative hydraulic boundary between the two aquifers is leaky at shallow depths .

At 785 m (ring 357w), the tunnel entered a 70 meter stretch comprising amphibolite dikes and veins in a complex pattern. Being overall of good quality, it is divided midway by an approximately 25 m wide fault zone.

On the surface, the unusually dry conditions during the first two months of production (March and April, 2011) added to the impact from the groundwater drawdown. When May comes with more precipitation, the southern tributary from the wetlands still runs dry during days without rainfall. Continuous irrigation of Böskestorpsbäcken was started at June 15 2011.

June-July 2011:②③

After the construction of a drilling chamber for performing service on the TBM head, the production made a planned maintenance stop. To ensure dry working conditions, a backfilling barrier was built before the excavation of the chamber, thereby sealing water conducting features in contact with MK56 (2). The groundwater levels recovered until the production resumed (3). The groundwater of both aquifers were affected. At section 1120 m (ring 510w) the tunnel passed a 4 m-wide segment of dolerite followed by almost 200 meters of gneiss interspersed with amphibolite veins and dikes.

On the ground surface, the southern pasture was affected, particularly the ponds and the wetlands. The artesian discharging water by the ponds seized, and the water levels in the ponds were sinking . The groundwater levels in the wetlands to the east were lower than normally, but still moist at the surface due to high rainfall. There was therefore no visible impact. The pond in the northern pasture was unaffected.

August 2011: ④

At 1144 m a backfilling barrier was built and the drawdown of groundwater in the southern aquifer is stopped. Short term recovery in the northern aquifer (4).

Impact of TBM production through the northern aquifer

At 1329 m (ring 604w) the tunnel reached the primarily negative hydraulic boundary between the two aquifers of the studied area. The boundary comprise a roughly 55 m thick dolerite, dry at tunnel level. The studied well BP08 was drilled through the northern contact between the dolerite and the gneiss to the north.

September 2011: ⑤⑥

The TBM entered the highly fractured contact zone between gneiss and dolerite, located north of the dolerite dyke, and encountered high water influx. Once entered the massive dolerite, a backfilling barrier was built, which allowed the groundwater in the southern aquifer to recover (5). The level in the northern aquifer recovered temporarily.

BP08

Partly core drilled, partly percussion drilled.

Location:

At tunnel length 1311 m

⊥ **Distance from tunnel:** 190 m.

Strike/dip: 35/80

Overburden:

Till, 4 m (7 m grouted casing).

Rock type:

90 m dolerite,followed by interspersed gneiss and amphibolite, gneiss dominating the deeper parts of the borehole.

Fracture minerals:

Not mapped. In gneiss at a distance from basic intrusions, commonly clay and calcite.

The northern contact, between the dolerite and the gneiss/amphibolite of the northern aquifer, is highly fractured and hydraulically conductive. The probe drillings yielded water (6), which caused a quick drawdown in the northern aquifer. The southern aquifer, however, stayed unaffected, protected by the backfilling barrier in the waterproofing system of the tunnel. Along this section, the tunnel was built using continuously repeated cycles of (consecutively) excavation, backfilling barrier construction and pregrouting.

On the surface, the ponds in the southern pasture became almost completely dry. The water level in the pond in the northern pasture was visibly affected. However, the unusually intensive rainfall mitigated the impact on the ground waters as well as the surface waters. The period was characterized by large groundwater recharge, saturated soils, high runoff, and consequently generally an abundance of water in the ponds and streams. As the flow rate in the affected

Böskestorpsbäcken is immediately depending on the rainfall due to absence of discharging groundwater, it is continuously irrigated (3,5 l/s). Three small ponds in the eastern part of the southern pasture seem not to be affected according to ocular monitoring.

November 2011: ⑦

Finally, at 1650 m (ring 750w), a backfilling barrier was built (7) that effectively reduced the water influx from behind the lining into the tunnel, and hence allowed the groundwater levels in the studied aquifers to recover. In the Hallandsås area, November (over a period of 30 years) is the month with highest rainfall according to measurements carried out 1961-1990. However, during the study period, the rainfall for November was less than normal. The rainfall was one third of the normal, and the wetlands and ponds of the studied area became dry.

January 2012: ⑧

Further north, the rock is moderately (or less) hydraulically conductive, hence, pregrouting was not necessary and few backfilling barriers were constructed. The rock mass consists of gneiss, with an intruded amphibolite dike, slightly wider than the tunnel, and almost parallel to the tunnel. When the tunnel front finally left the dike, it continued through competent gneiss interspersed with irregularly distributed amphibolite dykes or veins. In this rock volume, the most northerly of the studied boreholes, MK60, is located.

The rock volume with interspersed gneiss/amphibolite stretch ends in a fractured and slightly weathered contact zone towards a 20 meter thick dolerite dyke at 2077 m (ring 944w). The dolerite dyke acts as the northern hydraulic boundary for the studied area (8).

MK60

Location:

At tunnel length 1729 m (ring 786w).

Strike/dip: ?/?

Overburden:

Deposit till and heavily fractured rock (alternating gneiss and amphibolite) covered by 42 m grouted casing.

Rock type:

Alternating gneiss/ (garnet) amphibolite continues until full depth of 160 m.

Fracture minerals:

Commonly chlorite, often in thick layers, and calcite. In adjacent wells as well as in the eastern tunnel, relatively large amounts of pyrite was encountered.

When the construction through the northerly dyke was completed, the groundwater levels of the southernmost part of the studied area were recovered as presented in Figure 9. In the southern pasture around the ponds, a few meters lack for complete recovery of the groundwaters. On the ground surface, the wetlands are still affected, but the ponds are slowly filling.

The construction through this section occured at a time period with less precipitation than normal (compared to averages for 1961-1990). After the TBM passage and the completion of the backfilling barrier between the tunnel and the surrounding rock, the five bigger ponds on the ground surface (inkluderas viltvårdsdammen?) were still affected, but the groundwater levels gradually recovering. By early February 2012, MK56 was fully recovered and the levels in the other two boreholes were rising. The wetlands are gradually recovering. The irrigation of Böskestorpsbäcken was discontinued on January 13, 2012.

Impact of construction of cross tunnels

Before the groundwater levels in the northern aquifer were completely recovered following the construction of the western main tunnel, the construction of two cross tunnels at sections 440 m and 1720 m was initiated in May 2012. By October 2012, groundwater levels in both aquifers remained a few meters below the unaffected levels with a gradual recovery. Two other cross tunnels are located within the aquifers of the study area, however, the impact from those was less significant.

Results and discussion

The leakage to the tunnels caused changes to the hydrochemistry in the shallow systems as well as in the bedrock. However, the magnitude of the changes varied substantially based on the geological conditions, both in the shallow systems as well as in the bedrock.

Surface waters and shallow groundwater

The construction affected the hydrochemistry at most sampling locations in the Vadebäcken stream within the study area. The most common changes were caused by the temporary disappearance of baseflow in the stream (discharging groundwater) during the construction of the tunnels in the vicinity of the study area. For some of the sampling locations, there was also an influence from the chemical oxidation of wetlands, where notable results include SO_4 surges and temporarily decreasing pH. The Vadebäcken watershed consists of two main tributaries, one southern and one northern tributary.Furthermore, the southern tributary is divided into two forks that confluences water from a wetland with water from areas located to the east of the tunnel, as presented in Figure X.

Physical changes were also observed as a result of that the shallow systems locally becam dry. In the study area, the main wetland became affected during the construction periods. The construction of the eastern tunnel caused the surface level of the sphagnum peat wetland to subside and springs along the Vadebäcken stream to dry up (Björkman, 2010). Similar hydrological changes were observed during the construction of the western tunnel tube in 2011.

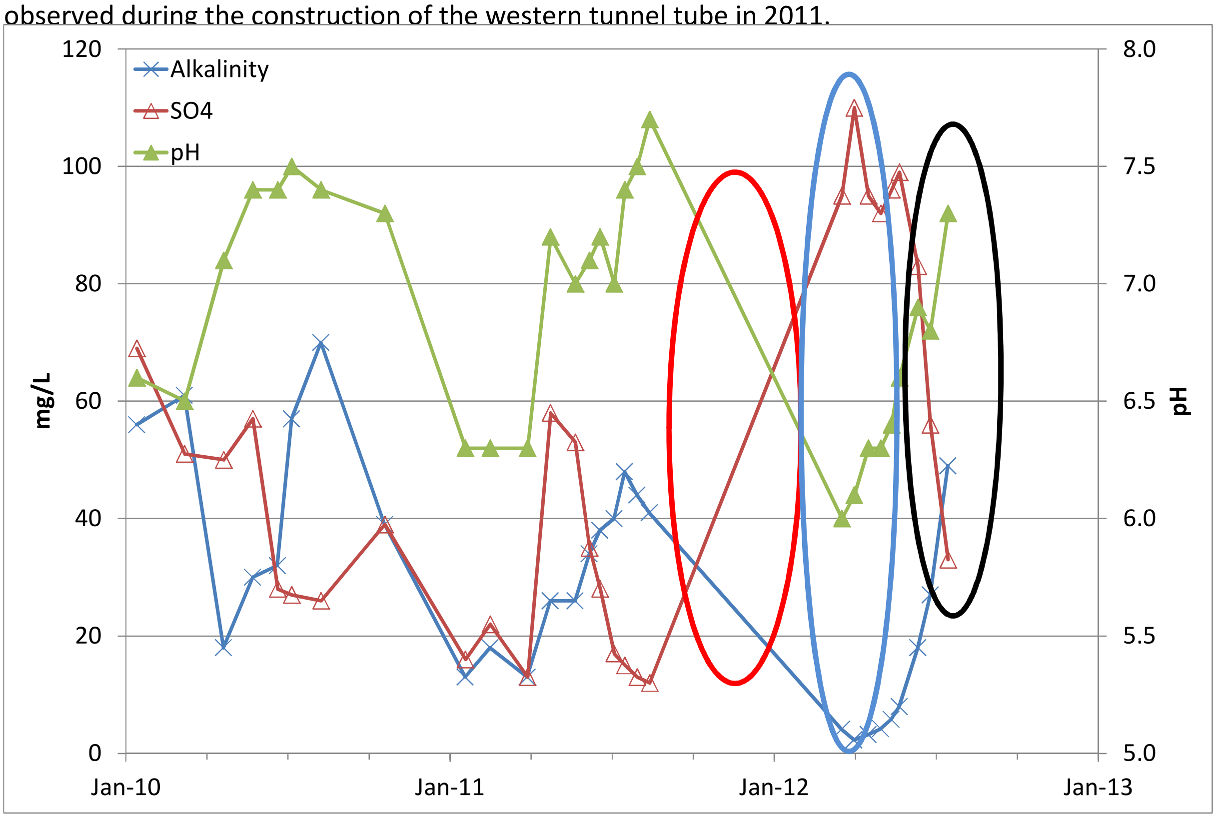

Figure 10. Alkalinity, pH and SO4 concentrations in sampling location PO3. The stram became dry during the autumn of 2011 and sampling was therefor not possible (1). In the spring of 2012, the flow recovered and an acid pulse with high SO4 concentrations and diminished alkalinity occurred (2). Hydrochemical recovery was observed during the summer of 2012 (3).

At Y44, the easternmost sampling location in the southern tributary, alkalinity was non-existing during the construction of the eastern tunnel tube in 2007 (Mossmark et al., 2010). During the period with recovered groundwater levels 2008-2011, alkalinity was again present. The disappearance of alkalinity was iterated during the construction of the western main tunnel as displayed in Figure 11. Furthermore, the concentrations of SO_4 were affected during the periods of tunneling. These changes were likely caused by the varying presence of baseflow (discharging groundwater) in the stream as well as by oxidation of a wetland located upstream from Y44.

During the summer of 2011, the baseflow decreased at Y44 and once again disappeared resulting in the absence of alkalinity as well as decreasing pH (marked with number 1 in Figure 11). In early 2012, the groundwater levels recovered and the baseflow became evident through reappearance of alkalinity. Meanwhile, the recovery of the groundwater levels in a previously dried and aerated wetland probably caused the release of S and hence increased SO_4 concentrations. Despite the SO_4 surge, the alkalinity recovered as well as pH because of the recovery of baseflow fed from discharging groundwater.

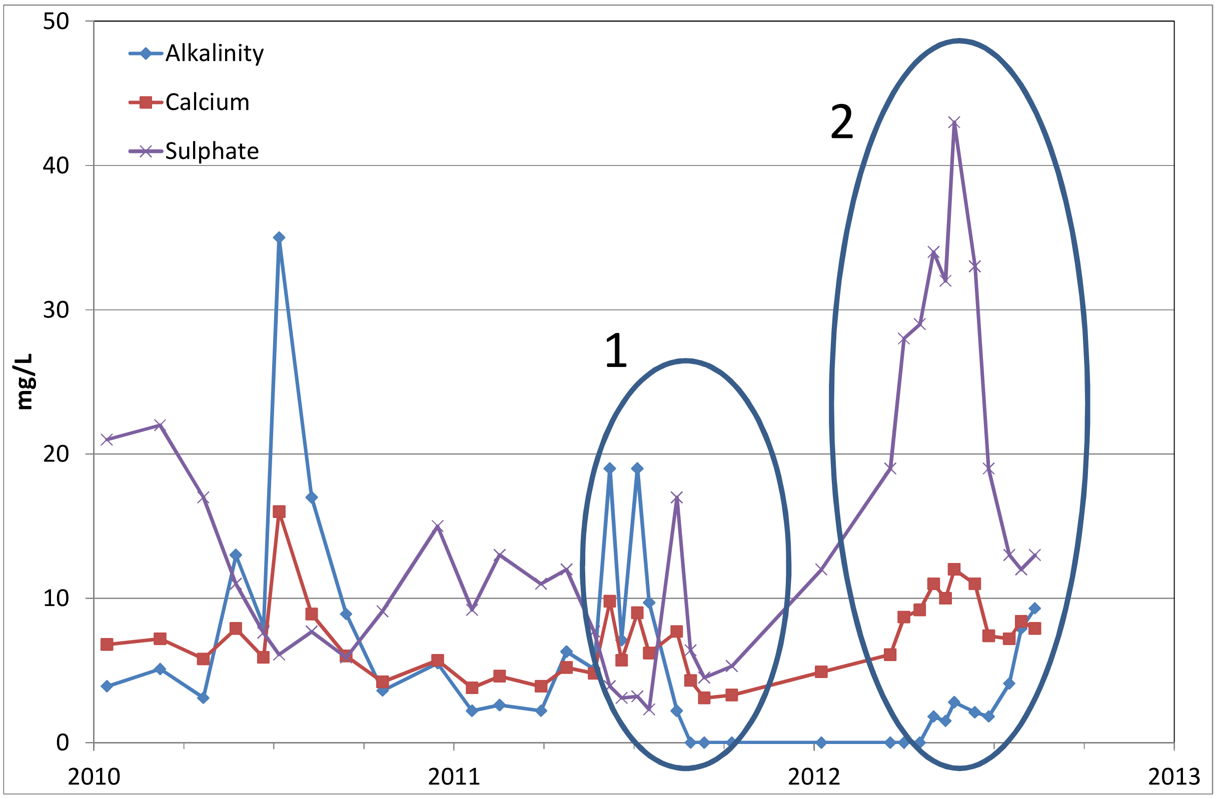

Figure 11. Alkalinity, Ca and SO_4 concentrations in the sampling location Y44. The baseflow disappeared during the summer 2011 resulting in the decrease

In the sampling location P36,situated at the confluence between the two forks of the southern tributary of Vadebäcken, the baseflow (discharging groundwater) likely disappeared during the tunnel construction through the area. Alike at Y44, alkalinity was absent and pH decreased during the 2007 as well as during the 2011/2012 periods of construction activities. However, the decrease of pH was more significant during the construction of the eastern tunnel tube in 2007 (pH 4.0) compared to during the construction of the western tunnel in 2011-2012 (pH 5.5). The concentration of SO_4 increased to approximately 60 mg/L during the spring of 2012,however, a recovery with decreasing concentrations was seen during the following summer and autumn.

In the sampling location P37, located downstream from P36 and Y44, pH became lower during the periods of tunnel construction works in the vicinity of the study area alike in the upstream locations. When comparing P36 to P37, the alkalinity concentrations were parallel during the periods of recovery. However, during the periods of tunnel construction, the alkalinity was higher in P37 than in P36. This indicates that the baseflow from discharged groundwater persisted in P37 during periods when it disappeared in P36.

In the sampling location Q14, located in the northern tributary of Vadebäcken, a weak SO_4 increase as well as a lowering of pH was observed during the spring of 2012. Similarly, in the sampling location UJ345, low pH values were measured during the spring of 2012. In this location, SO_4 surges were also observed during the recovery after the two periods of tunnel construction, in 2006/2007 as well as in 2011/2012. A SO_4 surge was also observed in late 2009, this may be caused by the natural hydrological cycle. Such surges have been noticed to commonly occur at the end of the dry season when water levels recover in wetlands that had previously become dry and aerated (Mossmark, 2008).

In the sampling location Y46, a SO_4 surge was observed during the spring of 2012 when the recovery of water levels occurred following the construction of the western tunnel tube. The surge in Y46 was less significant than in UJ345, this could be the effect of dilution. The alkalinity was observed to be parallel in UJ345 to Y46 during periods with less impact from tunneling construction albeit slightly lower in UJ345 compared to Y46. The alkalinity in UJ345 decreased during the periods with tunneling in the vicinity of the study area.

Shallow groundwater was monitored in filter well GVR892, however, samples were only successfully collected on two occasions. The well turned dry during the autumn of 2011 and sampling was therefore not possible. The measurments show increased SO_4, disappearance of alkalinity and a lowering of pH during the spring of 2012 compared to the summer of 2011. These changes were simllar to the findings in the nearby streams.

When discharge areas consisting of streams were being affected, this usually resulted in the absence of baseflow. Hydrochemical changes frequently comprised a lowering of the ionic strength including the temporary absence of alkalinity. For groundwater discharge areas comprising wetlands, the changes were more complex. The wetlands were affected by a lowering of the groundwater levels causing chemical oxidation. Wetlands comprise organic matter and include substantial pools of sulfur, some as inorganic sulfides that are available and may become dissolved as acids and SO_4.

Groundwater in the bedrock

The three monitored boreholes revealed hydrochemical properties that had been affected by the tunneling of the western tube, the changes were similar to those that were observed during the construction of the eastern tube. However, the hydrochemical conditions and their changes differed between the boreholes based on the geological conditions, with two of the boreholes exhibiting more significant changes for pH and major anions and cations.

The southernmost borehole MK56 revealed changes for the concentrations of Fe, Mn and SO_4 during the construction of the western tube. However, according to the observations the changes were smaller during the construction of the western tube (2011-2012) compared to during the construction of the eastern tube (2007). During the period with lowering of the groundwater levels in

MK56, the concentrations of Fe (Figure 12) and Mn decreased. This was likely caused by increased redox concentrations and thereby decreased solubility of Mn and Fe. The concentrations of SO_4 increased approximately 50 % during the recovery of groundwater levels, such changes may be caused by redox changes the changes to Fe and Mn with the resulting oxidation of sulphides int the bedrockalike. However, there may also be an influx of shallow groundwater from surrounding wetlands that were subjected to oxidation and thereby the release of SO_4.

Borehole loggings of redox potential and a number of other parameters were successfully carried out on five occasions in MK56. These results have been studied to correlate changes to redox dependent parameters as presented in Figure 14. The measurement results from December 2011 were deemed unreliable and have been omitted. The measurement results show an increasing redox potential from February to April 2011. The redox potential decreased slightly between April and July, however, redox potential again increased between July and August. During the autumn of 2011, a recovery could be seen. The observed redox changes coincide with tunneling activities in the vicinity of MK56. The measureable impact to the groundwater levels from the tunneling with TBM were initiated in late March 2011, this has likely caused increasing redox potential through the induced groundwater recharge. The decrease in redox potential in July of 2011 coincided with the recovery of groundwater levels during a planned standstill for maintenance work on the TBM. The redox potential once again increased after the tunneling works commenced in late July. The decreasing redox potential in October of 2011 is likely caused by the recovery of the groundwater levels after the completion of the waterproofing system of the tunnel in the vicinity of MK56.

The concentrations of Alkalinity, Ca and Mg paralleled those of SO_4 in MK56 as shown in Figure 13. The concentrations of those parameters increased during the recovery of the groundwater levels. Such increase could be observed during the recovery after the tunneling of the eastern tube in 2007 as well (Mossmark et al., 2010). During the construction of the western tunnel tube in the vicinity of MK56, pH was only slightly affected. A small decrease in pH could be observed from early 2011 to mid-2012.

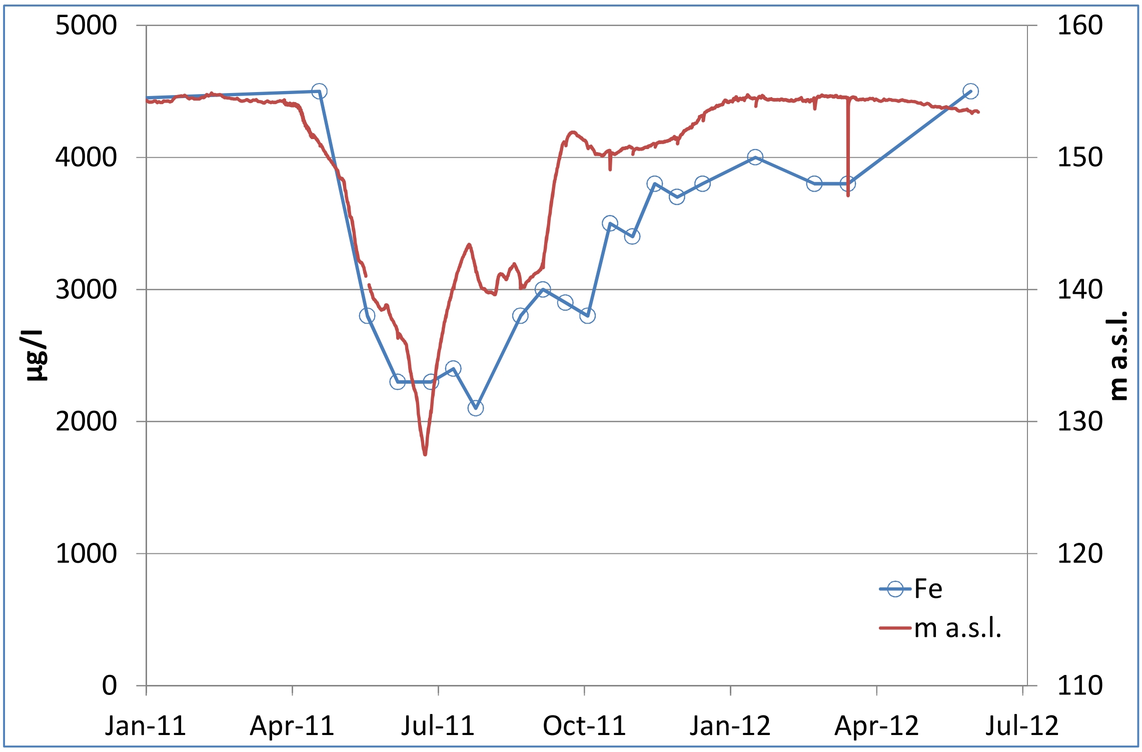

Figure 12. Concentrations of dissolved Fe and groundwater levels in borehole MK56.

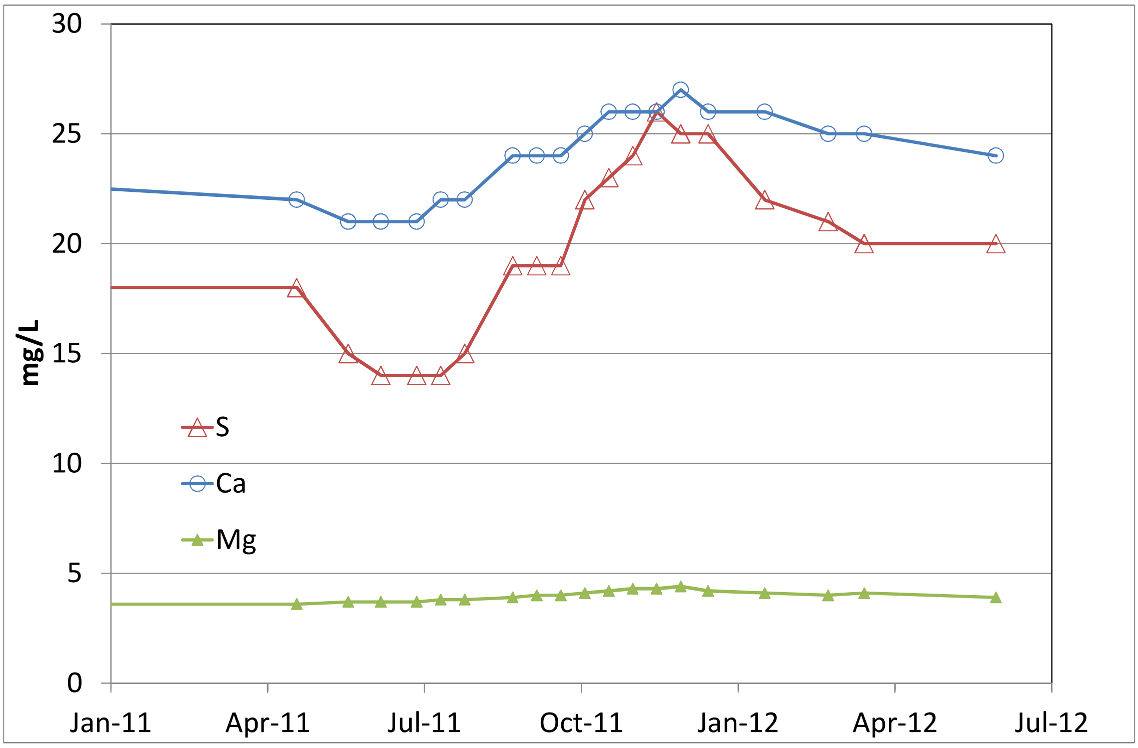

Figure 13. Concentrations of S, Ca and Mg in MK56. The concentrations increased during the recovery of the groundwater levels after the western main tunnel and its waterproofing system had been completed during the autumn of 2011.

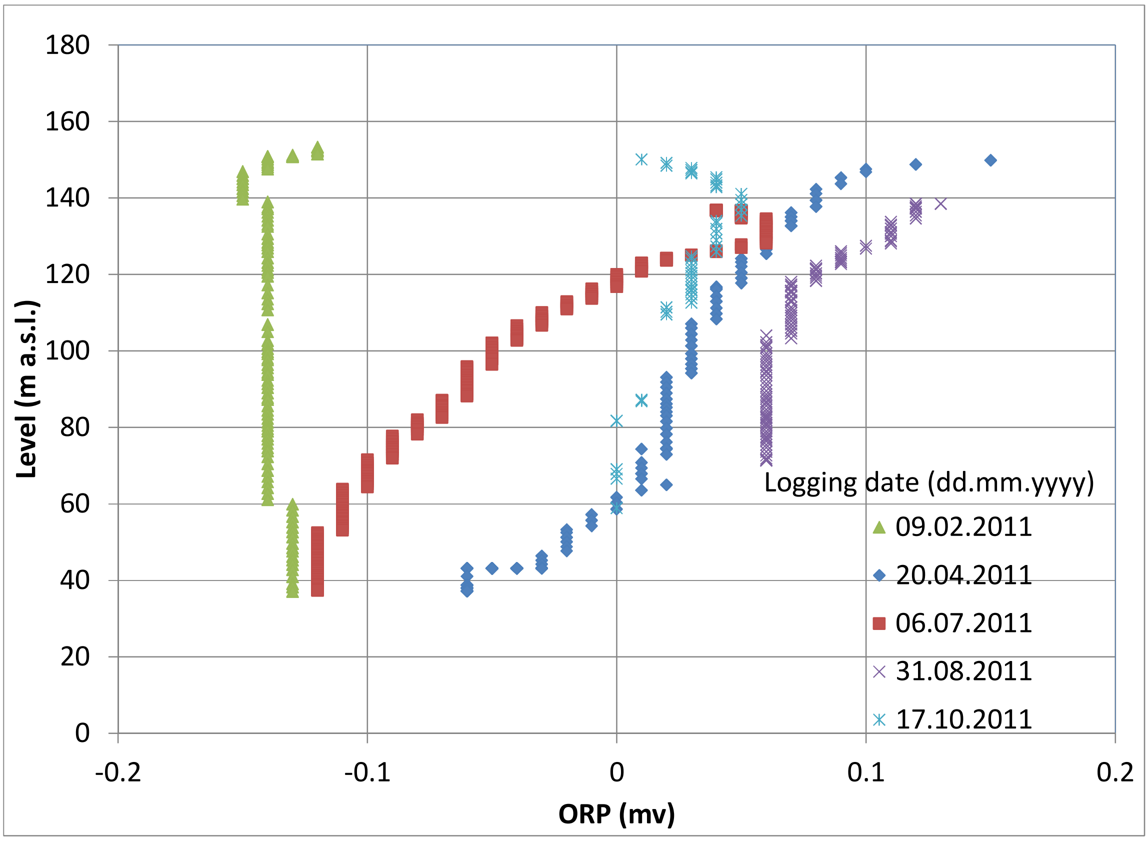

Figure 14. Borehole loggings in MK56, the results reveal increasing redox potential during the drawdown of the groundwater level. The redox potential decreased during the recovery of the groundwater levels in the autumn of 2011.

In MK56, TOC was not present before the construction of the eastern tunnel tube through the use TBM in 2007. Since the study area became affected by the construction activities, TOC has been persistently present with a brief peak during the construction of the western tunnel tube in 2011.

For the two other boreholes, BP08 and MK60, similar changes to the hydrochemistry were observed. The changes were more significant than in MK56 for several parameters that are of concern for the durability of construction materials in a tunnel. The TOC concentrations increased in BP08 and MK60 during periods of lowering of the groundwater levels that had been caused by the construction of the eastern (2007) and western (2011-2012) main tunnels. Before the construction of the eastern tunnel tube in the vicinity of the study area during , the concentrations of TOC were below the detection limit in both boreholes. After the two passages of the TBM , the concentrations of TOC remained detectable albeit lower than during the periods construction activities nearby. The changes for TOC in BP08 and MK60 were similar to those observed in MK56 were likely to be caused by increased groundwater recharge and thereby influence from shallow waters with higher organic content.

The decay (oxidation) of organic matter consumes oxygen and thus decrease the redox potential (Appelo and Postma, 2005). However, repeated borehole loggings that were conducted during 2011 in the two boreholes indicate that the impact from increased recharge of oxidized shallow groundwater countered and exceeded the effect of degrading organic matter. It is likely that the existence or partially unsaturated conditions in the bedrock groundwater with free access to oxygen became more common during the construction periods. Under such conditions organic matter is generally degraded without causing the depletion of oxygen, or processes causing the increase of

CO_2 in the groundwater or reduction of other dissolved elements or compounds. Figure 15 displays increasing redox potential in MK60 during the construction activities with similar results as in MK56.

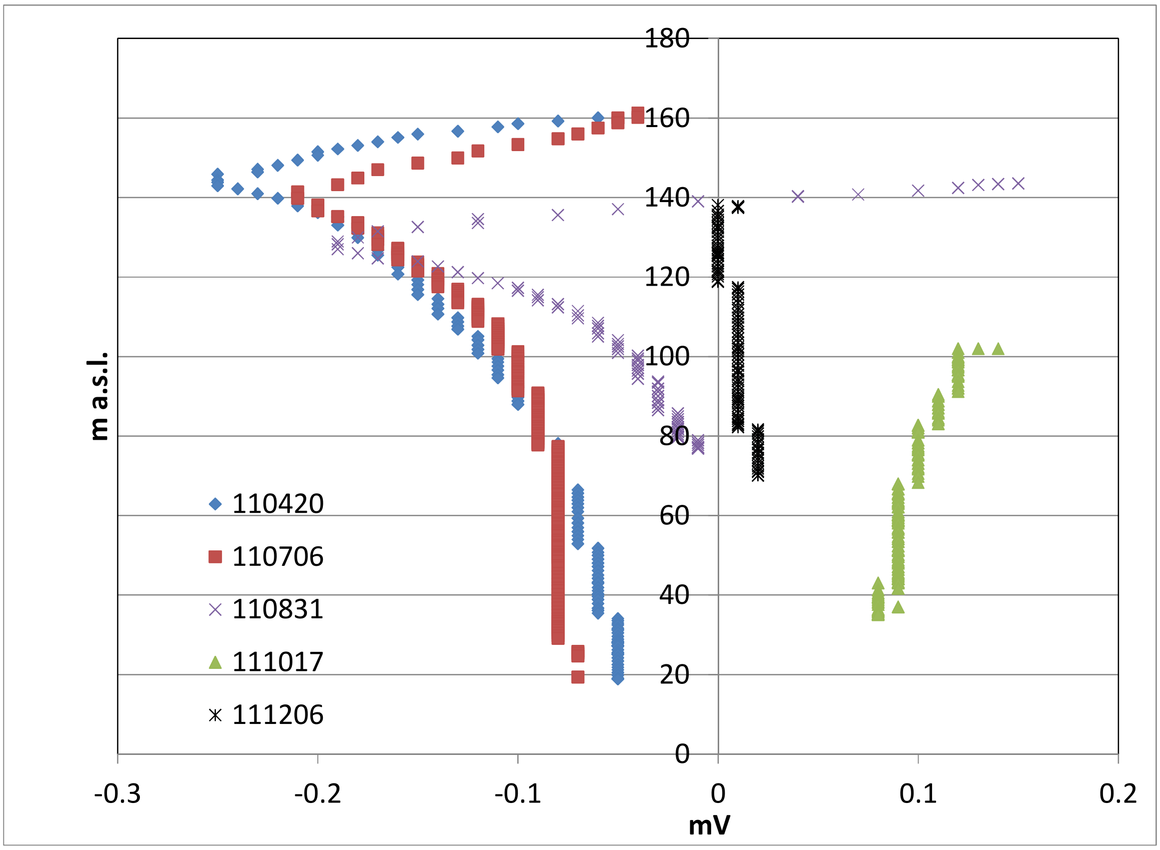

Figure 15. The redox potential increased in MK60 during the period of tunneling activities within the study area.

Before the construction of the eastern tunnel tube in the year of 2007, the SO_4 concentrations in BP08 were approximately 20 mg/L as seen in Figure 16. During the period when the groundwater levels recovered to near the unaffected levels, the SO_4 concentrations increased to more than 150 mg/L. After the recoverey to more stable levels, the SO_4 concentrations varied between 40 mg/L and 70 mg/L (mid-2008 to mid-2011). When the groundwater levels recovered after the construction of the western main tunnel through the study area, the concentrations increased to more than 200 mg/L. This episode was followed by a recovery for SO_4 with decreasing concentrations. Alkalinity and pH decreased during the episodes of high SO_4. A decreasing trend for those two parameters can be observed for the entire monitoring period from 2007 to 2012. The concentrations of the base cations Ca, Mg and Na, as well as the concentrations of Mn, paralleled those of SO_4.

Alike BP08, the concentrations of SO_4 in MK60 also increased more than fivefold during the recovery of the groundwater levels following the construction of the main tunnels through the area. During the period with lowered groundwater levels during the tunneling of the western tube in the vicinity of the study area (2011-2012), Fe concentrations in the two boreholes decreased. The concentrations recovered simultaneously with the groundwater levels.

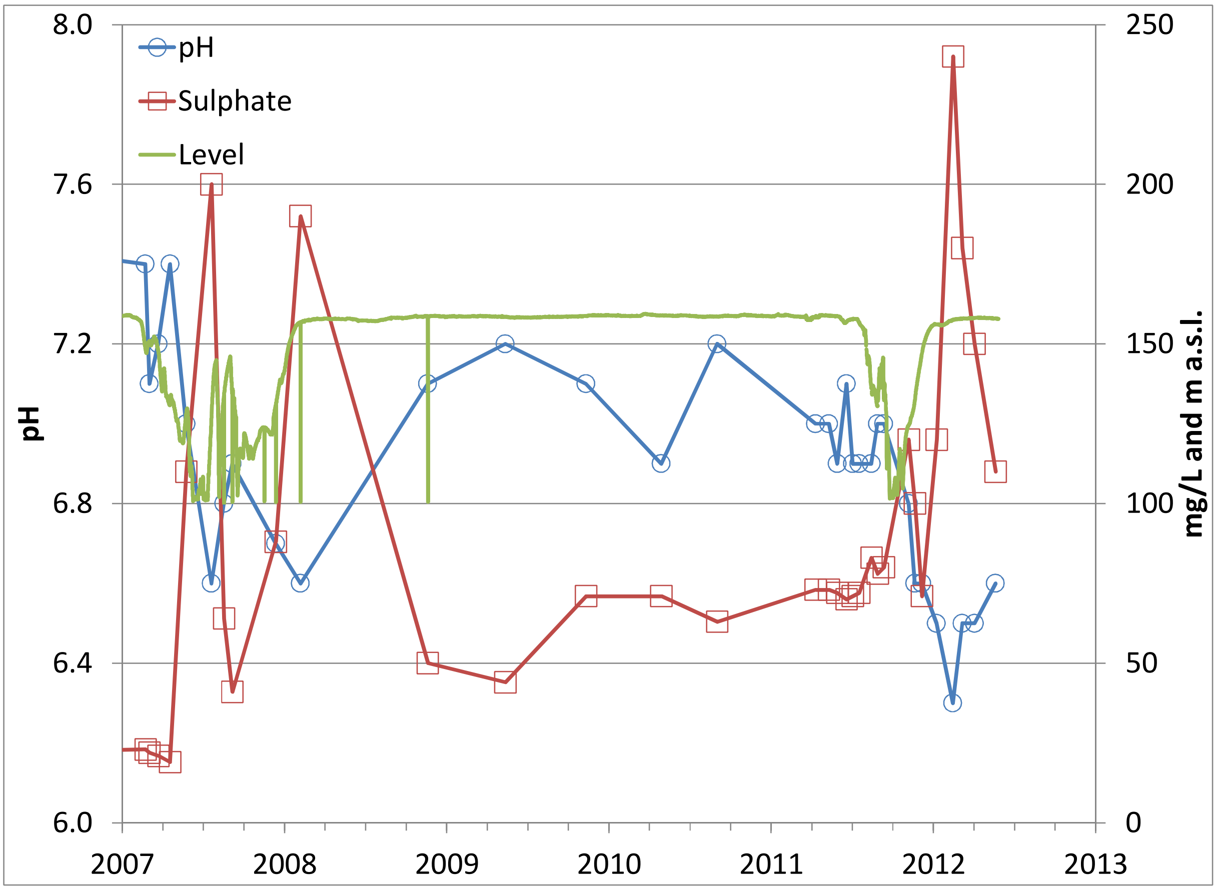

Figure 16. SO_4, pH and groundwater level in borehole BP08 during the construction of the two tunnel tubes with TBM.

The increased SO_4 concentrations in BP08 and MK60 are likely caused by sulfide oxidation, logs from the drilling of the boreholes indicate the presence of pyrite in the bedrock (Sangskär, 2010). Hence, this would, along with a decrease of Fe concentrations, confirm the measured increase in redox potential. The observed changes to redox are likely to be caused by increased groundwater recharge. The Ca and Mg concentrations, as well as Mn concentations, paralleled those of SO_4 in MK60. It is, however, difficult to isolate the results from processes occurring in the bedrock from those occurring in the overburden. According to Giblin and Wieder (1992), sulfide minerals are abundant and availale in sphagnum wetlands, similarly to fracture minerals.

The increased SO_4 concentrations caused a lowering of pH and alkalinity. Figure 17 reveals pH measurements from borehole loggings in MK60. The results show a general alkaline environment in the upper parts of the borehole. The loggings that were conducted on August 31 and December 6, 2011 were carried out with equipment that had limited pressure interval. Therefore, only the upper part of the aquifer could be logged on those occasions. The two initial logging occasions exhibitied pH of approximately 6.5 at levels below 80 m a.s.l.. The three following measurements revealed lower pH of approximately 6.0 at levels below 80 m a.s.l..

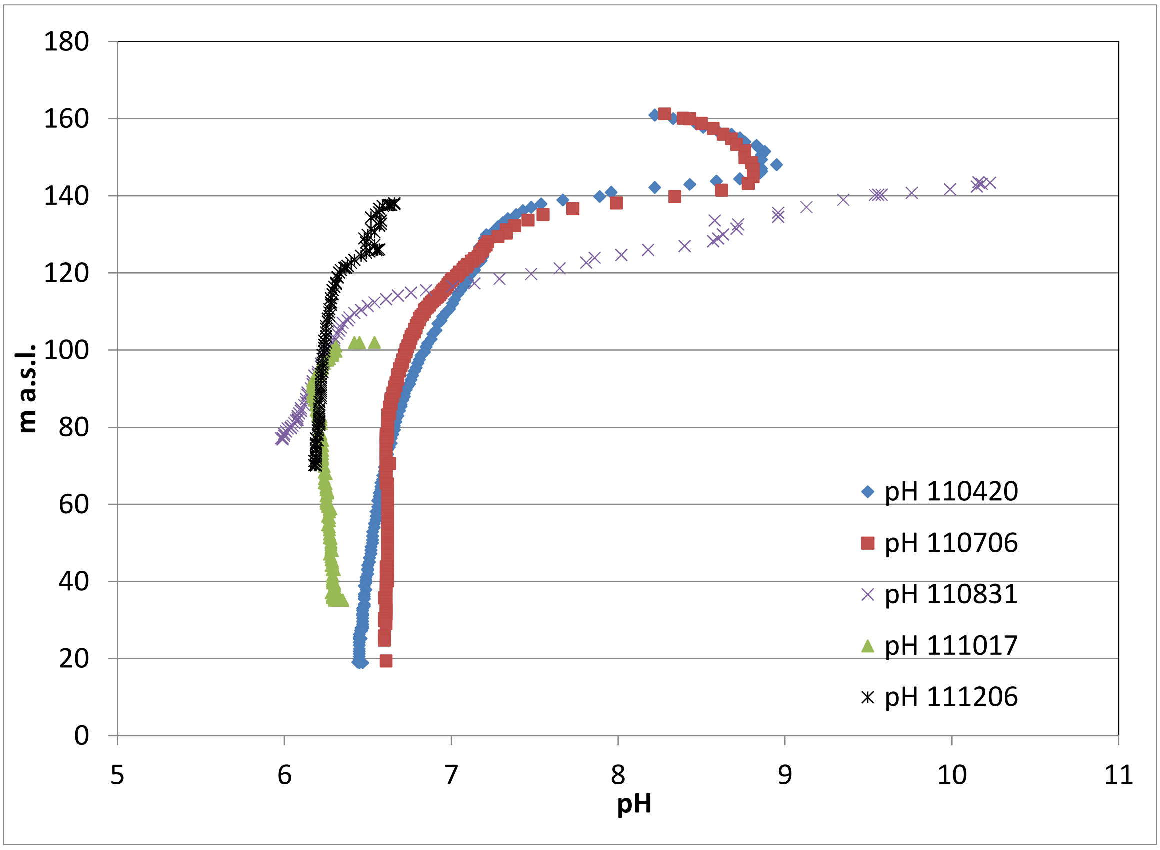

Figure 17. Logging of pH in borehole MK60. The pH decreased during the construction activities in the vicinity of the borehole.

Figure 18 shows a bar plot displaying the major anions and cations for groundwater in BP08. The concentrations of SO_4 increased during the recovery of the groundwater levels during early 2012. SO_4 became more prevalent compared to the other major anions, Cl and HCO_3. For the cations, Ca, Mg and Na, the concentrations increased along with the sum of anion. In contrary to the anions, the ratio between the cations remained fairly constant.

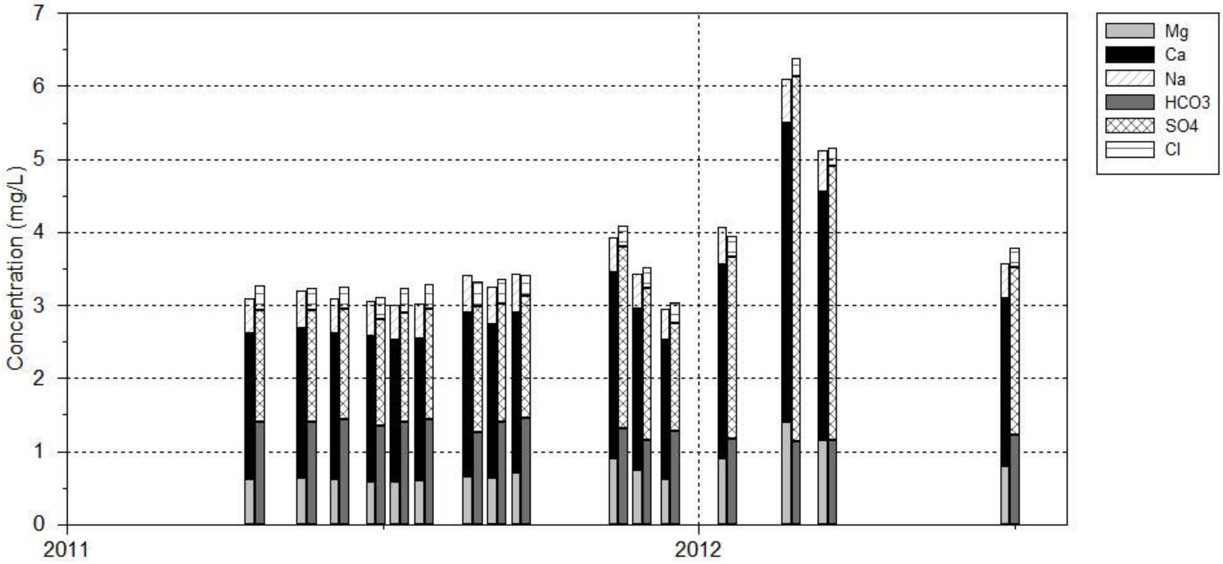

Figure 18. Bar plot showing changes for major cations and anions in BP08. Whereas, the most significant changes were for SO_4 among the anions. For the cations, the concentrations of Ca, Mg and Na increased proportionally during the recovery of groundwater levels in borehole BP08.

The results confirm results from previous studies that the geological conditions are of significant importance for the hydrochemical changes that occur during the constructional and operational phases of underground constructions. The borehole MK56 has been drilled through fairly homogenous rock and display primarily changes to redox and the solubility of Fe and Mn. BP08 intersects a contact zone between a dolerite dyke and surrounding gneissic host rock and reveals more significant changes to SO_4, alkalinity, base cations and pH. The borehole MK60 revealed significant hydrochemical changes similar to those in BP08 despite not intersecting a major contact zone. Borehole logs show that thebedrock surrounding the two boreholes include the presence of pyrite, this is likely the main cause to the changes to SO_4, alkalinity, base cations and pH.

Implications for construction materials

The three monitored boreholes displayed different response to the construction activities. While borehole MK56 exhibited minor changes to most parameters that are of concern for the durability of steel and concrete, the changes in the boreholes MK60 and BP08 were more significant. In order to evaluate the implications for the construction materials, corrosion indexes have been calculated.

The Larson-Skold index (Larson and Skold, 1958) was established to assess the corrosivity of water in steel pipes. To calculate the index, the ratio between the sum of Cl, SO_4 and alkalinity (HCO3) as mEq is calculated. If the ratio is below 0.8, the water is considered as non-corrossive. If the ratio is between 0.8-1.2 it is likely that a corrosion rate that is higher than desired may occur. If a ratio greater than 1.2 is found, higher corrosion rates with an increasing ratio is being expected.

Figure 19 shows the Larson-Skold for the groundwater in the bedrock. Analogue to the results for the most hydrochemical parameters, little time-based variations were found for groundwater in the borehole MK56. The water in MK56 was non-corrosive according to the Larson-Skold Index. For the two other boreholes, a sharp increase could be seen at the time when the groundwater levels recovered in early 2012. Before the tunnel construction with TBM in the vicinity of the study area, the water was more corrosive in BP08 than in MK60. However, during the recovery of the groundwater levels post the construction of the main the western main tunnel, the Larson-SKold Index increased more significantly in MK60 than in BP08.

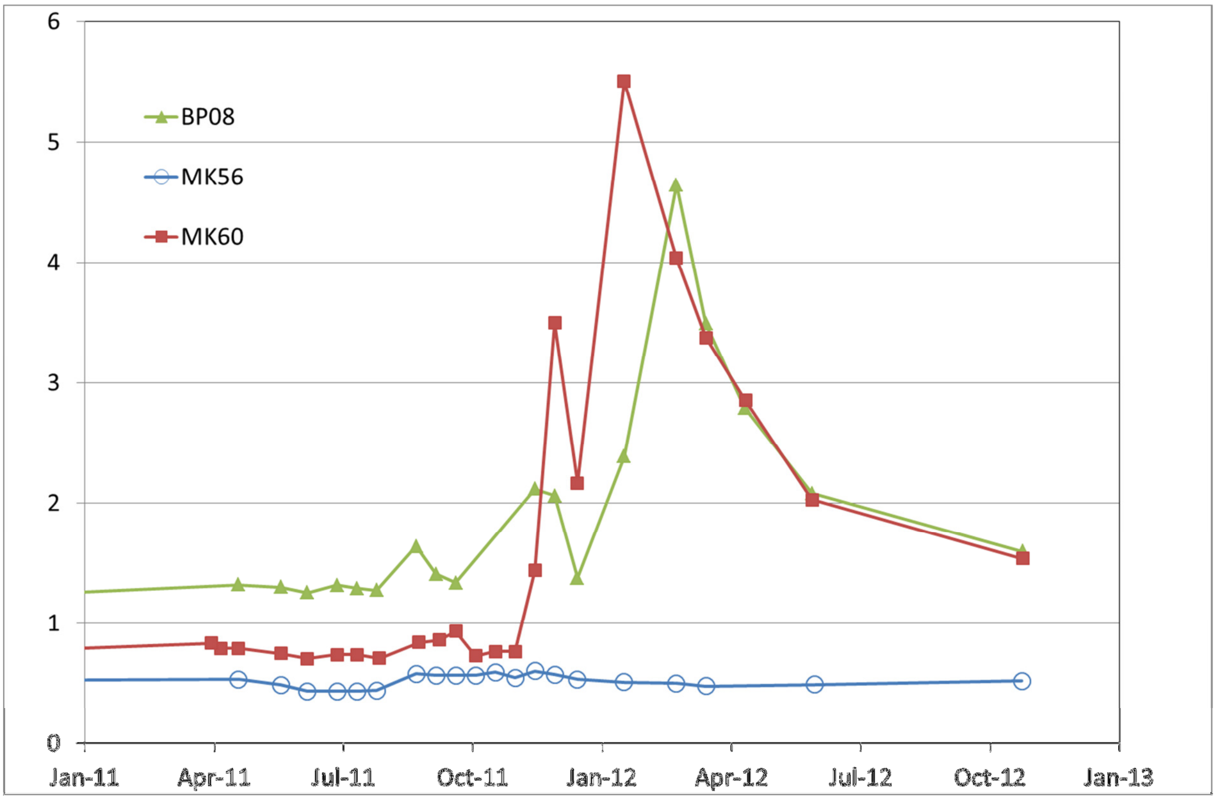

Figure 19. Larson-Skold Index for groundwater in the three monitored boreholes. The groundwater in two of the boreholes was assessed to have become more corrosive towards steel.

According to calculations of Ryznar's index as well as Langelier's index based on hydrochemical data, less variations than for the Larson-Skold Index were observed. However, the calculations confirm that the changes were more significant for BP08 and MK60 compared to MK56. Furthermore, they indicate a slightly less corrosive environment in MK56 compared to the other two boreholes. The calculations show that calcite formation is unlikely and that the environment, both before and during the period of construction activities, is slightly corrosive. Langelier index was between -1 and -3 while Ryznar index varied between 9 and 12.

Conclusions

The hydrochemistry of shallow waters as well as the groundwater in the overburden and in the bedrock became affected by the construction activities. The observed hydrochemical changes are the results of changes in water flow driven by the seepage into the tunnels and the chemical processes that were thereby induced.

For the surface waters, the main cause because of temporarily absence (or decrease) of discharging groundwater. This change is related to the seepage into the tunnel resulting in a lowering of the groundwater levels and changing groundwater discharge areas into recharge areas. The most important hydrochemical changes were:

- Lower ionic strength (diminished discharge)
- SO_4 surges from the wetlands
- Absence or lower alkalinity (combined/alternating effect of the above mentioned changes)

For the shallow waters, the magnitude of the hydrochemical changes varied between the sampling locations and was affected by the proportion of the relative decrease of discharging groundwater.

The hydrochemical changes to deep groundwater in the bedrock differed between the three monitored boreholes. The geological conditions were the most important factor causing the differencies. However, some results were universal for all monitored boreholes:

- Increasing redox potentials were observed in all of the three monitored boreholes during the drawdown of the groundwater level.
  - The solubility of Fe and Mn temporarily decreased.
  - Increased presence of organic matter.
    - Degradation(oxidation) of organic matter did not significantly reduce Fe or Mn into soluble species.
- Two out of three boreholes revealed significant hydrochemical changes. The two boreholes were installed in relatively fractured bedrock with the presence of pyrite. The hydrochemical changes were primarily caused by hydraulical connections with shallow waters and by the oxidation of pyrite. The changes included:
  - Increased SO_4 concentrations to levels more than fivefold the unaffected concentrations.
  - Lowering of pH and alkalinity
  - Changes to major cations
- One of the three boreholes revealed less changes to the major anions, cations and to pH. The concentrations of SO_4 increased approximately 50%. This borehole is penetrating gneissic rock with few fractures, hence the absence of contact zones and less hydraulic contact with shallow waters. Pyrite was not observed during the installation of this borehole.

According to calculations of corrosion indices, the groundwater in the two boreholes that revealed the most hydrochemical changes also became corrosive towards steel construction materials. The corrosivity decreased gradually along with the recovery of the hydrochemistry.

Acknowledgement

Financial support for the research presented in this paper has been granted by the Development Fund of the Swedish Construction Industry, SBUF. Trafikverket Hallandsås provided support on-site, invaluable for the success of this research project.

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