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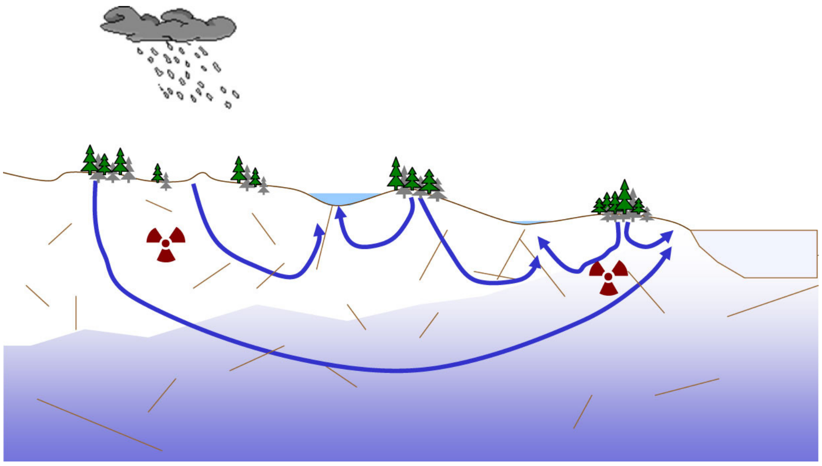
SSI:s granskning av SKB:s storregionala grundvattenmodellering för östra Småland

(SKB Rapport 06-64)

Björn Dverstorp



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SSI:s verksamhetssymboler

UV, sol och optisk strålning
Ultravialett (UV) strålning från solen och solarier kan ge både lång- och kortsiktiga skador. Även annan optisk strålning, främst från lasrar, kan vara skadlig. Vi ger råd och information.

Solarier
Risken med att sola i solarium är sannolikt densamma som att sola i naturlig sol. SSI har därför tagit fram föreskrifter som även innehåller råd för den som solar i solarium.

Radon
i inomhusluft står för den största andelen av den totala stråldosen till befolkningen i Sverige.Vi arbetar med riskbedömning, mätteknik och rådgivning till andra myndigheter.

Sjukvård
står för den näst största andelen av den totala stråldosen till befolkningen. Genom föreskrifter och tillsyn strävar SSI efter att minska stråldoserna för personal och patienter.

Strålning inom industri och forskning
Enligt strålskyddslagen krävs tillstånd för verksamhet med joniserande strålning. SSI ger ut föreskrifter och kontrollerar att de efterlevs, gör inspektioner, utredningar och kan stoppa farlig verksamhet.

Kärnkraft
SSI ställer krav på kärnkraftverken att strålskyddet för allmänhet, personal och miljö ska vara bra och kontrollerar fortlöpande att kraven uppfylls.

Avfall
SSI arbetar för att allt radioaktivt avfall tas omhand på ett från strålskyddssynpunkt säkert sätt.

Mobiltelefoni
Mobiltelefoner och basstationer avger elektromagnetiska fält. SSI följer utveckling och forskning för mobiltelefoni och dess eventuella hälsorisker.

Transporter
SSI verkar nationellt och internationellt för att radioaktiva preparat inom sjukvården, strålkällor inom industrin och utbränt kärnbränsle ska transporteras på ett säkert sätt.

Miljö
Säker strålmiljö är ett av de 15 miljömål som riksdagen beslutat om för att uppnå en ekologiskt hållbar utveckling i samhället. SSI ansvarar för att detta mål uppnås.

Biobränsle
från träd som innehåller cesium, till exempel från Tjernobylolyckan, är ett problem som SSI idag forskar kring.

Kosmisk strålning
Flygpersonal kan i sitt arbete utsättas för höga nivåer av kosmisk strålning. SSI deltar i ett internationellt samarbete för att kartlägga stråldoserna till denna yrkesgrupp.

Elektriska och magnetiska fält
SSI arbetar med risker av elektromagnetiska fält och vidtar åtgärder om risker identifieras.

Beredskap
SSI har dygnet-runt-beredskap för att skydda människor och miljö från konsekvenser av kärnenergiolyckor och andra strålningsolyckor.

SSI Utbildning
ska bidra till att tillgodose det utbildningsbehov som finns på strålskyddsområdet. Verksamheten finansieras genom kursavgifter.

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TITEL/ TITLE: SSI:s granskning av SKB:s storregionala grundvattenmodellering för östra Småland (SKB Rapport 06-64/ SSI's review of the Swedish Nuclear Fuel and Waste Management Co's (SKB) report on large-scale groundwater flow modelling for eastern Småland in Sweden (SKB Report 06-64).

SAMMANFATTNING: Denna rapport redovisar SSI:s granskning av Svensk Kärnbränslehantering ABs (SKB) fördjupade analys av storregionala strömningsförhållanden i östra Småland (SKB Rapport 06-64). Som stöd för granskningen har SSI anlitat två externa experter, Anders Wörman vid KTH i Stockholm och Clifford Voss från USGS i USA, vars rapporter redovisas som bilagor.

Granskningen har genomförts inom det samråd som SKB enligt ett regeringsbeslut håller med SSI och Statens kärnkraftinspektion (SKI) om platsundersökningarna för ett kärnbränsleförvar, vilket innebär att synpunkterna i denna granskning ska ses som ett allmänt råd till SKB. SSI:s bedömning är att SKB:s studie är väl genomförd och att den bidrar till en ökad förståelse för olika faktorer av betydelse för grundvattnets strömningsmönster. SSI anser dock att utvärderingen av beräkningsresultaten är otillräcklig för att kunna dra entydiga slutsatser om betydelsen av storregional grundvattenströmning som lokaliseringsfaktor för ett slutförvar.

SSI anser därför att SKB bör komplettera sin studie på ett antal punkter och även illustrera vad resultaten innebär för bedömningen av slutförvarets långsiktiga skyddsförmåga. SSI anser även att SKB bör utreda vissa modellosäkerheter som kan ha påverkat beräkningsresultaten. SSI kommer att göra en samlad bedömning av hur SKB beaktat olika lokaliseringsfaktorer i sitt arbete med att finna en lämplig plats för ett slutförvar i samband med granskningen av SKB:s planerade tillståndsansökan 2009

SUMMARY: This report presents SSI's review of the Swedish Nuclear Fuel and Waste Management Co's (SKB) report (SKB Report 06-64) on large-scale groundwater flow modelling for eastern Små-land in Sweden. SSI review is supported by two external review documents (included as appen-dices) by prof. Anders Wörman (the Royal Institute of Technology in Stockholm) and Dr. Clifford Voss (United States Geological Survey in Reston, USA).

SSI's review is part of a government decided consultation process on SKB's site investigations aimed at finding a suitable site for a spent nuclear fuel repository. SSI considers that SKB has presented a comprehensive study that contributes to the scientific understanding of how different factors influence the regional groundwater flow pattern. However, in SSI's opinion, SKB's evaluation of the modelling results is not complete enough to support SKB's conclusion that superregional flow conditions can be dismissed as a siting factor. SSI therefore recommends SKB to supplement their study in that respect and also to discuss the implications of identified differences in radionuclide travel times and migration distances on the overall assessment of the repository's longterm protective capability.

SSI also recommends SKB to revisit some of their modelling assumptions to ensure that the model is set up in a way that does not block out large groundwater circulation cells. SSI's recommendations in this review should be regarded as guidance to SKB. SSI will make a formal assessment of how SKB has taken into account different siting factors, in connection with the review of SKB's license application to be submitted in 2009.

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Innehållsförteckning

1 Bakgrund

1.1 De aktuella frågeställningarna

Grundvattnets flödesmönster i berggrunden och dess kemiska sammansättning är två viktiga geovetenskapliga faktorer som både kan påverka den långsiktiga utvecklingen av de tekniska barriärerna hos ett slutförvar för använt kärnbränsle och hur eventuellt utläckande radionuklider transporteras med grundvattnet till den marknära miljön.

Grundvattnets sammansättning på förvarsdjup (bl.a. dess salthalt) påverkar den långsiktiga funktionen (bl.a. svälltrycket) hos bentonitbufferten kring kapslarna och hos återfyllnaden av deponeringstunnlarna. Mycket höga salthalter kan leda till att bentoniten inte får de svällande egenskaper som förutsätts i säkerhetsanalysen. Svensk Kärnbränslehantering AB (SKB) har därför satt upp som ett absolut krav att den totala salthalten på förvarsdjup ska understiga 100 gram per liter [1]. SKB har senare på ett samrådsmöte om platsundersökningar den 7 september 2006 angivit att återfyllningen av deponeringstunnlarna dimensioneras för att tåla den lägre totala salthalten på 35 gram per liter [2]. SKB:s senaste säkerhetsanalys SR-Can [3] innehåller en mer utförlig diskussion om betydelsen av grundvattnets salthalt för återfyllningens svällningsegenskaper. SKB anger där att man i dagsläget inte kan specificera kvantitativa kriterier eftersom man för närvarande undersöker alternativa material för återfyllningen med olika känslighet för grundvattnets salthalt. Mycket utspädda grundvatten som kan uppträda i samband en glaciation kan å andra sidan leda till att bentonitleran bildar kolloidala partiklar och förs bort med grundvattnet. Av SR-Can framgår att SKB bedömer att sådan erosion av bufferten är betydligt mer problematisk jämfört med osäkerheter kring höga salthalters inverkan på bentonitlerans svällningsförmåga.

Grundvattnets flödesmönster bestämmer flödesvägarna för eventuellt utläckande radionuklider från ett slutförvar. Om det går att hitta en plats där flödesvägarna är sådana att de radioaktiva ämnena transporteras en lång väg genom berget ökar möjligheten att de fördröjs och i vissa fall kvarhålls så länge att deras radioaktivitet avsevärt hinner minska innan de når den mänskliga miljön. Sådana långa transportvägar anses vara förknippade med i inlandet belägna inströmningsområden, se t.ex. [4]. I kustnära områden kan flödesvägarna från ett slutförvar förväntas vara korta eftersom grundvattnet strömmar uppåt eller ut i havet i dessa områden.

Möjligheten att beskriva det storskaliga flödesmönstret och tillgodoräkna sig långa flödesvägar i säkerhetsanalyser för slutförvar begränsas av den ringa tillgången på data från stora djup i berget. Men två amerikanska forskare visade, i en studie för SKI, på en metod för att analysera det storskaliga strömningsmönstret med hjälp av topografiska data och hydrogeologiska modeller [4]. Metoden går ut på att söka efter hydrogeologiskt fördelaktiga områden genom att pröva en bred uppsättning antaganden om bergets spricksystem och övriga egenskaper. Om det är möjligt att identifiera områden som ger långa flödesvägar *oberoende av antaganden om bergets egenskaper* kan man genom att välja en sådan plats öka förutsättningarna för en god hydrogeologisk barriärfunktion, d.v.s. bergets förmåga att fördröja uttransporten av radioaktiva ämnen till den mänskliga miljön.

Vid val av platser för slutförvar är det nödvändigt att värdera platserna med hänsyn till flera geovetenskapliga faktorer som kan påverka slutförvarets långsiktiga skyddsförmåga. De ovan nämnda faktorerna kan alltså inte bedömas separat. Enligt SSI:s uppfattning har dock SKB inte tillräckligt väl utrett betydelsen av just grundvattnets salthalt och grundvattnets storskaliga strömningsmönster och de eventuella säkerhetsmässiga fördelar som ett inlandsalternativ med långa transportvägar skulle kunna erbjuda.

I denna promemoria diskuteras enbart betydelsen av grundvattnets flödesmönster. Frågorna kring grundvattnets salthalt kommer att följas upp i SSI:s och SKI:s granskning av SKB:s säkerhetsanalys SR-Can [3] och i kommande granskningar av SKB:s program för forskning, utveckling och demonstration. I det följande ges en kort historik av tidigare redovisningar och granskningar. Därefter redovisas SSI:s granskning av SKB:s senaste rapport om betydelsen av regional grundvattenströmning.

1.2 SKB:s val av platser för platsundersökningar

I samband med att SKB i kompletteringen av FUD-program 1998 presenterade sitt val av platser för platsundersökningar [5] framförde SSI att betydelsen av vissa geovetenskapliga lokaliseringsfaktorer borde utredas på ett bättre sätt [6,7]. SSI pekade särskilt på betydelsen av grundvattnets storskaliga strömningsmönster och grundvattnets salthalt för slutförvarets långsiktiga skyddsförmåga. Även Statens kärnkraftinspektion framhöll i sitt yttrande över SKB:s platsval [8] att SKB bör ta fram ett bättre underlag för sin bedömning av in- och utströmningsområden. Myndigheterna fick stöd för sina synpunkter i regeringens beslut angående SKB:s platsval [9]. Regeringen angav bl.a. att ”…bolaget inte bör utesluta Hultsfred från platsvalsprogrammet innan vissa frågeställningar av hydrogeologisk art har utretts ytterligare”.

1.3 SKB:s första kompletterande studie

För att möta myndigheternas och regeringens begäran redovisade SKB under 2003/2004 en analys av grundvattnets regionala flödesmönster och sammansättning och deras betydelse för lokalisering av ett slutförvar. Redovisningen bestod av en sammanfattande rapport [10] och två modelleringsstudier för norra Uppland [11] respektive östra Götaland [12].

SSI genomförde under 2004 en granskning av dessa rapporter som redovisas i en SSI-PM [13]. Som stöd för granskningen anlitade SSI även en internationell hydrologiexpert, Clifford Voss vid U.S. Geological Survey i USA, som genomfört den ovan refererade utredningen för Statens kärnkraftinspektion [4]. SSI:s övergripande slutsats var att SKB:s studie var otillräcklig för att kunna bedöma om SKB tagit tillräcklig hänsyn till grundvattnets strömningsmönster och sammansättning i sitt val av platser för platsundersökningar. SSI framförde bl.a. att SKB:s rapporter inte gav svar på den kritiska frågan om ”om det går att göra troligt att det finns områden med långa transportvägar i berget och om sådana platser kan ge väsentliga fördelar för slutförvarets långsiktiga säkerhet”. SSI ansåg vidare att SKB inte tillräckligt väl redogjort för de eventuella fördelar en inlandslokalisering med en lägre salthalt i grundvattnet kan tänkas ge, med hänsyn till buffertens och framförallt tunnelåterfyllningens långsiktiga funktion. SSI angav som stöd för sina granskningssynpunkter de krav på tillämpning av bästa möjliga teknik (BAT) och optimering som finns i SSI:s föreskrifter om slutligt omhändertagande av kärnavfall SSI FS 1998:1 [14] (se även kapitel 2).

SKI:s yttrande över SKB:s rapporter redovisades i ett brev till SKB [15]. SKI pekar i sitt brev på svårigheter med att använda regionala flödesförhållanden som en lokaliseringsfaktor. SKI anger bl.a. att ”de modelleringsstudier som presenterats inte kan motivera att beräkningar av regionalt grundvattenflöde kan tillmätas avgörande betydelse varken för lokaliseringsfrågan eller för den långsiktiga säkerheten” och att en fullständig lokaliseringsstrategi ”måste beakta en rad faktorer inte minst de som kan påverka de tekniska barriärernas långsiktiga integritet”. SKI framför dock att SKB bör överväga att utreda vissa frågeställningar ytterligare kring bl.a. modellförenklingar, flödesförhållanden i östra Småland och salta respektive söta grundvattens påverkan på de tekniska barriärerna.

1.4 SKB:s andra komplettering: storregional grundvattenmodellering för östra Småland

Mot bakgrund av ovanstående kritik och de ytterligare synpunkter som SSI och SKI framförde inom samrådet om SKB:s platsundersökningar (se SSI diarienummer 2004/780-26, 2005/182-26), bestämde sig SKB för att göra ytterligare en fördjupad studie av de regionala grundvattenflödesförhållandena i östra Småland. Det är slutrapporten från denna andra SKB-studie, SKB R-06-64 [16], som granskas i denna promemoria. En preliminär utgåva blev tillgänglig för SSI under våren 2006 och en tryckt slutrapport var färdig i juni samma år.

2 SSI:s bedömningsgrunder

SSI:s föreskrifter för slutligt omhändertagande av använt kärnbränsle och kärnavfall SSI FS 1998:1 [14] anger de allmänna strålskyddskraven på ett slutförvar. SSI:s allmänna råd om geologisk slutförvaring SSI FS 2005:5 [17] ger mer detaljerade rekommendationer om hur föreskriftskraven bör tolkas och vilken redovisning som förväntas inför en tillståndsansökan. SSI:s föreskrifter kan kort sägas bestå av tre huvuddelar:

- Riskkriterium för skydd av människors hälsa
- Krav på skydd av natur och miljö
- Krav på optimering och användning av bästa möjliga teknik (BAT)

Kraven på optimering och BAT ska ses som ett tilläggskrav till riskkriteriet och miljöskyddskraven och innebär i korthet att SKB ska redovisa att man beaktat alla möjligheter göra slutförvaret så säkert som möjligt, med hänsyn till ekonomiska och samhälleliga begränsningar. Ett viktigt motiv för dessa tilläggskrav är att riskanalyser för ett slutförvar alltid kommer att vara behäftade med osäkerheter, vilket gör att man inte kan bedöma slutförvarets långsiktiga skyddsförmåga i någon absolut mening. I de allmänna råden [17] preciseras hur principerna för BAT och optimering bör beaktas vid hela utvecklingsarbetet med ett slutförvar, inklusive vid val av plats. SSI:s synpunkter i denna PM om betydelsen av grundvattnets strömningsmönster för platsvalet tar således stöd i föreskriftskraven på användning av optimering och BAT.

De grundläggande frågorna som SKB, enligt SSI:s uppfattning, bör klargöra för att SSI ska kunna bedöma om SKB tagit tillräcklig hänsyn till betydelsen av storregionala strömningsförhållanden i valet av plats för slutförvar är:

1. Är det möjligt att identifiera platser vars flödesmönster bidrar till att förbättra bergets barriäregenskaper utifrån tillgängliga data och modellanalyser? Finns det områden som faller ut som fördelaktiga oberoende av antaganden om bergets egenskaper?

2. Vad karakteriserar områden med långa flödesvägar från förvarsdjup? Vilka lokala bergegenskaper skulle kunna bryta upp ett sådant flödesmönster? Kan dessa egenskaper mätas?
3. Hur stora strålskyddsmässiga fördelar kan erhållas genom att välja en plats med ett fördelaktigt strömningsmönster och hur har dessa eventuella fördelar värderats i förhållande till övriga geovetenskapliga egenskaper?

3 SSI:s genomförande av granskningen

SSI:s granskning av SKB:s rapport (SKB R-06-64) har genomförts inom ramen för det samråd som SKB enligt tidigare regeringsbeslut angående SKB:s FUD-program [18,9] är skyldig att hålla med SSI och SKI. Denna granskning ska därför ses som ett allmänt råd till SKB inom ramen för FUD-granskningarna. Den formella granskningen av hur SKB uppfyller SSI:s strålskyddskrav kommer att göras senare i samband med att SKB lämnar in sin ansökan om att få bygga ett slutförvar på en plats, vilket enligt SKB:s nuvarande tidsplaner kommer att ske sent år 2009.

Som stöd för granskningen har SSI tagit hjälp av två externa hydrologiexperter, prof. Anders Wörman från Kungliga tekniska högskolan i Stockholm och Dr. Clifford Voss från United States Geological Survey i Reston, USA (ung. motsvarigheten till Sveriges Geologiska Undersökning, SGU). Experterna har dels granskat SKB:s rapport, dels gjort en egen utvärdering av de beräkningsresultat som redovisas i SKB:s rapport. Utöver SKB:s rapport har experterna haft tillgång till beräkningsresultaten (fördelningar av transporttider, transportvägarnas längd, specifika flöden och andelen nedåtriktade strömningsvägar) för samtliga förvarsområden och beräkningsfall i SKB R-06-04. Experternas granskning redovisas separat i bilagorna 1 och 2 och de synpunkter som redovisas där står för respektive författare. SSI:s egna bedömningar redovisas i huvudtexten i denna PM.

Utöver SKB:s rapport (SKB R-06-64) har SSI även beaktat följande yttranden från SKB:

- SKB:s svar på MKB-fråga nr 7 från Oskarshamns kommun, SKB brev 1062685 (SSI Dnr. 2006/655-26) [19]
- SKB:s kommentarer med anledning av R-06-64, SKB PM 1060135, Bilaga 6 till samråd 2006-09-07 om SKB:s platsundersökningar med SKI och SSI, möte nr 10 (SSI Dnr. 2006/655-26) [20]
- SKB:s var på e-mail från Björn Dverstorp, SSI, daterat 2007-01-17: Hur berget i den storregionala modellen har tilldelats värden på genomsläpplighet, SKB dok. Id 1067006 (SSI Dnr. 2007/46-26) [21]
- SKB:s påpekanden med anledning av utkast till granskningsrapporter [från SSI:s konsulter A. Wörman och C. Voss], SKB dok. Id. 1073467 (SSI Dnr. 2007/46-26) [22]

4 SKB:s redovisning

SKB:s rapport SKB R-06-64 [16] redovisar en storregional hydrologisk modellering över ett område i östra Småland. Målet med studien anges vara att utvärdera konceptuella förenklingar och modellosäkerheter vid storregional grundvattenmodellering samt att genomföra en fördjupad och förutsättningslös analys av regionala flödesförhållanden i östra Småland. Analysen omfattar en utvärdering av flödesvägar från 500 m djup i berget över hela det studerade området. I förordet betonas att projektet enbart har ”syftat till ett fördjupat vetenskapligt underlag i en lokaliseringsdiskussion” och att ”en eventuell lokalisering av ett förvar i någon speciell region måste bedömas av SKB med hänsyn till betydligt fler faktorer och den övergripande säkerhetsfilosofi som tillämpas”.

Betydelsen av olika egenskaper i berget har utvärderats med hjälp av en uppsättning alternativa konceptuella modeller avseende topografi, kvartära avlagringar, förekomst av sprickor och sprickzoner och andra hydrologiska egenskaper i berget etc. Tillgängliga topografiska, geologiska, och hydrologiska data från bland annat Lantmäteriverket, Sveriges Geologiska Undersökningar (SGU) och SKB:s pågående platsundersökningar har utnyttjats för att ta fram en referensmodell mot vilken de alternativa konceptuella modellerna jämförts. Analysen omfattar även beräkningar av tidsberoende flöde och känslighetsanalyser av modelldjup.

För varje beräkningsfall har flödesvägarna bestämts genom att beräkna partikelbanor från hypotetiska, 1 km^2 stora, förvarsområden till biosfären. Flödesvägarna har sedan karakteriserats med ett antal parametrar som födesvägarnas längd och utströmningspunkter i biosfären, transporttid från förvarsnivå, specifika flöden på förvarsnivå m.m. Resultaten av beräkningarna presenteras i form av statistiska beskrivningar av flödesmönstret och flödesvägarnas egenskaper. Vidare redovisas en uppsättning statistiska tester och jämförelser mellan olika förvarsområden.

Av författarnas slutsatser framgår att:

- Topografin är den enskilt viktigaste parametern för det regionala flödesmönstret.
- Flödesmönstret styrs i första hand av lokala faktorer och flödesvägarna från förvarsdjup är överlag förhållandevis korta (några få km). Det förekommer dock ett icke obetydligt antal gemensamma förvarsområden som alla har långa flödesvägar och/eller nedåtriktade flöden även för systembeskrivningar som är mycket olika varandra.
- Det lokala grundvattenflödet beror i hög utsträckning på den lokala vattengenomsläppligheten, vilken måste bestämmas i förvarsplatsens lokala perspektiv genom borrhålsundersökningar.
- Förvarsområden i inlandet har generellt sett inte längre genombrottstider, längre flödeslängder eller mindre specifika flöden än förvarsområden nära kustlinjen.

På SSI:s begäran har SKB efter publiceringen av SKB R-06-64 tagit fram en PM [20] där man tar ställning till författarnas slutsatser i R-06-64. SKB framhåller där att:

- slutsatserna endast är endast giltiga för de modeller och systemvariationer som analyserats och att resultaten inte kan användas för att uttala sig om enskilda platser
- gynnsamma flödesförhållanden är kopplade till antagna låga vattengenomsläppligheter i modellen som måste verifieras med data från platsundersökningar
- det kan finnas enskilda förvarslägen som kännetecknas av långa strömningsvägar/tider men SKB ser inga möjligheter att tillgodoräkna sig dessa fördelar, bland annat på grund av svårigheter att verifiera dessa egenskaper på en specifik plats.

SKB:s samlade slutsats är att ”det inte är motiverat att överväga undersökningar av Hultsfred Östra (eller någon annan plats, utöver de två som är föremål för platsundersökningar)”. Man framhåller också att prognosen är gynnsam för de kandidatplatser som undersöka i Forsmark och Laxemar vad gäller möjligheten att tillgodose kraven på förvarets långsiktiga skyddsförmåga.

5 SSI:s bedömningar

I detta kapitel redovisas först SSI:s detaljerade synpunkter på modelleringsstudien i R-06-64 [16]. I kapitel 6 sammanfattas slutsatserna från en egen utvärdering av modelleringsresultaten i R-06-64 som SSI genomfört med stöd av sina konsulter. SSI:s slutsatser redovisas i kapitel 7.

5.1 Syfte och målsättning

SKB:s studie är utformad för att ge ett fördjupat vetenskapligt underlag beträffande grundvattnets strömningsmönster. Enligt SSI:s bedömning har dock avgränsningarna av studiens medfört att rapporten inte ger ett fullständigt underlag för att bedöma de kritiska frågorna om grundvattenströmningens betydelse för platsvalet som SSI framfört till SKB (se kapitel 2 och [13]). Den viktigaste invändningen är att SKB:s rapport (R-06-64) inte utvärderar och jämför specifika platser/regioner, trots att författarna själva anger att sådana platser kan identifieras från modelleringen.

5.2 Modellverktyg och data

SSI anser att studien baseras på en mycket förtjänstfull genomgång av tillgängliga topografiska, geologiska och hydrogeologiska data av betydelse för modelleringen av det regionala grundvattenflödet i östra Småland. SSI bedömer också att de modellverktyg (DarcyTools) som använts för att beräkna grundvattenflödet är väl lämpade för uppgiften. Tillämpningen av modellen och utformningen av beräkningsfall kommenteras i följande avsnitt.

5.3 Modellering

I detta avsnitt sammanfattas SSI:s tekniska synpunkter på genomförandet av modelleringen i R-06-64. För mer detaljerade synpunkter hänvisas till rapporterna från SSI:s konsulter i bilagorna 1 och 2.

SSI anser att SKB:s studie (R-06-64) innehåller en i huvudsak bra och heltäckande modellering av olika faktorer som påverkar grundvattenströmningen i olika skalor. SSI ser positivt på att SKB tagit fram en bred uppsättning alternativa modeller för att belysa hur topografi, bergegenskaper och andra faktorer påverkar bedömningen av grundvattnets strömningsmönster. I avsaknad av detaljerade data om bergets egenskaper på djupet är detta ett nödvändigt angreppssätt för att kunna bedöma om det finns platser eller områden som kan ge särskilt god fördröjning vid ett eventuellt utläckage av radioaktiva ämnen från ett slutförvar. SSI anser dock att det finns några antaganden och förenklingar, av betydelse för modelleringsresultaten, vilka bör utredas ytterligare med känslighetsanalyser eller motiveras bättre.

5.3.1 Modelldjup

SSI:s konsulter (bilaga 1 och 2) pekar på att grundvattenflödesmodellens begränsade djup och antaganden om minskad vattengenomsläpplighet kan leda till en artificiell begränsning av långa flödes- och transportvägar i berget, och att dessa faktorers inverkan på modelleringsresultaten inte utretts tillräckligt i SKB:s studie. Anders Wörman (bilaga 1) visar från en teoretisk analys att det begränsade modelldjupet medför att de storskaliga topografiska drivkrafterna inte kan belysas korrekt i modelleringen. Han framhåller också att det faktum att modellen inte tar hänsyn till att vattnets viskositet minskar mot djupet kan leda till att andelen djupa flödesvägar underskattas.

SKB:s studie innehåller en begränsad känslighetsanalys med avseende på modelldjup (-1100 m, -1800 m, -2500 m och -3300 m djup). SSI anser, mot bakgrund av konsulternas granskning, att denna känslighetsanalys är otillräcklig. Enligt SSI:s uppfattning finns det inte tillräckligt stöd i data (t.ex. vattengenomsläpplighetens djupavtagande och djup till salt grundvatten) för att utesluta rörligt grundvatten även under modellens referensdjup på 2500 m. Clifford Voss framhåller dessutom att förekomst av saltvatten (med en högre densitet än sött vatten) i sig inte behöver innebära att grundvattnet är stagnant (se bilaga 2). För att kunna utesluta att modellbegränsningarna inte allvarligt påverkar möjligheten att identifiera platser med långa flödes- och transportvägar är det enligt SSI:s uppfattning nödvändigt att utöka den redovisade känslighetsanalysen mot större modelldjup och eventuellt belysa osäkerheter i antaganden om vattengenomsläpplighetens djupavtagande.

5.3.2 Topografins betydelse

Två av huvudslutsatserna från SKB:s studie är att topografin är den enskilt viktigaste faktorn för det regionala flödesmönstret och att flödesvägarna från förvarsdjup i huvudsak styrs av lokala topografiska förhållanden. SSI ifrågasätter inte att dessa slutsatser kan vara riktiga men anser att de borde underbyggas med en mer systematisk analys av hur olika topografiska skalor (våglängder) påverkar flödesmönstret på några specifika platser. Ett sätt att göra detta kan vara att definiera några beräkningsfall som illustrerar effekten av några intermediära topografiska våglängdsfördelningar utöver de två fall som ingår i studien, d.v.s.”lutande plan” respektive den detaljerade höjdmodellen från Lantmäteriverket. SSI:s konsult Wörman (bilaga 1) visar på en spektral metod som dock är begränsad till homogena förhållanden i berget.

5.3.3 Grundvattenytans läge

I SKB:s modellering antas som ytrandvillkor att grundvattenytan följer marktopografin, vilket generellt sett är en rimlig approximation för svenska tempererade klimatförhållanden. Wörman (bilaga 1) påpekar dock att man kan förvänta sig lokala avvikelser, särskilt kring lokala högpunkter i terrängen, vilket leder till mer utjämnad grundvattenyta. Om det existerar en sådan utjämning kan SKB:s modell leda till en överskattning av betydelsen den lokala topografin och därmed också de lokala flödescellerna. Det kan också innebära att modellen under lokala högpunkter i terrängen ger orimligt höga värden på grundvatteninfiltrationen.

Författarna till R-06-64 har identifierat ovanstående problem och redovisar en känslighetsanalys avseende grundvattenytans läge (lokala avsänkningar ned till 5 m). Författarna konstaterar att den analyserade förändringen i grundvattenytans läge har ringa betydelse för flödesvägarnas längd (vilket enligt SSI:s uppfattning upplevs som lite förvånande med tanke på rapportens slutsats att just den lokala topografin är styrande för grundvattenflödet).

SSI är medveten om att det skulle det krävas fältundersökningar och borrhålsdata för att reducera osäkerheter om grundvattenytans djup under olika topografiska formationer. SSI bedömer dock att det bör vara möjligt belysa randvillkorets betydelse med en mer omfattande känslighetsanalys (det framgår heller inte i detalj hur den redovisade känslighetsanalysen genomförts).

5.3.4 Modellens sidoränder

Sidorna på SKB:s modell är täta och har placerats så att de följer regionala topografiska ytvattendelare. SSI:s konsulter framhåller att en ytvattendelare inte nödvändigtvis fungerar som vattendelare för grundvattnet i berget och att de täta sidorandvillkoren till viss del blockerar långa flödesvägar som annars skulle fortsätta utanför modelleringsområdet (bilaga 1 och 2). Enligt konsulternas uppfattning borde dessa effekter ha utretts genom att pröva olika domänstorlekar.

SSI noterar liksom konsulterna att de laterala modellränderna har viss påverkan på det beräknade flödesfältet, men har svårt att bedöma om det har någon betydelse för slutsatserna från studien.

5.3.5 Diskretisering

Wörman (bilaga 1) påpekar att diskretiseringen av modellen (antalet celler) är en faktor som kan påverka beräkningsresultaten och det saknas argument för den valda diskretiseringen i SKB:s studie. SSI har förståelse för de praktiska begränsningar som man måste hänsyn till av bl.a. beräkningstekniska skäl och upplösningen på tillgängliga topografiska data. SSI håller dock med konsulten om att det är oklart om begränsningar i antalet celler kan ha påverkat beräkningsresultaten och slutsatserna från studien. Enligt SSI:s uppfattning borde denna fråga kunnat belysas förhållandevis enkelt med en begränsad känslighetsstudie.

5.3.6 Representation av geologiska strukturer

Författarna till R-06-64 konstaterar i sina slutsatser att ”områden med potentiellt intressanta flödesmönster kan identifieras med viss konfidens”. I sina kommentarer till studien betonar SKB att resultaten i studien endast är giltiga för den uppsättning modeller som analyserats [20]. SSI håller med om detta men anser att resonemanget bör kompletteras med en diskussion om fullständighet, d.v.s. om det skulle kunna finnas några uppenbara bergegenskaper (sprickzoner, impermeabla strukturer och heterogenitet etc.) som skulle invalidera författarnas slutsatser att det går att hitta områden med särskilt fördelaktiga hydrogeologiska barriärfunktioner. För detaljerade synpunkter på representationen av geologiska strukturer i SKB:s studie hänvisas till bilagorna 1 och 2. SSI:s helhetsbedömning är dock att studien omfattar en bred uppsättning modeller för olika bergegenskaper.

5.3.7 Bestämning av flödesvägar

Flödesvägarna från förvarsdjup har utvärderats genom att beräkna hur fiktiva partiklar (36 partiklar/km^2) transporteras med grundvattnet från förvarsdjup (- 500m) till biosfären. För varje kvadratkilometerstort område (totalt 6000 förvarsområden) har medianvärden av bl.a. lokalt flöde, transporttid och flödesvägarna längd beräknats. Det är dessa medianvärden som sedan använts vid analysen av det storregionala flödet. Författarna till R-06-64 anger att motivet för att använda medianvärden är att modellen inte är tillräckligt detaljerad för att kunna beskriva enskilda flödesvägar, t.ex. från kapselpositioner.

SSI instämmer i att tillgängliga data och modellens upplösning är otillräckliga för att dra meningsfulla slutsatser om detaljer i flödesmönstret. Med tanke på att enskilda flödesvägar ändå beräknats anser SSI att det hade varit värdefullt att få något mått på spridningen av flödes- och transportegenskaperna inom några potentiellt intressanta förvarsområden. Om det t.ex. kan konstateras att det finns en stor variation av transportvägarnas längd redan för de förhållandevis homogena bergegenskaperna i modellen, så visar det i sig på svårigheter att med hög konfidens identifiera områden med goda hydrogeologiska fördröjningsegenskaper.

5.4 Analys och redovisning av modelleringsresultaten

Som nämnts ovan bedömer SSI att de analyserade beräkningsfallen (totalt 30 stycken) tillsammans ger en bra täckning av olika faktorer som påverkar det storregionala strömningsmönstret. SSI:s kritik rör istället det sätt på vilket beräkningsresultaten utvärderats och redovisats.

Kapitel 6 i R-06-64 innehåller en genomgång av hur de enskilda modellvarianterna påverkar strömningsmönstret och i kapitel 7 redovisas en uppsättning tester och statistiska jämförelser av förvarsområden med avseende på flödesvägarnas längd, transporttider, lokala flöden och andelen nedåtriktade flödesbanor på förvarsdjup. Även om den statistiskt präglade utvärderingen ger intressanta vetenskapliga insikter ger den inte svar på de kritiska frågorna om betydelsen av storregional strömning som lokaliseringsfaktor (se kapitel 2).

De kriterier som använts för att filtrera ut förvarsområden och för olika statistiska tester fokuserar delvis på irrelevanta aspekter och ger inte en bra bild av förekomst av hydrogeologiskt intressanta områden. T.ex. används lokalt flöde på förvarsdjup som ett gallringskriterium i vissa tester tillsammans med transportlängd och tid, trots att lokala flöden, enligt författarna själva, inte kan beskrivas på ett meningsfullt sätt i den storregionala modellen. Det faktum att urvalet av intressanta områden i testerna baserats på rankning (1000 bästa förvarsområdena för respektive modell), snarare än absoluta värden på de kritiska parametrarna, försvårar ytterligare bedömningen av enskilda geografiska områdens potentiella fördelar. Det är också en brist att det saknas en diskussion om hur de två kandidatplatserna, Laxemar och Simpevarp, står sig i förhållande till andra områden. Ytterligare synpunkter på utvärderingen av modellresultaten ges av SSI:s konsulter i bilagorna 1 och 2.

Enligt SSI:s uppfattning bör man aktivt söka efter potentiellt intressanta geografiska områden eller regioner, d.v.s. områden som ger långa transporttider eller långa transportvägar. Dessa områdens egenskaper bör sedan utvärderas mer i detalj för att klarlägga vad det är som gör att just dessa områden ger långa transportvägar eller transporttider och hur känsliga resultaten är för olika antaganden om bergets lokala hydrauliska egenskaper. Om det finns lokala platsegenskaper som skulle kunna ”förstöra” platsens goda egenskaper är det naturligtvis viktigt att klarlägga om sådana platsegenskaper kan identifieras utifrån tillgängliga data.

5.5 Rapportens slutsatser

SSI har i sak inga invändningar mot de slutsatser som redovisas i R-06-64, kapitel 8. Problemet är, som diskuterats ovan, att slutsatserna är begränsade till generella statistiska bedömningar av flödesmönstret i modellen och därmed inte belyser de kritiska frågorna om möjligheten att kunna tillgodoräkna sig fördelar av grundvattnets strömningsmönster på specifika platser. Författarna konstaterar t.ex. att det sannolikt är möjligt att identifiera områden med potentiellt intressanta flödesmönster, men det saknas en diskussion om var de uppträder, vad som kännetecknar sådana områden, och hur stora säkerhetsfördelar de skulle kunna ge.

6 SSI:s egen utvärdering av beräkningsdata

För att få en bättre förståelse för resultaten i SKB:s studie (R-06-64), gav SSI i uppdrag till konsulterna (Anders Wörman och Clifford Voss) att göra en egen utvärdering av de beräkningsresultaten från SKB:s modell. Resultaten av denna utvärdering redovisas i respektive konsults rapport (se bilagorna 1 och 2).

Även om konsulternas utvärdering är mycket begränsad illustrerar den att det är möjligt att på ett tydligare sätt dra slutsatser om skillnader i transportlängder och tider mellan olika platser eller områden från modellberäkningarna. Wörman visar utifrån en systematisk genomgång av samtliga konceptuella modellbeskrivningar i SKB:s modell att det går att identifiera enskilda förvarsområden i inlandet som har åtminstone 5 gånger längre transportvägar från förvarsdjup till biosfären jämfört med områden nära kusten, t.ex. kandidatområdet Laxemar. Voss valde att illustrera specifika skillnader i transporttider och transportlängder för två enskilda områden, nämligen kandidatområdet Laxemar och ett exempelområde i inlandet i Viråns avrinningsområde mellan Hultsfred och Oskarshamn. Från Voss jämförelse framgår att exempelområdet har väsentligt längre transportvägar (ca 4 gånger längre) och transporttider (drygt 20 gånger längre) jämfört med Laxemar. Om man tittar på andelen riktigt korta transportvägar och tider så är skillnaden mellan områdena ännu större. Både Wörman och Voss framhåller också att flera av de modellbegränsningar som diskuterats ovan (kapitel 5) sannolikt medför att andelen långa transportvägar underskattats i SKB:s modell, vilket innebär att skillnaderna mellan olika platser kan vara ännu större.

SKB har på fråga från SSI svarat att de långa transporttiderna för exempelområdet till viss del kan förklaras av att man i modellen ansatt en lägre vattengenomsläpplighet för de bergarter, gabbro och sura vulkaniter, som förekommer där [21]. Eftersom dessa antaganden måste verifieras med platsundersökningsdata anser inte SKB att det är rimligt att använda den här typen av modeller för att välja ut områden som skulle varar lämpliga för ett slutförvar. SSI håller med om att de lokala bergegenskaperna i detta fall sannolikt är en del av förklaringen till de långa transporttiderna för exempelområdet, även om de inte förklarar skillnaderna i transportvägarnas längd. SSI anser dock att resultatet av konsulternas begränsade utvärdering är tillräckligt intressant för motivera en mer fullständig utvärdering av modellberäkningarna jämfört med den som redovisas R-06-64.

7 SSI:s slutsatser

SKB har med rapporten R-06-64 redovisat en omfattande analys av olika faktorer som påverkar grundvattnets strömningsmönster i ett storregionalt perspektiv. SKB:s modelleringsstudie ger enligt SSI:s uppfattning ett värdefullt bidrag till den vetenskapliga förståelsen av storregionala strömningsmönster i urberget. SSI bedömer också att analysen baseras på en förtjänstfull genomgång av tillgängliga data av betydelse för det regionala grundvattenflödet i östra Småland.

SSI anser att SKB:s studie bekräftar att lokalisering av ett slutförvar i inströmningsområden ökar chansen för långa transportvägar. SSI:s begränsade utvärdering av SKB:s beräkningsresultat antyder dock att skillnaderna mellan platser inte är så dramatiska som tidigare diskuterats [4].

I SKB:s kommentarer [20] till studien (SKB R-06-64) framgår att SKB inte anser sig kunna tillgodoräkna sig några fördelar med att välja områden som kännetecknas av långa transportvägar/tider med hänvisning till svårigheterna att kvantifiera regionala strömningsmönster. SSI är införstådd med att det inte kommer att vara möjligt att belägga regionala strömningsmönster i någon absolut mening. SSI vill dock poängtera att flera av de lokala platsegenskaperna som kan mätas i en platsundersökning också kommer att vara behäftade med osäkerheter.

SSI är medveten om att frågan om storregional grundvattenströmning bara är en av flera viktiga faktorer som behöver beaktas vid lokalisering av ett slutförvar och att olika typer av avvägningar mellan olika lokaliseringsfaktorer och andra åtgärder kan vara nödvändiga. För att SSI ska kunna bedöma uppfyllelse av SSI:s föreskriftskrav på bästa möjliga teknik och optimering [14, 17] är det dock nödvändigt att SKB kan visa att man gjort en uttömmande värdering av de lokaliseringsfaktorer som kan påverka slutförvarets långsiktiga skyddsförmåga och att man tagit tillvara de möjligheter som finns att göra slutförvaret så säkert som möjligt med hänsyn till samhälleliga och ekonomiska begränsningar.

SSI anser därför att SKB bör komplettera studien på följande punkter inför den planerade tillståndsansökan 2009:

- SSI har i denna granskning identifierat vissa antaganden och modellförenklingar som kan misstänkas påverka andelen beräknade långa transportvägar och transporttider. SSI anser att dessa faktorer bör utredas ytterligare för att stärka trovärdigheten i beräkningsresultaten.
- Resultaten från SKB:s modellering visar att det finns skillnader mellan olika platsers förmåga att fördröja eventuella utsläpp av radioaktiva ämnen från ett slutförvar på 500 m djup. Detta framgår av slutsatserna i R-06-64 och den utvärdering av beräkningsdata som genomförts av SSI:s konsulter (bilagorna 1 och 2). Den statistiskt präglade utvärderingen av modellberäkningarna i R-06-64 ger dock en otydlig bild av hur stora dessa skillnader kan vara för specifika platser och bör därför vidareutvecklas för att kunna dra säkrare slutsatser om betydelsen av storregional grundvattenströmning som lokaliseringsfaktor. Eventuella områden som bedöms som intressanta inom förstudiekommunerna Oskarshamn och Hultsfred bör utvärderas mer i detalj för att klarlägga vilka faktorer som gör att just dessa områden ger långa transportvägar eller transporttider och hur känsliga resultaten är för olika antaganden om bergets lokala hydrauliska egenskaper. Det bör också finnas med en diskussion om det finns

uppenbara lokala platsegenskaper som skulle kunna ”förstöra” en sådan plats goda egenskaper, d.v.s. en diskussion om fullständighet i analyserade konceptuella modellbeskrivningar, och om dessa platsegenskaper kan identifieras utifrån tillgängliga data.

- SKB:s studie är begränsad till att illustrera grundvattnets strömningsmönster med ett antal hydrogeologiska parametrar som transportvägarnas längd och transporttider. SSI anser att SKB även bör illustrera i vilken utsträckning eventuella platsspecifika skillnader i dessa parametrar påverkar säkerhetsanalysens resultat, t.ex. genom att utnyttja konsekvensberäkningarna i SKB:s senaste säkerhetsanalys SR-Can.

Med ovanstående kompletteringar bedömer SSI att SKB kan anses ha presenterat de ytterligare utredningar kring grundvattnets strömningsmönster som regeringen avsåg i sitt beslut angående SKB:s val av platser för platsundersökningar [9].

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Bilaga 1. Anders Wörmans granskning av SKB R-06-64

Review of “Storregional grundvattenmodellering… R-06-64” by Lars O Ericsson, Johan Holmén, Ingvar Rhén and Niklas Blomkvist

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Summary

This report is written on the request of the Swedish Radiation Protection Authority (SSI) as a basis for the authorities review of the work the Swedish Nuclear Management Company (SKB) has done in Report R-06-64 (Ericsson et al., 2006) regarding modelling supra-regional groundwater flow. The objectives of Report R-06-64 are 1) to evaluate conceptual simplifications and model uncertainties in "super-regional" groundwater modelling and 2) to perform an in-depth (independent) analysis of regional flow conditions in Eastern Småland. The report provides an interesting study on the groundwater flow behaviour in the Fennoscandian Shield that in certain aspects has contributed to a better general understanding of the importance of large versus small topographical scales for the generation of sub-surface flows. A main conclusion is that the flow is controlled predominantly by (in a certain defined sense) "local" topography. However, a problem is that all modelling simplifications are not fully motivated and systematically tested. The factors that seem to be most responsible for producing the relatively short sub-surface flow pathways are the depth limitation of the flow and the non-free groundwater surface. The effects of these two simplifying assumptions have not been thoroughly studied.

In a flow analysis with homogeneous hydraulic conductivity to great depths the groundwater in the Fennoscandian Shield, Eastern Småland in particular, shows a clear tendency to flow from the inland to the Baltic Sea. This is found in the complimentary analysis presented in Appendix 1. However, as the depth limitation of the flow becomes more pronounced the flow becomes more and more controlled by the complex local topography and at some point the flow does not contain super-regional flow components at all (theoretically). Consequently, to be able to predict the local flow structure one has to assure a reliable description of the decay of hydraulic conductivity with depth, anisotropy in the K-values and salinity gradients. Therefore, it would have been good had the report highlighted the sensitivity of the conclusions to the assumptions associated with the depth limitation of the flow. Regardless of this lack of analysis, the description of the decaying hydraulic conductivity with depth is mainly plausible except for the cut-off at 2.5 km where an impermeable surface is introduced. The effect of this cut-off could have been investigated by expanding the domain downwards (using coarser resolution). Only a small interval of depths (1.1 - 3.3 km) was investigated, which resulted in a slight change in the distribution of flow path lengths and flow residence times. The depth of the Earths crust is about 35 km, which leaves room for speculations what effect results from the domain cut-off at 3.3 km.

Another complicated factor - discussed briefly in the report R-06-64 (e.g. pp 89-91) - is the top-boundary condition. By assuming that the groundwater surface follows the ground surface one implicitly prescribes a vertical (Darcy) velocity that corresponds to the infiltration velocity. Generally, in Scandinavia there is a surplus of surface water, which means that, on a sufficiently large scale/resolution (resolution > ~ 500 m), the assumption would be acceptable. However, in a very detailed, fine-scaled resolution of the surface topography and groundwater flow one represents small landscape elements that are particularly steep and associate with large hydraulic gradients. Especially in mountainous areas, there are spots where this assumption leads to infiltration velocities that exceed the available precipitation. This means that the effect of small-scale topography on the groundwater flow field is exaggerated. To investigate this problem the authors used reference cases in which the groundwater surface was lowered under topographic highs as described on p. 163 and found only a minor effect on the water flow. However, it is not clear if the groundwater surface was modified to an extent sufficient to produce realistic infiltration velocities. The water flux at 500 m depth (corresponding to SqMax in case 5H) was 493 l/(m^2 a) or 493 mm/year. If this value corresponds to the infiltration at z=0 (which is not clear from the presentation) it amounts to approximately the entire annual precipitation, which

indicates that the model assumptions can lead to unreasonable high infiltration velocities at the ground surface. Exactly, how this simplifying assumption exaggerates the impact of the local flow cells is not thoroughly investigated. Especially, since the extreme water fluxes are orders of magnitude higher than the average water flux and probably dominate the water circulation, their realism is a key issue.

A main question raised formally by the Swedish Radiation Protection Authority is if it is possible to find locations (mainly in the inland) that show definite downward flow (recharge conditions) with some degree of confidence. Unfortunately, report R-06-64 does not clearly shed light on this problem. The report contains convincing arguments that the flow is to a large degree controlled by the local topography and most likely this conclusion holds even if the simplifying assumptions discussed above introduces some doubts. The report did not include an analysis on the confidence by which locations with favourable hydrological conditions can be appointed.

Hence, this study included a brief analysis of the simulation data produced in report R-06-64 (Appendix 2). The analysis suggested that it is possible to identify locations, mainly narrow spots 20-40 km from the coastline, at which the recharge comes from very long sub-surface flow paths, up to 100 km. These pathlengths are averaged over 1 km^2 and identified only in individual model setups. On the other hand, the confidence by which these locations with very long pathways can be identified in the 28 different model set-ups used by SKB is relatively low. The maximum pathlengths averaged over 1 km^2 and also averaged between the 28 different model setups are about 10 km.

The robustness by which the “hydrologically good” areas can be identified can be expressed qualitatively by the percentage of models that appoint a certain area with a flow path exceeding a limiting value. This robustness depends on the how the limit of the long paths are selected, which means that a lowering of the demanded pathway length increases the robustness or confidence. Based on the SKB simulation data in report R-06-64 it is not possible with a very high degree of robustness to find inland sites with more than 5 times longer flow pathway or more compared to coastal sites. By searching for inland sites with less than about five times longer flow pathways we can increase this robustness significantly. Another way of increasing this confidence is to increase the general knowledge of the hydro-geological conditions of the Fennoscandian Shield, which would thereby facilitate to narrow down possible model set-ups (number of possible model cases) and decrease parameter uncertainty. At this point, however, the lack of specific hydro-geological knowledge and effects of model simplifications seem to be limiting factors for the identification of favourable hydrological conditions for the waste repository.

1. Introduction

This memorandum contains a review of the currently performed “super-regional” flow modelling performed by SKB; SKB Report R-06-64 (Ericsson et al., 2006), performed on the request of the Swedish Radiation Protection Authority. The review focuses on

1. evaluation of the objectives of the report versus the requests from the Swedish authorities which are background to the study,
2. the scientific motivations for generic model simplifications proposed in the “super-regional” groundwater modelling,
3. the authors position on the regional groundwater flow pattern in Eastern Småland.

To illuminate these issues the report contains a couple of independent analyses that address a) the relative importance of two different topographical scales on the local flow behaviour and b) the possibility to identify hydrological conditions with exceptionally long flow paths with some confidence based on the SKB data presented in report R-06-64 (Appendices 1 and 2).

2. Purposes of the report and overall approach

One factor for selection of a beneficial site is recharge condition (downward groundwater flow) with relatively long and long lasting flow paths in the subsurface. In addition, the safety depends on a wide range of other hydrological and geoscientific factors that contribute to low radiological doses to humans. For instance, a safe siting of the repository of spent nuclear fuel depends on such local hydrological conditions expressed by the SKB's suitability criteria (Andersson et al., 2000) - focused primarily on isolation of the waste - as well as criteria representing risks – focused on scenarios in case the isolation fails. A safe siting with respect to the "super-regional" hydrological conditions can be seen as a way of providing an additional isolation of the waste due to the prolonged transport of radionuclides in the geological environment as well as a way of reducing the radiological risk due to an enhanced radioactive decay.

The complicated impact of hydrology on the safety of a particular site should be revealed in a full safety evaluation focused among various criteria on radiological risks (SSI, 2000; SSI 2005). The current scientific understanding, however, is that *it is possible* to locate recharge areas that associate with long and slow flow paths in the subsurface, which would reduce the radiological dose (Tóth and Sheng, 1996). From a scientific point of view, this claim has not seriously been challenged (scientifically) to date and would be considered to form an important basis for the best available technique at this point. This explains why Swedish authorities have shown a particular interest for siting technology that accounts specifically for the recharge conditions on a "super-regional" perspective.

The Nuclear Power Inspectorate performed a tentative and pioneering modelling work by means of Voss and Provost (2001). The Swedish Radiation Protection Authority has recently raised the issue of localising the repository for spent nuclear fuel with account taken to regional hydrological conditions (SSI, 2004). SSI requested that SKB clarifies the role of selection of site with respect to the regional groundwater flow pattern and the chemical composition of the water. Particular interest is shown in the importance of the distance to the coast for the repository safety. The rational for such a particular focus on a specific design factor is to be able to provide highest possible safety in all significant aspects or design steps, which is supported legally both by the Swedish Nuclear and Radiation Protection Act (Kärnteknik och strålskyddslagen) as well as the authority's instructions (föreskrifter) (SSI, 2000).

As a response to the previous requests of the Swedish authorities, SKB has performed three "larger" hydrological modelling exercises, one for Forsmark (Holmén and Forsman, 2005) and two for Östra Småland (Follin and Svensson, 2003; Ericsson, 2006). The report R-06-64 does not claim to be a full response to the authority's request. Rather the report should be seen as a relatively interesting contribution that is independent from the response still remaining to be produced. The report addresses several essential questions with an overall suitable approach and would, therefore, make one valuable support to the expected response from SKB. Report R-06-64 has the following stated purposes

1) to evaluate conceptual simplifications and model uncertainties in "super-regional" groundwater modelling
2) to perform an in-depth (independent) analysis of regional flow conditions in Eastern Småland

A main problem is the that the report does not fully provide an answer if the modelling approach is acceptable and it is not entirely clear if it is possible to find repository sites that coincide with extreme recharge areas and relatively long sub-surface flow pathways. This could be seen as a drawback, since this report will be one of the main supports for the up-coming SKB response to the authority's request (oral statements on SKB seminar 21st of March, Stockholm).

While the report covers many general modelling issues in a relevant manner, it does not provide a definite answer which model simplifications are acceptable or if there exists a single acceptable, recommended model. For instance, which computational domain is sufficient in size (depth and horizontally) to capture all topographical scales of importance to the super-regional flow? Is it appropriate to neglect the temperature dependence with depth on the kinematic viscosity? Unfortunately, all relevant issues are not covered by the report, which implies a risk for possible model flaws. These problems are discussed in section 3.

While the report provides a quite interesting overview over factors controlling the "super-regional" flow behaviour in Eastern Småland, it does not answer the question if it is possible to definitely find recharge areas with long residence times. Generally, most analyses are focused on general statistical pattern in the groundwater flow based on residence times for particles release arbitrarily in the horizontal plane on exactly 500 m depth. The study illustrates in an interesting and also pioneering manner that the groundwater flow is generally controlled by the local topography and that it is difficult to discriminate between the inland and coastal groundwater flow pattern. This is an interesting finding, but does not really tell us that the super-regional or local flow pattern cannot provide an additional safety for the siting of the waste repository. Since recharge areas induced by "super-regional" topographical scales are relatively small contributions on the landscape perspective such an averaging or statistical approach would tend to smooth out anomalies in the residence time distribution. Factors that can be used to identify recharge areas – statistical extremes in residence times - are generally not well captured because of the limitations of the analyses accounted for in Report R-06-64.

A main conclusion is that there is no systematic difference between the groundwater flow pattern with distance from the coast (characterised in terms of flow residence times from the repository depth). In contrast, an exact solution to the groundwater flow field based on homogeneous hydraulic conductivity (Wörman, et al., 2006) shows a systematic difference in re- and discharge distribution with topography on various scales whereof distance to the coast is one important factor in Scandinavia. In the analysis shown in Appendix 1, it is clarified that the most likely causes that the SKB-study shows no significant super-regional flow components are the depth limitation of the flow and the extreme representation of the top-boundary condition. The depth limitation of the flow is especially stressed by the "cut-off" of the vertical depth due to numerical constraints and partly due to physical reasons (decaying hydraulic conductivity with depth and salinity gradients).

3. Do conceptual model simplifications have acceptable motivations?

The report addresses several conceptual simplifications in the model and the importance of various factors for the regional modelling of the groundwater flow. For instance, it is concluded that topography is a prime driver for the groundwater flow and that heterogeneity in the hydraulic conductivity is of lesser importance. Second most important factor is the depth dependence of hydraulic conductivity. All those conclusions are relevant and seem to be supported by relatively rigorous model formulations and specific data.

However, there are a few issues related to model simplification and applicability that were not dealt with thoroughly. How large does the modelling flow domain need to be to provide a reliable description of local flow and transport at the repository site? How fine topographical resolution is needed to provide a reliable description of local flow and transport at the repository site? The latter issue has a special relevance for the representation of the top-boundary condition. Unfortunately, neither of these issues have sufficient answers in the report.

If the model does not handle geometrical scales in an appropriate manner, the calculation results may not be useful. Especially, the vertical depth limitation of the flow is crucial to the relative importance of small-scale versus large-scale topography on the flow behaviour at depths. Basically, the study makes use of one arbitrarily defined computational domain with vertical, closed boundaries that coincide with surface water divides. This is exactly the same technique as used in the previous report R-04-31 (focused on Forsmark) with the exception that the domain is bigger. However, the report does not provide answers to the question which domain size is needed to address the problems outlined in the report.

The depth variation of hydraulic conductivity is said to be modelled according to Appendix 5, in which the depth of the domain is 2.5 km. Domains with depths in the interval 1.1 – 3.3 km are also tested with a slight change in the result. However, it is never shown in the report that the selected depth, 2.5 km, is enough or appropriate for the issues dealt with. This artificial depth limitation could be a problem especially for the longer wavelengths of the landscape (Appendix 1). An exact solution indicates that the ratio between topographical wavelength and domain depth controls the blocking impact on the groundwater flow (Wörman, et al., 2006). This means that longer wavelengths are more blocked/damped than shorter wavelengths due to depth limitations. If the longer wavelengths are effectively prohibited to act on the deep groundwater flow this could tilt the relative importance of the super-regional and local flows. In this case, the investigators are working with a domain that is 120 km long and only 2.5 km deep, i.e. a film type of domain in which long wavelengths would be effectively blocked.

Topography is concluded to be the most important factor for controlling the groundwater circulation pattern and the decay of hydraulic conductivity with depth is second most important. The temperature at 2.5 km depth would be 37.5 ^{o}C and dynamic viscosity of water would decrease at least a factor of 2 compared to the surface. This decrease counteracts the depth limitation due to decreasing hydraulic conductivity and its effect is of the same order as the density-salinity dependence that is also identified as an important factor.

Another important assumption is that the groundwater surface follows the ground topography. Locally, this assumption can lead to unreasonable vertical (infiltration) velocities that are not supported by the precipitation of the area. A simple analysis accounted for in Appendix 1 show that this is possible on a sufficiently small scale under mountains or hills. If this occurs, it would imply an exaggeration of the effect of local topography on the groundwater flow field. Since, the SKB study use a resolution of 50x50 meter both for the land topography and bathymetry this could be a problem for the objectives and conclusions. To investigate the severity of this problem the authors defines two sensitivity cases called 5J1 and 5J2 in which the groundwater surface is smoothed out in recharge areas according to p. 163. It is unclear if these modified top-boundary conditions resulted in acceptable infiltration velocities. Anyway, it was noted that the effect on the flow path lengths due to the modified groundwater surface was small.

It should be noted that water surface divides do generally not act as divides for the groundwater circulation due the fundamental difference in topographical control on the 2D vs. 3D flows. This is why it would have been appropriate to check, especially, the impact of the vertical (watershed) impermeable/closed boundaries that extends in the East-West direction (towards the coast). It is likely that their curved shape affects the computational results with a particular impact on the long residence times (e.g. Fig. 6-12 and 6-13 on p. 124, see also section 4 below). It is difficult to explain the anomaly in the percentile curves for reference case 0 in which the domain is completely homogeneous without the spatially variable boundary (condition). There should be an impact of the coastline shape, but regardless of which factor dominates it would definitely be important to show clearly that the computational domain is adequate. The report omits this problem and the reason is unclear. A comparison of the undulations of the curves in Fig. 6-12 with those obtained for reference case 5 in Fig. 6-1 on p. 101 (most realistic and complex case) indicates that the effect of the vertical boundaries can be significant.

4. Can one identify repository sites with recharge conditions?

This review report does not suggest that the super-regional flow behaviour necessarily provides a unique safety implication for the repository. However, regardless of the overall safety aspect, the issue has been raised if it is possible to find locations (mainly) in the inland that show recharge conditions with exceptionally long flow paths.

The SKB report concludes that there is no significant difference in the re- and discharge patterns of the inland and coastal sites of Eastern Småland. Despite the limitation of the study, the authors rule out "the recharge area concept" (including the supra-regional groundwater flow) as an important safety factor (conclusion section). This is consistent with SKB's identification of the six plus fourteen suitability criteria (Andersson et al., 2000) as well as with the proposed overall (full) safety evaluation (e.g SKB, 2004, chap. 9). In other words, SKB is not using the supra-regional flow characteristics as an important selection criterion (suitability criterion) in the siting process and not as a clear basis for the site-specific safety analysis. Given this scientific-technological standpoint, it is logical that we can find no clear strategy in the report R-06-64 to look for controlling super-regional hydrological factors relevant for the siting process. It is not an explicit part of the report objectives and it is fully in line with the safety criteria previously stated by SKB. A main problem of the report R-06-64 is, therefore, the lack of completeness as a support for the SSI's request (SSI, 2004).

The test criteria (R-06-64, section 7.2 – 7.5) are primarily focused on identifying number of locations that satisfy certain hydrological requirements as well as the average residence time distributions. The general (average) re- and discharge situation is characterised by averaging the surface water exchange in squares 1x1 km in size (pp. 76-77). This is an interesting approach because it allows an analysis of the relative importance of "secondary" factors for identifying hydrologic good locations. By adding additional system complexity it would also be possible to see if previously identified locations fail when new model complexity is added and in this way we can qualitatively estimate the robustness by which the locations are identified. However, there is a limitation due to the relatively "blurry" criteria that focus on the average flow behaviour and do not capture the extreme recharge areas. Because the flow is controlled to a large degree by local topography according to the authors own conclusions and the identification criteria used in R-06-64 focus on a statistical (average) difference, it is expected to find no significant differences with location in the groundwater flow under the super-regional landscape. However, even if there is no significant difference in relatively shallow (<500 m) groundwater in a statistical perspective there may still be difference in the super-regional characteristics of the flow. It would have been important to specifically identify the extreme recharge locations existing in the inland and not focus too much on the statistical difference between inland and coastal groundwater flows.

The authors find that changing the vertical depth of the flow domain from 1.1 to 3.3 km gave a minor change in the result, but did not pursue this issue further. This limitation may have importance for the possibilities of finding locations with good hydrological siting conditions.

Furthermore, the minor flaws existing in the simulation procedure probably make it difficult to identify extremes in the flow pattern. Diagrams 6-12 and 7-17 to 7-20 show unexpected flaws or disturbances in the R_p vs flow path length relationship that are likely associated with perturbations caused by the artificial vertical boundaries (See section 3 for details). The boundaries follow the water divides that meet/cut the coastline and their undulations disturb the flow. These disturbances should be most pronounced for the 99% percentile, which should prohibit identification of the extreme flow paths.

It is well known that the super-regional flow can be superimposed (linearly) on the local flow field and that this must lead to systematic, more pronounced recharge in the inland and discharge at the coast.

Even if the local topography dominates local and shallow (< 500m) groundwater flow fields, the super-regional flow still remain as a linear contribution to the overall flow pattern and controls the extremes in residence time and flow paths (Tóth, 1962; Zijl, 1999; Wörman et al., 2006). An issue that was investigated in Appendix 2 is if it is possible with some confidence to identify those extreme recharge spots in the inland. This simplified analysis was based on the SKB simulation data and indicates that it can be difficult with a high degree of robustness to identify locations with more than about 5-10 times longer flow paths compared to coastal locations. Inland locations with only moderately longer (< ~5 times) flow paths can be identified with a relatively high robustness. However, it is not sure to what extent the unverified model simplifications (the 28 model setups) affect this conclusion. Especially, the depth limitation of the flow is crucial for the "local behaviour" of the flow and the assumption that the groundwater surface follows the topography enhances this effect.

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Appendix 1: Relative importance of regional vs. Continental topography for the groundwater circulation in Eastern Småland

Summary

Small-scale or regional topography of the landscape can generate local flow cells that counteract the large-scale flow generated by the continental shape of the landscape to the extent that the continental-scale flow disappear. This occurs for certain combinations of topographical indices and depth limiting factors. Such a situation would imply that there is no large-scale groundwater flow from inland to the coast, since the local circulation controls the overall flow pattern. This study aims at providing a simplified criterion, including topographical indices, for which such a "localized" flow circulation occurs and compares the criterion with the topographical spectrum of Eastern Småland.

The relevant topographical indices and depth limiting factor are derived from a simplified model which assumes a homogeneous subsurface, an impermeable surface at depth, ε, and a groundwater surface that follows the landscape topography. If the topography is described by one large (continental) and one small (regional) harmonic function, the relative importance of the smaller flow cells are described by three numbers; the depth ratio ε/λ_1, the wavelength ratio λ_1/λ_2, and the steepness ratio $[h_{m,2}/\lambda_2]/[h_{m,1}/\lambda_1]$, where λ is landform wavelength, ε is depth to an impermeable surface, h_m is landform amplitude and subscripts 1 and 2 denote the large (long-waved) and the small (short-waved) landform, respectively. If, as an example, we assume a significant difference in size between the long- and the short-waved landforms, say $\lambda_1/\lambda_2 \geq 10$, the steepness ratio needs to be larger than 10.7 for the short-waved landform to generate local flow cells that completely demolish/dominates the large-scale groundwater flow (assuming $\varepsilon/\lambda_1 = 0.035$). If the impermeable surface is lowered to the double depth, the required steepness ratio needs to be more than 209 for the large-scale groundwater flow to disappear.

The use of the discussed methodology is limited due to the simplifying assumptions such as a homogeneous sub-surface and the top-boundary condition that states that the groundwater surface follows the ground surface topography. Another complication is the type of criteria used to define the relative influence of the various wavelengths in the spectrum of wavelengths existing in a real landscape. Despite these complications the criterion proposed here cay provide qualitative guidance.

A spectral analysis of Southern Sweden and Eastern Småland indicates that the commonly appearing landscape elements have wavelengths in the interval 300 m to 10 km in Eastern Småland. There are also frequent landscape elements that reflect the shape of the Fennoscandian Shield and which have a large influence on the groundwater flow. The steepness of the smaller landforms varies from 0.03 to 0.35 and these cannot break up the continental flow unless a significant depth limitation is asserted on the continental flow. Based on the simplified homogeneous model, the depth to the impermeable surface would have to be a few hundred meters for the continental flow to disappear completely.

Exactly, how the depth limitation should be simulated in a more detailed and realistic model set-up is not entirely clear. Only a few investigations have been performed on the depth variation of the flow.

Another important factor for the relative influence of small-scale topography on the groundwater flow is how these features are reflected in the boundary condition for the flow. In this type of analysis the top groundwater surface is assumed to follow the ground surface topography, which can cause extremely high infiltration velocities in narrow areas (< 300 m in radius). These infiltration velocities cannot be supported by precipitation and this implies that the groundwater surface is actually not aligned with the ground surface. Hence, in order to model the impact of local topography (< 300 m in

radius) we need to employ a coupled model approach in which infiltrating water is derived from the surface hydrology and used as boundary condition for the groundwater flow.

Theoretical criterion based on two wavelengths

Topography is the primary driver for groundwater flow. To be able to compare the relative importance of the local or regional topography in comparison to the large-scale or continental topography only two wavelengths are considered here. A main issue is which topographical conditions would be required for the regional topography to completely dominate the groundwater flow field to the extent that the continental flow is prevented from the inland-highlands to the coastal lowlands.

As a working model we define the landscape in terms of the following harmonic function

$$Z = h_m \sin(2 \pi x/\lambda) \cos(2 \pi y/\lambda) \qquad (1)$$

in which h_m = maximum amplitude of landscape topography, λ = wavelength of landscape topography. This hill-type function is represented in Fig. 1 with λ = 500 km and h_m = 400 m, i.e. the ”steepness” and corresponding (driving) hydraulic gradient is $h_m/\lambda = 0.0008$. On top of this continental landscape topography we superimpose a small-scale, regional topography with a much shorter wavelength, but the same steepness. We take λ = 10 km and h_m = 8 m for this secondary wavelength and obtain a flow field as shown in Fig. 2. The graph is derived from the exact solution proposed by Wörman et al. (2006) assuming an impermeable bottom surface at ε = 10 km.

As can be seen in the graph, the regional topography causes local flow cells that extends downwards and disturbs the continental flow. However, given the specific topography used in this example there is still an underflow caused by the continental topography that drives water from left to right in the figure. For the regional flow cells to be completely connected to the bottom, these regional flow cells have to counteract completely the maximum bottom velocities caused by the continental topography at the bottom surface of the flow domain.

Based on the exact solution of Wörman et al. (2006) we can express the bottom velocity in x-direction for two superimposed harmonic topography-functions as

$$V_{z=-\varepsilon} = 2\pi K \alpha_1 \frac{h_{m,1}}{\lambda_1} \cos(2\pi \frac{x}{\lambda_1}) \cos(2\pi \frac{y}{\lambda_1}) + 2\pi K \alpha_2 \frac{h_{m,2}}{\lambda_2} \cos(2\pi \frac{x}{\lambda_2}) \cos(2\pi \frac{y}{\lambda_2}) \quad (2)$$

in which K = hydraulic conductivity, subscript 1 refers to the continental wavelength, subscript 2 refers to the regional wavelength and the auxiliary α-function is defined as

$$\alpha_{z=-\varepsilon} = \frac{2\exp\left(-2\pi\sqrt{2}\varepsilon/\lambda\right)}{1+\exp\left(-4\pi\sqrt{2}\varepsilon/\lambda\right)} \tag{3}$$

As a measure of the counteraction that the shorter wavelength contributes to flow generated by the longer wavelength we evaluate the bottom velocity in a point in which cos(2 π y/λ_1) = cos(2 π y/λ_2) = 1, cos(2 π x/λ_1) = 1 and cos(2 π x/λ_2) = -1. Hence, (2) can be rewritten as

$$V_{z=-\varepsilon} = \underbrace{2\pi K\alpha_1 \frac{h_{m,1}}{\lambda_1}}_{\substack{Large-scale\\ flow\ component}} \underbrace{\left(1-\exp\left(-2\pi\sqrt{2}\frac{\varepsilon}{\lambda_1}\left(\frac{\lambda_1}{\lambda_2}-1\right)\right)\frac{1+\exp\left(-4\pi\sqrt{2}\frac{\varepsilon}{\lambda_1}\right)}{1+\exp\left(-4\pi\sqrt{2}\frac{\lambda_1}{\lambda_2}\frac{\varepsilon}{\lambda_1}\right)}\frac{h_{m,2}/\lambda_2}{h_{m,1}/\lambda_1}\right)}_{Counteraction\ \ function\ due\ to\ small-scale\ topography} \tag{4}$$

The velocity component generated by the continental (large-scale) topography is stated outside the parenthesis expression and the parenthesis expression reflects the counteracting effect of the small-scale, regional topography. This means that a continental flow exists as long as the following inequality is satisfied

$$F_R = 1-\exp\left(-2\pi\sqrt{2}\frac{\varepsilon}{\lambda_1}\left(\frac{\lambda_1}{\lambda_2}-1\right)\right)\frac{1+\exp\left(-4\pi\sqrt{2}\frac{\varepsilon}{\lambda_1}\right)}{1+\exp\left(-4\pi\sqrt{2}\frac{\lambda_1}{\lambda_2}\frac{\varepsilon}{\lambda_1}\right)}\frac{h_{m,2}/\lambda_2}{h_{m,1}/\lambda_1} > 0 \tag{5}$$

From the graphical representation in Fig. 3 we can see that $F_R > 0$ for all wavelength combinations ($\lambda_1/\lambda_2 > 1$) if the steepness (h_m/λ) of the smallest wavelength is smaller than that of the longer wavelength (regardless of depth to the impermeable surface). On the other hand, if the steepness of the short waved landscape is 4 times larger than the continental topography it can completely counteract the large-scale flow generated by landforms with up to almost 7 times longer wavelengths (given that $\varepsilon/\lambda_1 = 0.035$).

A main conclusion is that the small-scale regional topography can generate local flow cells that completely counteract the large-scale flow generated on the continental scale for reasonable topographical indices. This would imply that there is no large-scale flow from inland to the coast. If this occurs in reality depends on the topographical indices on specific locations.

Topographical spectra of Eastern Småland

In order to evaluate the distribution of landscape topography in Eastern Småland, we employ spectral analysis. To be sure that the spectral density is representative to the map data, we use a Fourier function that is periodic with a wavelength equal to the side length of the map area. It is possible to use a Fourier function that have a wavelength that is larger than the map domain, which would improve the surface fit but provide a less representative spectrum. The approach with a wavelength equal to the map side length is slightly more restrictive than the method proposed by Wörman et al. (2006), which leads to a worse surface fit, but a spectral density that is typical exclusively to the map data. Two domain sizes are tested as shown in Fig. 4. The largest domain, the entire Southern Sweden, was about 450 x 450 km^2 is size, a minimum resolution (distance between map points) of 329 m and totally 22,500 map points. The Eastern Småland domain was 160 x 160 km^2, had a minimum resolution of 512 m (more equally spaced map points than Southern Sweden) and totally 19,600 map points.

The topographical spectrum was determined by pre-assigning wavelengths in the interval from the minimum map resolution to twice the domain size and evaluating the amplitudes of each of 484 Fourier series terms that provided the best least square fit to the topographical surface. The topographical spectra are slightly different for the two areas as can be seen in Fig. 5. In Southern Sweden the steepest Fourier functions tend to concentrate on the short wavelengths, whereas the opposite occurs in the Eastern Småland domain. In more detail, we can see that in both cases the steepness for the short-waved landforms (in the interval 300 m to 10 km) varies up to about only 0.35. However, the analysis of Eastern Småland reveals exceptionally steep landforms in the landscape wavelength interval 200 km to more than 1,000 km. These wavelengths do not show up equally clear in the analysis of the entire Southern Sweden. The shorter wavelength band (from 300 m to 10 km) reflects the small-scale topographical features of the landscape, whereas the longer wavelength band (200 km to 1,000 km) reflects the continental shape.

Relative importance of landscape topography of various scales

The relative influence of the landscape wavelengths on the groundwater flow is not reflected directly by the steepness, h_m/λ, but rather by the ratio of the steepness of small vs. large land forms. From the left-hand side, upper diagram of Fig. 5, we can see that Southern Sweden exhibits steeper small-scale features in the range 300 m to 10 km than larger features. The wavelength $\lambda_{x,2} = 1$ km wavelength has a steepness of about $h_{m,2}/\lambda_{x,2} = 0.15$. The wavelengths around $\lambda_{x,1} = 400$ km has a steepness of about $h_{m,1}/\lambda_{x,1} = 0.03$. By using the wavelength ratio $\lambda_{x,1}/\lambda_{x,2} = 400$ and the steepness ratio $[h_{m,2}/\lambda_{x,2}]/[h_{m,1}/\lambda_{x,1}] = 5$, we can see from the diagrams in Fig. 3 that the shorter wavelength cannot counteract completely the longer wavelengths.

Relative importance of the depth limitation of the flow

Consistently, we can see in Fig. 4 how the spectral method predicts continental stream-lines that stretches over the entire Scandinavian continent. In these simulations the bottom surface is placed at 14 and 20 km depth, respectively. The placement of the impermeable bottom surface is critical for the destruction of the continental flow as is clear from a comparison of the left-hand side and the right-hand side graphs of Fig. 3. It should be noted that the spectral method is based on a homogeneous hydraulic conductivity, whereas in reality the depth limitation of the flow is controlled by the decreasing hydraulic conductivity with depth (and salinity effects). Such depth limitations can cause the local topography to counteract the continental flow. As an example using $\lambda_{x,1}/\lambda_{x,2} = 400$ and $[h_{m,2}/\lambda_{x,2}]/[h_{m,1}/\lambda_{x,1}] = 5$, we find the root to the left-hand side of (5) to be $\varepsilon/\lambda_1 = 0.00064$ or $\varepsilon = 260$ m.

The distribution of steepness ratios that were found in Eastern Småland is reflected also in the left-hand side diagram of Fig. 6 (for Southern Sweden), in which we can see a tendency of increasing steepness ratio, $[h_{m,2}/\lambda_{x,2}]/[h_{m,1}/\lambda_{x,1}]$, with wavelength ratio, $\lambda_{x,1}/\lambda_{x,2}$, where subscript 1 denotes longest wavelength and 2 shortest wavelength. Figure 6 is derived by first grouping the wavelengths in 10 length classes, evaluating the mean values of λ and h_m in each class and forming pairs between the mean values of the classes. This averaging decreases the importance of individual terms in the Fourier series that can sometimes represents artefacts of the numerical procedure (accuracy) and stress the relative importance of the wavelength class. The steep features in the wavelength interval 200 km to 1,000 km in the upper, right-hand side diagram of Fig. 5, probably are partly representing artefacts of the numerical procedure (since these are too steep to be relevant as natural objects).

Relative importance of topographical scales for surface boundary condition

An important factor for the effect of topographical features on the groundwater flow is how features of various size can be represented in terms of boundary condition of the flow. In this study it has been assumed that the groundwater surface follows the groundwater topography. This implicitly provides a distribution of groundwater velocities over the same top boundary of the calculation domain, which corresponds to the infiltrating water due to precipitation. The infiltrating velocities obtained in Southern Sweden (domain shown in left-hand side graph of Fig. 4) is at the maximum 15 mm/year (Fig. 7), which can be compared with the annual precipitation of the area of 600 mm/year.

In a higher resolution, local topography may be very steep and cause relatively higher hydraulic gradients. This can result in infiltration velocities that are higher than can possibly be supported by precipitation and infiltration. Such an example is shown in Fig. 8 were the grid resolution was 50 m. The calculation indicates local infiltration velocities of 70,000 mm/year, which is an unreasonable value for this area of the world. The interpretation of this result would be that the groundwater surface does not follow the topography at least in those areas were the infiltration velocity exceeds the access of water. This can cause local disturbances of the flow that decays exponentially with depth as $\exp(-\sqrt{2}\, 2 \pi z/\lambda)$. However, the overall pattern on a rougher resolution would be acceptable.

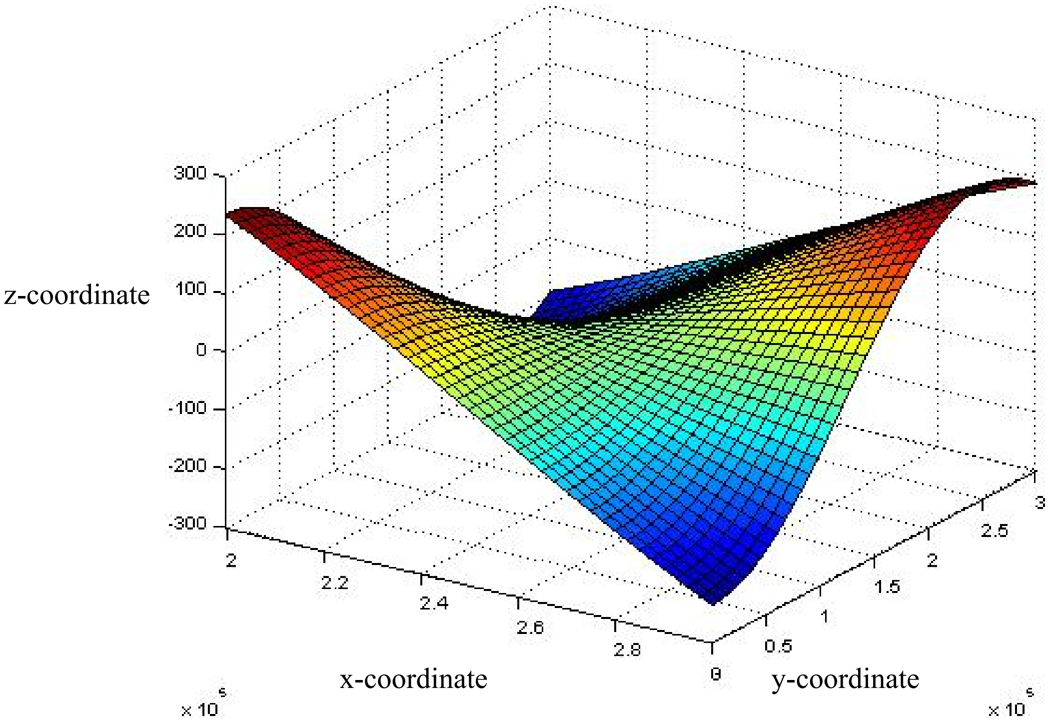

Fig.1 Topographical surface represented by the hill-type of function used in the spectral methodology. This graph shows only the function that corresponds to the continental scale, whereas the smaller hill-type function representing the local topography remains to be superimposed. The flow in Fig 2 is evaluated along the x-axis for y = 0.

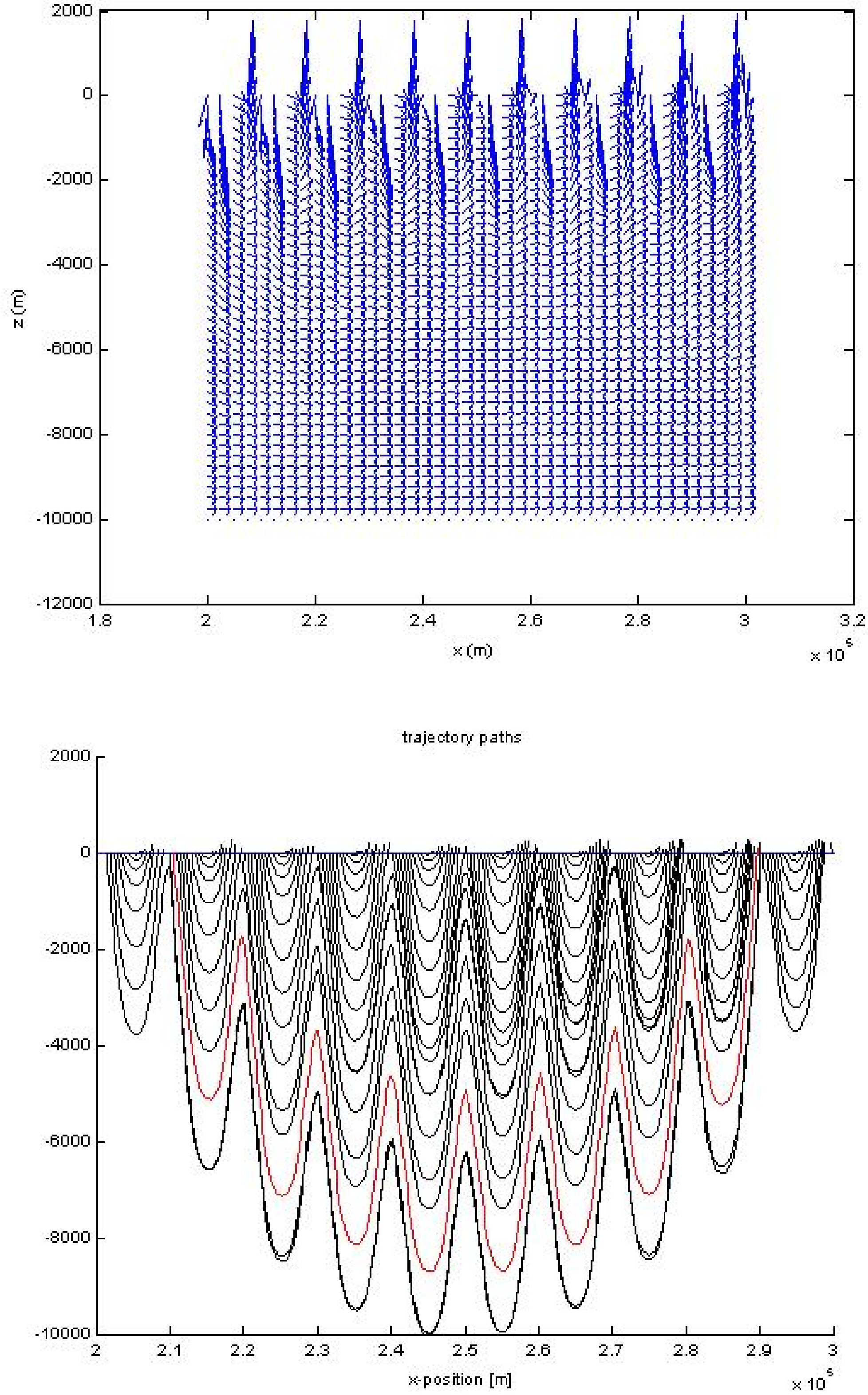

Fig.2 Flow field along y = 0 with two superimposed harmonic topography-functions with $\lambda_1/\lambda_2 = 50$ and $h_1/\lambda_1 = h_1/\lambda_1$. The small-scale topography affects the flow field to great depth, but in this example

there is still an underflow caused by the large-scale topography. The red streamline indicates such an underflow caused by the longer wavelength in topography.

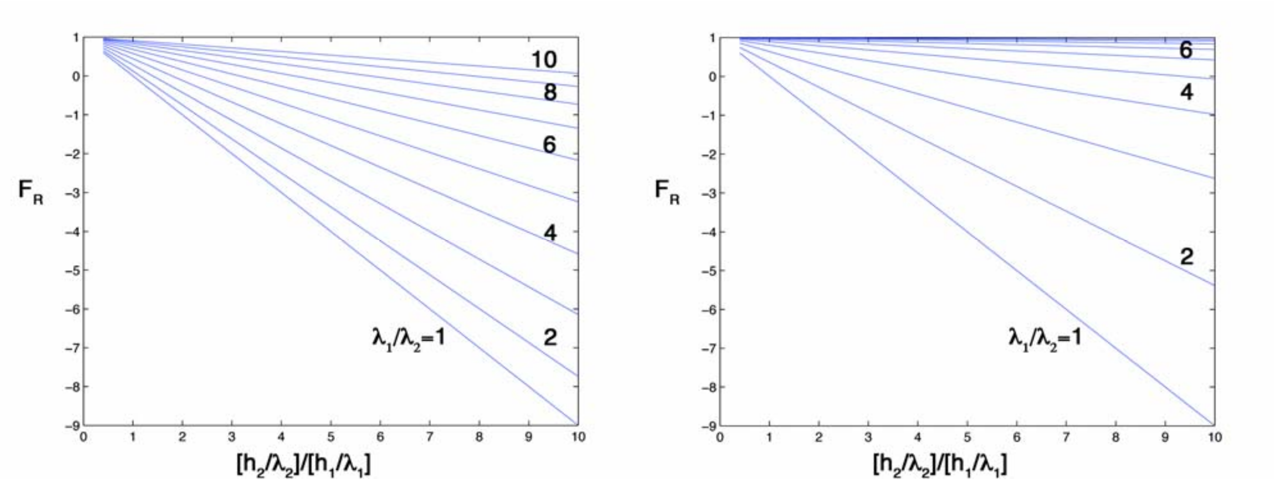

Fig. 3 The $F_R$function represented for $\varepsilon/\lambda_1 = 0.035$ (left-hand side) and $\varepsilon/\lambda_1 = 0.07$ (right-hand side).

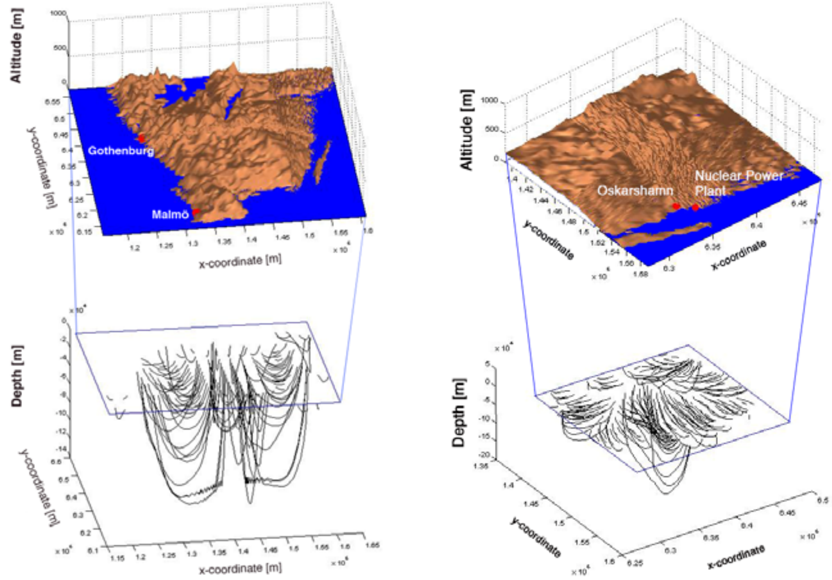

Fig. 4 Flow analyses over Southern Sweden and Eastern Småland using the spectral method of Wörman et al. (2006).

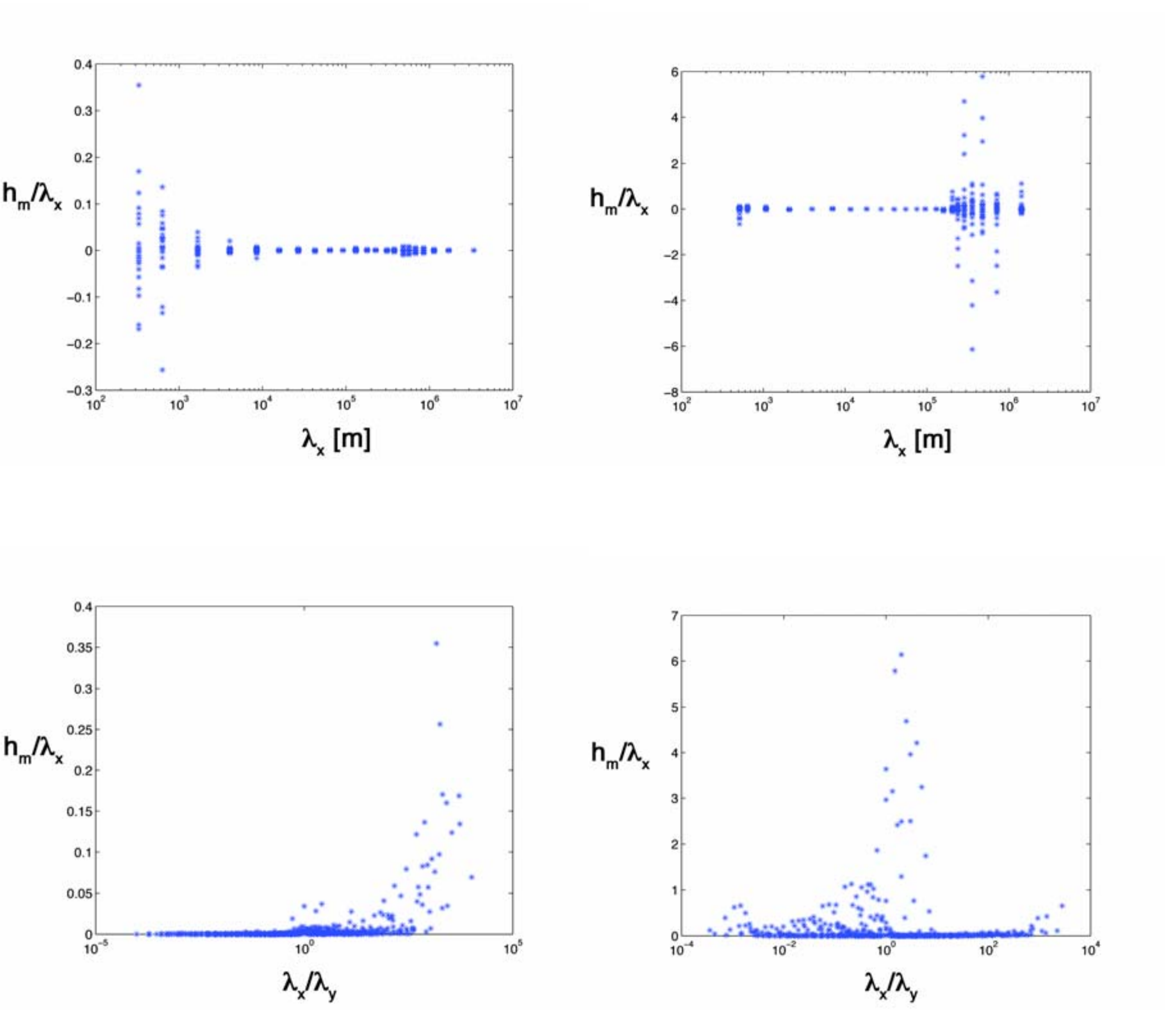

Fig. 5 Topographical spectra represented for as steepness, h_m/λ_x, of each of ~400 terms in a Fourier function as function of the wavelength of the term and the anisotropy ratio, λ_x/λ_y. Southern Sweden are included in the left-hand side diagrams and Eastern Småland to the right.

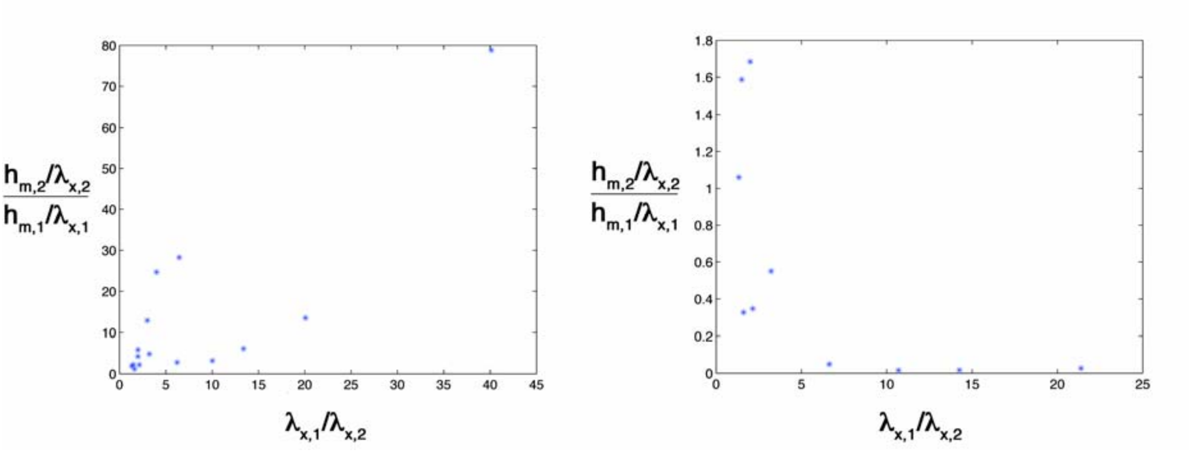

Fig. 6 Steepness ratio between short and long wavelengths as function of the wavelength ratio. Southern Sweden are included in the left-hand side diagrams and Eastern Småland to the right. These diagrams are derived from forming 10 wavelength classes and evaluating mean values of the wavelength

λ_x, and amplitudes h_m within the classes. By forming pairs between the classes it is possible to obtain the relationhsip between $\lambda_{x,1}/\lambda_{x,2}$ and $[h_{m,2}/\lambda_{x,2}]/[h_{m,1}/\lambda_{x,1}]$.

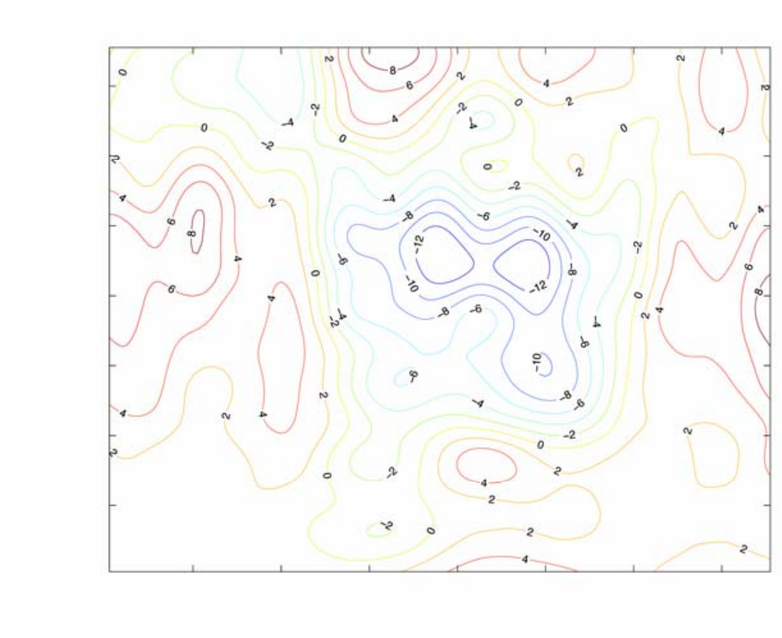

Fig. 7 Distribution of vertical velocities at z = 1 km in the domain shown on the left-hand side in Fig. 4 (i.e. Southern Sweden). The unit is mm/year. As is clear from the figure, the maximum infiltration is about 12 mm per year, which can be supported by the precipitation of the area.

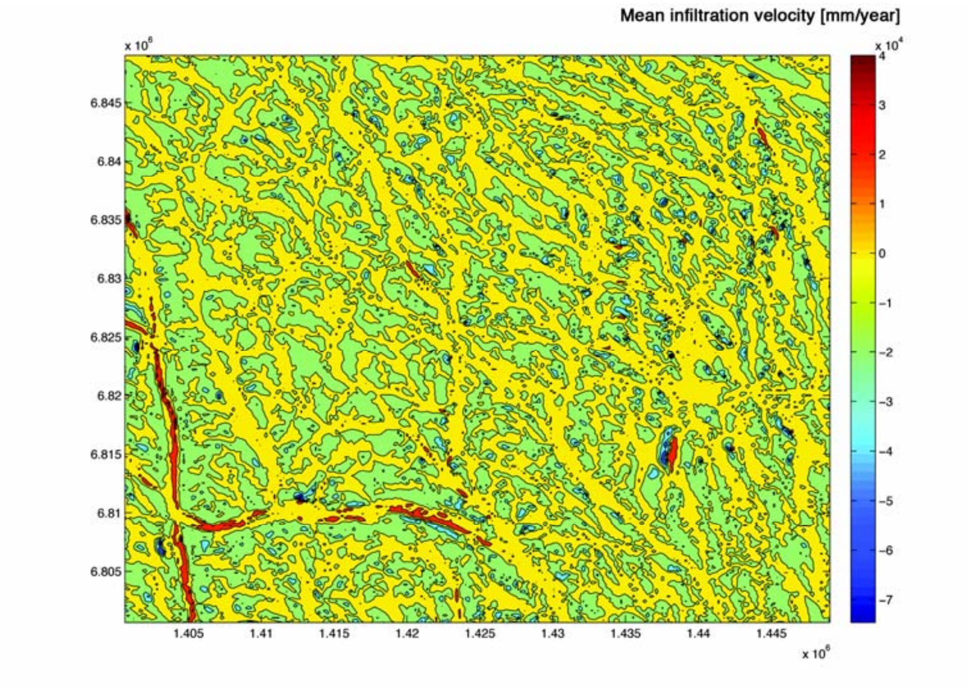

Fig. 8 Simulated infiltration velocities over a 50x50 km^2 area in Älvdalen Sweden using the simualtion package of Wörman et al. (2005) and assuming that the groundwater surface follows the topography. The grid resolution was 50 m.

Appendix 2: Analysis of SKB simulation data underlying report R-06-64 with the aim of evaluating the prediction robustness of extreme recharge areas

Method

An important issue is if it is possible to find locations with exceptionally long pathways for leaking radionuclides before they enter into the biosphere. This section aims to test weather the SKB simulation data presented in report R-06-64 can be used in this purpose. Hence, in each of the 28 model setups used by SKB a certain percentile of the longest flow paths (mean value for each 1km^2 square) were selected (Fig. 1). Furthermore, it was tested if the locations associated with the long flow paths were the same as the locations found in the other model setups, i.e. if the results overlapped between the model setups. The 67%, 95% and 100% overlaps, shown in Fig. 1, represents qualitatively the confidence by which these areas are appointed. However, the percents cannot be interpreted as confidence levels due to the lack of statistical basis of the analysis.

Results

We can see in Fig. 1 that the long pathways (99% or 95% percentile of the longest pathways) cannot be determined with a high degree of confidence. As an example, none of the locations selected with this criterion on the mean flow path length appeared in 27 (of 28) model setups or more. Generally, when the degree of overlap or robustness between models is added as a criterion, the squares/areas fall off markedly. Only three 1 km^2 areas can be determined with a 95% confidence (in all but one of the 28 cases) if the starting point is the 90% percentile of the longest mean flow path lengths. By applying a milder selection criterion such as the 80% longest flow paths it is possible to find one overlapping area in all 28 cases.

Individual model setups yield very long flow paths for the selected points, up to 100 km long. This result suggests that it is possible to find flow paths that extends from the inland to the coast. However, if the flow path lengths are averaged between the model setups that overlap the flow path is significantly shorter. The three areas that are selected based on the 10%-percentile of the longest pathways and overlap in 95% in all cases have an average (of 27 cases) path length of 8, 6 and 9 km and the coefficient of variation at the locations spread from 0.66 to 2.1 (last frame on row three in Fig. 1). The single area that is selected based on the 80%-percentile of the longest pathways and overlap in all cases has an average (of 28 cases) path length of 7.1 km with a coefficient of variation of 0.3.

Discussion

In a few model setups, very long flow pathways can be found in the inland. Depending to which case you refer, these pathways are up to 100 km long and can only be found in the inland. A problem is that the areas that have such very long flow paths are narrow and cannot be determined with a very high confidence based solely on the 28 model assumptions made by SKB (no statistical basis for confidence level).

The factor that seems to be most responsible for the generally relatively short sub-surface flow pathways that are sensitive to local topography is the shallow calculation domain and the decaying hydraulic conductivity with depth. Also the assumption that the groundwater surface follows the topography exaggerates the influence of local topography. If the hydraulic conductivity is assumed to be homogeneous with depth, this local character of the groundwater flow field becomes much less apparent. On the other hand, the decay of hydraulic conductivity with depth seems to be handled with account taken to the concurrent understanding of this phenomenon.

One can conclude that none of the hydrologically good 1 km^2 squares (based on the pathlength criterion alone) fall into the Simpevarp sub-area. The longest travel paths are not contained in either of the Laxemar nor the Simpevarp areas (with the 67% robustness criterion used here) as seen in Fig. 2. Fig. 3 shows that it is possible to find longer travel paths than the mean (80%-percentile) in the Western part of the Laxemar area using the 80% robustness criterion, but not in the Simpevarp area. However, the overall pattern is that neither Laxemar nor Simpevarp belongs to the areas with longest travel path lengths.

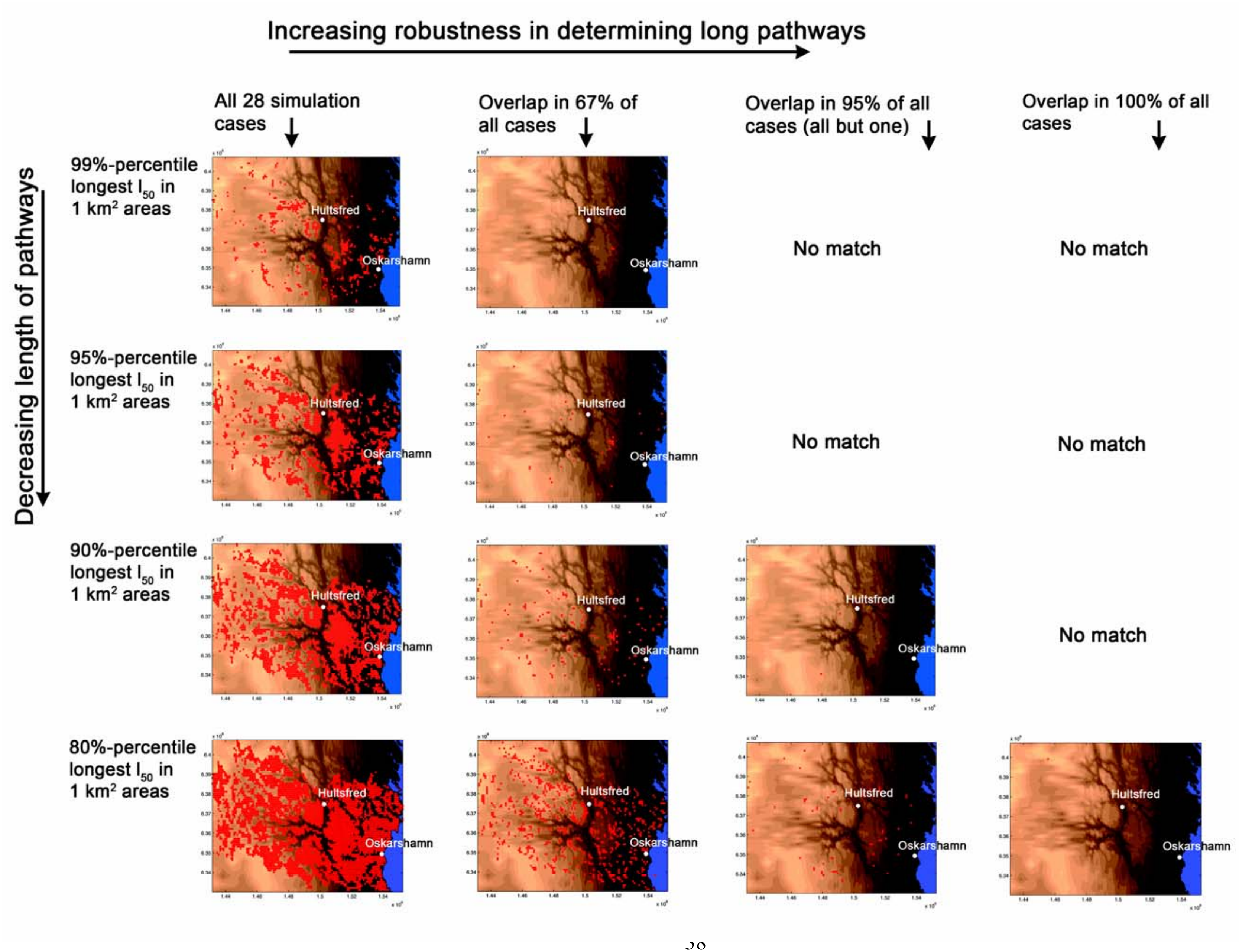

Fig. 1 Distribution various percentiles of longest flow paths in 6026 1 km^2 areas in 28 calculation cases presented by SKB report R-06-64 (left-hand side column) and different degree of overlapping areas between the 28 cases (confidence in area appointment).

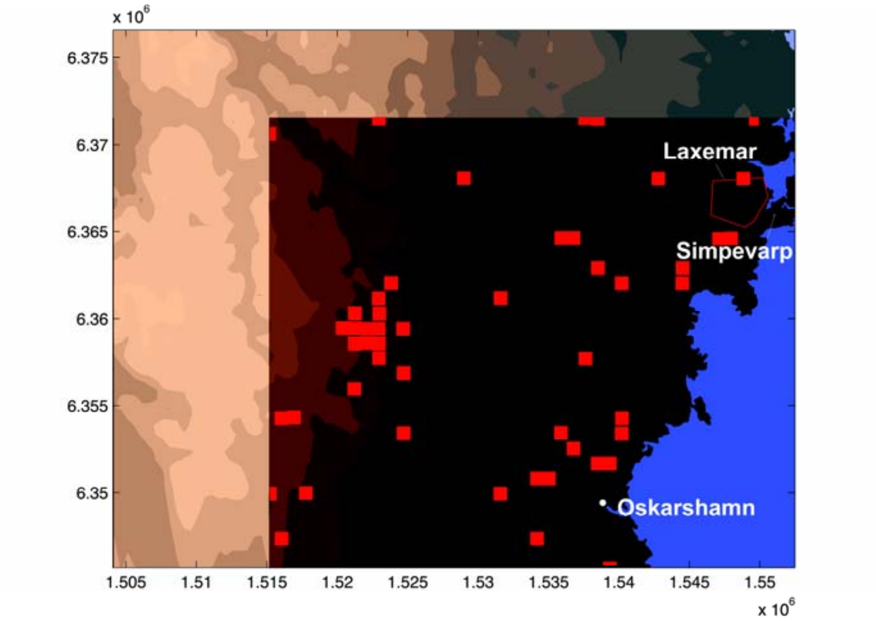

Fig. 2 Enlargement of case “Overlap in 67% of all cases” and “90%-percentile longest l_{50} in 1 km^2 areas”. The Laxemar investigation area is marked with red border. Simpevarp investigation area is located on the Peninsula further East towards the Baltic Sea. The longest travel paths are not contained in either of the Laxemar nor the Simpevarp areas (with the 67% robustness criterion used here).

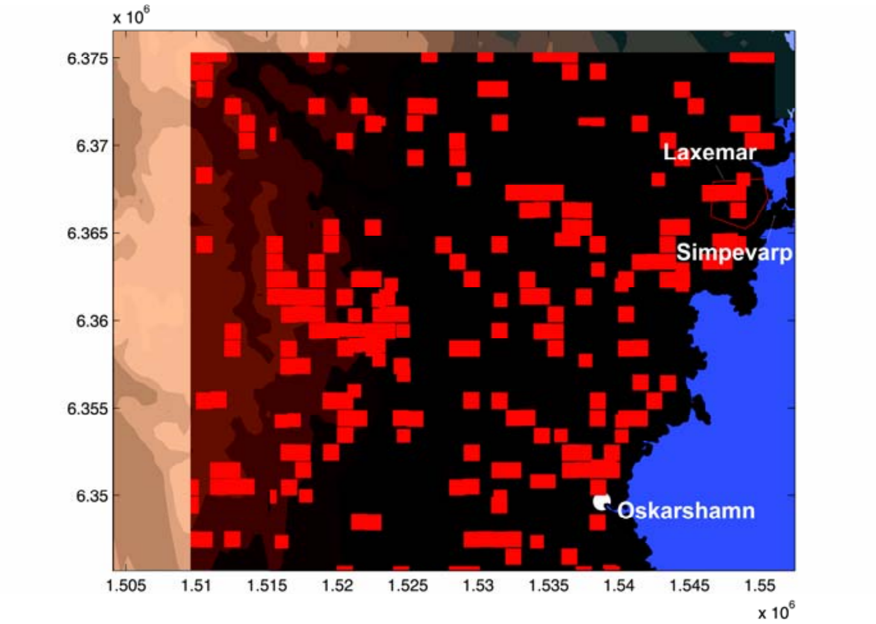

Fig. 2 Enlargement of case “Overlap in 67% of all cases” and “80%-percentile longest l_{50} in 1 km^2 areas”. The Laxemar investigation area is marked with red border. Simpevarp investigation area is located on the Peninsula further East towards the Baltic Sea. Somewhat longer travel paths than the mean (80%-percentile) can be found in the Western part of the Laxemar area using the 80% robustness criterion, but not in the Simpevarp area.

Bilaga 2. Clifford Voss granskning av SKB R-06-64

Technical Review for SSI of: ”Storregional grundvattenmodellering – fördjupad analys av flödesförhållanden i östra Småland. Jämförelse av olika konceptuella beskrivningar” by L.-O. Ericsson, J. Holmén, I. Rhén and N. Blomquist, SKB R-06-64, May 2006.

Clifford I. Voss, U.S. Geological Survey

30 August 2006

This review consists of five parts.

1 - Overview: A great quantity of insightful analysis has been done to evaluate the groundwater flow field in eastern Småland and to evaluate and report factors that control the length of paths from repositories located at 500 m depth. However, the report and model analysis does not address a key point underlying the questions noted by the authorities – whether (inland) sites with good properties of the hydrogeologic barrier exist in the region and whether any of these are better than the (coastal) Laxemar site. The hydrogeologic barrier is more effective in containing potentially released radionuclides from a repository when path length and transport time from the repository site to the termination point of the release path at the surface are greater. The reviewed report shows maps of locations of such sites for various modeled cases, but does not select good inland sites and compare them with Laxemar.

2 - General comments on the report, modeling assumptions and techniques: This list includes a variety of technical comments.

3 - Assumptions that tend to shorten lengths of modeled flow paths: This list mentions important model features that are included in most model cases devised for this study. These features (particularly shallow model bottom and decreasing hydraulic conductivity with depth) tend to cause modeled path lengths to be relatively short in all modeled cases. Evaluation of the impact of these features on the effectiveness of the hydrogeologic barrier was not done fully and independently for each and was most often included in a modeled case that contains other features that also reduce path length. Thus, the results reported come from a conservative analysis of the flow fields in the region, reducing the potential superiority of recharge-area sites (inland) over discharge area sites (e.g. near the coast).

4 - Comparison of sites using 7 modeled cases: Despite the conservativeness of the model analysis, inland sites with good properties in 7 modeled cases were selected by this reviewer and one was compared to Laxemar to demonstrate what the next steps should be. The selected example site is superior to Laxemar overall, in terms of both primary hydrogeologic barrier factors that control radiologic consequences of releases from a repository to the surface environment, path length and travel time.

5 - Conclusions

6 - References

1- Overview

General procedure: I am impressed with both the quality and great quantity of geological and analytical work that was done and reported by the authors, Ericsson, Holmén, Rhén and Blomquist (2006) (herein referred to as EHRB) and I congratulate them on their excellent effort and excellent results. The authors have followed the basic approach to finding sites that have good hydrogeologic barrier properties that I set out in Voss and Provost (2001), in my review (Voss, 2003) of SKB's response report, Follin and Svensson (2003), and in a subsequent series of lectures I presented in Sweden (Voss, 2004a, 2004b, 2005a, 2005b, 2005c).

The approach I suggested builds on the idea that due to implicit and permanent uncertainty in our knowledge of the hydrogeologic structure and parameters of the Swedish bedrock, it would be necessary to create many candidate models of a region and then find sites that have good hydrogeologic barrier properties (mainly long <u>path lengths</u> and <u>travel times</u> for nuclides that may leak from a repository) in all or many of these representations of the region. If a site has good predicted properties in all or many possible conceptual models of the bedrock, then it will most likely have good properties in the true bedrock, which has properties that will never be known with certainty, even after extensive field characterization. This approach should provide the most reliable results possible in the face of our uncertainty in the bedrock structure and properties, and should select places that have good hydrogeologic barrier properties irrespective of which conceptual description of the bedrock is used. To express this another way, this means that, no matter how we believe the hydrogeology of the site to be, it will still have good barrier properties. As mentioned above, EHRB generally followed this approach and they provided maps of sites within their model domain that have good barrier properties.

In this review, the <u>path length</u> and <u>travel time</u> will be referred to as 'primary hydrogeologic barrier factors' that control radiologic consequences of releases from a repository to the surface environment. These are key parts of the "F-parameter", which is the most accepted measure of the hydrogeologic barrier's ability to retard decaying radionuclides before their arrival at the surface environment. This review focuses on the impact of these two parameters on site selection.

Note that EHRB spent much effort evaluating the impact of two other factors besides path length and travel time, the *groundwater flux through the site* and the *direction of flow at the site (upward or downward)*. These latter factors do not have as much influence on the retardation of radionuclides as do path length and/or travel time and may be considered of lesser importance. When finding good sites, it is sufficient to find sites with either long paths or long travel times to increase hydrogeologic barrier function. The authors concluded their work by attempting to identify sites that simultaneously optimize as many as 3 or 4 of these factors, and in doing so, reduced the number of good sites that could be produced by their analysis.

Note also that most conceptual models EHRB selected for analysis tend to reduce the length of flow paths. Most models considered have a shallow bottom and decreasing hydraulic conductivity with depth, making the bottom 'feel' even shallower to the flow system. Whether these two factors are correctly specified in this manner is highly uncertain, but EHRB chose to assume that these would be included in most models. Thus, the flow field analysis should be considered to be highly conservative (i.e. providing highest certainty) for selection of good sites, inasmuch as most models will produce relatively short flow paths compared to other model concepts that could have been used.

A major criticism of the work presented, from the point of view of what I believe the Swedish Authorities expected, concerns the fact that EHRB have not brought their analysis to pertinent conclusions in their report about the relative safety of sites. The ambitious analysis presented remains rather academic, reporting only results of a sensitivity analysis that elucidates the model factors most important in controlling the existence of short and long flow paths in the region. These are reported to be 1- the undulating topography of the water table, and 2- the vertical distribution of permeability. This result is certainly valuable general knowledge, but it is only the first step in the type of analysis that SKB needs to do. What do the current results imply about better and worse repository locations in the region in terms of safety derived from the hydrogeologic barrier – the main question? The authors never mention any rating or comparison of alternative sites in terms of hydrogeologic barrier factors in their actual analysis and conclusions. The authors never mention how the Laxemar site compares with other places within the studied area.

Review of EHRB's conclusions: The authors conclude that inland sites do not generally have longer paths and travel times than do coastal sites. (No one had ever anticipated the opposite, as only particular inland locations in major recharge areas would have the expected good properties.) The authors then conclude that there are particular contiguous regions with good hydrogeologic barrier properties that exist, irrespective of which conceptual model of the bedrock is used as the basis of their model. This reported result is exactly in the spirit of the analysis that I had suggested. The authors end by saying that when more hydrogeologic barrier parameters are optimized simultaneously, fewer good sites can be identified. They focus on the inclusion of the magnitude of groundwater flux through a site as a parameter that, when included in the optimization, greatly reduces the number of sites with good barrier properties. They finally point out that this local groundwater flux through a site depends strongly on local structure and hydraulic parameters, which must be measured by a local field program – and so cannot be evaluated in a regional analysis.

Lack of site comparisons: In not going further with the analysis and discussion, the authors leave the impression in their report that, if all models are considered simultaneously and with equal likelihood, there are no advantageous repository sites in the region when simultaneously optimizing path length, travel time and other factors such as amount of groundwater flux through the site. I would point out that this would imply that Laxemar is as good as any other site in the region, in terms of the hydrogeological barrier function. It is clear from SKB's point of view why this was a politic way to end the discussion of their analysis. However, the authors never compared sites in the model with one another and thus never proved this.

The current and previously-considered candidate repository sites are never shown on the maps presented in the subject report. I drew in approximate locations for Hultsfred and Laxemar sites (Figure 1) and compared these sites with key figures 7-1 through 7-9, of EHRB, which show the 'best locations' for the hydrogeologic parameters of importance, at least among some of the conceptual models preferred by the authors for the comparison. The best locations never occur in the Laxemar site, and some of the best locations are within or just east of the eastern margins of SKB's Hultsfred east candidate site of a few years ago.

Implications for SKB: If other sites were found by EHRB to have better hydrogeologic barrier function than Laxemar, it might be difficult for SKB to present such results without calling into question the optimality of hydrogeologic safety margins of the Laxemar site. Indeed Sweden's Radiation Protection Act (1988:220) and the regulations implemented by the Swedish Radiation Protection Authority (SSI, 1998), require that the principles of best available technique and optimization must be employed when developing repositories for spent nuclear fuel and nuclear waste. These requirements are further developed in SSI's guidance (SSI, 2005) that states that the implementer must be able to motivate all important choices and decisions during the development of a repository, including *siting*, design, construction and operation, in relation to the repository's long-term protective capability. Consequently, the question at hand is whether SKB has sufficiently considered the role of hydrogeologic conditions and their importance for repository safety in their selection of candidate sites for the spent fuel repository. SSI has also asked SKB for clarification of additional safety related issues, including differences in groundwater chemistry and, in particular, depth to saline groundwaters between coastal and inland sites (e.g. see SSI, 2002). These issues are, however, not addressed further here.

Considering that the discussion of the possible safety advantages of recharge area repositories has been going on in public for almost 6 years, since 2000, one might expect at this late date, that a primary objective of SKB's current analysis would have been to compare different sites in eastern Småland with regard to important hydrogeologic parameters that tend to increase predicted safety of a subsurface repository. This part of the work was not carried out by the current authors.

Should SKB acknowledge that hydrogeologic conditions can be found to improve safety margins of a nuclear waste repository and that sites that maximize this factor can be sought would not be the same as admitting that current sites are not good enough. Rather, the contribution of hydrogeology to safety is only one of several factors to be weighed by SKB when selecting an optimal site. The potential value of additional radiologic safety margins at actual sites that optimize the hydrogeologic barrier should have been thoroughly evaluated and considered by SKB when proposing their final repository site. The current report is only a first step towards achieving this goal.

Hydrogeologic reasons for good sites: The figures provided in the EHRB report show that the best locations are clearly clustered in particular regions of eastern Småland. These locations appear in patterns. One of the results of greatest interest and importance in safe siting of a repository based on the type of analysis done by EHRB is to examine the spatial patterns of best locations and to develop an understanding of the hydrogeologic reasons for the advantages provided by these particular locations. This would allow model analysis that is based on many conceptual models to be used in a prospective manner to find advantageous sites, as suggested by Voss and Provost (2001). Indeed, I believe that this should be a primary point of analysis described in the subject report, but it was not included.

One such cluster is in the Virån catchment, beginning in the north several kilometers east of Hultsfred and trending south-southeast for about 25 km (Figure 1). This cluster passes the eastern margins of the Hultsfred-east candidate site and all or part of this cluster appears in most of the selections of best sites shown in the report. Comparison with topography (Figure 2-3 of EHRB) and topographic gradient (Figure 4-3 of EHRB) maps shows that this cluster occurs within an elevated area of very low topographic gradient – a plateau. It should not be a surprise that repository sites below a broad smooth inland plateau would have longer flow paths, longer transport times and lower specific flux than other sites. Such areas of 'best sites' with many contiguous best locations would provide a robust region in which to locate a recharge-area repository with rather long paths lengths and travel times. In the cluster indicated in the figure, some contiguous groups of best locations cover areas of maybe 20 km^2, large enough for securely locating a repository within a region of good hydrogeologic properties with regard to subsurface flow. The authors present various combinations of '1000 best sites' in the above-mentioned figures but never present the type of interpretive discussion begun just above to elucidate the reasons for the locations of good sites.

Demonstration of site selection and comparison: EHRB never proceeded to the next steps of using the modelling analysis as a prospective tool to select sites that are advantageous and then to compare sites with one another. These are both necessary steps in optimizing the hydrogeologic barrier function of the site finally selected for a repository. As part of this review, I have attempted to take these 'next steps' as a demonstration, albeit in a limited manner due to time available for this review. I carried out a quick analysis of modelling results created by EHRB (and kindly provided in data files by SKB via Johan Holmén), in order to find hydrogeologically advantageous sites. I also compared one of these with the Laxemar site. The site

I compared turns out to be superior to Laxemar in terms of path length and travel time. It may not be difficult to demonstrate that there are other inland sites superior to Laxemar that can be found among EHRB model results, even given the conservative nature (discussed later) of the EHRB model cases.

2- General comments on the report, modeling assumptions and techniques

- The hydraulic conductivity values for ‘intact bedrock’ in various lithologies seem high to me by a couple of orders of magnitude (listed in Table 2-1 of EHRB). This concern is tied to the question of what is meant by ‘intact bedrock’ and the importance of local fracturing, at small scales not explicitly modeled in the regional model. Indeed, the third most important factor controlling flow path length was found, by the authors, to be the existence of local fracturing. How much local fracturing is included in the type of rock represented in Table 2-1? It would seem to be a lot. It is certainly not clear how to separate scales of fracturing when assigning conductivity values and discrete fractures or zones. Further, the separation of ‘intact rock’ from fracture zones seems to be arbitrary, as in many cases, the ranges of conductivity of both are similar. This question underlies the analysis done and brings into question the meaning of model assumptions when permeable structures are included as discrete objects.
- The importance of local heterogeneity should have been included in the list of important factors in the conclusions; at present, I do not believe it is highlighted again after being presented as a strong factor in Sections 6.9 and 6.10.
- It is not clear which pressure values are prescribed below the Baltic Sea and what their impact is on the flow field. Do these include the higher density of the seawater? If so, the equivalent freshwater heads should increase with distance from shore (i.e. with depth of seawater). Does this cause a reverse flow from the sea towards shore in the constant density model, and if so, how does this impact results for the inland flow field?
- There are aspects of the variable-density computer code that are described but never used in the analysis. Particularly, the discussion of dead-end diffusion and multi-rate diffusion is of no practical use in the report.
- The fact that flow path length does not increase monotonically with distance from the shore is not interesting because it is self-evident, though EHRB apparently have spent significant effort to prove this. Such behavior would not normally be expected in any hydrogeologic system with real (not perfectly smooth) topography. The plots and analysis of flow path length with distance from shore to have little value in explaining how the flow field functions. It is not the distance from shore that is being discussed as a factor in finding optimal hydrogeologic conditions for a repository site, but rather any conditions in any location that provides long flow paths, long travel times and low specific flux; most such locations will be in groundwater recharge areas. The only reason that previous discussions of optimizing location reflects against coastal sites is because only coastal sites have been selected by SKB.
- The conclusions lack a discussion of the hydrogeologic factors that provide the best conditions for optimizing the hydrogeologic safety margins and should indicate which areas in the region best fulfill these criteria, given the analysis of the conceptual models considered.
- The conclusions lack a discussion of other possible conceptual models that were not considered via modeling, but that may be of interest for further analysis.
- It is suggested that the brines are stagnant (implying very slow flow) because of their great ages. This view seems typical of most SKB reports. It is quite possible that brines are not stagnant and that the reason for great age is a very long flow path. Along such a flow path, brine velocities may be as high as shallower freshwater velocities. While the brine tends to act as a barrier to freshwater flow, it may not itself be static.
- The initial conditions for variable density flow simulation are either uniformly increasing concentrations with depth, or a depth-function of the topography. This does not match the steady state concentration conditions calculated previously by Voss and Provost (2001) or those used by Follin and Svensson (2003). Further, these initial conditions are not synchronized with the topographically-driven flow in the freshwater above. Both assumptions are not natural and will thus generate their own artificial flows caused by density imbalances in the assumed distributions. The impact on re-

sults for flow paths of type of initial conditions selected (those in the present study and those previously reported) were not evaluated and may be important in these simulations.

3- Assumptions that tend to shorten lengths of modeled flow paths

- EHRB assigned a depth-dependent decrease in hydraulic conductivity, K. The variability of existing K data with depth is so great that such assignment has very high uncertainty. One can easily argue that there is actually no trend, or that there is only a generally higher value in the uppermost 200 m than below. High K values, as high as near the surface, can be found at any depth. The same is true for low K values. In most model cases considered by EHRB, a depth-decrease in K has been applied to lithologic units and to vertical and horizontal deformation zones. This assumption decreases modeled path lengths by effectively bringing the flow 'bottom' of the model closer to the modeled ground surface. Depth decrease of hydraulic conductivity is found to be an important factor controlling the flow field, and this overshadows the effects that many other features exert on the flow field. This choice by EHRB has caused modeled paths to be shorter in most models they considered because most models include the depth dependence. The impact of vertical conductivity variation needs to be evaluated independently of other model features if an objective analysis is to be carried out.
- Regarding diabase dikes, if they indeed have an impermeable core and permeable crust, then they should generate springs wherever they outcrop in a groundwater discharge area. This may be one way to check their actual hydrogeologic behavior. Also, I believe that the model assumes that the diabase dikes interrupt the hydraulic continuity of conductive fracture zones; this appears to be an uncertain assumption and its impact on the flow results might be tested by assuming the opposite as well. This assumption may tend to shorten flow paths.
- The lateral boundaries are considered to be impermeable in the modeling because they are located at divides in surface water systems. While this may be a correct assumption for the upper 10m of the system, this is almost certainly incorrect for greater depths. At greater depths, other conditions (based on patterns heterogeneity and more regional gradients) control flow across the selected boundary location (as mentioned in the report). The closed lateral boundaries at depth in the modelling would tend to shorten flow paths and travel times because paths that would normally cross these boundaries at depth are here forced to discharge. Modeled sites with good properties near the model boundaries would be less likely given this aspect of the model construction. No model tests were carried out to evaluate the impact of these boundary conditions on results.
- Most cases considered use the ground surface topography as the water table boundary condition on the top surface of the model. It is clear that this would exaggerate local gradients, decreasing modeled path lengths, whereas in the real world, the water table is smoother than the topography. The report considers one kind of smoothing: decreasing top boundary condition heads in inflow areas by a few meters (Cases 5J1, 5J2). However this is only one possible smoothing and it is applied only to a model with a shallow bottom and decreasing K with depth. The impact on path lengths of a smoother groundwater table might be evaluated more thoroughly and objectively with other smoothing approaches and for other hydrogeologic model structures.
- For a model that considers possible flow in a 100 km region, setting the model bottom at 2500m depth would not be reasonable unless it was certain that the bedrock was impermeable below this depth. However, there is no indication that this is the case in Sweden's bedrock. As mentioned above, the depth dependency of K is highly uncertain and high K values have been measured at all depths explored in Sweden. The deepest model considered had a bottom at 3300 m, and it also included a depth-dependent decrease in K. Not only was this model not deep enough to evaluate the effect of bottom boundary depth, but it also reduced the impact of the bottom location on the flow field by significantly decreasing conductivity before the depth of the bottom. Using such a shallow model bottom is a critical modeling constraint that shortens the length of flow paths in the model.

- The bottom of the model was set to a constant value of -2500 m for most simulations. This precludes deeper flow paths that may exist for some sites. The discussion provided about stagnant brine being a flow boundary is partly true, inasmuch as the brine velocity should mostly be much lower than freshwater velocity. However, there are not only two fluids separated by a sharp interface as suggested by the discussion and approach, but a full range of mixtures of freshwater and brine. Brine concentration increases gradually with depth. Thus, fluid velocities of the mixture should decrease gradually with depth and there is no sharp bottom to the flow field as modeled. Previous simulations by Voss and Provost (2001) with a 10 km deep model and full variable density simulation indicate that the brine mixtures do flow, and not necessarily in the same direction as topographic water-table gradients. Further, the previous simulations show that there are windows to the deep brine system, from which paths of fresh groundwater recharge enter the deep salty flow system. These are among the longest paths in the flow field with the longest travel times. The approach used in the reviewed report excludes the existence of such deep flow paths and this excludes the possibility of finding repository locations in such windows to deep flow. These may be the best locations in the region.
- Following a more than 10ka simulation starting from the initial conditions, the salt distribution achieved is sometimes peculiar (e.g. Figure 6-17 Case 1s1), wherein there remains a high concentration gradient near the bottom of the model due to incomplete flushing by freshwater. This may indicate a need for a deeper model wherein the saltwater would move downward beyond the current bottom boundary in some locations within the 10ka period. During long periods, the brines may migrate considerable distances laterally and vertically; the shallow model boundary may prevent some of this migration from occurring in some modeled cases. This would tend to reduce modeled path lengths from repository depth.

4- Comparison of sites using 7 modeled cases

OVERALL PHILOSOPHY
There may exist inland sites with very long (regional scale) flow paths, but it is not an absolute requirement that SKB find the absolutely best sites that have flow paths ending in the sea. Inland, there are likely good sites that are significantly better than Laxemar or other coastal sites in terms of the primary hydrogeologic barrier factors for radiologic safety: long flow paths and long travel times. To demonstrate the point that sites with advantageous hydrogeologic barrier function may be found and compared, I only attempted to identify and compare a single site that is relatively better than Laxemar, and not necessarily the "best" one that recharges the longest regional-scale flow path.

An analysis with multiple conceptual models is the first important step towards building confidence in such a site. There are many ways to sort and rank locations, given the type of data provided by the EHRB modeling. My search for good locations did not only attempt to find the locations with the longest path lengths and travel times. Rather I tried to select sites that optimized four extreme hydrogeologic safety characteristics:

> The first part of this approach is intended to find sites for which the shortest paths and times are the longest of all possible locations in the region. The reason for this objective is that site safety is most compromised by short paths and travel times – so one goal should be to find sites that have the fewest (or longest) short paths and travel times. I began by considering the 10 percentile length and time statistics for each 1 km^2 block reported by EHRB and selected the best 10% of these among all ca. 6000 blocks in the modeled region, for each of 7 model cases. Each block in the model was given a score of between 0 and 7, depending on the number of model cases in which it appeared among the selected blocks.
>
> The second part of this approach is intended to find sites for which the longest paths and times are the longest of all possible locations in the region. The reason for this objective is that site safety is most improved by long paths and travel times – so one goal should be to find sites that have the longest paths and travel times. I ranked all locations in the region by the 90 percentile statistics for length and time, seeking the 10% of blocks with the longest paths and times among all blocks in the modeled region, for each of 7 model cases. Each block in the model was given a score of between 0 and 7, depending on for how many model cases it appeared among the selected blocks.
>
> Comparison of scores for both sets of blocks selected by the above criteria (i.e. longest short times and longest long times) showed that many blocks that performed well for several models were in the same spatial locations.

One requirement of a site with robust superior hydrogeologic properties is that there should be several contiguous blocks with good properties included in the site, indicating that the site exists because of some overriding hydrogeologic factors in the vicinity. Laxemar was represented by 6 contiguous blocks within the existing site boundary (though most of these were not in either list of selected blocks), and other good sites I found from the above manual optimization had between 4 and 8 contiguous blocks.

EXAMPLE COMPARISON SITE: SITE A
For example, I have illustrated results for one of the good sites found as described just above. I called it Site A. I believe it is just east of the Hultsfred east site considered a few years ago by SKB. Site A is also within the example region of interest for superior sites shown on Figure 1. In the EHRB report, some locations within Site A were also selected to be among the locations in the model area that have both the 1000 longest median paths and 1000 longest median times for two series of models (Series 2 in Figure 7-22, and Series 4 in Figure 7-23 of

EHRB). The actual location of this site does not matter here; the objective of this analysis is only to show that such sites can be identified using the type of analysis reported by EHRB, and that these may be better than Laxemar. Site A is only an example. The map of Site A and Laxemar is Figure 2. There is a small dot on the map for each block in the model and colored circles for the blocks within each site.

Site A consists of 8 contiguous blocks (8 km^2) and Laxemar consists of 6 blocks (6 km^2). (These 6 were picked by Prof. Anders Wörman, KTH, and me to fit completely within the site boundary, and most closely approximate the Laxemar site, given the discretization used in the modeling.) See Table 1 for coordinates.

MODELS IN THIS COMPARISON

I had intended to use Series 2 from the report, but I found that the variable-density model had very different block coordinates and numbering from the constant-density model. This meant that it would have been too much work to include the variable-density model results in my Excel analysis - however, the EHRB report showed that, for their particular models, the impact of variable-density on their results were minimal – so if we accept this, ignoring their variable-density models should not change the result I am reporting. I selected most of Series 2 model cases from EHRB (Cases 1, 2, 3, 4, and 5). Then, instead of the variable-density models, I added two other constant-density models, (Cases 8A and 8B). These are like Case 5 (the EHRB base case) but with added local (stochastically-generated) heterogeneity; each reflects a different realization. The belief previously expressed by many scientists was that local heterogeneity would significantly shorten flow paths and would ‘break’ the regional flow paths, even in regional recharge areas. In total I have 7 models in my series (Cases 1, 2, 3, 4, 5, 8A and 8B).

AVAILABLE DATA FROM MODELS

For each block, statistics were kindly provided by Johan Holmén for path length (L) and travel time (T) (min and max, 10%, 50% and 90% percentiles of the distribution within each block). There is one set of values for each modeled case.

COMBINING STATISTICS FROM DIFFERENT MODELS

I took these block statistics and calculated an average value considering all 7 models. One might have more belief in or criticism of some models than in others, leading to possible weighting when doing such averaging. However, for this analysis, I considered all 7 models to be equally likely and took a simple average to create combined statistics.

RESULTS OF COMPARISON

-- *Site A vs. Laxemar for Each Statistic and for Each Model*

Considering individual statistics (min L, 10% L, 50% L, 90% L, max L, min T, 10% T, 50% T, 90% T, and max T) for each of the 7 model cases, Site A is better than Laxemar in 94% of the individual statistics (66 of 70 possible instances). Site A is about 12 times better than Laxemar overall when simultaneously considering path length and travel time. Here, ‘overall’ means the average of all 70 values of the individual ratio of each length and time statistic for Site A to that of Laxemar.

Considering only path length, L, for all of the 7 model cases, Site A is better than Laxemar in 97% of the individual statistics (34 of 35 possible instances). Site A is about 4 times better than Laxemar overall considering only path length in the 7 models. Here, ‘overall’ means the average over all 35 values of the individual ratio of each length statistic for Site A to that of Laxemar.

Considering only travel time, T, for all 7 model cases, Site A is better than Laxemar in 91% of the individual statistics (32 of 35 possible instances). Site A is about 21 times better than Laxemar overall considering only travel time in the 7 models. Here, ‘overall’ means the average over all 35 values of the individual ratio of each time statistic for Site A to that of Laxemar.

--*Site A vs. Laxemar for Each Statistic as Averaged Over All Models*

Considering the average of each statistic for all 7 model cases, Site A is superior to Laxemar for each available statistic (see Table 2).

The shortest travel times are improved most for the Site A site compared with Laxemar: 30 times for 50% T, 27 times for 10% T, and 29 times for min T.

Path length statistics are about 4 or 5 times better for Site A than Laxemar.

The bar charts of Figure 3 show the combined (average) value for all 7 models for each path length and travel time statistic for Site A and Laxemar. The charts show that Site A is superior to Laxemar for every combined path length statistic and for every combined travel time statistic. Site A combined path lengths range from 10 km to 28 km, in comparison with Laxemar lengths ranging from 2 km to 8 km. Site A combined travel times range from 30 ka to 700 ka, in comparison with Laxemar times ranging from 1 ka to 140 ka.

Summary of results: For all statistics and no matter how these were compared among the 7 different model cases, Site A has superior hydrogeologic barrier properties in comparison with Laxemar in terms of both greater path lengths and travel times.

Table 3 provides all data from the 7 models used in this analysis. We noticed that the highest travel time reported by EHRB is exactly 1000127 years. Though model times were greater, no greater numbers were reported for some technical reason. “1000127” appears often in Site A results, most often for the higher percentile times in 6 of the 7 model cases. For Laxemar, the number occurs only for the two highest time statistics (90% and max) in only 2 of the 7 cases. Thus, modeled travel times at Site A are even greater than reported in this analysis, while under-reporting of Laxemar travel times is much less significant. This means that the travel time advantage of Site A over Laxemar is actually <u>greater</u> than found in the present analysis.

5- Conclusions

DEMONSTRATION OF SITE SELECTION AND SITE COMPARISON
The models developed by SKB are complex and varied providing a wide variety of possible groundwater flow fields for study. [Despite this, I have specific criticisms of some important aspects of the models that likely cause flow paths to be shorter than in reality (e.g. bottom too shallow, lateral boundaries are no-flow, etc.).] In my comparison analysis, I included models with the highest level of local detail in heterogeneity, two models with stochastically generated local structures that are thought to short-circuit long flow paths. Thus, we have a highly conservative analysis of the flow field, inasmuch as short flow paths have been given strong preference in the way most of the models are set up.

Remember that the comparison results presented in this review are for many models of the sites and should be robust; of course this was the whole intent of making an analysis with many conceptual models. In addition, this reviewer believes that the model cases set up by EHRB tend to produce conservatively short flow paths and travel times. Thus, we should truly believe that Site A has much better properties for the hydrogeologic barrier than Laxemar with overall longer paths and travel times. [The EHRB report falls short of providing what was needed from SKB at this time, inasmuch as these kinds of comparisons were not made.]

For the model cases considered, other sites may be found with better hydrogeologic safety characteristics than Laxemar. The approach used here was intended to select sites that maximize the shortest and longest path lengths and travel times (rather than maximizing only the longest ones). Particularly for Site A, the shortest paths and travel times are significantly improved over the shortest paths and travel times for Laxemar, a site that would never have been selected if using thse site-selection criteria.

Despite the conservativeness of the EHRB analysis, it is still possible, on the basis of their results, to find inland sites with superior hydrogeologic safety margins. This was demonstrated by comparing one inland site and Laxemar. SKB has not used hydrogeology as a positive siting factor, rather as something to work against and that may spoil safety. This reviewer believes that the EHRB and current analyses bears out the idea that regional flow can be used to benefit the radiological safety of a high-level nuclear waste site in Sweden. Indeed, sites in or near major recharge areas can be found with longer flow paths and longer travel times and that provide a hydrogeologic barrier to escaping radionuclides of much greater effect than sites in or near a major discharge area such as Laxemar.

CONSIDERATIONS CONCERNING HYDROGEOLOGIC BARRIER FUNCTION
Relation of path length to travel time: Results from the EHRB report show that path length L and travel time T do not increase in proportion to each other for site statistics as one might expect from overly simple consideration of the statistics based on a single streamline and Darcy's Law. For Site A, the improvement in travel time statistics is greater than the improvement in path length statistics in comparison with Laxemar. These differences would imply different improvements in the F-parameter when considering alternative length or time forms that define the parameter.

Extra retardation of long paths for some nuclides: Moderate increases in the F-parameter may strongly decrease peak doses and increase transport times of some radionuclides. The relation between the value of F and dose is not necessarily linear. Thus, even a site with only moderately longer path lengths or travel times may disproportionately increase the effectiveness of the hydrogeologic barrier.

Effect of lateral spread of radionuclide plume: Higher path length also implies greater subsurface volume of rock within an escaping radionuclide plume. The lateral spread of the plume is due to heterogeneous flow distribution resulting in transverse dispersion of solutes in terms of the classical conceptual description of solute transport. Plumes tend to become wider with greater transport distance from their source. This implies lower concentrations of radionuclides within the plume and lower solute concentrations (and doses) at points where the plume discharges. Concentration would be approximately inversely proportional to the cross-sectional area of the plume – with a large reducing effect on the dose obtainable at any part of the cross section. A plume of only 10 times greater cross-sectional radius would have 100 times lower concentrations of radionuclides. A plume would widen as it moved away from the repository, so longer path length would imply a wider plume and lower doses at any point where the plume discharges.

Though doses will be much lower than if the flow path is short and discharges in a small region of the surface, it may be argued that one disadvantage of lateral spread is that the discharge will be distributed over a larger area of the ground surface. It is also possible that even if the plume widens along its path in the subsurface, it may refocus if its discharge is concentrated in small regions of the ground surface.

Lateral mixing does not impact the predicted effect of the F-parameter on retardation (this effect is independent of concentration) but it reduces doses at any point because of the concentration decrease due to mixing with non-contaminated ground water. Lateral spreading effects and impacts on radiological safety require further study using three-dimensional groundwater flow and transport models.

Geometric factors impacting available surface for sorption/diffusion: There are two geometric behaviors of three-dimensional plumes related to flow in fractured rock that would tend to increase the retardation of radionuclides more as a function of path length than would be predicted by simple application of the F-parameter to one-dimensional flow paths from the repository to the discharge point. Both behaviors are caused by changes in the area available for radionuclide sorption and diffusion into the side rock that occur along the plume's path through the rock. Current analysis assumes only a constant area (per rock volume or per flowing water volume) available for sorption/decay along the entire travel path of a radionuclide plume.

Both behaviors noted here consider an individual radionuclide plume that begins with a very small cross-sectional area near a leaking canister. Both behaviors deal with modes of transport-scale-dependence of the area available for sorption/decay of radionuclides.

1- In a network description of the flowing structures in the rock, when the plume splits between two channels at some downstream location (either in different fractures or within the same fracture) then the available area for sorption/diffusion increases for the plume water. Each time the plume branches into additional paths, this area increases; thus the area and the F-parameter increase with travel distance. This behavior assumes that the plume water does not mix laterally with water on other paths. Paths may both split and coalesce, but the overall effect is of more available surface area when the distance of travel through the rock is greater than would have been available had the travel distance been short.
2- When the initially-narrow plume spreads laterally, mixing with non-contaminated groundwaters, parts of the plume may experience zones of much higher available surface area for sorption/diffusion, such as zones containing fracture breccia. Thus, the available area for sorption/decay should increase with increasing travel distance through the bedrock, increasing the F-parameter with distance travelled.

All of the effects discussed above (extra retardation for certain nuclides, transverse spreading that decreases concentrations, branching plumes, and plumes sampling larger volumes of the bedrock with extra travel distance) tend to enhance the safety contributed by the hydrogeologic barrier of a recharge-area repository more than by simple proportionate increase of the F-parameter by the increased path length or travel time. It is not simple to quantify the increase in hydrogeologic barrier function implied by these processes, but it is clear that these effects would make the standard one-dimensional analysis a conservative estimate of retardation. The added safety provided may be an additional reason to prefer sites that provide the longest possible paths. More analysis would be required to quantify these effects.

Acknowledgements

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	x-origin		y-origin		
	1429064		6329723		
N	XINIC		YINIC		**SITE**
4351	86504	1515568	31526	6361249	**A**
4407	87514	1516578	30478	6360201	**A**
4408	87502	1516566	31506	6361229	**A**
4462	88503	1517567	30524	6360247	**A**
4463	88524	1517588	31473	6361196	**A**
4516	89496	1518560	29501	6359224	**A**
4517	89493	1518557	30481	6360204	**A**
4518	89467	1518531	31490	6361213	**A**
5947	**118513**	**1547577**	**36499**	**6366222**	**Lax**
5948	**118490**	**1547554**	**37496**	**6367219**	**Lax**
5970	**119496**	**1548560**	**36482**	**6366205**	**Lax**
5971	**119498**	**1548562**	**37481**	**6367204**	**Lax**
5993	**120508**	**1549572**	**36491**	**6366214**	**Lax**
5994	**120512**	**1549576**	**37474**	**6367197**	**Lax**

Table 1 – Locations of blocks within Site A (A) and Laxemar (Lax). N is the block number used by EHRB, XINIC and YINIC are local coordinates to which x-origin and y-origin must be added to obtain map coordinates, as given in the adjoining columns.

Averages for all 7 models	**L**	**L**	**L**	**L**	**L**
(1,2,3,4,5,8A,8D)	**min**	**10**	**50**	**90**	**max**
A	9837	11068	17326	23109	27739
Lax	1935	2348	4008	6203	7784
A/Lax	5	5	4	4	4

Averages for all 7 models	**T**	**T**	**T**	**T**	**T**
(1,2,3,4,5,8A,8D)	**min**	**10**	**50**	**90**	**max**
A	30448	47733	204164	555480	697288
Lax	1062	1766	6898	95347	139678
A/Lax	29	27	30	6	5

Table 2 – Averages of each statistic among all 7 model cases. Time T in years, Length L in meters. Ratio (A/Lax) for each statistic is also included.

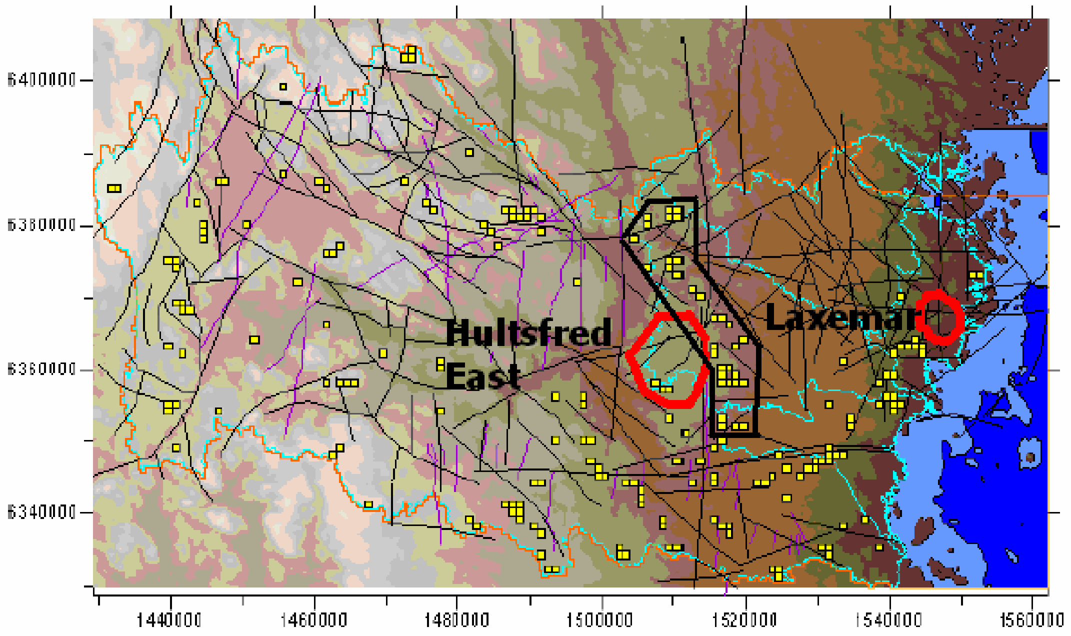


Figure 1 *– Modified from Figure 7-8 in Ericsson and others (2006). The figure shows blocks from one modeled case (8As2 with variable-density flow and local heterogeneity) that are among the 1000 blocks with longest travel times, lowest specific flux, and longest path lengths. The* ***red regions*** *are the approximate locations of the Hultsfred East and Laxemar sites. The* ***black region*** *includes a band of good sites within the eastern portion of a topographic plateau. Site A (used for comparison in this review) is within the second cluster of blocks from the southern end of this region.*

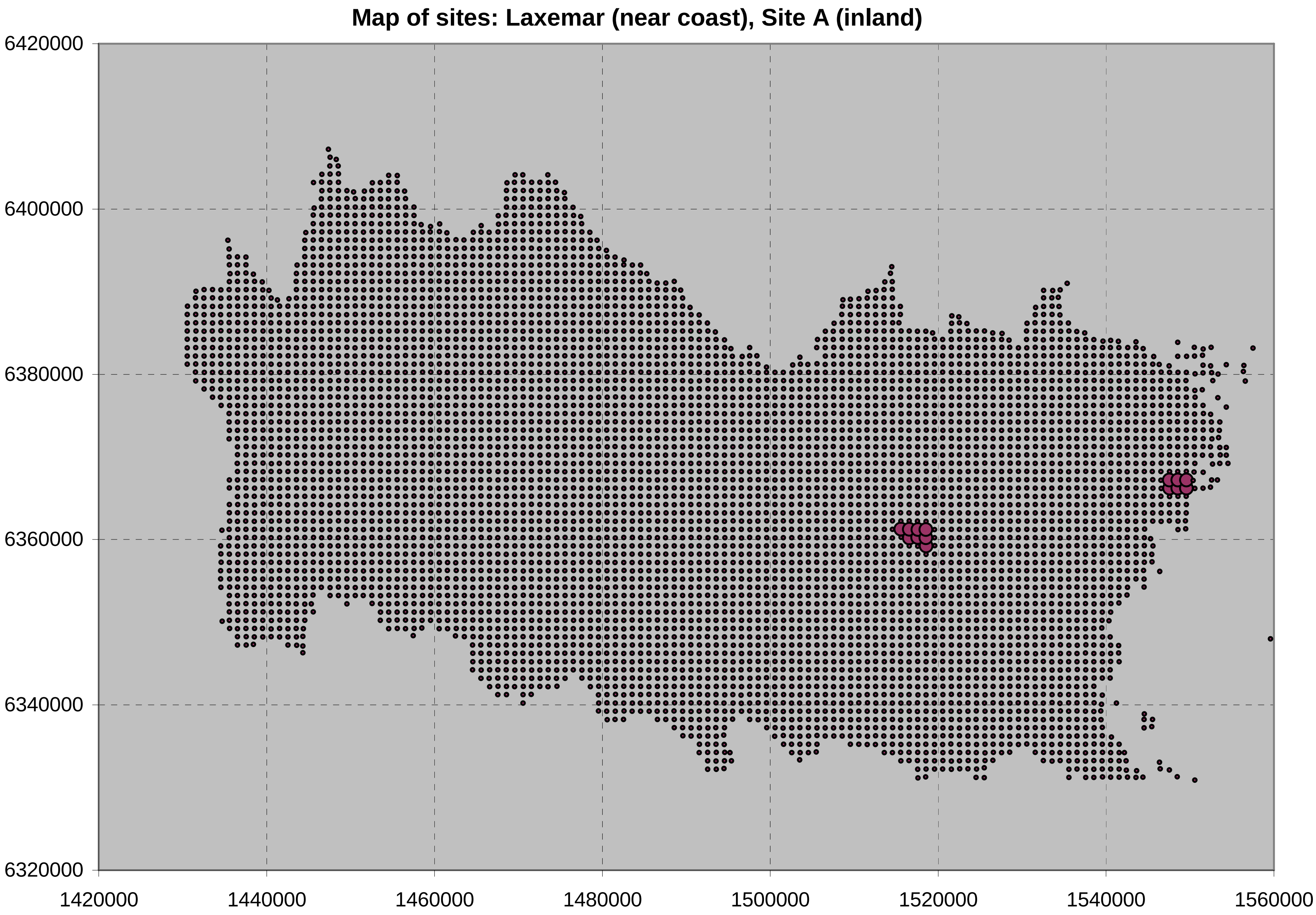
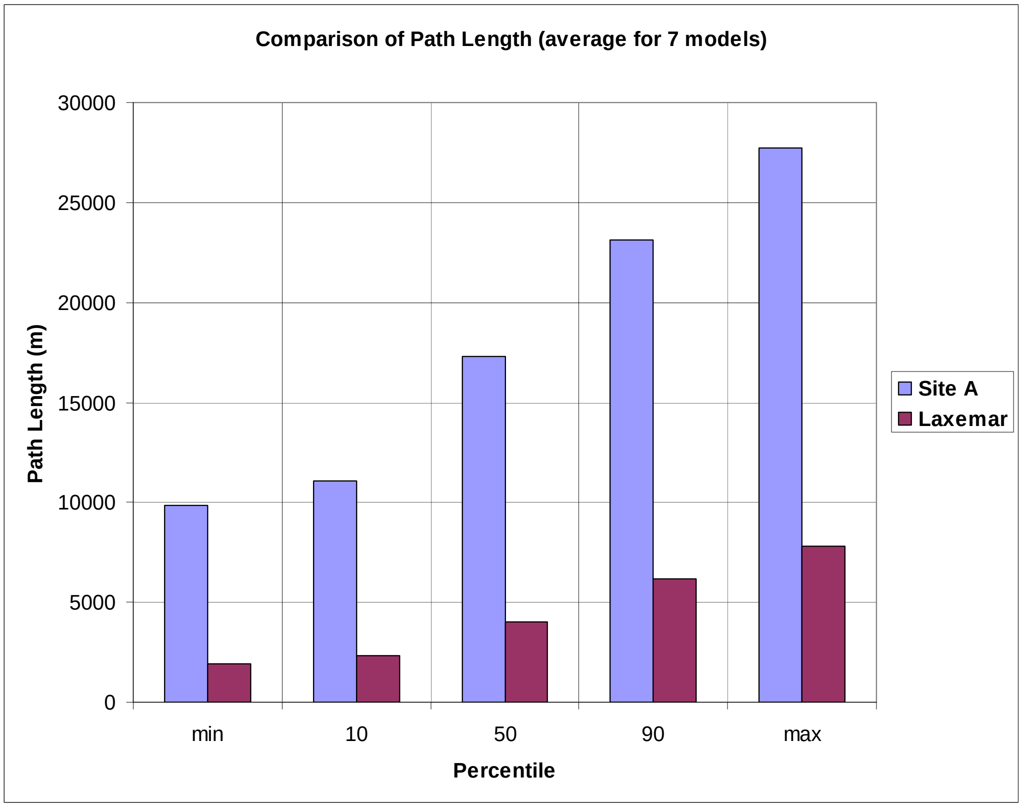


***Figure 2** – Locations of Site A (inland) and Laxemar (near coast).*



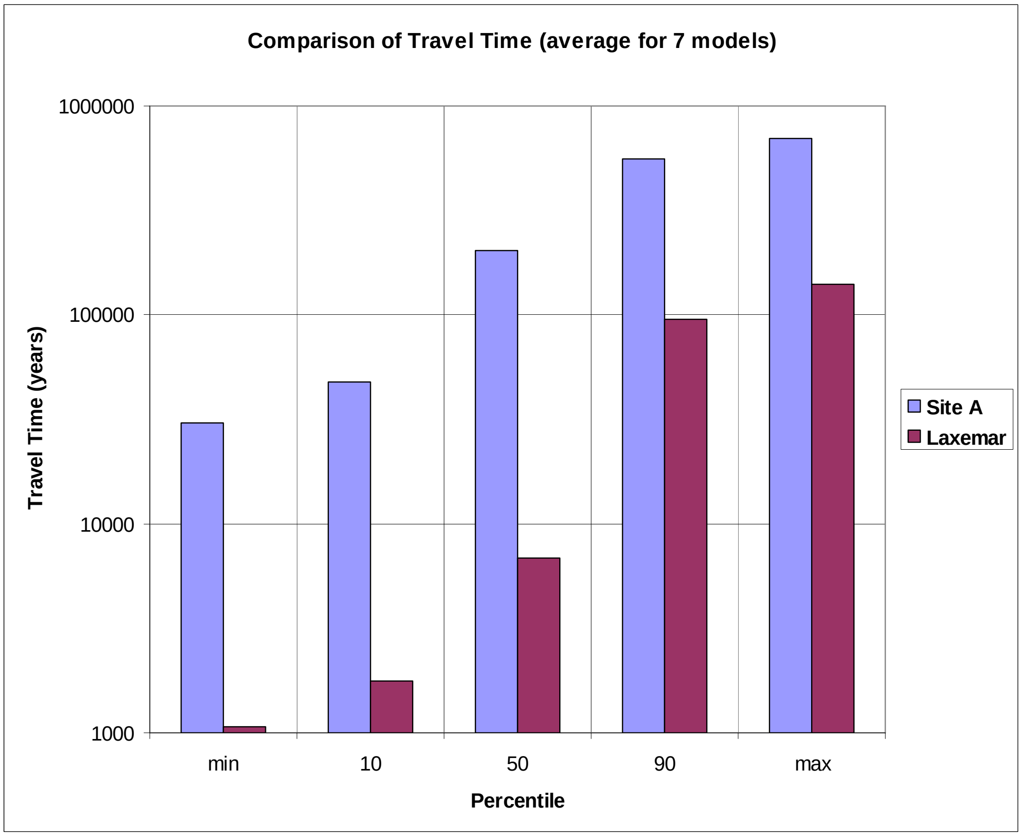


Figure 3 – Visual comparison of each average statistic among all 7 model cases between Site A and Laxemar.

Table 3: see caption below.

1	1	1	1	1	1	1	1	1	1
minL	*10%L*	*50%L*	*90%L*	*maxL*	minT	10%T	50%T	90%T	maxT
44861	*45475*	*46620*	*47547*	*48193*	1000127	1000127	1000127	1000127	1000127
38725	*40170*	*43840*	*44710*	*46502*	74336	107480	1000127	1000127	1000127
12480	*13268*	*44729*	*45407*	*46672*	11948	14306	1000127	1000127	1000127
10683	*13068*	*40010*	*43568*	*45678*	10627	14760	107708	1000127	1000127
10294	*11009*	*12873*	*44773*	*45369*	8868	9260	14630	1000127	1000127
6527	*7598*	*9872*	*41898*	*42791*	6186	6897	9904	1000127	1000127
10562	*10986*	*42805*	*44394*	*46380*	9814	10000	1000127	1000127	1000127
9086	*9568*	*11468*	*14646*	*43752*	6903	7652	9679	12539	1000127
791	*991*	*4426*	*6947*	*8073*	622	1680	6531	10307	12856
2873	*4141*	*8587*	*10443*	*11003*	3526	7292	15249	30389	33937
3084	*3383*	*4871*	*6544*	*7068*	3082	3657	7388	8697	10505
2145	*2904*	*4599*	*8343*	*9251*	2456	3946	7721	19352	21008
1051	*1302*	*3434*	*4590*	*5448*	1178	1822	5412	8132	9492
1129	*1351*	*2036*	*6218*	*6913*	884	1115	2291	11837	12759

2	2	2	2	2	2	2	2	2	2
minL	*10%L*	*50%L*	*90%L*	*maxL*	minT	10%T	50%T	90%T	maxT
46855	*52896*	*57219*	*58430*	*60996*	22725	63564	91901	92134	92482
39933	*40839*	*43788*	*45248*	*45673*	9888	11188	15184	19078	19136
44676	*45524*	*56616*	*58748*	*59191*	15210	18987	90571	92310	92437
37476	*38277*	*40309*	*43155*	*43450*	8348	9657	11743	15143	15170
39166	*39434*	*43768*	*47557*	*58343*	9631	9663	15144	25277	92146
33680	*34023*	*35061*	*35851*	*36192*	6694	6767	7727	8491	8540
34177	*35960*	*37343*	*38446*	*38702*	6696	8216	8403	9599	9621
36848	*37249*	*39574*	*44668*	*44987*	7328	7355	8544	18729	18784
4708	*4872*	*5267*	*5647*	*5743*	826	888	1109	1303	1372
5768	*6031*	*6786*	*7634*	*8069*	1329	1484	1698	1923	2109
3490	*3643*	*4318*	*4987*	*5121*	707	722	875	1104	1189
4814	*5093*	*5838*	*6704*	*7091*	1189	1233	1492	1693	1785
2864	*3045*	*3670*	*4097*	*4492*	667	697	796	991	1100
4219	*4376*	*4960*	*5853*	*6238*	996	1067	1255	1445	1514

3	3	3	3	3	3	3	3	3	3
minL	*10%L*	*50%L*	*90%L*	*maxL*	minT	10%T	50%T	90%T	maxT
1335	*1597*	*5878*	*12568*	*40380*	261	357	4670	1000127	1000127
664	*677*	*7724*	*14040*	*14817*	168	277	4867	407222	1000127
675	*803*	*6241*	*12665*	*14522*	221	243	3725	1000127	1000127
621	*905*	*7621*	*12909*	*39128*	300	334	3429	9112	1000127
729	*1245*	*8202*	*11096*	*14413*	225	317	3861	1000127	1000127
1363	*1606*	*3617*	*7911*	*39223*	413	587	1795	5100	1000127
2407	*2923*	*4042*	*6604*	*9764*	650	720	1353	3287	7047
529	*862*	*3756*	*12520*	*13760*	95	207	1790	8092	1000127
582	*623*	*1072*	*3413*	*4066*	63	144	491	2851	3332
753	*2256*	*4838*	*7331*	*10594*	474	1218	3437	1000127	1000127
850	*952*	*4305*	*6435*	*9136*	235	289	3325	5394	23460
646	*1621*	*5334*	*8864*	*10414*	343	506	3434	1000127	1000127
520	*597*	*1034*	*2578*	*3330*	71	105	363	1218	1687
816	*1392*	*2529*	*4356*	*5511*	245	366	1038	2402	3859

Table 3: see caption below.

4	4	4	4	4	4	4	4	4	4
minL	10%L	50%L	90%L	maxL	minT	10%T	50%T	90%T	maxT
2377	2518	4243	17051	23760	1071	1119	16887	1000127	1000127
681	892	4689	12724	15803	666	726	6567	117114	224712
1018	1186	10449	13984	19352	737	930	39914	177010	230157
825	2972	10721	17891	18635	541	2184	64835	241499	244483
874	1672	4678	13223	19374	448	845	6763	113677	245209
1512	1644	2733	4055	11978	614	730	2367	7046	49159
1992	2105	2917	12016	17629	1099	1226	3467	32328	237397
1009	2765	3885	12393	12710	338	1656	7794	68215	86955
687	873	1373	3360	5375	205	284	1000	3826	11898
2241	2722	5663	8892	9987	1875	3411	31769	94624	300368
1193	1244	4534	5201	5690	793	879	6371	18259	24737
1220	2042	3865	6693	9737	791	2283	12290	64682	234366
621	684	1246	2671	5407	265	351	655	4265	20535
1137	1443	2002	3070	5990	465	794	1830	6658	44226

5	5	5	5	5	5	5	5	5	5
minL	10%L	50%L	90%L	maxL	minT	10%T	50%T	90%T	maxT
2383	2510	3997	18087	18809	2144	2264	46086	1000127	1000127
762	969	5803	16445	19161	2206	6990	74582	1000127	1000127
1094	2156	15348	19120	19408	10772	19286	390528	1000127	1000127
934	4314	11501	13027	15114	7613	36122	328340	389507	456040
967	1661	12824	15575	18927	977	1686	367728	1000127	1000127
2106	2214	8643	10456	10729	4533	7617	65635	263171	291619
3875	4380	9649	10402	10775	4773	4971	53494	74285	95104
1161	1435	5536	12184	13717	373	666	9479	211369	1000127
694	880	1416	4852	6147	335	465	1976	7741	16263
3621	4108	6735	10592	11432	3904	9508	44674	204783	321996
2206	2690	3749	5438	6212	738	1815	6090	22509	36951
2397	2681	4338	5964	7268	425	746	10582	39921	68363
717	757	1650	2784	3936	96	109	905	2416	7308
1367	1438	2335	3143	3658	239	569	1644	7356	10350

8A	8A	8A	8A	8A	8A	8A	8A	8A	8A
minL	10%L	50%L	90%L	maxL	minT	10%T	50%T	90%T	maxT
2252	2461	4661	20992	31917	780	5370	20573	1000127	1000127
4597	13982	18555	21576	22348	39634	248836	1000127	1000127	1000127
15761	15866	16356	18512	22819	298492	771776	1000127	1000127	1000127
4370	7732	16408	21217	24377	27944	57245	1000127	1000127	1000127
1815	1948	15222	16013	18284	2350	2506	1000127	1000127	1000127
2434	2773	10540	19062	19590	3955	4726	170613	1000127	1000127
3671	6442	13847	15625	17927	3334	29656	85291	191896	1000127
1368	1612	7714	15181	17100	1507	1907	32608	1000127	1000127
899	1169	3482	7401	10811	315	531	5696	30059	221560
3096	3669	6985	13157	14505	2438	4124	36221	1000127	1000127
2473	3048	5387	8603	9686	1800	2010	10797	52518	95289
2455	3240	5227	7688	10351	1001	3261	9855	70782	237124
686	777	1467	2234	4060	69	108	617	2308	7740
1328	1858	2768	4821	6157	291	398	3365	10120	35391

8D	8D	8D	8D	8D	8D	8D	8D	8D	8D
minL	*10%L*	*50%L*	*90%L*	*maxL*	minT	10%T	50%T	90%T	maxT
2412	*2548*	*3940*	*16273*	*20107*	1461	1804	12807	1000127	1000127
3367	*3877*	*15270*	*18658*	*22603*	11868	14207	392166	1000127	1000127
3779	*9410*	*15888*	*17693*	*18662*	15329	41148	324227	1000127	1000127
2162	*8047*	*14823*	*18138*	*19842*	4935	31059	111948	815660	1000127
5480	*8294*	*15191*	*17850*	*18040*	21358	36982	158153	1000127	1000127
4033	*4513*	*9926*	*14992*	*39199*	4982	7020	92568	305422	1000127
4195	*6425*	*13944*	*17542*	*18077*	10061	19810	106319	942432	1000127
1244	*2512*	*7402*	*16761*	*17709*	539	1046	23797	426854	527359
1120	*1240*	*1553*	*7488*	*11415*	663	924	1654	11859	110024
2012	*3353*	*7108*	*8978*	*12944*	2796	5777	12612	99589	227013
1569	*2906*	*6170*	*10795*	*11179*	799	1662	6299	80179	220437
3710	*4039*	*5196*	*6349*	*12784*	4988	5416	13493	36224	367522
746	*894*	*2822*	*4934*	*9527*	53	105	688	13194	80689
1959	*2298*	*3359*	*4424*	*5124*	355	410	4714	11298	23973

Table 3 – Data analyzed from Site A (black) and Laxemar (red). Includes 8 blocks for Site A and 6 blocks for Laxemar in order shown in Table 1. One data set shown for each of the 7 model cases considered. Length statistics in meters and time statistics in years. (The travel time of 1000127 years, appearing in statistics from most of the above model cases is an arbitrary maximum time reported by EHRB. Where this value is reported, the actual travel time predicted by the model is greater.)

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