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Swedish Radiation Safety Authority

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2014:46

QA in SKB's Groundwater Flow Modelling

Main Review Phase

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SSM perspektiv

Bakgrund

Strålsäkerhetsmyndigheten (SSM) granskar Svensk Kärnbränslehantering AB:s (SKB) ansökningar enligt lagen (1984:3) om kärnteknisk verksamhet om uppförande, innehav och drift av ett slutförvar för använt kärnbränsle och av en inkapslingsanläggning. Som en del i granskningen ger SSM konsulter uppdrag för att inhämta information och göra expertbedömningar i avgränsade frågor. I SSM:s Technical note-serie rapporteras resultaten från dessa konsultuppdrag.

Projektets syfte

Det övergripande syftet med projektet är att ta fram synpunkter på SKB:s säkerhetsanalys SR-Site för den långsiktiga strålsäkerheten hos det planerade slutförvaret i Forsmark. Det specifika syftet är att få en förståelse för och en bedömning av SKB:s kvalitetssäkring i samband med grundvattenflödesmodelleringen i SR-Site. Tillförlitligheten i grundvattenmodelleringens resultat är bl.a. avhängig kvalitetssäkringen, i synnerhet i ett så komplext modelleringsarbete som SKB har genomfört i samband med SR-Site.

Författarens sammanfattning

Kvalitetssäkringen av grundvattenflödesmodelleringen i samband med säkerhetsanalysen SR-Site har granskats med avseende på modelleringens tillförlitlighet och spårbarheten av indata och resultat i säkerhetsanalysen. Övergripande kvalitetssäkringsfrågor i samband med flödesmodellering identifierades och granskningen fokuserade på hur dessa har hanterats i kvalitetssäkringsprocedurerna som SKB och dess leverantörer har följt. Granskningen syftade inte till att kontrollera bestämda värden eller beslut som har varit föremål för andra granskningar som SSM har genomfört.

I samband med granskningen har ett möte hållits med SKB och dess leverantörer och därutöver har dokumentationen av grundvattenmodelleringen granskats. Mötet gav ett tillfälle att få en bild av SKB:s befintliga procedurer för grundvattenmodellering och hur procedurerna har tillämpats i SR-Site. SKB har i många år använt datakoderna ConnectFlow och DarcyTools för grundvattenmodellering. På mötet beskrev SKB kvalitetssäkringsplanerna som tillämpades vid användningen av dessa koder i samband med SR-Site. SKB förklarade även procedurerna som tillämpades vid utvecklingen och testningen av koderna. SKB beskrev vidare hur dataöverföringen mellan grundvattenmodellerna och leverantörerna hanterades under arbetet med SR-Site. SKB demonstrerade hur indata och resultatfiler lagras, avropas och säkerhetskopieras samt hur modellresultat kan spåras med hjälp av identifieringsnummer i dokumenthanteringssystemet SKBdoc. Under arbetet med SR-Site och den tidigare platsmodelleringen var SKB:s HydroNet-grupp ett viktigt forum för diskussion av hydrogeologiska frågor och utvecklingen och styrningen av modelleringsuppgifterna. Uppgiftsbeskrivningarna och protokollen från HydroNet mötena lagras i SKBdoc systemet. Granskningen fokuserade även på SKB:s modellkalibreringsprocess. SKB utvecklade en specifik modellkalibreringsprocess för SR-Site som till stor del förlitade sig på expertbedömningar som diskuterades i samband med HydroNet-mötena. Detta tillvägagångssätt grundade sig i en avsaknad av publicerade kalibreringsmetoder för sprickfattigt berg. Den av SKB utvecklade kalibreringsprocessen har sedan publicerats i en vetenskaplig tidskrift.

Kvalitetsgranskningen av SR-Site-dokumentationen visade sig vara besvärlig och tidskrävande pga. bristande korshänvisningar mellan SR-Site huvudrapporten, dokumentationen av grundvattenflödesmodelleringen och andra relevanta rapporter. I många fall var det möjligt att hitta informationen från SR-Site huvudrapporten i den underliggande dokumentationen, dock endast efter långvarigt sökande i ofta omfattande dokument. In några få fall var det inte möjligt att återfinna förklaringar eller källorna till använda data. Korshänvisningar till specifika avsnitt, figurer och tabeller i de stödjande dokumenten skulle avsevärt förbättra spårbarheten av data och av tillämpningen av resultaten i den vidare analysen.

På det hela taget skapade mötet med SKB en hög nivå av tillförlit till att grundvattenflödesmodelleringen har hanterats på ett ändamålsenligt sätt i SR-Site genom att beskrivningarna av modelleringsuppgifterna och protokollen från HydroNet-gruppens möten har dokumenterats. Koderna som användes har genomlöpt en utveckling och testning som är i linje med lämpliga kvalitetssäkringsrutiner. Däremot lider SR-Site dokumentationen av en brist på korsreferenser som försvårar spårbarheten av hur resultaten från grundvattenmodelleringen har tillämpats i SR-Site.

Projektinformation

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Diarienummer ramavtal: SSM2011-4244
Diarienummer avrop: SSM2013-5305
Aktivitetsnummer: 3030012-4070

SSM perspective

Background

The Swedish Radiation Safety Authority (SSM) reviews the Swedish Nuclear Fuel Company's (SKB) applications under the Act on Nuclear Activities (SFS 1984:3) for the construction and operation of a repository for spent nuclear fuel and for an encapsulation facility. As part of the review, SSM commissions consultants to carry out work in order to obtain information and provide expert opinion on specific issues. The results from the consultants' tasks are reported in SSM's Technical Note series.

Objectives of the project

The general objective of the project is to provide review comments on SKB's postclosure safety analysis, SR-Site, for the proposed repository at Forsmark. The specific objective is to get an understanding and an assessment of SKB's quality assurance of the groundwater flow modelling in connection to SR-Site. The reliability of the results of the groundwater flow modelling depends inter alia on the quality assurance, in particular in such a complex modelling work that SKB has performed in connection to the safety assessment SR-Site.

Summary by the author

The quality assurance (QA) review of the groundwater flow modelling that supported the SR-Site safety assessment involved checking the reliability of the modelling work and the traceability of the modelling analysis and results through the safety assessment. General QA issues in groundwater flow modelling were identified and the QA review focused on how these issues had been addressed in the QA procedures followed by SKB and its contractors in the SR-Site groundwater flow modelling work; the review did not necessarily aim to check specific values or decisions that have been highlighted in other SSM reviews.

The review involved a QA meeting with SKB staff and contractors as well as checks of the SR-Site documentation relating to groundwater flow modelling. The QA review meeting provided an opportunity to check the existence and application of suitable groundwater flow modelling procedures. SKB has used the ConnectFlow and DarcyTools codes for groundwater flow modeling for many years and, at the meeting, SKB described (and provided examples of) the QA plans used in application of these codes in support of the SR-Site safety assessment. SKB explained the procedures used for developing and testing these groundwater flow modelling codes. Also, SKB described how data transfer had been managed between groundwater flow models and contractors during SR-Site work, and demonstrated how input and output files relating to SR-Site modelling are stored, accessed and backed-up, and how modelling results can be traced using document identifiers in the SKBdoc document management system. During SR-Site and the earlier Site Descriptive Modelling work, SKB's HydroNet group was an important forum for discussing hydrogeology issues and developing and directing groundwater flow modelling tasks. Modelling task descriptions and

HydroNet meeting minutes are stored on the SKBdoc system. The flow model calibration process followed by SKB was a particular focus of the QA review. SKB developed a specific model calibration process for SR-Site that largely relied on expert judgments made at HydroNet meetings, because of the lack of availability of published methods for sparsely fracture rock. The calibration process developed by SKB has been published in a peer-reviewed journal.

The QA review of SR-Site documentation proved difficult and time-consuming because of the inadequate cross-referencing between the SR-Site Main Report and the supporting groundwater flow modelling and related reports. In many cases, it was possible to locate the information reported in the SR-Site Main Report, but only after lengthy searches through large documents. In a few instances, it was not possible to locate explanations or sources of data used. Cross-referencing to specific sections, figures and tables in supporting documents would greatly improve the traceability of data and use of results.

Broadly, the QA review meeting engendered a high level of confidence that the groundwater flow modelling work during SR-Site had been suitably managed via task descriptions and HydroNet group meetings and that the codes used had undergone development and testing according to appropriate QA procedures. However, the SR-Site documentation suffers from a poverty of cross-referencing that hampers attempts to trace how groundwater flow modelling results have been used in SR-Site.

Project information

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Contents

1. Introduction

The Swedish Radiation Safety Authority (SSM) has completed the initial phase of its review of the SR-Site safety assessment produced by the Swedish Nuclear Fuel and Waste Management Company (SKB). The review subsequently entered its main phase, with assignments targeted on prioritised tasks and issues and aimed at supporting SSM's compliance judgements. As part of the main review, SSM tasked Galson Sciences Limited to undertake an assessment of SKB's documentation and quality assurance (QA) of groundwater flow modelling in the SR-Site safety assessment. This report presents the results of the QA review.

The groundwater flow modelling QA assignment has involved two main components:

- A QA review meeting with SKB staff and its contractors who were involved in the SR-Site groundwater flow modelling.
- A QA review of SR-Site documentation relating to groundwater flow modelling.

Section 2 of this report presents the findings of the QA review meeting and the results of the SR-Site documentation review. The conclusions of the overall assessment are presented in Section 3. Appendix 1 lists the SKB reports that have been reviewed.

2. QA Review of SKB's Groundwater Flow Modelling

2.1. Groundwater Flow Modelling in SR-Site

SKB's hydrogeological modelling for the SR-Site assessment (SKB, 2011) aimed to support understanding of repository evolution at Forsmark over a 1,000,000 year assessment period. For the analysis, the reference evolution of a Forsmark repository was defined in terms of:

- A base case 120,000 year glacial cycle with seven repetitions to cover the entire 1,000,000 year assessment period.
- A global warming variant in which the future climate is influenced by anthropogenic greenhouse gas emissions.

For the hydrogeological modelling the geosphere was divided into three types of hydraulic domains (see Figure 1):

- Hydraulic Conductor Domains (HCDs), which represent deterministically modelled deformation zones.
- Hydraulic Rock mass Domains (HRDs), which represent less fractured bedrock in between the deformation zones.
- Hydraulic Soil Domains (HSDs), which represent the regolith.

The SR-Site assessment relied on the results of the following three hydrogeological modelling studies of the bedrock domains (HCDs, HRDs and HSDs):

- Svensson and Follin (2010) addressed the repository excavation and operational phases.
- Joyce *et al*. (2010) considered periods with temperate climate conditions.
- Vidstrand *et al*. (2010) considered periods with periglacial and glacial climate conditions.

In addition, Selroos and Follin (2010) provided a synthesis of the mathematical and numerical modelling approach, the data used, and the hydrogeological modelling results produced by Svensson and Follin (2010), Joyce *et al*. (2010) and Vidstrand *et al*. (2010).

These hydrogeological modelling studies provide direct input to the SR-Site Main Report (SKB, 2011) and indirect input via the Data Report (SKB, 2010a). Figure 2 illustrates the periods covered by the three hydrogeological modelling studies and where the results of the studies provide direct inputs to the SR-Site Main Report.

The studies undertaken by Svensson and Follin (2010) and Vidstrand *et al*. (2010) involved the use of DarcyTools, whereas Joyce *et al*. (2010) used ConnectFlow. The hydrogeological base case model derived in the temperate phase modelling (Joyce *et al*., 2010) is similar to SKB's Site Descriptive Model SDM-Site (SKB, 2008a). Base cases for the other two phases were derived from the hydrogeological base case. The relationship between the different models is shown in Figure 3.

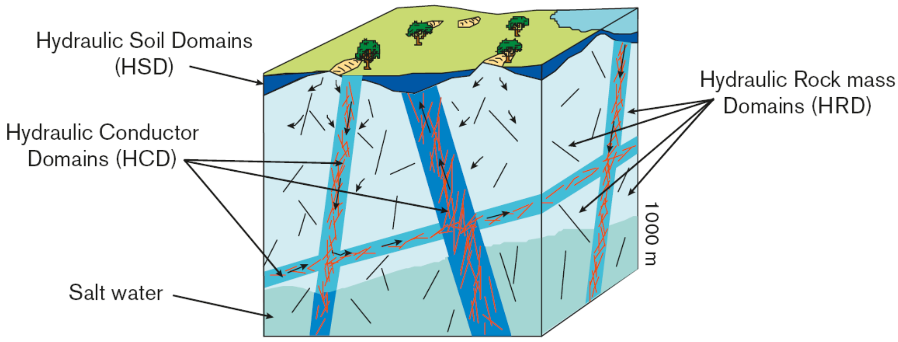

Figure 1: Illustration of the three geosphere hydraulic domains assumed in SKB's hydrogeological modelling studies. (From Selroos and Follin, 2010, Figure 3-2.)

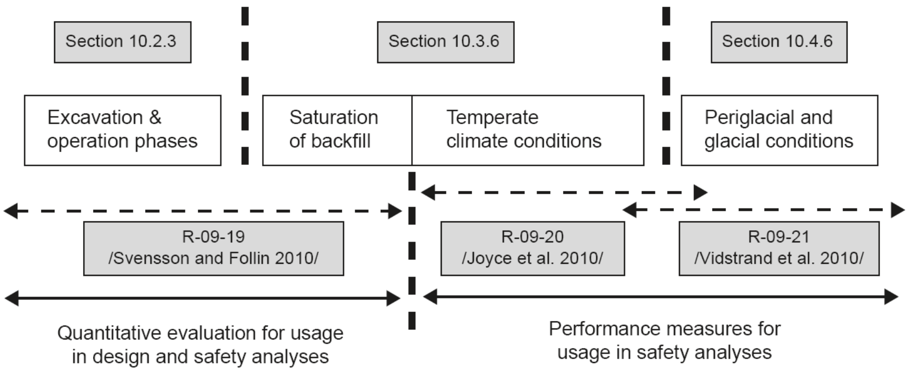

Figure 2: Organisation of groundwater flow modelling studies undertaken for SR-Site and the sections of the Main Report (SKB, 2011) in which the modelling results are discussed. (From Selroos and Follin, 2010, Figure 3-1.)

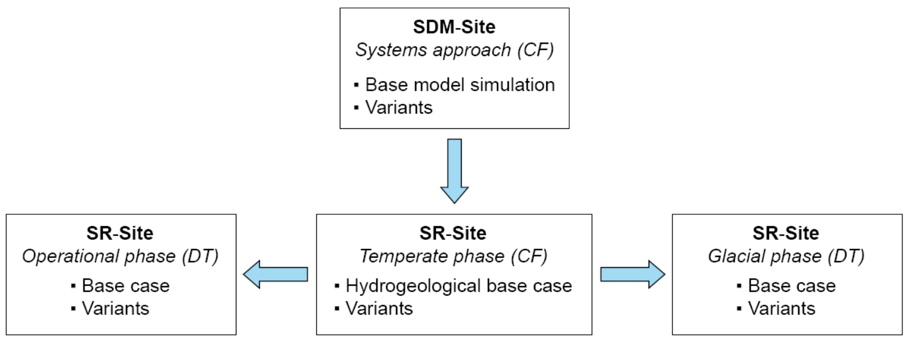

Figure 3: Relationship between the SDM-Site model, the hydrogeological base case of the temperate phase, the base cases of the other phases and the variants. CF and DT denote ConnectFlow and DarcyTools, respectively. (From Selroos and Follin, 2010, Figure 3-3.)

2.2. Groundwater Flow Modelling QA Review Meeting

The first part of the QA review of SKB's groundwater flow modelling in the SR-Site safety assessment involved development of a list of QA issues (in the form of a checklist) to be discussed during a meeting with SKB (and its contractors who were involved in the SR-Site groundwater flow modelling). The list of QA issues focused on the protocols that have been followed by SKB and its contractors and their implementation in the SR-Site groundwater flow modelling, and was organised in terms of the following:

- Procedures for groundwater flow modelling.
- Procedures for use of groundwater flow modelling results.
- Procedures for hydrogeological conceptual model development.
- Procedures for hydraulic data interpretation.
- Procedures for control and use of hydraulic data.

The objective of the review meeting was to obtain an understanding of the QA procedures that have been used at each step in the process of groundwater flow modelling and the use of modelling results in the SR-Site safety assessment. The review meeting did not necessarily aim to check specific values or decisions that have been highlighted in other reviews, but to check the existence and application of appropriate procedures during all stages of the groundwater modelling process. This was done by asking to see project documentation, including both the procedures themselves and evidence of their application. Demonstrations of the links between results presented in the licence application and the specific model runs used to generate them were sought.

The QA review meeting took place at SKB's offices in Stockholm on 24th April 2014. The results of the discussion of the list of QA issues are presented in the following sub-sections (see SSM (2014) for the approved meeting minutes, including an appendix with SKB's written responses to the list of QA issues).

2.2.1. Procedures for groundwater flow modelling

1. Is there a QA plan for the SR-Site groundwater flow modelling?

SKB reported that there is a high-level QA plan for SR-Site. However, there is no single groundwater flow modelling QA plan for SKB and its contractors. Instead, organisations contracted by SKB are required to have a QA system in place that is agreed by SKB. The QA plan used by TerraSolve for an SR-Site groundwater flow modelling task using DarcyTools was provided during the meeting[1]. The QA plan is built on the ISO standards for quality management, but the plan is not ISO certified.

SKB noted that there is a model management system, but that there was no code development during SR-Site and the same codes were used throughout the SR-Site work. However, it had been necessary at one point to recover versions of DarcyTools that had been used in 2008. The old source codes were compiled and the codes run with old data. The results were found to match those produced by the current code, apart from some differences in calculated salinity distributions.

[1] Forsmark SR-Site, Glaciation, QA-plan, TerraSolve document: QA-plan_SR-Site Glaciation F2.3 v0.1.docx.

SKB had agreed the QA Plan for ConnectFlow before work on SR-Site began. The QA Plan was not available at the meeting, but SKB would be able to provide it if required. The QA plan describes run management, backups, etc.

2. DarcyTools and ConnectFlow have been used. What criteria were used for model selection? That is, how was it determined that the models are applicable to the conceptual model and the modelling objectives?

SKB has used ConnectFlow and DarcyTools for many years. SKB used these codes because it had confidence in their suitability for its modelling tasks and the competence of the individuals available to use them.

ConnectFlow has been used more in safety assessments and has been used by several other organisations for such applications. It is owned and developed by AMEC (formerly Serco) in the UK. ConnectFlow was used in SKB's SR-97 safety assessment. SKB commented that ConnectFlow is more computationally expensive than DarcyTools.

DarcyTools was developed by Computational-Fluid Dynamics on behalf of SKB from scratch to support analysis and understanding of experiments at Äspö. During SR-Site, CFE (Computer-aided Fluid Engineering AB) and TerraSolve supported SKB in running DarcyTools.

Both codes were used in SKB's Site Descriptive Model (SDM) work, although only ConnectFlow was used in the completion phase of the SDM work, mainly due to resource constraints.

The codes produced similar results in code comparison exercises and SKB commented that in many respects they could replace each other, although each would require some developments to do so. For instance, there are more features in DarcyTools to handle permafrost and glacial conditions, but ConnectFlow can allow nesting of models. Neither in ConnectFlow nor in DarcyTools are near-surface conditions particularly well presented and so SKB instead uses the Mike-She code for such applications.

During the SR-Site modelling work, discrete fracture network (DFN) data were transferred from ConnectFlow for use in DarcyTools. This involved AMEC uploading the DFN data to SKB's server for CFE AB to download, which meant that SKB could keep a track of task data exchange, and avoided the contractors sending data directly to each other. AMEC provided a description of what had been uploaded and records were kept of any errors identified. Questions and discussions about the data were communicated directly between the contractors and not necessarily documented by SKB. Errors were sometimes detected when DarcyTools read the data and sense checks were carried out (e.g. a wrong parameter setting had been used in one case).

3. How are organisation(s) selected to undertake the modelling work and how is the necessary expertise ensured?

SKB chooses to work with experienced individuals who can be trusted to do the work. When a groundwater flow modelling expert has changed company, SKB has continued to use the expert rather than the original company.

SKB does have a licence to run ConnectFlow but does not have access to the source codes. SKB relies on AMEC to do the work. One reason why SKB also uses DarcyTools is to avoid total reliance on AMEC for groundwater flow modelling. SKB ensures DarcyTools expertise is retained by continuing to commission DarcyTools applications. AMEC has many customers, which ensures that skills in ConnectFlow usage are maintained. SKB is a member of the iConnect club, which provides a forum in which developments of the ConnectFlow code can be influenced.

4. Have alternative modelling codes been considered?

SKB undertook an alternative models project, which included the use of CHAN3D (Selroos *et al*. 2002). However, CHAN3D used some of the data produced by ConnectFlow and was in a way conceptually similar to ConnectFlow. SKB explained that the use of CHAN3D provided more of a QA check than an alternative modelling approach.

SKB considers that it is important to characterise geological structures, but recognises that others consider that the focus should be more on a tomographic characterisation based on hydraulic testing.

5. What procedures are in place for ensuring management and control of contractors' work and ensuring that knowledge of the codes and modelling studies is retained?

SKB has discipline-specific groups and the HydroNet group was set up as a forum for discussing hydrogeology issues at Forsmark. About 50 HydroNet meetings took place during SDM and SR-Site work. HydroNet discussed groundwater flow modelling and task descriptions; task descriptions had been used in SDM work and a similar approach was adopted for use in SR-Site work. The SR-Site groundwater flow modelling work was reported at HydroNet meetings and any changes to the modelling tasks were discussed and agreed at the meetings, and documented in meeting minutes. The task descriptions were not revised to reflect such changes and the modelling reports do not necessarily match the original task descriptions. The task descriptions and HydroNet meeting minutes are stored on SKB's document management system (SKBdoc).

SKB tries to encourage a broad base of DarcyTools users and, as noted previously, has commissioned new DarcyTools applications since SR-Site. For example, Posiva has access to DarcyTools and is involved in a co-funded project with SKB that involves DarcyTools usage. AMEC and Kemakta are relied on for knowledge of ConnectFlow.

6. How are source codes stored?

AMEC stores ConnectFlow under version control and with backup procedures. SKB does not have access to AMEC's system.

DarcyTools source codes are provided on two CDs and are also stored on SKB's project database (Projectplace). DarcyTools comprises two codes, one of which is a flow solver called MIGAL that is owned by a consultant. The consultant stores all historic versions of MIGAL. SKB is reliant on the consultant for maintaining and developing MIGAL. However, MIGAL is called by one line of code in DarcyTools and SKB considers that MIGAL could be replaced by another code if necessary. SKB has a contract to retain the final version of MIGAL if the consultant stops developing it.

All new versions of DarcyTools including new versions of MIGAL are quality tested by running verification cases. This testing focuses on specific components of the modelled system and includes the use of analytical solutions.

7. What procedures were used to check the availability of input data for the modelling?

SKB had a staged approach to site investigation. There was a stage in which a model was produced and consideration was given as to whether the model could be used for predictions. This involved prediction of what would be seen from a borehole before drilling, as a test of site understanding. SKB concluded that the drilling of more boreholes would not result in significant additional site understanding and that significantly enhanced understanding would require underground investigations.

Paleohydrogeology was also considered important in determining whether there was sufficient understanding for the safety assessment to be undertaken. Modelling of flow conditions up to the present day was used to evaluate and match current groundwater chemistry conditions successfully.

SKB published the site descriptive modelling report (SDM report) and, based on consideration of all aspects, judged that it was sufficient for the SR-Site safety assessment to be undertaken. Chapter 11 of the SDM report (SKB, 2008a) discusses the decisions made about the SDM.

8. Are there procedures for documenting and re-testing the models when changes are made to the model codes and new versions are released?

AMEC checks new versions of ConnectFlow and SKB relies on this testing being done. SKB relied on AMEC to use the latest version of the code in SR-Site and to report developments that have been made.

SKB has documentation about changes in DarcyTools and requires automatic testing to be undertaken when developments are made. Verification cases are run as discussed previously (see Question 6). Recent changes have involved process developments (e.g. mechanical coupling), a particle tracking algorithm and code parallelisation, as well as fixing errors. Comparisons are made with other codes (e.g. permafrost modelling codes).

9. What procedures are there for keeping records of the model application process?

SKB noted that model application is described in the groundwater flow modelling reports. The process of running DarcyTools is reported in the code user guide. All commands produce a log file which is stored in a project directory. Each simulation has its own project directory that is backed up on a separate hard drive. SKB noted that the model application process is traceable. SKB understands that a similar process is in place for ConnectFlow.

10. How are the modelling cases selected that are carried forward to subsequent modelling steps? Are the modelling cases that have been discarded documented?

SKB aimed for the SDM to be a realistic description of the site. A base case was selected that best represented the site. In SR-Site some of the uncertainties remaining from the SDM were adopted (e.g. correlation cases). SR-Site had additional cases that didn't originate from SDM (e.g. future conditions). The SDM report (SKB, 2008a) provided recommendations for SR-Site and the connection between SDM and SR-Site is discussed in the report by Joyce *et al*., (2010) on groundwater flow modelling of periods with temperature climate conditions.

All parameters used and changes made in the calibration process are listed in the report by Follin *et al*. (2007a, 2008) on hydrogeological conceptual model development and numerical modelling using ConnectFlow. Tests were made to demonstrate that the base case was robust. The base case was propagated to SR-Site. SKB was uncertain as to whether AMEC would have stored all of the code runs that were discarded in the calibration process.

11. How are input and output data for model runs stored, including runs to support the calibration process?

Individual simulations are stored in a project file and data are transferred via an SKB database (Trac). SKBdoc was not used during the SR-Site work, but was used to store data on completion of tasks. Files are listed in Appendix C of Vidstrand *et al*., (2010); references to SKB documents are shown, including cover letters and files that contain input data found in zip files.

SKB demonstrated the SKBdoc system during the meeting. Document numbers were entered in the system and the document, cover letter and zip files were found. Various files could be accessed via the zip file (e.g. spreadsheets with fracture data). Experience of DarcyTools would be required in order to understand the files shown during the meeting.

Folders that contain the various SDM models (e.g. bedrock, geology, hydrogeochemistry, surface systems) were shown and any updates to the SDM would be made to the files in these folders. Storage locations of earlier versions of the SDM were shown.

12. Are there procedures to ensure that the documentation provides enough detail to allow for reconstruction of the work?

Information is stored in the SKBdoc system as described previously. As an example, SKB has successfully reconstructed work following the request for complementary information on glacial flow modelling. All documents are version controlled.

13. Are there procedures for ensuring that results presented in the licence application can be traced back to particular sets of data and code versions?

SKB noted that all files are delivered according to a task specific QA programme. Results can be traced back to input files.

The cover letter for output from hydrogeological simulations was shown via the SKBdoc system. The cover letter gives the location and size of files. Some files were produced by ConnectFlow and some by DarcyTools. The Data report (SKB, 2010a, Table 6-82) indicates the data produced by ConnectFlow for, for example, FARF31. There are similar listings for DarcyTools results usage (SKB, 2010a, Table 6-84).

The Model Summary Report (SKB, 2010b, Table 1-2) shows SKBdoc document numbers for archived modelling data. The document number indicates the cover letter, and the cover letter gives the SKBdoc number where the data are stored. During the meeting, SKB showed the data used for analytical erosion/corrosion calculations, starting from the cover letter and the files listed, including zipped folders with the results for each case.

14. What protocols were followed in model calibration, including limits on parameter adjustments, identification of calibration goals, and determining that acceptable matches have been made? What "goodness-of-fit" measures are used and what is regarded as an acceptable fit? Have independent data been used for calibration and, if so, how are the sub-sets defined?

SKB discussed a series of papers that described how the calibration was undertaken (Follin and Hartley, 2014; Follin and Stigsson, 2014; Follin *et al.* 2014; Selroos and Follin, 2014). Follin and Hartley (2014) describe the modelling protocol. A protocol for calibration in fractured media was not available and so had to be developed for the project. It was possible to match groundwater chemistry data and cross hole hydraulic tests, but a general match was required for other quantities (single hole hydraulic tests and groundwater levels).

At Forsmark, it was possible to get hydraulic responses across sub-horizontal sheet joints over long distances, but there are only a few responses at repository target depths (mainly in deformation zone ZFMENE0060). Chemistry at depth is quite old. The lack of hydraulically conductive fractures at repository depth means there is nothing to calibrate against. It was not possible to distinguish between size transmissivity correlation models since they give similar transmissivity results for the sizes that are most important for the flow in the rock.

SKB used the results of ten code runs (i.e. ten realisations of DFNs), which was a pragmatic choice. Calibration was done in an ensemble sense in that total inflow to a borehole was considered rather than flow in each fracture, although flows at different depths were considered, because the number of flowing features decreases with depth.

SKB noted that the approach was 'cutting edge' in terms of how flow modelling is done for low hydraulic conductivity, sparsely fractured networks. Ultimately, the calibration process relied on expert judgments. These judgments were made at HydroNet meetings. Minutes of HydroNet meetings are stored in the SKBdoc system. An example of a HydroNet meeting minutes was shown. The minutes included action lists.

Forsmark has very sparsely fractured rock and distinct characteristics of high rock stresses. Much of the modelling process was highly dependent on site understanding and the difficulty in finding flowing features in the rock. SKB stated that it was beneficial to the work conducted at Forsmark working in parallel on another site (Laxemar), where the number of flowing fractures is quite different. This allowed SKB to evaluate the generality of the modelling methodology developed.

15. How was it determined that final values lie within a reasonable range (e.g. physically realistic for the conditions)?

There is uncertainty in the data because of spatial variability. SKB focused on calibrating the properties of the fracture domains, as illustrated in the SDM reports. Sensitivities were checked to understand how the system works. Several calibration targets were used which gives a fairly good fit. The fit was not optimised for only one of the data sets.

16. What process was followed to address any data gaps identified?

It was not possible to get a good control of fracture sizes, which is a key parameter. The correlation structure between fracture sizes and transmissivities is unknown. This issue was addressed in SR-Site by using three different size-transmissivity models.

SR-Site requires information relating to engineering (deposition holes and tunnels) and so presents more of a sensitivity study in relation to gaps in understanding.

17. What process was used to decide model dimensions and the split between the discrete fracture network model region, the equivalent continuous porous medium model region and the continuous porous medium model region? How has the sensitivity of results to these assumptions been tested?

Decisions on defining model regions were largely based on borehole locations. A DFN was used for regions in which borehole data are available and a continuous medium was used for regions in which there are no boreholes. Borehole data were available from regions of most importance to the safety assessment.

As a variant, SKB tested the effects of using the DFN modelling approach on a regional scale by using data from the SFR repository investigations when those data became available. It was found that the results are sensitive to the modelling changes in terms of pathways through the model, but not in terms of flow in the repository vicinity (Joyce *et al*. 2010).

18. What protocols were followed for sensitivity and uncertainty analysis? How was the number of realisations determined in the stochastic analysis?

Ten realisations were used in SR-Site and little variation was found between realisations. SKB explained that one reason for this finding is that the system is governed by steady-state flow and large deterministic structures and the boundary conditions. But when sampling the rock mass, the spatial heterogeneity is sampled. The approach works in an ensemble sense, but not at a particular borehole location.

The DFN could generate large features that went from the repository to the ground surface and so allowed for unrealistic features to be present. These features were kept in the models rather than adjusting the statistics to eliminate them.

2.2.2. Procedures for use of groundwater flow modelling results

1. What procedures are in place for ensuring that model results have been used appropriately in SR-Site within prescribed limitations?

SKB explained that groundwater flow modelling results were used in terms of the 'triplet' of Darcy flux, travel time and flow-related transport resistance. Document identification numbers indicate how the triplets are used. Selroos and Follin (2010, Section 7.4) shows where results are used in other ways such as geochemistry. It was up to the downstream assessment to consider how to use the information.

In practice, the groundwater flow modelling was very much focused on flow issues, such as whether the flow would be increased at repository depth as a glacier passes over the site. Later, SKB wanted to know what effects glaciation would have in terms of salinity. Meetings were held to consider use of the modelling work for this problem and it was necessary to make sure that uncertainties were considered. Chemists wanted detailed information at repository depth, but had to use analytical transport solutions to complement larger scale groundwater flow modelling results. There were meetings between, say, hydrology and corrosion teams to discuss the use of modelling results.

2. How is the trail from specific model runs to results presented in the licence application recorded?

The modelling trail is recorded in the SKBdoc system, as already discussed (see Question 11 in the section on procedures for groundwater flow modelling).

3. **How are results verified against objectives?**

SKB set up task descriptions and tasks evolved at HydroNet meetings, as documented in meeting minutes. It was up to the HydroNet meetings to judge whether the work had obtained what was needed and had answered the questions that were asked.

Also SKB had its own review process involving consultants (three to five reviewers). The reviewers filled in comment forms and the report authors were required to respond. The review material is stored in the SKBdoc database. Discussion were held with e.g. climate and chemistry groups (e.g. at HydroNet meetings) in order to check that they got what they wanted.

There is no formal track record that old reports were reviewed, but now all reports must be reviewed, not just SR-Site reports.

2.2.3. Procedures for hydrogeological conceptual model development

1. **The hydrogeological description of the Forsmark site has three components: Hydraulic Conductor Domains (HCDs), Hydraulic Rock Mass Domains (HRDs) and the Hydraulic Soil Domain (HSD). What procedures are there for refining the conceptual model as new data are obtained?**

The division in modelling domains comes from geology. Site data were used to refine the conceptual modelling. It was noticed at Forsmark that there is a considerable number of rock structures near the ground surface and a lot of water is produced from them. But below this top layer of water conducting fractures there are practically no flowing fractures. Therefore, it was necessary to include different zones at depth to account for decreases in fracturing with depth, which changed the original conceptual model. A method for accounting for heterogeneity in deformation zones was also developed.

2. **What procedures are there for identifying and evaluating alternative conceptual models of hydrogeology?**

In Selroos *et al*. (2002), the conceptual models used by SKB are detailed. An alternative approach would be to account for channeling in single fractures, but SKB has not done that.

3. **What procedures are there for ensuring consistency with the geological model?**

The hydrogeologists tried to parameterize the features that geologists had not identified. Deformation zone intervals were isolated specifically to get their properties using packer tests. Posiva flow logs and borehole TV identify geological properties of fractures where flows are recorded.

The choice of statistical distributions was based on what was provided by the geological understanding. SKB employed the simplest models. The power law size distribution is the most important feature of the DFN model; this distribution gives the long geological features from the surface to depth.

2.2.4. Procedures for hydraulic data interpretation

1. **What procedures have been followed to interpret the hydraulic data and specify the deformation zone and fracture domain hydrological models (i.e. the deformation zone transmissivity and kinematic porosity models and the fracture domain transmissivity models)?**

As previously discussed (see Questions 14 and 15 on procedures for groundwater flow modelling).

2. **What procedures have been followed to determine fracture distributions?**

As previously discussed (see Question 16 on procedures for groundwater flow modelling).

3. **Have alternative interpretations and distributions been considered?**

SKB explained that the key parameter is fracture size. When the number of flowing fractures reduces per unit volume the system falls below the percolation threshold. Therefore, the size of flowing fractures had to be extended in order to form a connected network, which results in a semi-deterministic approach. This approach fits well with a power law model. Deformation zones were included and there is fracture clustering close to deformation zones. There are geological arguments that there should be clustering.

4. **What independent checks are done on the interpretations and models?**

The hydrogeology model was based on data freeze 2.2. The model predicted the outcome of a new borehole in collaboration with geology. It was possible to predict where the deformation zones would be and the number of flowing features was predicted. It was possible to forecast the borehole observations in great detail.

SKB asked GTK (Finland) to make an interpretation (geological) as a comparison with SKB’s model and they demonstrated a good agreement.

Also, Schwartz (2012) took data from SKB’s reports and generated a model of Forsmark looking at radionuclide transport, treating everything as a continuum. Schwartz (2012) concluded that SKB was overestimating risks, because there would be much more dilution and spreading, which you would get in a CPM model with dispersion, etc.

SKB noted that the interpretations and models will ultimately be tested when data from underground investigations are available.

5. Are there procedures for checking and revising the models and distributions as new data become available, and how are revisions communicated and managed?

SKB noted that work done so far reflects limitations from surface-based data. Once underground data are available, SKB will have to check that there are no contradictions with the surface-based data and explain any limitations.

SKB has a project on how the next generation of models should be created once data from underground investigations are available, and hopes that the current conceptual model will stand.

2.2.5. Procedures for control and use of hydraulic data

1. How are the data controlled, communicated, stored and backed-up, and how is the database managed?

SKB explained that the main results are the triplets. First SKB gets the delivery of data files with plots that show the distributions (e.g. as probability density functions). Visual checks of these plots are made. Preliminary analysis is undertaken using analytical models to check for errors. Checks on the input files are also made if the safety assessment results do not make sense. The most difficult errors to find are those that lead to apparently reasonable results.

All data were uploaded onto TRACK (Subversion) and were downloaded by subsequent users. The system keeps a track record (activity log) of who has provided or accessed data. The database is managed by SKB's IT department.

2. What are the uncertainties in the hydraulic data and how are they taken into account?

Two methods were used to manage uncertainties that work differently in parallel for the boreholes. Testing was done by different specialists with their own tools. Double packer injection tests were done as well as the Posiva flow logging. Most boreholes were analysed in this way. Also the generalised radial flow model approach (Barker, 1988) was used for three boreholes. The techniques have been scrutinised by reviewers.

3. How was it determined and demonstrated that a sufficient final data set had been obtained for the licence application?

SKB noted that this was a difficult question and found it hard to come up with a detailed account of how this was determined. In answer, SKB employed checks of input data and explored uncertainties through variance cases and different analysis. In the end, it was a project decision that sufficient information was available to demonstrate risk compliance and to have the licence application scrutinised by SSM.

Data freezes were part of the SDM work and new data are not available after SR-Site. However, SFR data were used late in SR-Site.

4. **What controls are in place and what checks are done that the data are used appropriately?**

As discussed previously (see Question 1 in this section).

2.3. QA Review of Documentation

Broadly, the QA review of documentation relating to groundwater flow modelling has aimed to check the traceability of the modelling analysis and the use of results through the SR-Site safety assessment documentation. This traceability check has served to support judgments on whether assumptions and conclusions relating to groundwater flow modelling are clearly and reliably supported by underpinning documentation.

The review focused on:

- Sections 10.2.3, 10.3.6 and 10.4.6 of the SR-Site Main Report (SKB, 2011). These sections cover groundwater flow modelling for the repository excavation and operational phases, temperate climate conditions, and periglacial and glacial climate conditions, respectively, as indicated in Figure 2.

- Svensson and Follin (2010), Joyce *et al*. (2010) and Vidstrand *et al*. (2010), which provided the details of the groundwater modelling undertaken for each of the three above-noted assessment phases. The Selroos and Follin (2010) synthesis of the groundwater flow modelling was also reviewed.

- Parts of Section 13 of the Main Report (SKB, 2011) on scenario analysis where the results of groundwater flow modelling have been used (Sections 13.2 and 13.4).

- Parts of the Data Report (SKB, 2010a) in which groundwater flow modelling is discussed (Section 6.6).

Other supporting reports and sections of the Main Report have been consulted where they provide information of relevance to groundwater flow modelling QA review. Additional information is available from a series of reports documenting queries by SSM concerning the documentation underlying the Main Report and answers from SKB. These reports were consulted where an issue raised by this QA review had previously been wholly or partly addressed through the request-response process.

The following sub-sections present the results of the QA review in terms of the analyses for the excavation and operational phases, temperate climate conditions, and periglacial and glacial climate conditions, respectively.

2.3.1. Excavation and operational phases

Code usage

Groundwater flow modelling of the excavation and operational phases was conducted by Svensson and Follin (2010) using DarcyTools. The version of DarcyTools used in the groundwater modelling work is unclear: Selroos and Follin (2010, §3.3.2) state that version 3.4 was used, but Svensson and Follin (2010, §1.2) state that version 3.2 was used. However, Vidstrand *et al*. (2010, §1.3.2) state that the differences between the two versions are insignificant for the SR-Site application and so this appears not to be an important issue.

Methodology and source data

The Main Report (SKB, 2011, §10.2.3) sets out the groundwater flow methodology for the excavation and operation phases with reference to Svensson and Follin (2010). However, there is a lack of direct cross-referencing to sections in Svensson and Follin (2010) for specific components of the methodology, and a lack of referencing to source data and literature in Svensson and Follin (2010), which hinders traceability.

For example, the Main Report (SKB, 2011, §10.2.3) refers to a phreatic surface algorithm used in the groundwater flow modelling, but without direct reference to a description of the algorithm. After some searching, a description of the phreatic surface algorithm was found in Appendix A of Svensson and Follin (2010). Further, Svensson and Follin (2010, Appendix A) mention two methods available in the literature to calculate the position of the groundwater table, but no references to this literature are provided.

Another example of the lack of traceability of information concerns the depth-dependence of grid cell properties. Table 4-1 of Svensson and Follin (2010) provides information on grid cell hydraulic properties above and below 20 m depth, but there are no references to the derivation or source of the values listed. The source of the values in Table 4-1 was queried by SSM (SKB, 2012a, Q2). In answer, SKB stated that properties for depth <20 m derive from the calibration of the groundwater level for undisturbed conditions, documented in Figures 4-7 and 5-2 of Svensson and Follin (2010). However, these figures still do not explain exactly how the values were measured or derived, and no explanation was provided for the values applied below this depth. The values in Table 4-1 are illustrated (apart from specific storage) in relation to field data in Figure 4-5. The source of data in this figure was stated by SKB (when questioned by SSM) to be Tables 3-7 and 3-8 in Follin *et al.* (2008), although the caption states that the source is Tables 2-5 and 2-6 of Svensson and Follin (2010), which are modified from Table 2-4 of Bosson *et al.* (2008). The values given among these three sets of potential source tables are slightly inconsistent, and in any case they correspond only to the field data, not the simulated values used in modelling.

Table 4-2 provides information about initial depth-dependent salinity conditions at Forsmark with reference to Selroos and Follin (2010), but the information on the salinity distribution could not be found in Selroos and Follin (2010). There is some discussion of groundwater salinity in the Main Report (SKB, 2011, §4.8.2) and in the Site Description Model for Forsmark (SKB, 2008a, §11.7.2), but the basis for the distribution assumed by Svensson and Follin (2010) is not given. In a request for additional information, SSM queried the derivation of these initial pressure and salinity conditions (SKB, 2012a, Q3). SKB clarified that the conditions at 2000 AD were calculated by simulating transient boundary conditions since 8000 BC (using initial conditions provided in Table 4-2). In an elaborated answer, SKB explained the shoreline recession simulation shown in Figure 4-6 and its implementation in the model by reference to two other reports (Follin *et al.*, 2007a and Follin *et al.*, 2008). However, it is not easy to identify where in these reports such a simulation is described. SKB also described in its answer the calculation of initial pressures from initial densities (equation 3-3 of Svensson and Follin, 2010) and hence initial salinities (equations 3-5 and 3-7 of Svensson and Follin, 2010). The traceability of this aspect is satisfactory, but there is still no explanation of the assumed initial conditions at 8000 BC.

The description of the modelling methodology in Selroos and Follin (2010, §3.2) would benefit from the inclusion of the dimensions of parameters and variables. It is good practice to include such information and it aids understanding. Also, a source reference for the DarcyTools power law fracture transmissivity equation in Section 3.2.3 should be provided. The selection of exchange rate coefficients for the diffusive exchange model for salt, as discussed in Section 3.2.5, is not well explained and the basis for the selected values is not provided.

Effects of SFR

The simultaneous operation of the spent fuel repository and SFR (the final repository for short-lived radioactive waste) is investigated in variant Cases 5 to 7 (Svensson and Follin, 2010, §4.3 and §5.5). Details of this sensitivity study are presented in Svensson and Follin (2010, Appendix D), although a different case naming convention is used (Cases A to D) and incorrect cross-references to the main text is used (§5.6 is cited rather than §5.5). Svensson and Follin (2010, Appendix D.4) provide a very brief discussion of the results of these sensitivity studies. Further discussion is provided by Svensson and Follin (2010, §5.5), where it is concluded that the effects on the final repository would be small. Interactions with SFR are further discussed in Section 10.2.5 of the Main Report, where it is stated that interactions between a closed SFR and an operating deep repository (not currently planned) cannot be excluded. It is stated that organic matter rich pore waters from SFR could find their way to the operating deep repository. The basis for this observation is not clear; while Appendix D of Svensson and Follin (2010) includes this case in the sensitivity study (Case D), Svensson and Follin (2010) do not discuss the results of this case.

Inflow calculations

Results of the inflow calculations are presented in Section 5.2.1 of Svensson and Follin (2010) and Section 10.2.3 of the Main Report. There are minor discrepancies in the reported range of inflow rates in Section 5.2.1, Section 6.2 and Table 5-1 of Svensson and Follin (2010) and Section 10.2.3 of the Main Report, but these discrepancies may be due to rounding.

According to Section 10.2.3 of the Main Report, the results of the inflow calculations are used in the assessment of buffer and backfill erosion during backfilling (§10.2.4 and §10.3.8 of the Main Report), but there seems to be no direct use of the derived values. Generally, it is difficult to trace how the results of the inflow calculations have been used in the Main Report. Several reports referred to in Sections 10.2.4 and 10.3.8 of the Main Report in relation to groundwater flow modelling and parameters (e.g. Sandén *et al.* 2008; Sandén and Börgesson, 2010) were produced earlier than Svensson and Follin (2010) and so the relationship between them is not clear. The same is true of the Repository Engineering report (SKB, 2009), which is also said to use the results of Svensson and Follin (2010).

Inflow to the repository

In Section 10.2.3 of the Main Report, it is stated that the tunnel routines used in the DarcyTools modelling have been shown to be accurate to within 10% of an analytical solution. However, Svensson and Follin (2010, Appendix B) show that the deviation from the analytical solution increases when the level of grouting efficiency is increased, and can be as high as 52%. Svensson and Follin (2010, Appendix B) explain that difference can be reduced to 10% by increasing the grid resolution near the tunnel, but it is not clear whether this was actually done in the SR-Site calculations and the comparison is not presented for all levels of grouting efficiency.

2.3.2. Temperate climate phase

Hydrogeological evolution

Section 10.3.6 of the SR-Site Main Report (SKB, 2011) discusses hydrogeological evolution, and is largely a summary of the results presented in Section 6 and the appendices of Joyce *et al*. (2010). The information in Section 10.3.6 of the Main Report is broadly consistent with the material presented by Joyce *et al*. (2010). Joyce *et al*. (2010) adopted a combination of DFN models and equivalent continuous porous medium and continuous porous media (ECPM and CPM) models using ConnectFlow. Models were developed at three scales: regional scale; repository scale and site scale. Selroos and Follin (2010, §3.4.4) note that the dimensions of the repository-scale model are limited because of computational constraints. As a result, three model blocks are used, but there is no discussion as to why this is a suitable discretisation.

The main issue with regards to QA is the lack of cross-referencing from the SR-Site Main Report to Joyce *et al*. (2010), which makes it difficult to trace, check and understand the background to the information. In particular, when presenting the summary findings, the Main Report rarely refers explicitly to sections or figures in Joyce *et al*. (2010), or to other relevant supporting reports.

Groundwater discharge points

An example of difficulty in tracing information is provided by the discussion of groundwater discharge points. The Main Report discusses the location of deep groundwater discharge points in several places, with reference to Joyce *et al*. (2010), but the relationship between discharge points and landscape features is difficult to track. In particular, in the biosphere discussion in Section 10.3.3 of the Main Report, it is stated that the discharge of deep groundwater will almost exclusively take place at low points in the landscape and in near-shore areas of the sea, and that the description of landscape development is focused on these areas where accumulation of potentially released radionuclides may occur. However, Joyce *et al*. (2010) do not discuss the details of exit locations in low-lying areas.

Instead, Section 13.2.2 of the Main Report was found to provide the link between the calculation of discharge points by Joyce *et al*. (2010) and predictions of the evolving Forsmark landscape. In Section 13.2.2, reference is made to the Landscape

Development Model (Lindborg, 2010). Lindborg (2010, §5.7.5) discusses land-use development and focuses on the Variant 2 distribution of land uses, upon which discharge points are superimposed (Figure 13-4 of the Main Report and Lindborg, 2010, §6.2.2). A cross-reference in Section 10.3.3 to Section 13.2.2 of the Main Report would have greatly improved traceability of arguments relating to the location of discharge points.

Also, in Section 10.3.6 of the Main Report, it is stated that the discharge locations follow the retreating shoreline in the period up to 12,000 AD. However, Joyce *et al*. (2010, §6.3.4 and §7.1) note that, for early times, the exit locations are dominated by the DFN features, particularly the deformation zones, but once the particles enter the ECPM and CPM they are more strongly influenced by the shoreline location. The influence of the shoreline is diminished in the extended spatial variability case reported by Joyce *et al*. (2010, §6.3.4, Figure 6-33), because the enhanced effect of the deformation zones causes more particles to exit closer to the repository. Joyce *et al*. (2010, Section 6.3.4) note that this finding emphasises the important role that deformation zones have in determining exit locations. Further, Joyce *et al*. (2010, Section 7.1) note that this finding shows that exit locations are affected by how the region outside the repository site is represented. This observation is repeated by Lindborg (2010, §6.5.1). However, the importance of this finding is not mentioned in the discussion of discharge area identification in Section 13.2.2 of the Main Report and its significance does not appear to have been considered further.

Buffer erosion

Section 12.2.2 of the Main Report discusses the number of deposition holes that have been calculated to be subject to advective conditions following buffer erosion in the one million year assessment period. Various references to supporting analyses are made in Section 12.2.2, but the rationale for the derived values is difficult to trace. For example, it is stated that erosion occurs during 25% of the one million year assessment period in the two percent of the deposition holes exposed to the highest flow rates. Reference is made to analyses summarised in Sections 10.3.7 and 10.4.7 of the Main Report, but the key discussion was in fact found in Section 10.4.8 of the Main Report (on colloid release from buffer and backfill). In the latter section, the basis for selecting a 25% erosion period is explained, with reference to the discussion of climate-related conditions in Section 10.4.1 of the Main Report (Figures 10-106 and 10-107). That two percent of the deposition holes experience dilute conditions is explained with reference to discussions of hydrogeological evolution in Section 10.3.6 (Figures 10-32) and Section 10.4.6 (Figures 10-139 and 10-140) of the Main Report. Also, in Section 10.4.8 of the Main Report, the expectation that fewer than one in a thousand of the 6,000 deposition holes will exhibit advective conditions during the first glacial cycle and that 23 deposition holes will reach advective conditions in one million years is explained. In Section 12.2.2, the variability in the number of deposition holes reaching advection conditions over ten realisations and the sensitivity to different assumptions about fracture properties and erosion are evaluated. Conclusions regarding the propagation of results to the canister corrosion scenario are presented in Section 12.2.3; the cases selected for the corrosion assessment (Section 12.6.2) cover the uncertainties associated with the hydrogeological DFN model used by SKB (correlated, semi-correlated and uncorrelated fracture transmissivity-size relationships).

In summary, although Sections 12.2.2 and 12.2.3 have attempted to bring together the results of several strands of work on groundwater flow modelling, climate evolution and buffer erosion, the poor cross-referencing and scattered nature of the information makes the arguments difficult to follow and trace. However, the information could be found with some searching.

Multiple realisations

As discussed in Section 12.2.2 of the Main Report (and noted above), ten realisations of the HRD were used in the calculations. The use of ten realisations to explore the effects of variability in rock properties is described by Joyce *et al*. (2010, §4.2.1), although there is no explanation as to why ten realisations were chosen. Joyce *et al*. (2010, §6.2.7) discuss the sensitivity of results (percentage of particles reaching the top surface of the model) to stochastic geometry.

During meetings with SKB in December 2011, the Nuclear Energy Agency's International Review Team discussed the number of realisations of the hydrogeological model performed by SKB (SKB, 2012b). However, the discussion related to the fully correlated model variant rather than the semi-correlated case referred to above. As a result of the discussion, SKB carried out a number of additional realisations of the fully correlated model variant, so that a total of 15 realisations were run in addition to five run within the SR-Site assessment. Results were assessed in terms of the number of deposition positions that have sufficiently high flow to cause canister failure due to corrosion. Although the mean value was unaffected by the additional realisations, the 95% confidence interval was substantially reduced. This document does not discuss realisation numbers for the semi-correlated model variant except in Figure 1, which indicates that there is a smaller confidence interval for the set of ten realisations than for both the initial five and the total of 20 realisations of the fully correlated variant. It is assumed that this comparison constitutes the justification for not performing more than ten realisations for the fully correlated variant, although this is not explicitly stated anywhere.

2.3.3. Glacial cycles

Hydrogeological evolution

Section 10.4.6 of the Main Report addresses hydrogeological flow modelling for assumed glacial and periglacial conditions, and is based on the results from Vidstrand *et al*. (2010). The hydrogeological flow modelling used DarcyTools (version 3.2), and used the results of the flow modelling by Joyce *et al*. (2010) and hydrogeochemical modelling from other reports (Salas *et al*. 2010 and Sidborn *et al*. 2010). The output parameters are pressure, Darcy flux and salinity at repository depth. The results of the modelling are used in Chapter 13 of the Main Report and as input to buffer erosion-corrosion analyses in Section 10.4.8 and 10.4.9.

The discussion of hydrogeological evolution mirrors the discussion in Vidstrand *et al*. (2010, §6.3), although there is limited direct cross-referencing. For example, Figures 10-129 to 10-135 are reproduced from Figures 6-4 to 6-10 of Vidstrand *et al*. (2010), but this is not mentioned in the figure captions. Similarly, the discussion of recharge and discharge locations in the biosphere is a direct repeat of text and figures from Vidstrand *et al*. (2010, §6.3), but there is no cross-referencing to Vidstrand *et al*. (2010, §6.3).

One minor discrepancy noted is that Table 10-25 of the Main Report is similar to Table 1-1 in Vidstrand *et al*. (2010), except that for case (d) Vidstrand *et al*. (2010)

includes the condition “Temperature-dependent permeability conditions”, which is inconsistent with the “Undistorted permeability conditions” listed in Table 10-25 of the Main Report.

DFN parameters

Section 6.6 of the Data Report (SKB, 2010a) discusses quantities for groundwater flow modelling, but is only concerned with quantities and properties of rock mass volumes found in between the deterministically modelled deformation zones. In an answer to SSM (SKB, 2012a, Q31), SKB acknowledges this, stating that a decision was taken for data qualification in SR-Site to focus on data related to the parameterisation of the fractured rock mass. However, readers not party to this information may find the lack of other hydrogeological data in the Data Report puzzling.

Tables of hydrogeological DFN parameters (Tables 6-75, 6-76, 6-77 and 6-78) are reproduced from Selroos and Follin (2010, §2.4.2). The values in Tables 6-75, 6-67 and 6-77 can be traced back through the groundwater flow modelling reports to Appendix C of Follin (2008), although with some difficulty owing to the lack of cross-referencing in Selroos and Follin (2010). The derivation of the parameters is documented ultimately in Follin *et al*. (2007b), but discovering this is time-consuming and involves tracing information back through numerous reports, many of which do not provide source references.

The traceability of DFN parameter values throughout SKB’s reports is summarised in Tables 1, 2 and 3, which illustrate the inconsistencies in referencing and difficulty of locating the ultimate source for the values. Compilation of these tables was aided by SKB’s response to a similar request for clarification (SKB, 2012a, Q33), and the inconsistencies identified in that document have since been corrected with the publication of errata for the affected reports. However, one error was not identified and remains: Table B-4 of Vidstrand *et al.* (2010) contains incorrect orientation data for fracture domain FFM02.

Table 6-78 comprises the hydraulic conductivity, kinematic porosity and flow-wetted fracture surface area in three depth zones for rock mass volume outside the six fracture domains. The values for hydraulic conductivity and kinematic porosity are given in Table 3-2 of Vidstrand *et al*. (2010), and Vidstrand *et al*. (2010) refer to Table 3-6 in Follin *et al*. (2007b) as the source of the values; however, this is an incorrect reference as there is no Table 3-6 in in Follin *et al*. (2007b). The source of the values is actually Follin *et al*. (2007a). However, the source of the values for flow-wetted fracture surface area remains unclear.

Table 1: Appearance and traceability of hydrogeological DFN parameters for FFM01 and FFM06 in SKB reports.

Report	Table, page	Consistent with Data Report?	References
TR-10-52 (Data Report; SKB, 2010a)	6-75, p. 337	N/A	None given
R-09-22 (Selroos and Follin, 2010)	2-2, p. 25	Yes	None given
R-09-21 (Vidstrand *et al*., 2010)	3-3, p. 41 B-1, p. 106	Yes Yes	R-08-95, Appendix C R-08-95, Appendix C
R-09-20 (Joyce *et al*., 2010)	2-3, p. 23	Yes	R-08-95, Appendix C
R-09-19 (Svensson and Follin, 2010)	2-3, p. 25	Yes	R-08-95, Appendix C
R-08-95 (Follin, 2008)	C-1, p. 161	Yes	R-07-49, Appendix F
TR-08-05 (SKB, 2008a)	8-8, p. 266	Yes	None given
R-08-23 (Follin *et al*., 2008)	3-10, p. 45	Yes	R-07-49
R-07-49 (Follin *et al*., 2007a)	F-1, p. 227	Yes	R-07-48
R-07-48 (Follin *et al*., 2007b)	11-20, p. 182	Yes – orientation sets are different but the correct ones can be found in Table 11-26, p. 192	None given for DFN parameters or orientation sets – original derivation

Table 2: Appearance and traceability of hydrogeological DFN parameters for FFM02 in SKB reports.

Report	Table, page	Consistent with Data Report?	References
TR-10-52 (Data Report; SKB, 2010)	6-76, p. 338	N/A	None given
R-09-22 (Selroos and Follin, 2010)	2-3, p. 25	Yes	None given
R-09-21 (Vidstrand *et al*., 2010)	B-4, p. 106	No – orientation data are those used for other fracture sets	None given
R-08-95 (Follin, 2008)	C-2, p. 162	Yes	R-07-49, Appendix F
R-07-49 (Follin *et al*., 2007a)	F-2, p. 228	Yes	R-07-48
R-07-48 (Follin *et al*., 2007b)	11-22, p. 186	Yes – orientation sets are different but the correct ones can be found in Table 11-26, p. 192	None given for DFN parameters or orientation sets – original derivation

Table 3: Appearance and traceability of hydrogeological DFN parameters for FFM03, FFM04 and FFM05 in SKB reports.

Report	Table, page	Consistent with Data Report?	References
TR-10-52 (Data Report; SKB, 2010)	6-77, p. 338	N/A	None given
R-09-22 (Selroos and Follin, 2010)	2-4, p. 26	Yes	None given
R-09-21 (Vidstrand *et al*., 2010)	B-7, p. 107	Yes	R-08-95, Appendix C
R-08-95 (Follin, 2008)	C-3, p. 162	Yes	R-07-49, Appendix F
R-07-49 (Follin *et al*., 2007a)	F-3, p. 228	Yes	R-07-48
R-07-48 (Follin *et al*., 2007b)	11-25, p. 189	Yes – orientation sets are different but the correct ones can be found in Table 11-26, p. 192	None given for DFN parameters or orientation sets – original derivation

Glacial melt water

The discussion of the penetration of glacial melt water in Section 10.4.6 of the Main Report is from Selroos and Follin (2010, §6.4.4) rather than Vidstrand *et al*. (2010). In particular, Figures 10-139 and 10-140 are reproduced from Figures 6-14 and 6-15 of Selroos and Follin (2010). However, Selroos and Follin (2010) are not cited.

There is some lack of clarity regarding the discussion in Section 10.4.6 of the Main Report on the initial estimate of 3 g/L for the salt concentration of the fracture water before the onset of the glacial period and the concentration of 0.3 g/L corresponding to dilute conditions with potential buffer erosion. There is a reference to Section 10.4.7 of the Main Report, but the rationale for the threshold values of 3 g/L and 0.3 g/L is not explained there. Instead, Section 10.3.7 contains passing references to 25% of repository groundwaters having less than 3 g/L of dissolved salts (p. 358), and a value for total dissolved solids of >0.27 g/L (p. 359). However, no justification is provided for the translation of these findings into the threshold values, and there are no further references to underlying reports where more detail might be given.. It is therefore difficult to fully verify the choice of these values.

Related to this topic, SSM queried (SKB, 2012a, Q29) as to why a relative rather than absolute measure is used as an indicator for when dilute waters reach the repository (as discussed on p. 95 of Selroos and Follin, 2010). In reply, SKB stated that the discussion here relates to a model that is only used to illustrate the large-scale salinity behaviour during a glacial period, rather than to directly assess the number of deposition holes that will experience dilute conditions.

Ice sheet retreat

Vidstrand *et al*., (2010, §1.3.3) note that the assumed ice sheet retreat speed of 100 m/y does not agree with the value of 300 m/y assumed in the Climate Report (SKB, 2010c). Vidstrand *et al*., (2010, §1.3.3) claim that the implications of this discrepancy are considered in Vidstrand *et al*., (2010, Appendix D), but the issue is not discussed in the appendix. However, the effects of differences in ice sheet retreat speed are evaluated in Vidstrand *et al*., (2010, §6.3), but the reasons for the use of a retreat speed different to that assumed in the Climate Report are not clear.

Darcy flux

The comparison of the Darcy flux at different times during glaciation and deglaciation is discussed in Section 10.4.6 of the Main Report, as well as in Section 6.4.7 of Selroos and Follin (2010). Three powers of Darcy flux are described as being of interest (q, $q^{0.41}$ and $q^{0.5}$), but there is little explanation of why these powers are of interest. Section 10.4.6 of the Main Report refers to Sections 10.4.8 and 10.4.9 for further details, but neither of these sections adequately explains why these powers of Darcy flux are of interest.

3. Conclusions

The review of groundwater flow modelling QA in the SR-Site safety assessment has involved a QA review meeting with SKB and a review of SR-Site documentation relating to groundwater flow modelling. The QA review meeting focused on a checklist of QA issues in groundwater flow modelling and was concerned with the QA procedures followed by SKB and its contractors and their implementation in the SR-Site groundwater flow modelling. The QA review of SR-Site documentation aimed to check the traceability of the groundwater flow modelling analysis and results through the safety assessment.

Broadly, it can be concluded that SKB had procedures in place during SR-Site that would be expected for groundwater flow modelling in support of a repository safety assessment. Task descriptions were prepared for the groundwater flow modelling work, as required by SKB's QA plan for the SR-Site safety assessment (SKB, 2008b), and QA plans were prepared for the tasks. The task QA plans address project management, code run management, data management, calculation checking, delivery of results, and report preparation and checking. During the QA review meeting, SKB elaborated on how the modelling work had been managed and how the QA procedures had been applied. The following more detailed observations are made in relation to the QA review meeting with SKB:

- SKB provided evidence that the groundwater flow modelling codes used in SR-Site have been developed and tested according to appropriate QA procedures.
- SKB was able to describe how data transfer was managed between groundwater flow models and contractors during SR-Site work using iteratively developed task descriptions and HydroNet meetings, and was able to demonstrate how input, output and other files relating to SR-Site modelling are currently stored, backed-up and accessed on the SKBdoc database. However, experience of code usage would be required in order to understand some of the examples of files shown during the meeting.
- SKB demonstrated how modelling results could be traced using the document identifiers in the SKBdoc system.
- SKB relies on experienced individuals to run the codes, although SKB is actively supporting DarcyTools applications partly to retain and expand understanding and use of the code. However, the MIGAL flow solver called in DarcyTools is developed and maintained by a single contractor. Code maintenance or developments may be a concern if that individual becomes unavailable, although SKB claims that MIGAL can be replaced if necessary. SKB relies on AMEC maintaining a broad level of knowledge and use of ConnectFlow, which SKB can call upon as required.
- SKB developed its own flow model calibration process for SR-Site due to the lack of availability of published methods for sparsely fracture rock. The calibration process has been published in a peer-reviewed journal. The calibration process largely relied on expert judgments made at Hydronet meetings.

No major concerns were identified during the QA review meeting and, indeed, the meeting engendered a degree of confidence that the modelling results presented in support of the SR-Site safety assessment are reliable, having been produced by suitably qualified experts using quality assured codes under the framework of task descriptions and QA plans.

However, in contrast, the QA review of SR-Site documentation proved difficult and time-consuming because of the inadequate cross-referencing between the SR-Site Main Report and the supporting groundwater flow modelling and related reports. In many cases, it was possible to locate the information reported in the SR-Site Main Report, but only after lengthy searches through large documents. In a few instances, it was not possible to locate explanations or sources of data used.

In summary, nearly all of the problems encountered with regard to QA in groundwater flow modelling and documentation concern traceability; only a very small number of actual inconsistencies were noted. Even these inconsistencies seem likely to be errors of recording rather than errors in the models, which should have been identified and corrected through the cross-checking procedures and expert oversight built into SKB's model and data management procedures.

It is recognised that SKB's licence application and supporting documentation represent a very large amount of work undertaken over many years. In such a project it is perhaps understandably difficult to ensure that all information is cross-referenced clearly and consistently, especially when those involved are familiar with the models, results and reports that constitute the project and require little sign-posting to aid navigation. However, for the intended audience of the SR-Site Main Report, cross-referencing to specific sections, figures and tables in supporting documents would have greatly improve the traceability of data and use of results. In particular, better cross-referencing would have enhanced confidence in the quality of the safety assessment and licence application.

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APPENDIX 1

Coverage of SKB reports

Table 4: Main reports checked in the QA review of groundwater flow modelling in SR-Site. Other reports were consulted as necessary to check specific issues as discussed in the main text of this report.

Reviewed report	Reviewed sections	Comments
TR-11-01: Long-term safety for the final repository for spent nuclear fuel at Forsmark: Main report of the SR-Site project.	Sections 10.2.3, 10.3.6, 10.4.6, 13.2 and 13.4	
R-09-19: Groundwater flow modelling of the excavation and operational phases – Forsmark.	Entire report	
R-09-20: Groundwater flow modelling of periods with temperature climate conditions – Forsmark..	Entire report	
R-09-21: Groundwater flow modelling of periods with periglacial and glacial climate conditions – Forsmark.	Entire report	
R-09-22: SR-Site groundwater flow modelling methodology, setup and results.	Entire report	
TR-10-52: Data Report for the Safety Assessment SR-Site.	Section 6.6	

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