

CHAPTER 6
RISK AND UNCERTAINTY**Debbie Polson*****Andrew Curtis**

School of Geosciences, Grant Institute,
University of Edinburgh, West Mains Road,
Edinburgh EH9 2JT

Claudia Vivalda

Schlumberger, Lambourn Court,
Wyndyke Furlong, Abingdon Business Park, Abingdon,
Oxfordshire OX14 1UJ

*Corresponding Author

6.1 INTRODUCTION

Ultimately, any storage site is required to have appropriate capacity, injectivity, security and monitorability. If the storage formation fails or does not perform within expected bounds in one of these features then there could potentially be severe impacts. Leakage of CO₂ and displacement of the formation fluids may result in acidification and/or contamination of groundwater and near-surface deposits, with uncontrolled leakage posing a risk to surface ecosystems, either onshore or offshore. Furthermore, there is a large financial risk in rolling out geological CCS on a major scale, with significant investment required both in improving technology and in identifying and characterising potential storage sites. Risk analysis therefore forms a vital part of any carbon storage project.

Typically, risk is defined as a combination of likelihood of occurrence and magnitude of the potential impact. Using a quantitative or semi-quantitative approach, it is possible to rank areas of potential risk to a project, for example, faults in the storage site that may provide leakage pathways for CO₂, petrophysical properties that may not allow for the required injection rates or volumes, or public opposition that may cause a project to be suspended.

A key factor in risk analysis for geological storage of carbon dioxide is uncertainty: the successful storage of CO₂ requires that it remains within the target formation far into the future. Given the large uncertainties associated with any work in the subsurface, it is impossible to know with 100% certainty what the fate of the injected CO₂ will be in the subsequent decades and centuries. Therefore, it is important that uncertainty in the properties of the subsurface and in behaviour of CO₂ in the formation are considered when assessing the suitability of a potential storage site. In this way we can quantify our uncertainty in the likely fate of the CO₂ in the system and make probabilistic assessments regarding the behaviour of CO₂ in the long term.

In this chapter we describe processes for assessing risk and uncertainty and show how these can feed into the decision-making process within a project. While assessment of risk and uncertainty are separate processes, they are closely linked, with uncertainty strongly influencing the risk and risk informing important decisions regarding future data acquisition aimed at better understanding uncertainty. Both are iterative processes that take place throughout the project lifetime, allowing changes to be tracked and the impact of individual activities to be assessed.

The chapter is divided into two sections: the first section describes the sensitivity and uncertainty analysis process used to identify key properties of the site, required to both model the behaviour of CO₂ in the storage formation and assess uncertainty in the models. The second section describes an assessment process used to quantify and rank areas of risk and to show how these feed directly into project decisions.

6.2 GEOLOGICAL UNCERTAINTY

Numerical simulations are the primary tool for predicting the fate of injected CO₂. These simulations aim to model true properties of the storage site and accurately simulate the behaviour of the system. However, the properties of the subsurface will always be uncertain (as highlighted in Chapters 3, 4 and 5) and, therefore, no simulation will be able to make completely accurate predictions. To properly assess a storage site will therefore require that these uncertainties are propagated through a simulation in such a way as to allow the uncertainty on the outputs to be estimated.

Given the large number of parameters in such models, identifying the key parameters controlling uncertainty on the model output is important for the prioritisation of resources for data acquisition.

This process is called sensitivity analysis. Quantifying the uncertainty in the input parameters and propagating these through the models, in order to estimate the uncertainty on key model outputs, is called uncertainty analysis.

Figure 6.1 shows how sensitivity and uncertainty analysis fit into the overall workflow, where the ultimate aim is to make a probabilistic assessment of security, capacity, injectivity or monitorability. However, the techniques used for this analysis can be applied to any model where uncertainty estimates are required

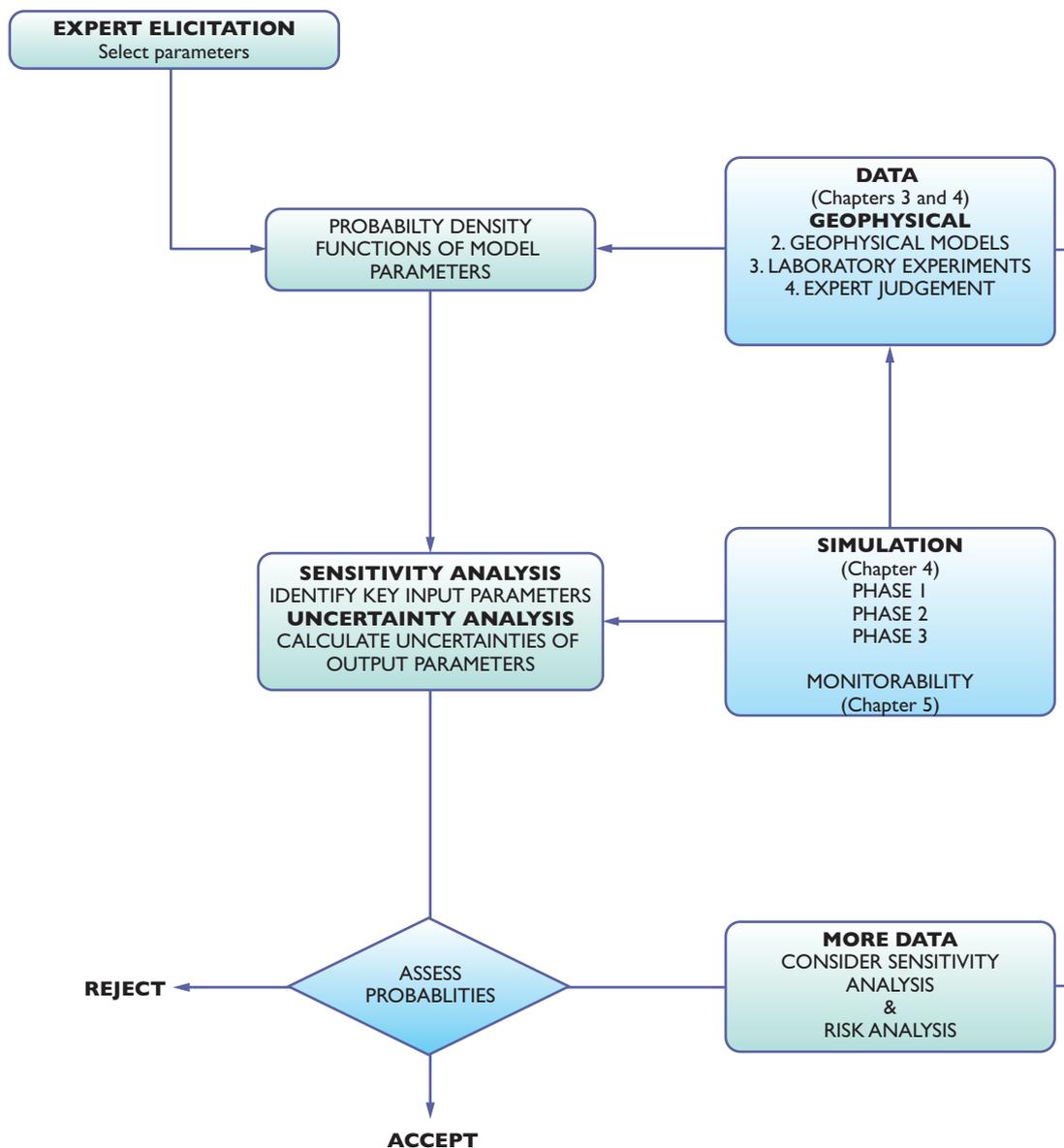


Figure 6.1 Workflow for sensitivity and uncertainty analysis.

Expert elicitation

The first step is to identify the particular model outputs for which uncertainty and sensitivity are to be assessed and the input parameters that are likely to influence these model outputs. Ideally, all input parameters would be included in the sensitivity and uncertainty analysis. However, this is likely to be impractical for many computer simulations and, therefore, a subset of parameters may be selected based on the judgement of experts. This is done using expert elicitation, where the experts consider the influence of the parameter and its associated uncertainty.

Care must be taken when eliciting expert opinion. All individuals, experts included, are subject to certain well-known cognitive biases which will affect their judgement in situations of uncertainty (Kahneman et al., 1982). These biases are the result of heuristics or rules of thumb that are used to simplify what are often extremely complex tasks. Types of bias include over-confidence, anchoring and adjustment, availability, and motivational bias (see Glossary). Explaining these biases to the experts at the start of the process and using a well-managed elicitation process can help to minimise the impact of bias on the results (Polson and Curtis, 2010a). However, expert judgement should be treated with caution and the effects of bias considered when interpreting results.

In the CASSEM project the sensitivity and uncertainty analyses were applied to the reservoir flow simulations described in Chapter 4, to quantify the uncertainties in the simulation predictions. An elicitation session with the set of experts responsible for constructing the flow simulations was used to decide which input and output parameters to investigate. The set of input parameters investigated are listed in Table 6.1 (details of their pdfs can be found in Polson et al., 2010b). The simulation outputs investigated were immobile and mobile CO₂ in the gas phase, dissolved CO₂, average pressure and bottom hole pressure, all as a function of time and, where relevant, space. It is important to know the state of CO₂ in the reservoir, as dissolved or immobile CO₂ should be trapped while mobile CO₂ remains free to potentially migrate to the surface. The pressure within the reservoir is important as it relates, not only to injectivity, but also to security, with higher pressures making it more likely that the cap rock may be damaged and hence provide migration pathways for CO₂. The pressure at the bottom of the injection well is important for the injectivity.

Input parameter
Depth of surfaces/interfaces between layer
Potential existence of lateral no-flow boundaries
Heterogeneity within each layer
Porosity of reservoir and caprock
Permeability of reservoir and caprock
Fault locations
Fault transmissivity
Relative permeability of carbon dioxide and water

Table 6.1 Input parameters investigated in sensitivity and uncertainty analysis.

Deriving probability density functions

Having selected the set of input parameters for investigation, probability density functions (pdfs) are estimated for each. The pdfs describe the range of possible values the input parameters could take and are estimated using a combination of data, expert judgement and, potentially, other modelling work. Work in the subsurface is inherently uncertain due to the natural variability in the geology and the comparative lack of information compared to other fields. Expert judgement is therefore often relied upon where data is lacking to fully constrain any particular property or characteristic

of a storage site. As expert judgement is influenced by cognitive bias, as described above, real data should be relied upon, as much as is possible, to estimate the pdfs of the input parameters. However, it is inevitable that expert judgement will play some role in any such study and, therefore, efforts must be made to minimise the impact of bias in the interpretation of the results, using careful elicitation. In addition, the uncertainty should be estimated conservatively (i.e. as large as is reasonable) and, where possible, the extremes considered.

An example of the parameter uncertainty is shown in Figure 6.2, which shows the estimated uncertainty in the surface depth of the Sherwood Sandstone Group for the Lincolnshire site. This represents the range of depths the geologist responsible for building the geological model (Chapter 3) believes the top of the layer could take in reality. It is based on a range of factors, including the seismic data, borehole data, geological complexity and expert judgement. This range is used to construct a pdf for the input parameter surface depth, assuming a Gaussian distribution with the mean value taken from the final geological model.

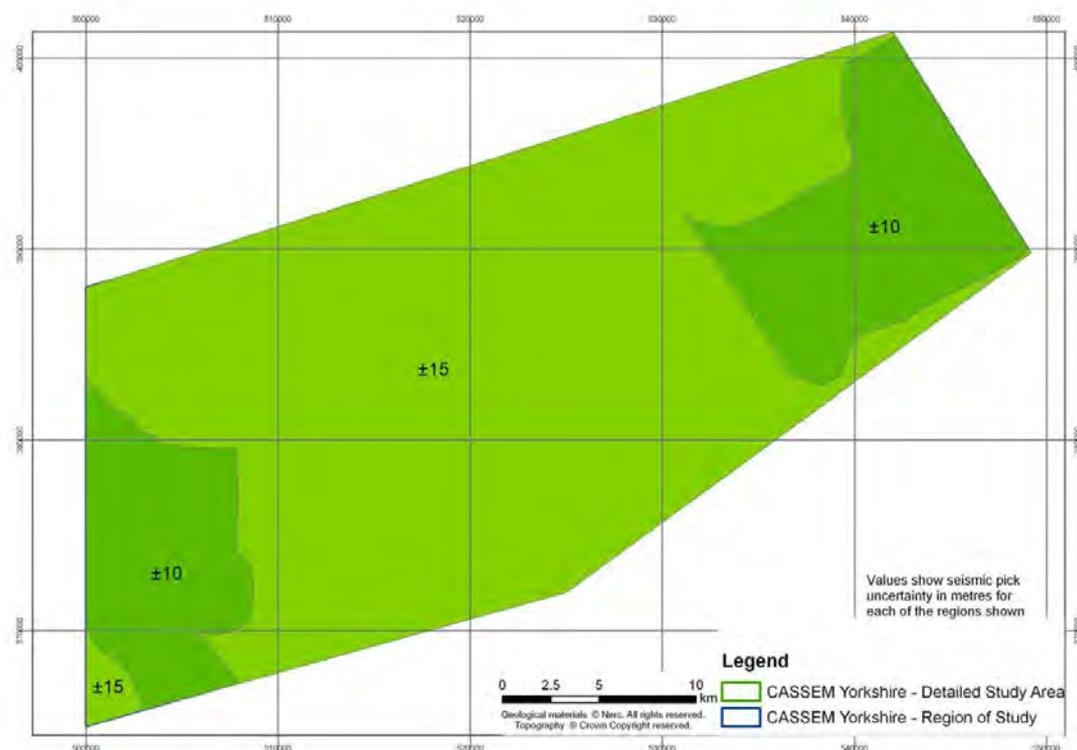


Figure 6.2 Seismic pick uncertainty map for the top Sherwood Sandstone Group.

Sensitivity and uncertainty analysis

The final step is to apply the sensitivity and uncertainty analysis to the simulation. Here, the analysis should be applied to the Phase 1, 2, and 3 reservoir flow simulations and the Phase 2 geomechanical and geochemical simulations and monitorability assessments. Applying the sensitivity analysis to the Phase 1 flow simulation identifies the key input parameters to the model. Data acquisition should be prioritised to reduce uncertainty in these parameters. The uncertainty analysis applied to the Phase 1 simulation should be used to validate the volume estimates of these models. Applying the uncertainty analysis to the Phase 2 simulations will show the impact of the final geological model on

the simulation predictions and show the impact of the geomechanical and geochemical modelling. Applying the uncertainty analysis to the Phase 3 flow simulation will produce the final pdfs for the simulation outputs. Given the predicted behaviour of CO₂ in the formation, monitorability also needs to be considered with uncertainty analysis applied here also, to assess the likelihood of being able to detect and monitor CO₂ in the future. Based on these predictions, a decision should be made as to whether the site meets the minimum requirements (i.e. the probability of having the required security, capacity, injectivity and monitorability exceeds some minimum acceptable limit) and, hence, whether to accept or reject the site for progression to the next stage of development. Alternatively, more data may be required, iterating around the workflow until some acceptable level of certainty is reached, to allow a decision to be made.

Monte Carlo techniques are widely used for uncertainty analysis. In this approach, the pdfs of the input parameters are defined, randomly sampled and used to drive different simulations. This approach requires thousands of simulations to be performed for different combinations of input parameters, to ensure that the pdfs of the input parameters are well sampled. The output from all runs can then be plotted as a histogram to give the pdf and the most likely value and uncertainty of the simulation output. The problem with this approach is that each simulation is usually extremely computationally costly; running thousands of simulations is usually infeasible. Using a metamodel (i.e. a model of the model) can allow the simulation output to be predicted in a fraction of the time and also allows us to easily identify which input parameters are most influential.

A metamodel is usually a function that approximates the behaviour of a numerical simulation. One well-established technique used in this study is response surface methodology (RSM) (Myers and Montgomery, 1995). However, a number of alternative metamodels do exist. The complexity of the simulation will dictate the form of the response function; although, typically, a quadratic polynomial, as shown in equation 6.1, which includes linear terms for each input parameter plus parameter interaction terms, is sufficient.

$$y = a_0 + \sum_{i=1}^n a_i x_i + \sum_{i=1}^n \sum_{j=i}^n a_{ij} x_i x_j + \varepsilon \tag{6.1}$$

Here y is the simulation output (the response), which might be, for example, CO₂ saturation in a particular sub-volume of the earth at a fixed time in the future. Terms x_i and x_j are any two input variables out of a total of n variables considered, a_0 is the so-called intercept term, and a_i and a_{ij} are coefficients associated with linear and quadratic interaction terms, respectively. The term ε is an error term representing higher-order sources of variability not accounted for in equation 6.1.

The coefficients for each term are calculated using a least-squares fitting technique. A carefully selected subset of simulations is run for different permutations of the input parameters. These runs are referred to as experiments, and the selection of runs is referred to as the experimental design. Different families of design exist, which allow the response function to be fitted accurately, using a minimal number of experiments. In the case of the CASSEM project, a composite design was chosen, which ran experiments using combinations of the minimum, maximum and mean of the input parameter distributions (Polson et al., 2010b).

Generally, the larger the magnitude of the coefficient, the more influential the term. However, as linear and interaction terms cannot be compared directly, the student t-values for the coefficient of each term are used instead.

$$t_i = \frac{a_i}{s(a_i)} \tag{6.2}$$

Here t_i is the student t-value of input parameter i , a_i is the value of the coefficient estimated by the least-squares fitting, and $s(a_i)$ is the estimated standard deviation associated with the coefficient. For each model output of interest and each time of interest, a unique response function is constructed and, hence, the influence of each input parameter for different outputs can be tracked over time. From this, the key parameters for the uncertainty in the simulations can be identified and recommendations made as to which properties of the site should be targeted with data acquisition activities.

CASE STUDY 6: RESULTS FOR FIRTH OF FORTH AND LINCOLNSHIRE

This study describes the results of a sensitivity analysis of flow simulations of the Firth of Forth and Lincolnshire sites at a range of times up to 1000 years post-injection, for the simulation outputs: total dissolved CO₂, total immobile CO₂, total mobile CO₂, average pressure and bottom hole pressure. The student t-values for the coefficient of each term in the response function are used to rank the influence of each term and, hence, the parameters in that term. It was found for the CASSEM sites that the first two or three most influential terms in the response function were generally much more influential than the remaining terms. Figure 6.3 shows the number of times each input parameter appeared in one of the three most influential terms in the response function for all five outputs and all times. Figure 6.3a shows the input parameters, itemised by site and injection and post-injection phases and Figure 6.3b shows the input parameters, itemised by simulation output. Thus, we can distinguish which input parameters are most influential for each site and at different phases of the storage and which input parameters are most influential for each simulation output.

The results show, importantly, that the most influential parameters are similar for both sites despite their distinct geologies and locations. Overall, the reservoir permeability, reservoir thickness (i.e. surface depth) and relative permeability are the most influential input parameters. Perhaps surprisingly, reservoir and cap rock porosity, cap rock permeability, faults location and transmissivity and heterogeneity are found, in comparison, to have negligible influence. It is important to note that this finding is dependent on the simulation outputs investigated and the pdfs defined for each input parameter; had these been different then input parameters, which were not found to be significant here, may well be found to be very influential.

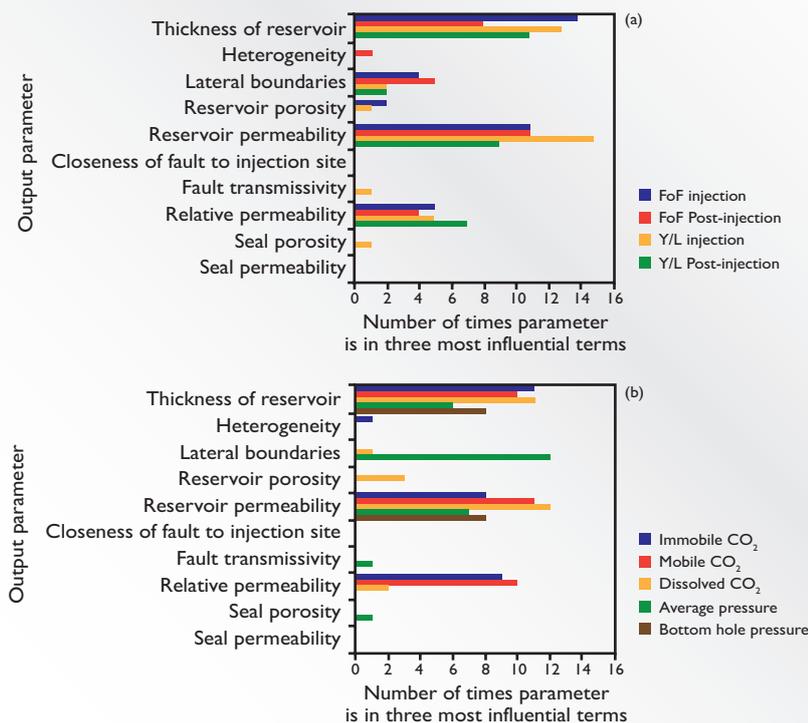


Figure 6.3 Number of times each input parameter appears in one of the three most influential terms in the response functions for the five simulation outputs: (a) for output times for injection (inj) and post-injection (post-inj) phases for the Firth of Forth (FoF) and Yorkshire/Lincolnshire (Y/L) sites and (b) for each of the five simulation outputs for both sites.

CASSEM CASE STUDY RESULTS: UNCERTAINTY ANALYSIS

Figure 6.4 shows the results of the uncertainty analysis of the flow simulations for total immobile CO_2 , total mobile CO_2 and total dissolved CO_2 for both sites, using the Phase 2 simulations at 100 years post-injection. For both sites the pdfs are approximately Gaussian, with the median (50th percentile) value for the Lincolnshire site consistently higher than the value for the Firth of Forth site. Comparing the relative uncertainties, where relative uncertainty is taken to be the 10th to 90th percentile as a percentage of the median value, we can show that the relative uncertainty is similar for both sites.

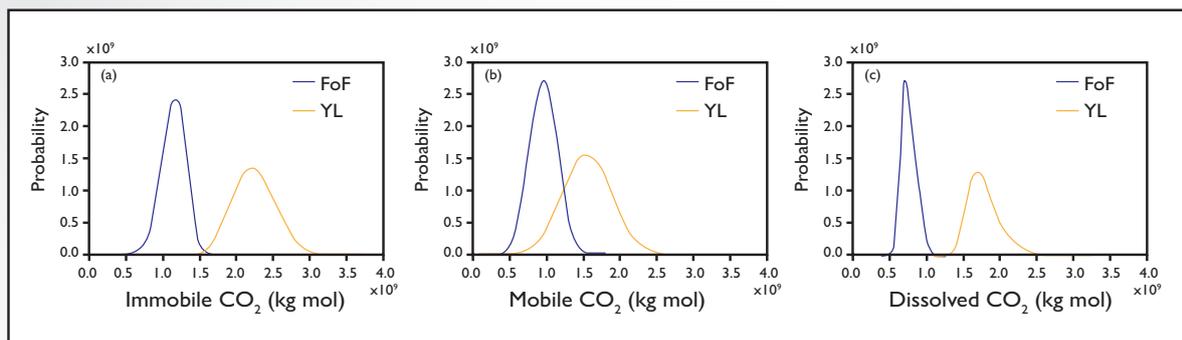


Figure 6.4 Probability density functions for (a) total immobile CO_2 in the gas phase (kg mol), (b) total mobile CO_2 in the gas phase (kg mol) and (c) total dissolved CO_2 (kg mol) for both sites at 100 years post-injection for the Phase 2 flow simulations

Uncertainty analysis performed on the Phase 1 simulations found that the results for the Lincolnshire site were consistent with those of the Phase 2 simulations, that is the pdfs of the two models for the various outputs tended to overlap significantly. However, for the Firth of Forth site, the Phase 1 and Phase 2 simulations could not be made consistent, even when extreme uncertainties were applied to the input parameters in the Phase 1 simulation. The Phase 1 simulation of the Firth of Forth was a simple box while the Phase 1 simulation of Lincolnshire contained detailed parameterisation from real data. This suggests that the simple form of the Phase 1 simulation for the Firth of Forth site can not capture even the most basic, critical aspect of behaviour of the CO_2 in the system, even allowing for very large uncertainties in the properties.

CASSEM CASE STUDY RESULTS: MIGRATION OF CO_2 INTO CAP ROCK

One of the key components of site assessment is security, i.e. the potential for leakage of CO_2 . In this section we describe a methodology for assessing the probability of CO_2 migrating upwards through the subsurface. To properly assess the risk of leakage we need to consider how the likelihood of leakage changes in time and space, as well as the impact of leakage (Vivalda et al., 2009). However, this may be computationally expensive, potentially requiring the whole subsurface to be modelled, as well as modelling of the impacts. Assuming that the cap rock is the primary barrier to upward migration of CO_2 , assessing the migration of CO_2 into and up through the cap rock should be a first step in assessing the security of the site. Should CO_2 be found to migrate through the cap rock, more detailed modelling of the subsurface, including the overburden, will be required to show whether additional seals may prevent further upward migration or whether CO_2 is likely to continue migrating to the surface.

We can apply the uncertainty analysis techniques to estimate the pdfs of the amount of CO_2 moving into the cap rock rather than being trapped within the reservoir. The probability of leakage to the top of the cap rock can be assessed by partitioning the top layer of the cap rock into regions and calculating the leakage rate of CO_2 into these regions at different times.

Figure 6.5 shows the median value from the probability density functions of total CO₂ in the cap rock in each phase over time, for the Firth of Forth site and the Lincolnshire site. These show that for the Firth of Forth site there is expected to be some CO₂ in all states, in the cap rock at virtually all times. For the Lincolnshire site there is expected to be some dissolved CO₂ in the cap rock at all times, while the median values for immobile and mobile CO₂ do not significantly exceed zero at most times. However, there is expected to be some CO₂ in both phases in the cap rock by 1000 years post-injection.

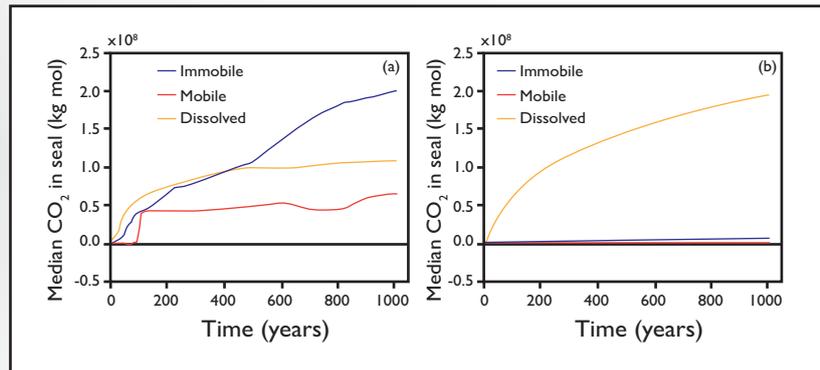


Figure 6.5 Median value (50th percentile) of probability density function of CO₂ in each phase (kg mol) in the cap rock at all times up to 1000 years post-injection for (a) the Firth of Forth site and (b) the Lincolnshire site.

Figures 6.6 and 6.7 show the median leakage rate (i.e. the 50th percentile from the pdfs) into the top layer of the cap rock for a range of times for the Firth of Forth and Lincolnshire sites, respectively (note the difference in scales between the two figures). Here the top layer of the cap rock is divided into four regions so that the spatial variation of the probability of leakage can be assessed, as well as variation with time. Figure 6.6 shows that leakage into all four regions at the top of the cap rock of the Firth of Forth site is expected in the decades and centuries following injection. For the Lincolnshire site, leakage is only expected in region 2 and the leakage rate is very low, never exceeding 10 kg mol year⁻¹. Results for mobile CO₂ show that for the Firth of Forth site there is a high probability of some leakage to the top of the cap rock. For the Lincolnshire site there is no mobile CO₂ in the upper cap rock, as all CO₂ in this region is dissolved in the formation fluids.

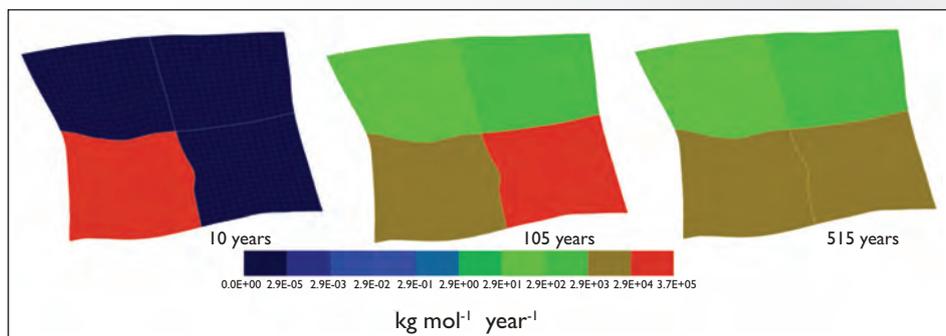


Figure 6.6 Median (50th percentile) leakage rate of total CO₂ (kg mol year⁻¹) in regions 1, 2, 3 and 4 (anticlockwise from bottom left) at the top of the cap rock of the Firth of Forth site.

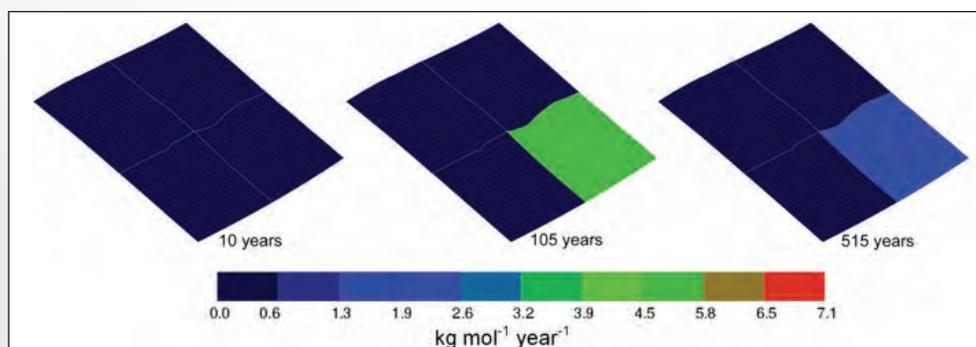


Figure 6.7 Median (50th percentile) leakage rate of total CO₂ (kg mol year⁻¹) in regions 1, 2, 3 and 4 (anticlockwise from bottom left) at the top of the cap rock of the Lincolnshire site. Note the different scale compared to Figure 6.6.

These results are for the Phase 2 flow simulations, not the final Phase 3 simulations, and hence should not be considered a conclusive assessment of these sites; they are presented here to demonstrate a methodology. Assuming these were the results for the most advanced simulations, the Firth of Forth site is unlikely to be suitable for storage, as mobile CO₂ is likely to be able to migrate into and upwards through the cap rock. The Lincolnshire site is likely to be more suitable, as although CO₂ does appear in the cap rock, it is mostly trapped in the dissolved and immobile form and therefore unlikely to migrate to the surface. Furthermore, only trace amounts of CO₂ reach the top of the cap rock and this is entirely dissolved in the formation fluids.

6.3 RISK ANALYSIS

In any CCS project there are many potential areas of risk which could impact on the success of a project. These impacts may be environmental or health and safety related, or they could be financial. In this chapter we describe step-by-step the risk assessment process, summarised in Figure 6.8, used in the CASSEM project to rank areas of risk, and describe how these assessments were used within the decision-making process within the project. The work described here is a scaled-down version of the type of process that would be required in a full-scale CCS project.

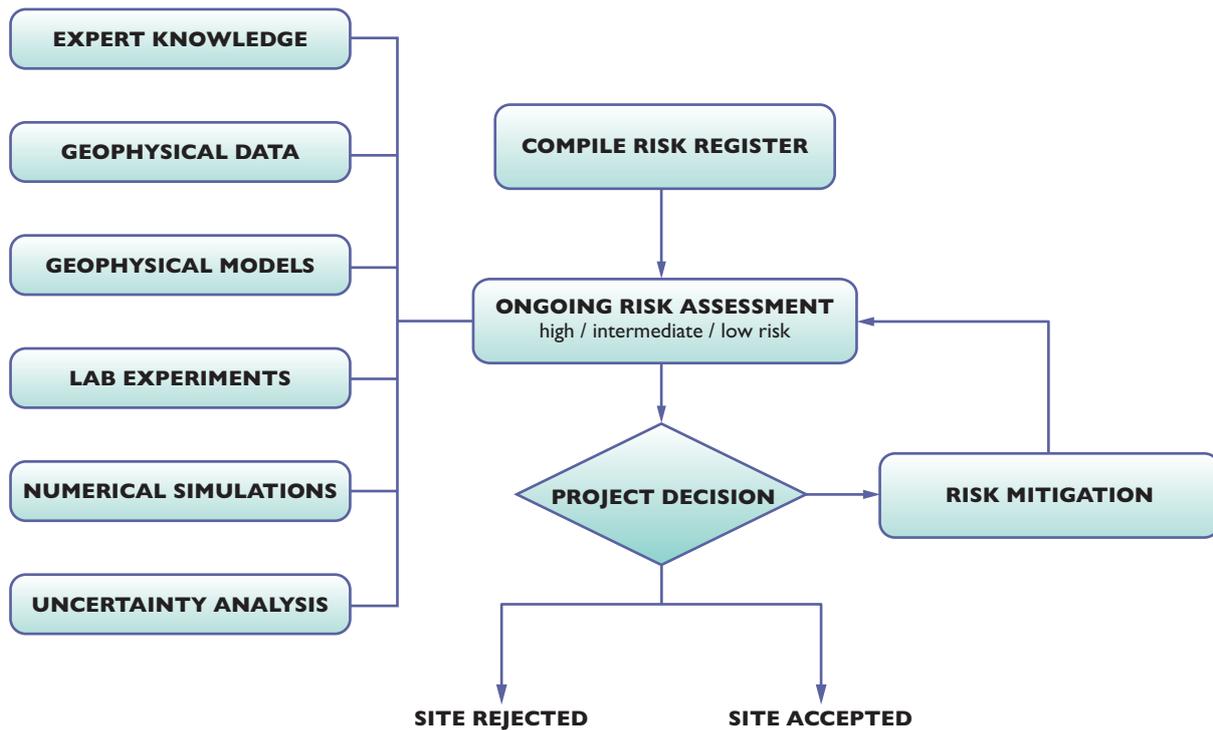


Figure 6.8 Workflow for risk analysis.

All CO₂ storage projects will require some form of register that can be used to quantify, rank and track risk. One such recommended approach is the use of ‘Features, Event and Processes’ (FEPs) (e.g. Maul et al., 2004; DET NORSE VERITAS, 2010), which includes an exhaustive list of all relevant possible scenarios and behaviours of CO₂ in the storage site which may impact on the project. These FEPs are assessed by experts for their likelihood and scale of impact on the project. Related FEPs are organised into categories, and for each individual FEP there is an expanded description, including relevance to performance and safety.

A six-step process is then used to compile the risk register in the initial months of the project:

- Step 1. List construction. Obtain a comprehensive list of all known possible FEPs that might conceivably pose a risk to the project, and construct preliminary likelihood and severity scales.
- Step 2. Initial group elicitation. Carry out elicitation of lower and upper bounds of likelihood and severity of each FEP affecting the potential storage sites, using all available experts. For each FEP also elicit the level of expertise of each participating expert.

- Step 3. Individual consultations. Discuss with project partners to ensure all areas of potential risk are included in the risk register and define any project-specific criteria for likelihood and severity scales.
- Step 4. Propose register. Based on the results of steps 2 and 3, a risk analyst produces a draft risk register of project-specific FEPs and draft likelihood and severity scales to be used consistently for all FEPs. The draft risk register takes the form of each of the original FEPs categorised as to keep, to remove, or for discussion by group.
- Step 5. Group discussion. Meeting of partners, to discuss the proposed list of FEPs to be kept, and to produce a finalised register.
- Step 6. Reflection and validation. After a pre-agreed period of reflection, all project partners agree on a final risk register.

Once the register is finalised, groups of experts are assigned to individual categories of FEPs. These experts are responsible for completing risk assessments at regular intervals, according to a structured elicitation process. In this way it is possible to track how the experts' perception of risk changes.

For each FEP, the expert scores the likelihood (L) and severity (S) on a scale of 1 to 5. These scales should be compiled during the consultation process with experts in the project. The severity scale is used to score impacts in different areas and care should be taken to ensure that the scores are equivalent. When completing the risk assessment, the expert should assess which is the highest impact across all areas and score the FEP accordingly. As experts are unlikely to be able to perfectly quantify their perception of risk, or will themselves be uncertain, they are directed to give lower and upper bound scores, in addition to their 'best guess'. This provides a range incorporating the experts' perception of their uncertainty into the risk assessment. As discussed in section 6.2, experts are subject to cognitive biases which affect their judgements in situations of uncertainty, and, therefore, care must be taken to minimise their impact (Polson et al., 2009).

To calculate the actual risk, the score for likelihood is multiplied by the score for severity. This gives a total score somewhere on the risk matrix (L x S) shown in Table 6.2. In this case, a score of 1 is defined as negligible risk, a score of 2 to 4 is defined as low risk, a score of 5 to 9 is defined as moderate risk, a score of 10 to 19 is defined as high risk and a score of 20 to 25 is defined as very high risk. The purpose of any risk assessment is to identify areas of unacceptably high risk and, where possible, determine suitable mitigation activities. Ideally, through the implementation of mitigation activities, the risk score for the FEP should decrease, moving from the bottom right of the risk matrix towards the top left. The regular assessments of risk allowed us to ensure the level of success of these mitigation activities.

For the CASSEM project, a project-specific risk register was developed, based on that of Jammes et al. (2006) and the Quintessa CO₂ FEP register, which was extended during the consultation process to include additional FEPs related to this particular project. When FEPs are referred to below, it is by title only, but each has a more detailed definition and description to avoid ambiguity. For the CASSEM project, two separate severity scales were used. Health and safety was assessed separately to other types of impact. The second severity scale included financial, environmental, research and industry impacts, and is referred to hereafter as the FERI scale. The likelihood, health and safety, and FERI severity scales are shown in Tables 6.3, 6.4, and 6.5, respectively.

		Likelihood				
		1	2	3	4	5
Severity	1	1	2	3	4	5
	2	2	4	6	8	10
	3	3	6	9	12	15
	4	4	8	12	16	20
	5	5	10	15	20	25

Table 6.2 Combine likelihood and severity (L x S). Blue = negligible, green = low, yellow = moderate, red = high, black = very high.

Likelihood		If there were 100 similar projects, impact related to this risk element (FEP) would occur:
Improbable	1	Probably not at all, never
Unlikely	2	Fewer than three times among the 100 projects
Possible	3	5 to 10 times among the 100 projects
Likely	4	In around half of the 100 projects
Probable	5	In most or nearly all of the projects

Table 6.3 Likelihood scale for the project.

Severity of impacts		Project values
		Health and safety
Light	1	Minor injury or illness, first aid
Serious	2	Reversible health effect, lost time injury less than 3 days
Major	3	Irreversible health effect, lost time > 3 days
Catastrophic	4	Life-threatening health effect, fatality
Multi - Catastrophic	5	Multi - fatality

Table 6.4 Health and safety severity scale for the project.

Risk mitigation and data acquisition

The results of the risk assessments are used to inform decision makers in the project as to how to proceed in such a way as to reduce the risk. For each high risk FEP, mitigation activities should be identified and the results should be used to help prioritise future project activities, using a transparent and comprehensive assessment process. For example, a key component in risk is uncertainty and, hence, risk should be explicitly included in decisions regarding allocation of resources when acquiring new data. A structured process is used to optimise additional knowledge expected to be gained, given the time and cost constraints and ensure that all options are given equal consideration. The results of the risk assessment will feed into this process as a key component in value of information. The selection criteria used in the CASSEM project were:

Severity of impacts		Project values			
		Financial	Environment	Research	Industry viability
Light	1	< £500k	No modification to initial state	Little to no progress to 1 of 4 goals	Project lost time > 1 day. Minor citations e.g. moving vehicle citations.
Serious	2	£500k–£5m	Modification to initial state within acceptable limits	Little to no progress to 2 of 4 goals	Project lost time > 1 week. Regulatory notice without fine. Local allegations of unethical practice or mismanagement
Major	3	£5m–£25m	Modification to initial state above acceptable limits but without damage	Little to no progress to 3 of 4 goals	Project lost time > 1 month. Permit suspension. Major local opposition or substantial negative local media coverage
Catastrophic	4	£25m–£50m	Modification to initial state above acceptable limit with repairable damage	Little to no progress to 4 of 4 goals	Project lost time > 1 year. International media coverage of law violations, questionable ethical practices or mismanagement.
Multi - Catastrophic	5	>£50m	Considerable modification to initial state which is not repairable with existing technologies	No gain in understanding applicable to future projects	Negative public experience results in legal ban on similar projects

Table 6.5 Financial, environmental, research and industry viability severity scale for the project. Categories are assessed together and the highest ranking category used to rate severity.

1. Information value. Significance of the gap in knowledge (the uncertainty) in the current geological model. Generic value of testing the action to gain information for future CCS projects. Criticality of associated risks to be mitigated, as identified in the risk assessment exercise.
2. Cost.
3. Timescale to completion.
4. Likelihood of failure of technique to provide new information.

Each potential activity is scored according to the categories shown in Table 6.6 and the highest scoring activities selected, given the cost and time constraints and likelihood of failure.

Score	Information value		
	Gap in existing model	Generic value of information (very site specific vs any subsurface application)	Criticality of risk (from FEP s)
5	Complete absence of information 0%	Widely applicable	Addresses multiple high risks
4	Mainly absent 2-5%	Applicable to majority of sites	Addresses one high risk
3	Reasonable information available, but many also absent, 50%	Applicable to some sites	Addresses multiple moderate risks
2	Mainly complete for site, 75%	Unique to one site	Addresses one moderate risk
1	Complete information on site 100%	Not applicable to any site	Addresses no risks

Table 6.6 Information value scoring scale used for data acquisition optimisation.

CASSEM Initial Risk Assessment Results

The FEPs which scored 10 or more (high risk) in the first risk assessment are shown in Figures 6.9 and 6.10 for the Firth of Forth and Lincolnshire sites, respectively. The scores shown are the average best guess, lower bounds and upper bounds from all experts assigned to each FEP, multiplied to give the combined L x S scores, with only the highest score from the health and safety and FERI severity scales shown for each site. Alternatively, the scores for each expert can be used to construct a triangular distribution, which is then averaged and the resulting average distributions for likelihood and severity then multiplied and the median of this distribution used to rank the FEP.

For the Firth of Forth site, the FEPs that were perceived as high risk at the start of the project were:

- Financial viability.
- Construction of pipeline.
- Geological heterogeneities.
- Fractures and faults.
- Undetected features.
- Formation pressure.
- Effects of pressurisation of reservoir on cap rock.
- Lithology.
- Construction and site logistics.
- Hydrogeology.
- Hydrological regime and water balance.
- Near-surface aquifers and surface water bodies.

For the Lincolnshire site, the FEPs that were perceived as high risk at the start of the project were:

- Financial viability.
- Construction of pipeline.
- Effects of pressurisation on cap rock.
- Construction and site logistics.
- Hydrogeology.

- Hydrological regime and water balance.
- Near-surface aquifers and surface water bodies.
- Storage concept.
- Public perception and security.

There is a correlation between the perception of risk and the uncertainty with which that risk can be assessed by experts: the range of the lower and upper bound increases significantly with perception of risk. This link was confirmed when experts were asked to explain why they assessed FEPs as high risk. In particular, the quality and quantity of the geological data associated with the Firth of Forth site and the complexity of the geology in the region led to significant uncertainty in the characteristics of the reservoir and cap rock formations in that region. This resulted in the higher scores for geological FEPs for this site than for the Lincolnshire site.

The most important contributor to the specific risks associated with the Lincolnshire site relate to the lack of full geometrical closure by the cap rock and the fresh water within the saline aquifer formation up-dip; the potential for leakage of formation fluids from the storage system to the shallower fresh water section of the aquifer in the near-surface is considered high risk, with three FEPs assessed as high risk relating to the hydrology. Overall, financial viability is the highest ranked FEP for both sites. Financial viability is not particularly site-specific compared to the other high risk FEPs, but it is clearly the greatest cause for concern amongst experts.

Mitigation activities

Table 6.7 shows the results of the data acquisition prioritisation exercise. The key activities for the risk mitigation informed a series of case studies, including the reprocessing of the relatively old seismic data for the Firth of Forth site, which aimed to reduce uncertainty in the structure of the subsurface (Case Study 2, Chapter 3); a hydrogeology study (Case Study 3, Chapter 3) of the Lincolnshire site, which aimed to predict the impact of CO₂ injection into the saline aquifer; a series of flow experiments on rock core (Case Study 4, Chapter 4) to derive measurements of relative permeabilities aimed at...; and use of analogue rock samples to derive combined acoustic velocity and relative permeabilities (Case Study 5, Chapter 5), aimed at constraining seismic monitoring. It is unlikely that any of these activities would have been carried out were it not for the early use of risk analysis.

Final risk assessment results

Also shown in Figures 6.9 and 6.10 are the final risk assessment results from the end of the project, for the high risk FEPs from the start of the project. The highest ranking FEP at the start of the project, 'financial viability', is a combination of a number of factors and in order to get a better handle on the risk associated with this area it was decided to divide this FEP into several individual FEPs. Hence, there is no overall score for financial viability at the end of the project, only for the individual FEPs. All of the financially related FEPs are perceived as high risk at the end of the project, except one, highlighting the high level of financial risk associated with CCS.

Comparing the site-specific high risk FEPs from the start of the project to the end of the project, we find that for a number, the scores have decreased from the start to the end of the project. The major risk mitigation activity for this site was the reprocessing of seismic data in order to reduce uncertainty in the characteristics of the subsurface. The major impact of this work was to decrease the perception of risk for the 'fractures and faults' FEP from high risk to moderate risk, based on the 'best guess' value. This is a result of the improvements to the quality of the data, which resulted in less uncertainty, but also in fewer faults being interpreted in the reprocessed data. Other FEPs that

have also moved from the high risk banding are: ‘hydrogeology’, which has gone from high risk to low risk; ‘hydrological regime and water balance’ and ‘near-surface aquifers and surface water bodies’, which have gone from high risk to moderate risk. This change is most likely the result of lessons learned from the hydrogeology study of the Lincolnshire site (Chapter 3).

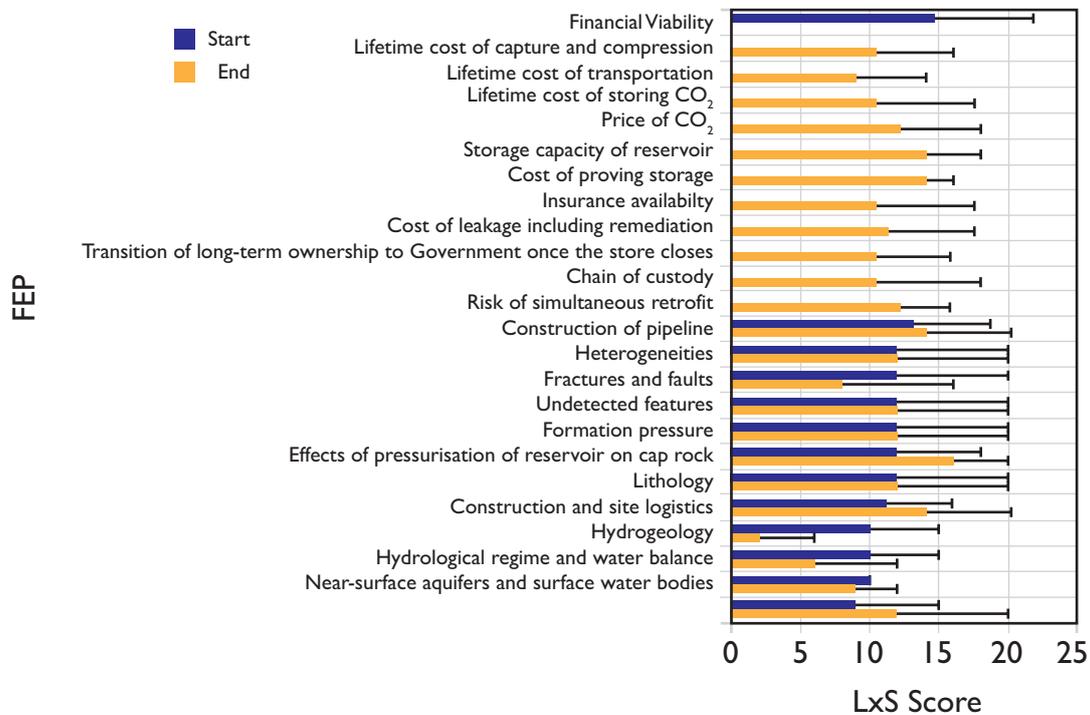


Figure 6.9 Likelihood (L) x severity (S) score for FEPs for the Firth of Forth site at the start and end of the project, for FEPs that score 10 or more in the first risk assessment. Solid bar shows ‘best guess’ value and line shows the upper bound. Only highest values from the health and safety and financial, environmental, research and industrial viability severity scales are shown. FEPs are ordered according to their ranking at the start of the project. The financial viability was divided into a range of individual FEPs after the first assessment, and consequently there is no final overall score for financial viability at the end of the project, with only the individual financial FEPs shown in orange.

A number of FEPs remained in or have moved into the high risk banding. It was not possible within this study to address all high risk areas, however, potential mitigation activities have been identified for all high risk FEPs for both sites (Polson et al., 2010c). For any potential mitigation activity, a careful estimate of the costs involved should be weighed against the potential reduction in risk. For example, a potential mitigation step for the ‘buoyancy-driven flow’ FEP (which is high risk for both sites) is to use a CO₂-brine surface dissolution strategy (Chapter 7).

The work that has been done demonstrates the type of process that should be applied in a full-scale CCS project and has shown that the mitigation activities implemented within the CASSEM project have been able to reduce the perception of risk in the targeted areas. For full details of results see Polson et al. (2010c).

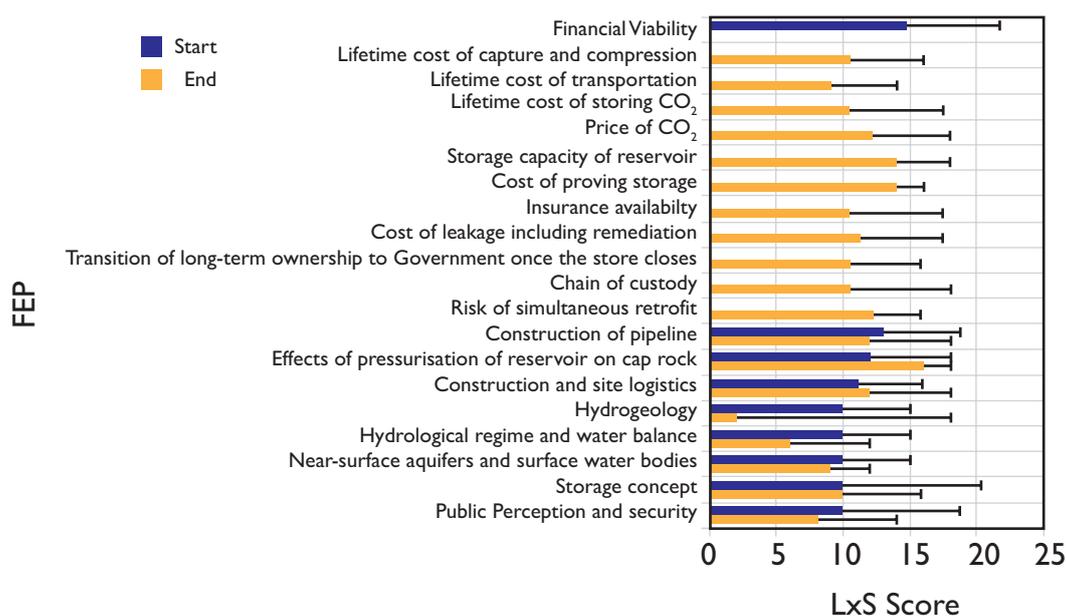


Figure 6.10 Likelihood (L) x severity (S) score for FEPs for the Lincolnshire site at the start and end of the project, for FEPs that score 10 or more in the first risk assessment. Solid bar shows 'best guess' value and line shows the upper bound. Only highest values from the health and safety and financial, environmental, research and industrial viability severity scales shown. FEPs are ordered according to their ranking at the start of the project. The financial viability was divided into a range of individual FEPs after the first assessment, and consequently there is no final overall score for financial viability at the end of the project, with only the individual financial FEPs shown in orange.

Data acquisition technique
Seismic reprocessed for Firth of Forth site
Proxy borehole archive (using existing samples from boreholes or outcrops as proxy for new borehole)
Hydrogeology study for Yorkshire/Lincolnshire site
Relative permeability
Monitorability assessment

Table 6.7 Data acquisition activities implemented to reduce uncertainty and risk.

6.4 SUMMARY AND CONCLUSIONS

In this chapter we described methods to assess risk and uncertainty associated with the geological aspects of CCS projects and applied this methodology to the flow simulations (Chapter 4) of the CASSEM case study sites. Using sensitivity analysis we demonstrated how to identify the key controlling properties of the storage site, allowing resources to be targeted on those factors that most influence uncertainty in the long-term fate of the injected CO₂.

Results for the two sites show that the key properties tend to be the same despite the differences in the two storage sites. Applying uncertainty analysis to the same flow simulations allowed this uncertainty to be calculated and compared for different sites. Thus, we were able to demonstrate a methodology for probabilistic assessment of leakage of CO₂ into and through the cap rock and showed how this could be tracked in space and time.

Using regular (quarterly) risk assessments, we were able to quantify and rank the experts' perception of risk and track this as it developed throughout the project. This allowed risk mitigation activities (case studies) to be identified and implemented and the impact of these activities to be assessed. The results show that the key factor influencing the experts' perception of risk at the start of the project was uncertainty, and that by reducing the uncertainty associated with particularly influential properties and characteristics of each site, the experts' perception of risk could be decreased. It does not necessarily follow that reducing uncertainty will decrease perception of risk, as was generally the case here. However, it is clear that unless the uncertainty associated with a storage site can be brought to within some acceptable limit, perception of risk is likely to remain high.

The overall results from the risk and uncertainty analysis work show that the Firth of Forth site is perceived to be much riskier than the Lincolnshire site, with many geological features, in particular, perceived to be high risk. This is primarily due to fewer data, poorer quality data and more complex geology for this site, which ultimately makes the uncertainty associated with the Firth of Forth site greater than that of the Lincolnshire site. The risk and uncertainty analysis has shown that at this stage the Lincolnshire site appears to be potentially more viable as a long-term storage site for CO₂, however, neither site would yet meet all the criteria for storage.

Overall, the two largest perceived generic risks for CCS identified by the CASSEM project are financial viability and pressurisation of the cap rock. Public perception and security, although reduced in risk during the study, has the potential to stop a CCS project in its tracks. These three activities are the subject of the following chapters.