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The evolving perception of risk during reservoir evaluation projects for geological storage of CO_2

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ABSTRACT

If carbon dioxide is to be stored in geological strata other than depleted hydrocarbon reservoirs (e.g. in saline aquifers), relatively little information will typically be available about the potential reservoirs. Significant risk associated with such projects therefore derives from uncertainty in reservoir evaluation. This paper describes a risk elicitation exercise carried out during geological reservoir evaluation for two exemplar carbon capture and storage (CCS) projects. A project-specific Features, Events and Processes (FEPs) register was developed through a structured elicitation process and discussions with experts. The register was used to elicit experts' perception of risk early in each project and thereafter at regular intervals, finding that the risk was moderate or low for the majority of FEPs. Where FEPs were perceived as high risk, lack of information and uncertainty tended to be the most influential factor. The results of the risk assessments were instrumental in identifying key project activities aimed at reducing uncertainty and addressing the highest areas of risk. Using the relatively inexpensive techniques of reprocessing legacy seismic data and conducting a hydrogeological study of the region around the storage site, uncertainty was reduced and the experts' perception of risk was lowered by the new information. However the risk assessment results also showed changes occurring in the absence of new information and where experts declared no change to their perception of risk. It is therefore vital to understand the uncertainty in the risk assessment results which can clearly be affected by factors other than information related to the storage formations.

1. Introduction

In the past two centuries industrialisation and population growth has led to a dramatic increase in anthropogenic emissions of air pollutants. The emissions of greenhouse gases (GHG) in particular are significantly impacting the environment and the climate system. The most significant greenhouse gas is CO_2 which has increased from pre-industrial concentrations of 280 ppm to 379 ppm in 2005 (IPCC, 2007). The largest anthropogenic sources of CO_2 are fossil fuel burning and deforestation (IPCC, 2007). Carbon capture and storage (CCS) is potentially an important technology to reduce emissions of CO_2, particularly as fossil fuels are likely to continue to supply much of the world's energy requirements for decades to come (Jempa and Munasinghe, 1998; Bajura, 2001; IEA, 2009).

In geological CCS, instead of allowing the CO_2 generated by large industrial point sources to be released directly to the atmosphere, it is captured and transported to a geological storage site. The CO_2 is injected into a reservoir deep within the Earth's subsurface where it is stored indefinitely in the pore space of the rock. Potential storage sites include saline brine reservoirs, depleted oil and gas reservoirs, and coal seams. The technology for CCS is currently also employed to enhance oil recovery (Moritis, 2003; Torp and Gale, 2004). However the scale of CO_2 sequestration required to significantly reduce anthropogenic emissions dwarves existing projects (Nordbotten et al., 2005). In addition, long term storage (hundreds of years) of CO_2 is required if negative climate impacts are to be avoided.

In order to prevent leakage of the CO_2, the reservoir must be secure. Supercritical CO_2 injected into the reservoir will initially be more buoyant than the existing formation fluids (Bachu, 2003). To prevent the CO_2 migrating upwards through the subsurface, a sealing caprock of low permeability rock is required to give geometrical closure to the system (IPCC, 2005). However leakage pathways may still exist such as through fractures, faults or injection wells, or due to over-pressurisation resulting in damage to the seal (Celia and Bachu, 2003; Zhang et al., 2009; Celia and Nordbotten, 2009).

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Leakage of CO_2 may result in acidification and/or contamination of groundwater and soils, with uncontrolled leakage posing a risk to near-surface ecosystems (Celia and Bachu, 2003; Farrar et al., 1995; Phillip et al., 2009; Beaubien et al., 2008) while CO_2 injection may have a hydrogeological impact on ground water resources through ground water pressure perturbations (Nicot, 2007; Birkholzer et al., 2009; Yamamoto et al., 2009). Singleton et al. (2009) conclude that there is little reason to think that geological storage of CO_2 will cause significant harm based on a qualitative assessment of likelihood, impact and uncertainty of the hazards of CO_2 including harm to human or animal health, soil acidification, subsurface contamination, ground water displacement, or physical surface damage. However this relies on proper site characterisation and selection which are the most important factors in minimising risk. There is also a significant financial risk in rolling out geological CCS on a large scale, with significant investment required both in improving technology and in identifying and characterising potential storage sites which may later be found not to have suitable security (e.g. non-sealing faults that provide leakage pathways), capacity (e.g. inadequate porosity) or injectivity (e.g. inadequate permeability).

To minimise these potential negative impacts a complete risk assessment of the full capture, injection and storage process is required for all CCS projects. We present a case study developed within the CO_2 Aquifer Storage Site Evaluation and Monitoring (CASSEM) project, henceforth referred to as Case Study 1, in which a complete, simulated assessment process was carried out for two exemplar storage sites for CO_2. Using the results of the initial risk assessment at the start of the CASSEM project, mitigation activities were identified for high risk areas in the project. The success of these activities in reducing the experts' perception of risk was assessed through regular risk assessments completed throughout the project.

We first describe a process for compiling a project-specific register of Features, Events and Processes (FEPs) (Singleton et al., 2009; Maul et al., 2005; Wildenborg et al., 2004, 2005; Chadwick et al., 2008; Det Norske Veritas, 2010) used to assess risk, and the method of elicitation of expert opinion to identify high risk areas to a project. We then describe how the results of the risk elicitation feed directly into the project decision making process, helping to identify appropriate risk mitigation activities. Further elicitation reveals the impact of those activities on experts' perception of risk. These methods and results reveal site-specific areas of risk, help to distinguish between opportunities at different potential storage sites, and identify areas of risk that may be common to all CCS projects.

2. Saline aquifers

Both sites are near-shore saline aquifer formations, but are geologically very distinct. While these sites are real, they are unlikely to be used for storage of CO_2 and instead were studied as analogues for off-shore formations. Both sites were chosen after a screening process to identify potential porous aquifer formations in the areas around the Longannet Power Station in the east of Scotland and the Ferrybridge Power Station in the Lincolnshire area. The full list of criteria for the site selection can be found in Smith et al. (2011); key criteria included permeability >200 mD and porosity >10% in the aquifer, and a minimum depth of 800 m below sea level. The selected sites had contrasting degrees of knowledge of the geometry and areal extent of the lithological and geomechanical properties of the overburden, caprock, and surrounding stratigraphies.

A target aquifer within the area of the Longannet Power Station was identified in the Firth of Forth. The primary aquifer comprises fluvial and aeolian sandstones and has a primary caprock of Carboniferous age. Minor aquifer and seals exists in the overburden. While these rocks in the aquifer had less than ideal permeability, this was the best target in the region given volume and depth criteria and provides a realistic test of offshore Central and Northern North Sea scenarios for saline aquifers. The data for this region were limited with only vintage 2D seimics and one offshore well. Furthermore the stratigraphical sequence and structural patterns are complex comprising a number of anticlines and synclines and faults with large throws. Due to the lack of data, salinity, permeability and porosity were unknown at the start of the project and the existence of the aquifer (thickness and volume) and of a caprock within the Firth of Forth was unproven (see Monaghan et al., 2008 for a detailed description).

The target aquifer in the Lincolnshire area is a Triassic age sandstone with corresponding mudstone seal. The geology in this region is relatively simple with limited structural complexity with an eastward dipping succession that extends from the coast at Saltfleetby to Lincoln in the west. The aquifer and mudstone meet most of the selection criteria, however the caprock fails to provide complete closure to the top of the aquifer formation which outcrops far up-dip from the theoretical injection site. Dynamic trapping of CO_2 through residual saturation and dissolution in the existing formation fluids would therefore be required to prevent eventual migration of CO_2 to the surface. This site provided the opportunity to study these mechanisms within a key target aquifer with offshore equivalents in the southern North Sea. Furthermore the aquifer becomes a source of potable aquifer up-dip and hence provided the opportunity to study the impact of CO_2 injection in a site where the aquifer would be used for purposes other than CO_2 storage. The data for this region were abundant, modern and good quality comprising seismic, well logs and core samples (see Ford et al., 2009 for detailed description).

3. Risk assessment method

3.1. Features, Events and Processes register

Risk refers to the probability and scale of eventualities which may negatively impact on a project. A six-step process has been developed for the compilation of a project-specific FEP register based on Jammes et al. (2006) and Hnottavange-Telleen and Krapac (2008). The register contains a list of Features, Events and Processes (FEPs) that define areas of potential risk to the CCS projects. These are assessed by experts for their likelihood (probability) of impacting the project, and for the severity (scale) of this impact. The FEPs are organised into categories of related FEPs, and for each individual FEP there is an expanded description including a description of its relevance to performance and safety. FEPs can typically be combined in such a way as to describe different scenarios, however in this project we consider the FEPs individually as the means of identifying key areas of risk at the earliest stages of a CCS project. Most engineering aspects of the project will have well established risk assessment methods already in place and hence are not included in a detailed way here.

This process took place during the initial months of Case Study 1, and the resulting register was used to assess risk at regular intervals over the lifetime of the project, allowing the evolution of the perception of risks to be tracked for both sites. The process to finalise the FEP register to be used throughout the project is as follows:

Step 1. *List construction*. Construct or obtain a comprehensive list of all known possible Features, Events and Processes (FEPs) that might conceivably pose a risk to the project. Construct or obtain consistent preliminary likelihood and severity scales to be used for all FEPs. In this case the initial likelihood and severity scales were taken from Hnottavange-Telleen and Krapac (2008) and the work

of compiling the register was done by a risk analyst in consultation with several experts.
Step 2. *Initial group elicitation.* General elicitation of lower and upper bound of likelihood and severity of each FEP affecting one or more of the possible storage sites using all available experts. For each FEP also elicit the level of expertise of each participating expert on a scale of 1–5 where 1 is novice and 5 is expert. Here the initial assessment included 19 experts in total whose expertise range from 1 to 5 depending on the particular expert and FEP. Where expertise was less than 3 for a particular FEP, the assessment of that expert was excluded from further analysis of that FEP.
Step 3. *Individual consultations*. Discussion with project partners to ensure all areas of potential risk are included in the 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 proposed register of project-specific FEPs and proposed likelihood and severity scales to be used consistently for all FEPs. The proposed register takes the form of each of the original FEPs categorised as *to keep*, *to remove*, and *for discussion* by group. A cautionary approach was adopted with only those FEPs for which all experts agree the upper bound of risk is low (from Step 2) being selected for removal from the register.
Step 5. *Group discussion.* Meeting of partners to discuss the proposed list of FEPs to be kept, and produce a finalised register.
Step 6. *Reflection and validation*. After a pre-agreed period of reflection, all project partners agree on a final register. This required unanimous agreement from all project partners on the FEPs to include and exclude from the register, and on the likelihood and severity scales.

For our case study the FEP register was compiled partly from the Quintessa CO_2 FEP register (Savage et al., 2004) which was extended to include additional FEPs. Each FEP is assigned for subsequent assessment to a small subset of the total set of experts, with each individual expert given responsibility for assessing only a small number of FEPs. The final group contained a total of 13 experts, chosen based on their self-assessed expertise from Step 2. We aimed to include as many experts as possible in each subgroup but practical limitations meant typically there were 2 or 3 experts per subgroup with a maximum of 4 in any one subgroup. At regular intervals throughout the project (quarterly in Case Study 1), each expert is asked to complete an assessments of their FEPs in the register according to a structured elicitation process.

Experts are asked to assess the best-guess, lower bound and upper bound for both the likelihood and severity, using the likelihood scale shown in Table 1 and the severity scales shown in Tables 2 and 3, assuming no mitigation activities are carried out in the future, but accounting for any mitigation activities that have already taken place. The experts assess health and safety impacts separately to the impacts on financial viability, environment, research, and industrial viability (FERI). For each FEP, the experts were directed to assess the likelihood that that FEP would impact the project given its description and in particular the information describing its relevance to performance and safety. That is they are asked "What is the likelihood that this FEP or some aspect of this FEP will impact the project in a negative way?" When assessing the likelihood, they are directed not to consider the scale of the impact, just whether some property of feature of the FEP may result in some negative outcome for the project. When assessing the severity, the experts are asked to assume that whatever aspect or aspects of the FEP that could lead to some negative outcome has occurred and then give their best-guess and lower and upper bound scores for the scale of the impact. Where there could be multiple impacts across different categories of the FERI scale, they are directed to base the score on the category for which they believe the impact will be highest, e.g. if a FEP could result in both a financial and environmental impact, then the severity score is for whichever of the two categories it would be highest. For both likelihood and severity, the lower and upper bound ranges aimed to capture the experts' own uncertainty and the range of possible impacts associated with a particular FEP. During the early stages of the project, discussions between the experts and risk analyst aimed to ensure that the experts were assessing the FEPs in a consistent way.

Table 1
Finalised likelihood scale for the Case Study 1 project as used in Hnottavange-Telleen and Krapac (2008).

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	5–10 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 2
Finalised health and safety severity scale for the Case Study 1 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

Adapted from Hnottavange-Telleen and Krapac (2008).

Risk is here defined to be the likelihood L of occurrence multiplied by the severity S of the impact if it occurred. The combined likelihood and severity ($L \times S$) matrix is shown in Table 4. FEPs which scored an $L \times S$ value of less than 5 are considered to be low risk. FEPs in the range $5 \leq L \times S < 10$ are moderate risk, in the range $10 \leq L \times S < 20$ are high risk and ≥ 20 are very high risk. For FEPs in the high and very high risk bands, the risk is considered to be unacceptable and mitigation activities are required to reduce risk. Though both high and very high risk bands constitute unacceptable risk, we distinguish between the two to identify the very highest areas of risk from those that are borderline moderate to high. FEPs in the moderate banding might be tolerable but ideally actions should take place to reduce these. The lowest band of FEPs are considered to pose a minimal and acceptable risk to the project. The purpose of risk assessment is to allow decisions and actions to be taken that reduce all FEPs to moderate or low risk. Full details of the risk assessment process can be found in Polson et al. (2009, 2010) and details of the FEP register, including descriptions of all FEPs can be found in Polson et al. (2008).

Initially the best-guess value of risk is used to rank the FEPs from low to high risk and the range between the lower and upper bounds to indicate the associated uncertainty. The experts were asked to assess the risk as though this were a real CCS project in which the storage sites may in the future be used as actual stores for CO_2. In addition to assessing the likelihood and severity, experts are asked to comment on their reasoning allowing traceability where perception of risk changed significantly (risk band changed). Where a FEP has been identified as high risk the experts are asked to suggest possible mitigation activities, these were documented and allowed FEPs to be distinguished based on the degree and ease with which risk could be mitigated.

Table 3
Finalised financial, environmental, research and industrial viability severity scale for the Case Study 1 project. Categories are assessed together and the highest ranking category used to rate severity.

Severity of impacts		Project values			
		Financial	Environment	Research	Industrial 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 to £5m	Modification to initial state within acceptable limits.	Little to no progress to 2 of 4 goals.	Project lost time >1 week. Regulatory notice with out fine. Local allegations of unethical practice or mismanagement.
Major	3	£5m to £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 to £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.

Adapted from Hnottavange-Telleen and Krapac (2008).

Table 4
Combine likelihood and severity (L × S). Blue = negligible, green = low, yellow = moderate, red = high, black = very high.

		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

3.2. Elicitation process

Any judgement is subject to cognitive bias, usually introduced by the use of heuristics (Kahneman et al., 1982). Experts are not immune to these biases and indeed are more prone to some than non-experts. Steps must therefore be taken to reduce their effects when asking experts to make judgements in situations of uncertainty.

Common biases are over-confidence, anchoring and adjustment, availability, and motivational bias. *Over-confidence* is intrinsic to experts as they tend to be expert in a selectively narrow field. It is often manifest as bounds on risk estimates being too narrow. *Motivational bias* occurs where an expert is not completely independent and their judgement is influenced by some conflict of interest. A common example is where an employee believes that a confident answer, or one consistent with a company view is more desirable. *Availability bias* results from the use of heuristics to judge the likelihood of an event. Instead of using the recollection of the number of similar events and their frequency to judge the probability of a future event, people tend to use ease of recollection as a short-hand for frequency. This can lead to bias with more recent or memorable events being judged as more likely than less recent or harder to recall events. *Anchoring and Adjustment* is the tendency for people to 'anchor' a numerical judgement to some initial estimate of its value. In the light of new information they tend to 'adjust' their initial estimate, rather than re-evaluate the situation from scratch, resulting in a bias towards the initial anchor value. Another manifestation can occur in each risk assessment because experts are asked to assess lower, best-guess and upper bounds for each FEP. The natural tendency in such situations is for an expert to assess the 'best-guess' first, followed by the lower and upper bounds. This will tend to lead to a narrowing of the distribution with both the lower and upper bound anchored to the best-guess: the lower bound estimate is then judged to be higher than it is in reality due to anchoring to the best-guess, and an upper bound is similarly assessed as too low.

There is evidence to suggest that group elicitation may reduce individual bias. However, group interaction has the potential to introduce other complex forms of bias. For example, interactions can lead experts to become overconfident in their assessments through a process known as 'group polarisation' where the final consensus judgement is more extreme than the average of the group members' individual judgements (Sniezek, 1992). A group may also show a herding tendency (e.g. Baddeley et al., 2004) where each expert incorporates the judgement of others in the group. While this process can lead to stable consensus distributions, there is a risk that the group can be guided in the wrong direction. Even in a well structured and managed elicitation session, herding behaviour can occur (Phillips, 1999; Polson and Curtis, 2010; Curtis, 2012) and such sessions are time consuming so making repeated assessments using this method difficult.

Explaining these possible biases to experts can reduce their impact, though not remove them entirely. Motivational bias in particular is relatively easy to overcome by stressing the importance of unbiased results. The availability bias is harder to reduce; however, directing experts to think of all relevant similar situations throughout their career rather than focusing on the most memorable or recent example can reduce its impact. Generally using a well structured elicitation process reduces all of the biases and also provides indicators of when certain biases remain significantly manifest (e.g. Polson and Curtis, 2010; Curtis, 2012).

It is therefore important that experts are warned of these biases early in the process before the first assessment in Step 2. In completing each assessment thereafter, experts should be reminded of the biases and directed to complete their assessments in a particular order: first the lower bound should be assessed, then the upper bound and finally the best-guess. This should reduce the affect of anchoring to the best-guess and widen the range of risks to more realistic levels.

Experts are directed to independently complete an assessment for each FEP for the likelihood and severity. The results from all experts are collected and analysed before revealing the results to any individual project partner.

4. Risk mitigation

4.1. Data acquisition for risk mitigation

From this initial risk assessment at the start of the project, key areas of potential risk were identified for both sites. The purpose of risk assessment is to inform decision makers of areas where the risk is unacceptably high, with results feeding directly into project decisions. In Case Study 1, decisions as to which data acquisition or processing activities were carried out were partly influenced by the results of the first risk assessment (see Sections 5.1.1 and 5.1.2). The approach taken to decide which activities to implement was designed to optimise additional knowledge expected to be gained given the time and cost constraints. The selection criteria used were:

1. Information value
   - Significance of the gap in knowledge (i.e. uncertainty) in the current geological model.
   - Generic value of testing the data acquisition or processing technique in terms of gaining information for future CCS projects.
   - Criticality or "level" of associated risks to be mitigated, as identified in the risk assessment exercise.
2. Cost
3. Timescale to completion
4. Risk involved in acquiring or processing the new data (i.e. likelihood of failure of technique to provide new information).

Information value was divided into three components with each component scored on a scale of 1–5 using the scales as shown in Table 5. Also scored on a 1–5 scale is the risk associated with the data acquisition activity itself, where (in this case only) 5 is a low risk of failing to provide additional information. Summing the scores for each activity, the highest scoring activities are selected given the allowed time and cost constraints.

4.2. Elicitation of change in perception of risk due to mitigation activities

In addition to the ongoing quarterly risk assessments, group elicitation exercises were also conducted to focus on specific areas of risk that might change as a consequence of new data acquisition. In order to assess the success of the risk mitigation activities in reducing experts' perception of risk, a group elicitation exercise was carried out around a quarterly project meeting. During the meeting, the progress in each work area of the project is reported, including the data acquisition activities. The experts present at the meeting were asked to assess their perception of risk at the start and end of the meeting for five key high risk geology FEPs as identified in the initial risk assessment for the Firth of Forth and three hydrology related FEPs identified as high risk for Lincolnshire. These FEPs were chosen as they are the areas in which the additional information from the data acquisition activities may have a significant impact. The risk assessment was the same as that described in Section 2. By eliciting experts' perception of risk before and after they had heard the reports from all other areas in the project, it was possible to ascertain whether any notable changes occurred. In addition to completing the normal risk assessments, the experts were asked to state whether their perception of the risk had increased or decreased for each FEP in order to verify if changes in the scores represented a conscious change.

5. Results

5.1. Results of first risk assessment

5.1.1. Firth of Forth

Taking the highest score from the two severity scales, the FEPs are ranked and for those FEPs identified as high risk, mitigation activities were identified. Fig. 1 shows the best-guess, lower and upper bound $L \times S$ risk score for each FEP for both sites, averaged over each subset of experts at the start of the project. The FEPs are plotted according to increasing $L \times S$ with highest ranked risk at the top. As the best-guess of risk increases, so the range (upper bound minus lower bound) also tends to increase, demonstrating how as experts become more uncertain, their perception of risk increases.

For the Firth of Forth site the FEPs that were perceived as high risk at the start of the project are listed in Table 6 along with a summarised description and reasons for the high risk elicited from experts. Financial viability was perceived to be the highest risk by the experts. Similarly the level of investment required in construction of capture and transport facilities and the associated uncertainty put these FEPs also in the high risk band. The assessment of these FEPs as high risk tended not to relate to the properties of this saline aquifer, but were seen as potential risks for any CCS project.

The remaining FEPs in the high risk group were all associated with the storage site itself, or with the potential for contamination of the near-surface environment. The uncertainty in the geological properties of the site resulted in 6 FEPs that describe the subsurface properties being perceived as high risk. Here the concern focused on the potential for leakage, lack of capacity or lack of injectivity in the aquifer itself. Non-sealing fractures and faults may provide leakage pathways while sealing faults may compartmentalise the aquifer. Heterogeneities (variation in the rock properties),

Table 5
Information value scoring scale used for data acquisition optimisation.

Score	Information value		
	Gap in existing model	Generic value of information (very site specific vs. general sub-surface application)	Criticality of risk (from FEPs)
5	Complete absence of information 0%	Widely applicable	Addresses multiple high risks
4	Mainly absent 25%	Applicable to majority of sites	Addresses 1 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 1 moderate risk
1	Complete information on site 100%	Not applicable to any site	Addresses no risks

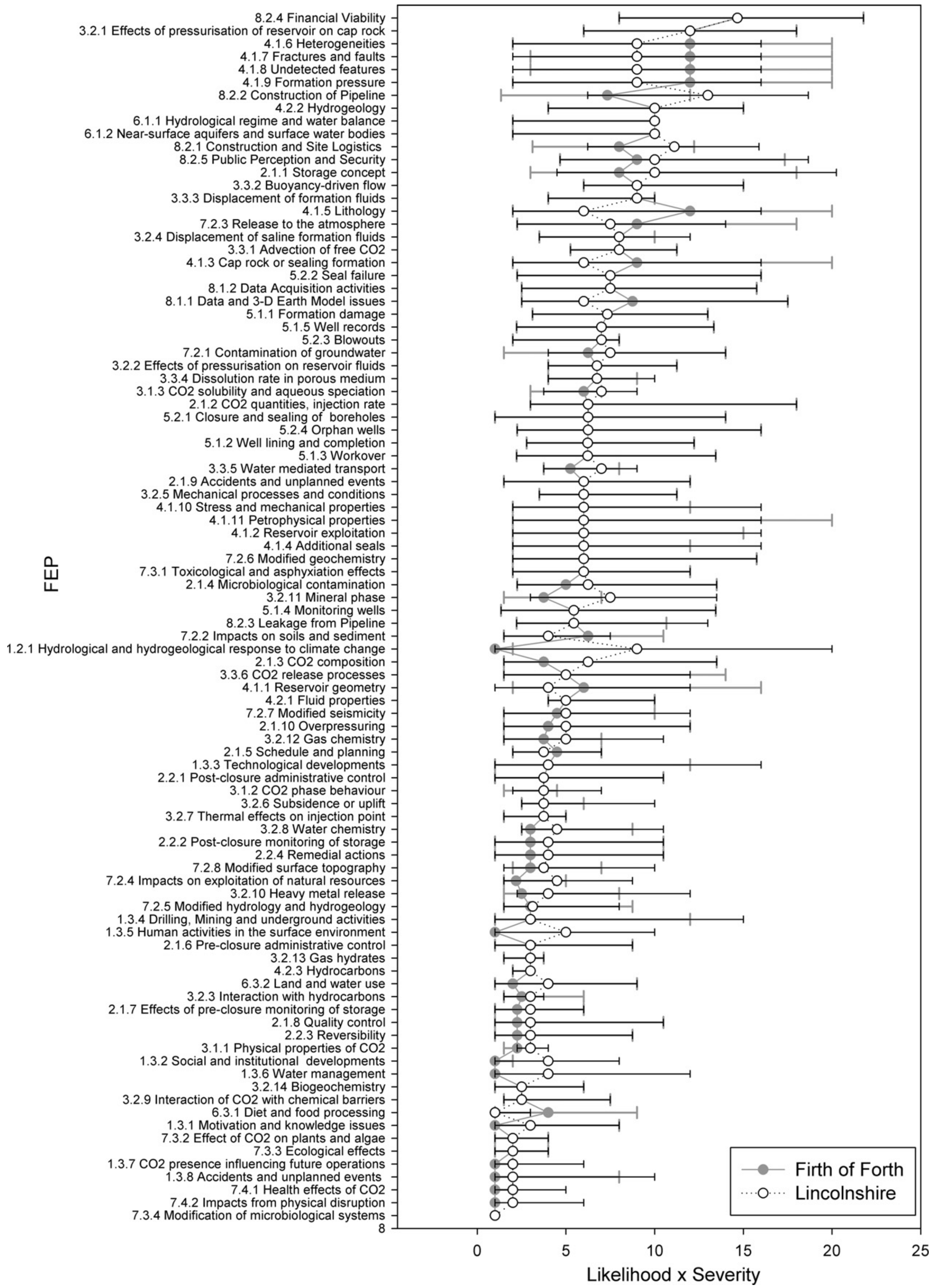

Fig. 1. Best-guess, lower and upper bound L × S score for each FEP for both sites at the start of the project, averaged over each subset of experts, using highest score from the health and safety and FERI severity scales. Ordered according to increasing average L × S for two sites. Where lower/upper bounds are not shown, they coincide with best-guess value.

Table 6
High risk Features, Events and Processes (FEPs) from the start of the project for the Firth of Forth site. The descriptions are taken from the Quintessa CO_2 FEP register. Reason gives the experts' explanation of why they perceived the FEP as high risk.

FEP	Description
Financial viability	*Description*: Whether CCS is financially viable will depend on a number of factors such as price of CO_2, cost of developing aquifer, relative price of gas or oil and coal, affect on efficiency and flexibility of plant and cost of construction. The biggest uncertainty is likely to be the cost of developing the aquifer. Crucial is the capacity of the aquifer with a high level of confidence required. This will require investment in data acquisition to reduce uncertainty of storage capacity and leakage. Whether CCS is viable will depend on the return in investment on high risk endeavour *Reason*: Large uncertainties on a number of factors at the investment stage (CO_2 price, construction costs) mean the predicted net present value could have a high level of risk
Construction of pipeline	*Description*: The construction of the pipeline will be affected by a number of factors. Many of these will not be unique to CO_2, however the pipeline route will be affected by regulations particular to CO_2 such as distance from populated and ecologically sensitive areas. The composition of the CO_2 will affect corrosion rates and therefore impact on the design of the pipeline as will the need for isolation points. In addition the pipeline design and construction will also be affected by the injection pressure which will determine whether it is more cost efficient to have onshore and offshore compression *Reason*: High level of risk/uncertainty on a large capital project is not abnormal. Can occur due to scope, market inflation, contracting strategy, contracting market conditions, etc., plus variation in ground conditions
Geological heterogeneities	*Description*: Heterogeneities are variations in the rock properties of a geological formation *Reason*: There is very little knowledge of the rock heterogeneity at depth as no borehole data exists. There is some knowledge of lithological variations at surface/shallow depths, but any data on permeability is not necessarily representative of permeability at depth. Also there is the fundamental problem that aeolian and fluvial deposits are generally very heterogeneous and not much is known about the target aquifer systems in this region
Fractures and faults	*Description*: Fractures are cracks or breaks in rock. Fractures along which displacement has occurred are called faults *Reason*: Seismic resolution at aquifer/caprock depths is poor and so several interpretations of fault presence or absence can be made. There are also likely to be subseismic scale (i.e. <40 m at the relevant depths) faults and fractures which cannot be interpreted from seismic. We have no rock samples of fault material from the Forth area to know if faults are sealing or non-sealing with respect to flow of CO_2
Undetected features	*Description*: Natural or man-made features within the geological environment that may not be detected during site investigations *Reason*: Given the very limited amount of data on the aquifer/caprock rocks at depth and the data quality it is highly likely that there will be undetected features of relevance
Formation pressure	*Description*: The pressure of fluids within the pores of a formation, normally hydrostatic pressure, or the pressure exerted by a column of water from the formations depth to the sea level prior to the injection of CO_2 *Reason*: There is no pressure data from aquifer/caprock rocks at CCS depths because there is no borehole. Previous pressure tests are from much higher in the geological succession and are unlikely to be representative
Effects of pressurisation of reservoir on cap rock	*Description*: A storage reservoir will experience enhanced pressure due to injection of CO_2. 'Overpressuring' of the reservoir may involve leakage of CO_2 through the cap rock due to fracturing or enhanced interactions with CO_2 *Reason*: The cap rock will be pressurised if injecting supercritical CO_2. The key is to manage this pressure increase with an appropriate injection strategy
Lithology	*Description*: The systematic description of rocks in terms of mineral assemblage and texture. Determines the reservoir physical and transport properties *Reason*: There are no rock samples of the main probable aquifer/caprock rocks at CCS depths in the Forth area, therefore the lithification/diagenesis at CCS depths is uncertain (the deepest samples are from 584 m depth). There are considerable changes in the rock lithification and diagenesis from shallow depths to 500 m. The changes are likely to be less dramatic at greater depths but there are likely to be some changes between rocks at 500 m and 2000 m depth (the likely CCS target depth in the Firth of Forth). As there are no boreholes the aquifer/seal lithologies are unproven at the proposed site
Construction and site logistics	*Description*: Construction and site logistical issues can affect the timescale, financial, safety and viability of the project. There are issues surrounding the ability to build on existing sites and the resources available to build carbon capture facilities *Reason*: This level of risk/uncertainty on a large capital project is not abnormal. Can occur due to scope, market inflation, contracting strategy, contracting market conditions, etc.
Hydrogeology	*Description*: Natural formation water flow pathways in the geosphere. Important in determining the long-term migration paths for CO_2 *Reason*: At present there is no data on the hydrogeology
Hydrological regime and water balance	*Description*: Processes related to near-surface hydrology at a catchment scale and also soil water balance, and their evolution with time *Reason*: The contamination of the shallow subsurface water has a low to very low likelihood but large potential severity
Near-surface aquifers and surface water bodies	*Description*: Features related to the characteristics of aquifers and water-bearing features and their evolution *Reason*: The contamination of the shallow subsurface water has a low to very low likelihood but large potential severity

Table 7
High risk Features, Events and Processes (FEP's) from the start of the project for the Lincolnshire site. The description is taken from the Quintessa CO_2 FEP register. Reason gives the experts' explanation of why they assessed the FEP a high risk.

FEP	Description
Financial viability	
Construction of pipeline	See Table 6
Effects of pressurisation on cap rock	See Table 6
Construction and site logistics	See Table 6
Hydrogeology	See Table 6
Hydrological regime and water balance	See Table 6
Near-surface aquifers and surface water bodies	See Table 6
Storage concept	*Description*: Features related to the concept of storage, such as whether closure exists or whether isolation of CO_2 is dependent upon slow diffusion rates through large, open structure *Reason*: There is not a geometrical trap in the Lincolnshire model, so CO_2 could reach the surface to the west where the aquifer outcrops. The likelihood of CO_2 escaping to surface in significant quantities would render the whole CO_2 storage concept invalid
Public perception and security	*Description*: Public perception could have negative or positive impacts through affects on planning applications. In addition negative public perception may lead to increased security risks with onsite protests and potentially sabotage *Reason*: Any public issue will result in delay of 1 month minimum, and potentially longer

lithology, formation pressure and undetected features may all affect the capacity and injectivity of the site and limit the volumes or rates of CO_2 injection. Similarly, lack of knowledge about the hydrogeological regime in the region and the high severity associated with contamination of the near-surface were also causes of concern for the experts. Potential damage to the seal through pressurisation of the aquifer that results in leakage pathways for the CO_2 was also seen as high risk.

5.1.2. Lincolnshire

A number of the high risk FEPs for the Lincolnshire site are the same as those for the Firth of Forth. Those that are unique to the Lincolnshire site relate to the lack of full closure of the saline aquifer by the caprock on its upper surface with the key areas of risk related to the potential for leakage of CO_2 or formation fluids from the storage system to shallower fresh water aquifers in the near-surface, or to CO_2 leaking to the atmosphere along this path. For the Lincolnshire site the FEPs that were perceived as high risk at the start (shown in Fig. 1) are listed in Table 7.

As with the Firth of Forth site, technical uncertainty is an important factor as at the time of the initial assessment, there was no data available to the experts on the hydrological regime of the region, making it difficult for them to assess the likelihood of CO_2 injection impacting the near-surface fresh water aquifers. Public perception is also seen as high risk for the Lincolnshire site, with local opposition seen as more likely for this site with onshore storage in an aquifer that is connected geologically to rock strata that are used as a source of potable water.

5.2. Data acquisition and uncertainty

For all high risk FEPs mitigation activities were identified (see Polson et al., 2010 for details). Within the project it was not possible

Table 8
Data acquisition activities implemented to reduce uncertainty.[a]

Data acquisition technique
Seismic reprocessed for Firth of Forth site
Create/analyse proxy borehole archive (using existing samples from boreholes or outcrops as proxy for drilling new borehole)
Hydrogeology study for Lincolnshire site
Estimate relative permeability
Monitorability assessment

[a] Seismic reprocessing involves reprocessing of legacy seismic data for Firth of Forth site using modern processing techniques and reinterpretation of the data. Create/analyse proxy borehole archive refers to analysis of samples from existing boreholes in the region for mineralogy and porosity as a proxy for a new (as yet un-drilled) borehole. Hydrogeology study refers to the collation and critical review of existing data from groundwater studies on aquifer properties, groundwater flow and chemistry to develop a conceptual model of wider groundwater flow of the area, and to build a simple groundwater model from onshore to offshore. Estimate relative permeability refers to laboratory measurement for the CO_2/water systems on existing borehole and proxy samples. Monitorability assessment refers to testing existing or new rock samples for various geophysical properties that will provide important information for the modelling of geophysical monitorability of CO_2.

to implement all such activities, however using the results from the initial risk assessment and the method described in Section 2, five data acquisition activities, shown in Table 8, were identified which could contribute to reducing uncertainty in the geology and hydrology of the region and hence which may contribute to reducing the perception of risk. In particular, reprocessing of the seismic data for the Firth of Forth site was considered critical to reducing uncertainty in the geological model for this site. A hydrogeological study of the region around the Lincolnshire site was the key activity to addressing the risk for this site due to its connection with potable water. Had a structured decision process not been used to select the data acquisition activities and the risk assessment results not been explicitly considered as part of the process, it is likely that a different set of activities would have been funded which reflected the primary interest of the researchers and were not necessarily suggested to address the key uncertainties and risks in the project. The impact of the additional information on the experts' perception of risk was tracked using the quarterly risk assessments.

Like many potential offshore storage targets, the Firth of Forth site was covered by relatively old seismic data from the 1980s. Modern re-processing techniques were applied to improve the poor quality data and increase confidence in the data interpretation (see Sansom, 2009 for technical details). Re-interpretation of the seismic data (McInroy and Hulbert, 2010; Smith et al., 2011) found that areas previously interpreted as faults were in fact coherent, steeply dipping and tightly folded reflectors, thus fewer faults were interpreted than in the original model. Better imaging led to the re-interpretation of seismic picks (surfaces) and there was a significant change in the depth of key rock layers.

The potential effects of onshore to near-shore injection of CO_2 in the Lincolnshire site on the hydrogeology of the freshwater aquifer are described by Bricker et al. (2010) and Smith et al. (2011). This work aimed to evaluate the hydrogeological properties of the geological formations which form the aquifer, the caprock and the overburden, and numerically simulate the injection of CO_2 and potential impacts on shallow (up-dip) groundwater systems. The key finding for the risk assessment was that for the shallow confined and unconfined areas of the aquifer, where the aquifer is used for potable water supply, the study indicates that there will be little impact from injection on groundwater heads and that river flows remain unaffected, assuming the groundwater flow is intergranular at depth. Large lateral movements of the saline interface are unlikely to occur due to injection and migration of CO_2 with water movement more strongly influenced by surface abstraction.

Financial viability was identified as the highest risk FEP for both sites. Due to importance and complexity of this FEP it was decided

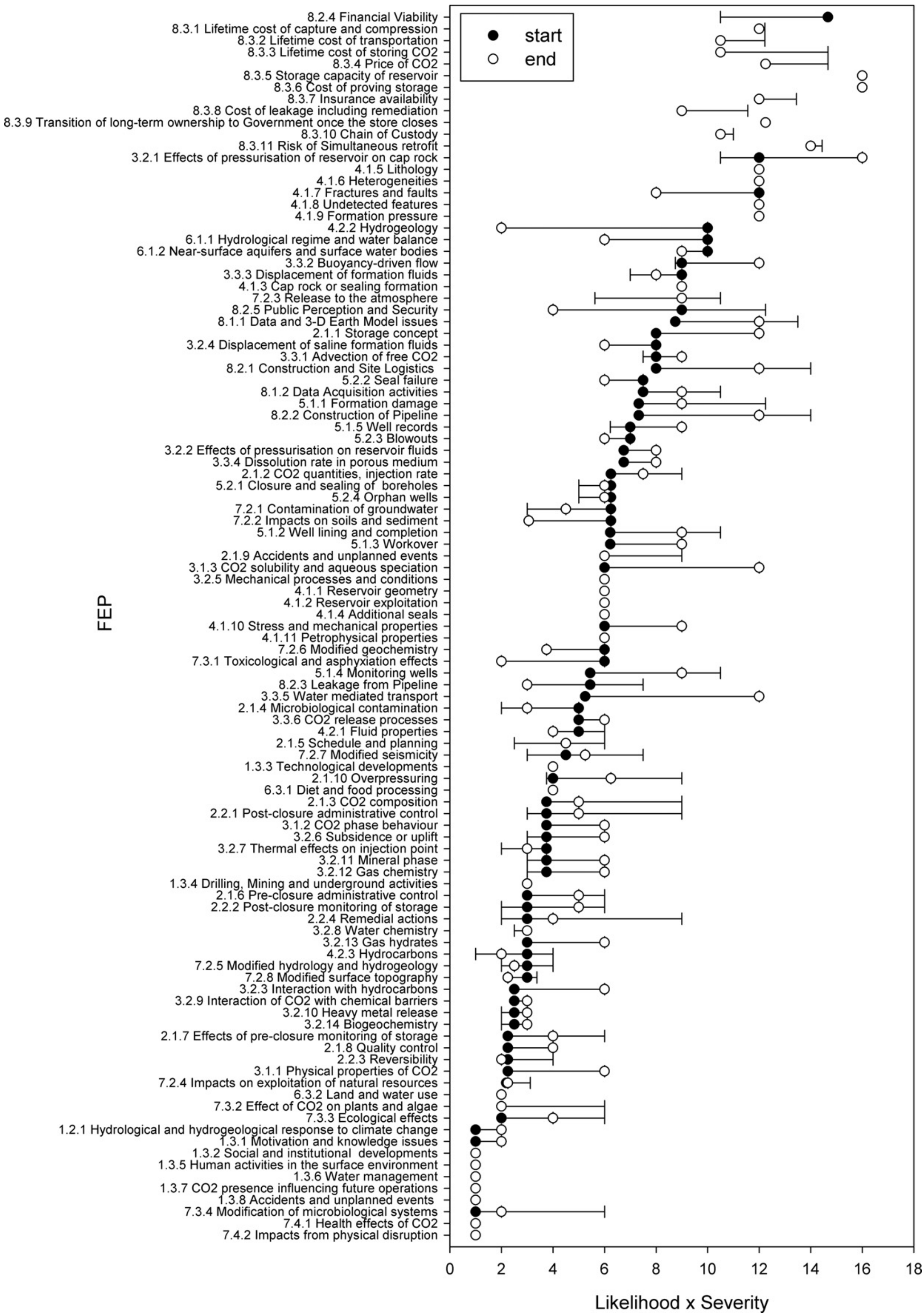

Fig. 2. Range of best-guess L × S over the whole project (–) for Firth of Forth site. Ordered according to increasing L × S from start of project (closed circles), with end of project L × S (open circles). Where lower/upper bounds are not shown, they coincide with best-guess value.

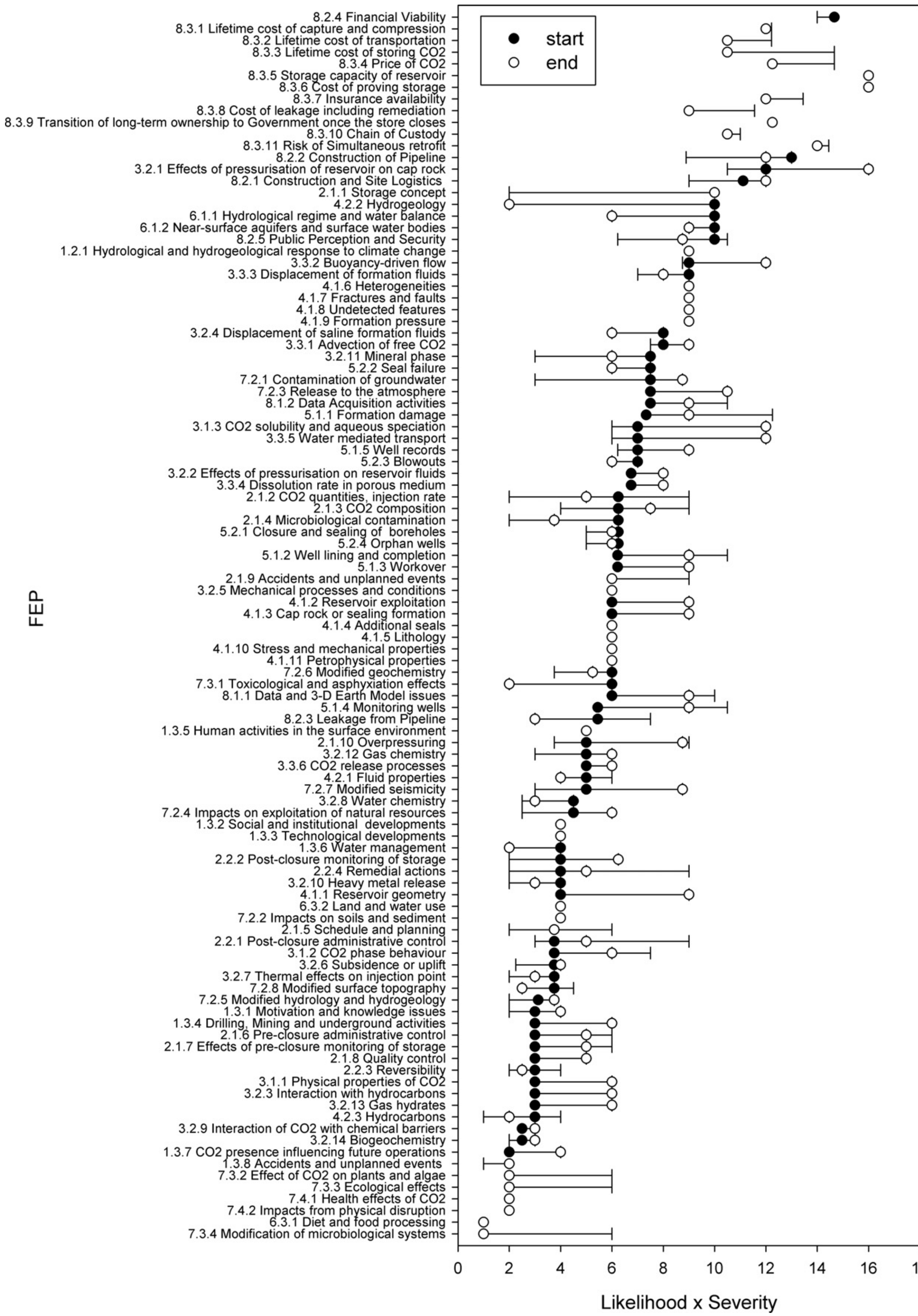

Fig. 3. Range of best-guess L × S over the whole project (–) for Lincolnshire site. Ordered according to increasing L × S from start of project (closed circles), with end of project L × S (open circles). Where lower/upper bounds are not shown, they coincide with best-guess value.

that it should be made into its own separate category and that a series of individual FEPs would be compiled and assessed; hence, in later risk assessments there is no 'Financial Viability' FEP.

5.3. Changing perception of risk

Experts were asked regularly to complete the risk assessments throughout the project. This served two purposes, firstly it allowed the impact of work done during the project on perception of risk to be assessed, and secondly it allowed the risk analyst to determine the most significant factors influencing the risk assessment results. Fig. 2 shows the range of 'best-guess' scores averaged over each subset of experts given to each FEP throughout the project for the Firth of Forth site. Also shown are the values for the start and the end of the project, indicating whether the change tended to represent an increase or decrease in the perception of risk.

From the figure it is clear that for many FEPs there was a significant change in the perception of risk during the project. The most significant changes tended to occur for one of two reasons: either some activity within the project or new data from other sources had altered the perception of risk of individual experts, or there was a change in personnel. A number of FEPs related to CO_2 properties, interactions and transport within the subsurface showed a significant increase in the perception of risk from the start to the end of the project. This is a direct result of a loss of one of the experts assessing these FEPs relatively late into the project. While the two experts assessing these FEPs had similar levels of expertise, the perception of risk of the expert who left tended to be lower overall. Similarly the change for FEPs related to boreholes was also a result of a change in personnel, with the replacement of one expert assessing these FEPs early in the project. Despite efforts to have the same group of experts assessing each group of FEPs throughout the project, there were occasions where individual experts were unavailable during some quarters or left the project altogether. Given the relatively small number of experts assessing each group of FEPs (maximum of 4), any change in personnel could lead to significant changes in the scores. It is inevitable that different experts will assess risk differently. However the distribution of best-guess values tended to be within the uncertainty that individual experts estimated for their own results, increasing confidence in those uncertainty estimates.

A number of the high risk FEPs from the start of the project have lower scores by the end for the Firth of Forth site. The major risk mitigation activity for this site was reprocessing of seismic data to reduce uncertainty in the characteristics of the subsurface. The major impact of this work was decreasing 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 lower uncertainty, but also fewer faults being interpreted in the reprocessed data. Other FEPs that have also moved from the high risk band are 'Hydrogeology' which has gone from high risk to low risk, and both 'Hydrological regime and water balance', and 'Near-surface aquifers and surface water bodies' which have moved from high risk to moderate risk. This change is most likely the result of general lessons learned and transferable knowledge obtained during the hydrogeology study of the Lincolnshire site.

The Lincolnshire site shows decreasing scores for a number of FEPs from the start to the end of the project (Fig. 3). A hydrogeology study of the area found that it was unlikely that there would be much change in the boundary between the fresh and salt water as a result of injecting CO_2 and hence that there was unlikely to be any contamination of the fresh water section of the aquifer. This resulted in a decrease in the perception of risk for these FEPs from high to low risk for 'Hydrogeology', and high to moderate for the 'Hydrological regime and water balance', and 'Near-surface aquifers and surface water bodies'. 'Storage Concept' remained high risk as the lack of geometrical closure remained a concern for the experts.

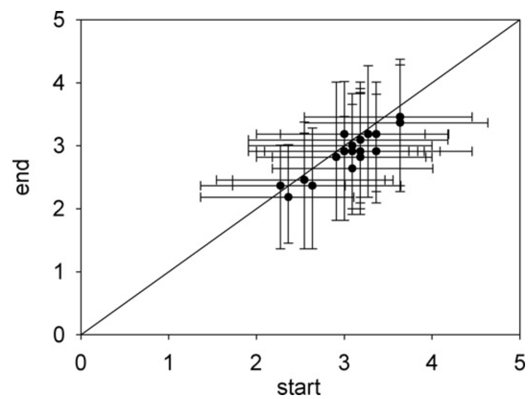

Fig. 4. Likelihood and severity from start and end of group meeting for the Firth of Forth site.

These high risk FEPs for which the data acquisition activities were performed were the focus of the risk assessments conducted at the start and end of a quarterly project meeting using all experts present. The experts were asked to state whether their perception of risk increased, decreased or stayed the same for each FEP over the course of the meeting, due to the additional information they learned while listening to the reports of the most recent work done in the project.

The results for the Firth of Forth show that the experts tended to reduce their scores for the lower, best-guess and upper bounds for both the likelihood and severity from the start of the meeting to the end. Fig. 4 shows a scatter plot of the best-guess for the start and end of session assessments with error bars representing the lower and upper bounds. The vast majority of the points lie below the diagonal line of no change showing that the best-guess tends to be lower at the end of the session, even though the risk uncertainties all still span the diagonal. However only four experts stated that they were conscious that their perception of risk had changed over the course of the meeting, with the majority declaring that their perception remained the same at the end as they had been at the start.

The results for the Lincolnshire site show that the cohort of experts tended to increase their scores at the end of the meeting compared to those at the start as shown in Fig. 5. The vast majority of the points lie above the diagonal line of no change showing that the best-guess tends be higher at the end of the session compared to the start. However, only one expert stated that their perception of risk had changed from the start of the meeting to the end: the

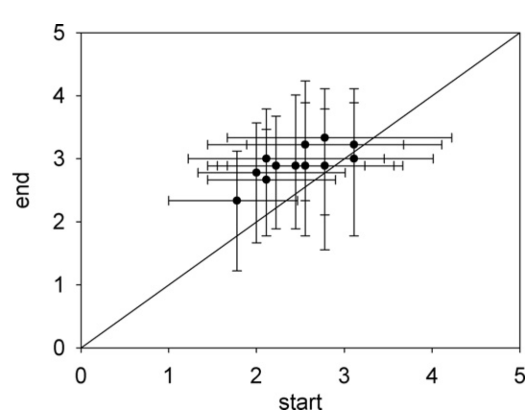

Fig. 5. Likelihood and severity from start and end of group meeting for the Lincolnshire site.

stated change was a decrease which was reflected in their scores. While some change in scores is expected because of the experts' inability to perfectly quantify their perception of risk resulting in random errors, the consistent increase in scores for all experts suggests that the experts' perception of risk has indeed increased, even if unconsciously.

This result highlights the uncertainty in the risk assessment results due to the potential random errors and bias in the assessment of individual experts. From the start to the end of the meeting, the experts present changed the scores given to the FEPs, though in most cases they were not aware that their perception of risk had changed. A similar result is found in the quarterly risk assessment where experts change their scores from one quarter to the next despite claiming that there is no change in their perception of risk.

6. Discussion

The results of the risk assessments for these two distinct analogue storage sites revealed that the majority of FEPs were assessed as moderate or low risk for both sites. The area of highest risk was financial viability which depends ultimately on the cost of continuing to emit CO_2 to the atmosphere compared to the cost of capture, transport, storage and long-term monitoring. The large investment in infrastructure and site evaluation and the uncertainty associated with a number of factors such as price of CO_2, storage site viability and potential remediation of leakage, are the basis for this perception of high risk. Dividing this FEP into individual areas of risk showed that the perception of risk was high for nearly all areas associated with financial viability and that this did not change significantly over the course of the project.

The results of the risk assessment also reveal a clear distinction between the perceptions of risk for the two storage sites at the start of the project. The Firth of Forth is perceived as higher risk than Lincolnshire primarily because of the greater uncertainty in the geological properties of the subsurface. The experts did not have sufficient information on the aquifer and caprock to be confident that the site would have the required properties such as porosity and permeability to provide sufficient capacity and injectivity, nor were they confident that the site would be secure given the lack of information on fractures and faults and the possibility of other undetected features within the formation. Reprocessing and reinterpretation of old seismic data were a key activity in the project. The impact on the risk assessment was to reduce the perception of risk from fractures and faults with fewer interpreted in the new model. However had more faults been interpreted in the new model, the risk may have increased. It is the fact that the new model is seen as having lower potential for leakage that has impacted the risk assessment directly, not the reprocessing of the seismic data in itself. However, reprocessing was relatively inexpensive compared to collecting new data, and the possibility that it can result in a significant reduction in uncertainty while moving the median risk either upwards or downwards can make reprocessing of legacy (old) seismic data a very cost-effective activity.

For the Lincolnshire site, there is more geological data available which is of better quality, and the site itself is less complex. The geology of the region is therefore better understood resulting in lower uncertainty and hence the experts were more confident that this site had suitable geophysical properties for storage. However, a number of areas were perceived as high risk relating to the hydrogeological properties of the region, with the potential of contamination of the potable sections of the aquifer up-dip. The lack of full closure on the upper surface of the aquifer by the caprock was also seen as a high risk for this site, even though dynamic trapping of CO_2 was thought to be likely. A hydrogeology study of the area addressed the uncertainty around the hydrological impact of CO_2 injection and found that CO_2 injection was unlikely to affect the fresh water sections of the aquifer. This result reassured the experts that the risk of contamination to the near-surface was low. As with the reprocessing of the seismic data, it was not the reduced uncertainty in itself that reduced the perception of risk, but the specific information that was gained through the additional data acquisition activities.

FEP based assessments have been applied to other aquifer evaluations to identify important areas of risk and scenarios for investigation. The most important FEPs identified for one site were; 'Geological features', 'Overpressuring', 'Effects of pressurisation of reservoir on caprock', 'Undetected features, faults at top of reservoir', 'Long-term fate of CO_2', 'Reversibility – Fingering leading to CO_2 escaping the trap', 'Impact on society and humans', 'Public opposition to the storage project' and 'Impacts on humans – health effects of CO_2' (Chadwick et al., 2008). For a second site the key FEPs were 'Leakage of CO_2 through a specific fault', 'Overpressure', 'Reservoir heterogeneity' and 'Leakage from a well' (Chadwick et al., 2008). These assessments use different risk registers and as with this study, the most important FEPs were site dependent. However these results are reasonably consistent with the results from this study with many of the same FEPs being identified as amongst the most important.

In addition to informing data acquisition and risk mitigation activities, risk assessment can also advise on the absolute and relative security of different storage sites. The Lincolnshire site is perceived to be the more geologically secure of the two sites. While a number of FEPs remain high risk, the work done so far seems to have reduced the experts' perception of risk in a key area, and hence further work concentrating on the additional high risk areas may be able to address these risks also. However, at this stage neither site meets the requirements for storage security as both continue to have a number of areas ranked as high risk. The decision to continue to the next stage of site evaluation would need to give careful consideration to cost of additional work required to further reduce the uncertainty against the likelihood that these risks would be reduced to some acceptable level and that the site would meet the requirements for storage.

The results of the FEP-based risk assessment demonstrate how perception of risk can change over the course of the project as a result of actions designed to influence risk and through the additional knowledge and information gained over the course of a project, but may also change in the absence of new information. This is seen in differences in the range of scores given for many FEPs for which the information available had not changed in the intervening months. In addition to independently completing risk assessments, experts were regularly asked to specify why and how their perception of risk had changed. This revealed inconsistencies in the scores given in the quarterly risk assessment and in the experts' belief in their perception of risk. For example, in the quarterly risk assessment following the group meeting elicitation, the geological expert responsible for the quarterly risk assessment for the FEPs assessed for the Firth of Forth site was asked whether their perception of risk was higher or lower for these FEPs than it had been at the end of the group meeting. The expert stated that their perception of risk was lower for a number of FEPs and yet the scores showed an increase. It is therefore not sufficient to rely simply on risk assessment results; more detailed discussions with experts are required to truly understand how their perception of risk is changing, and why.

While efforts were made to maintain a consistent group of experts assessing each group of FEPs across the whole project, inevitably changes in personnel and unavailability of individuals during some quarters meant that this was not always the case. Large changes in the scores of individual FEPs were observed due to changes in personnel throughout the project, an occurrence likely in any large-scale project. Using multiple experts to assess each

FEP can reduce the effect of changing personnel on the risk assessment results, though there are practical limitations to the number of experts that may be available. However it was found that the range of scores given by different experts tended to be within the estimated uncertainty of the individual experts, therefore by taking this uncertainty explicitly into account when analysing the results of the risk assessment, it is possible to minimise the impact of changing personnel.

In addition to maintaining a consistent set of experts throughout the project, with multiple experts assessing each FEP, group elicitation exercises can also help to provide more reliable risk assessment results. Bringing all experts together in a controlled and structured elicitation exercise can help to make them fully aware of the cognitive biases that may affect their results and ensure that they complete the assessments in such a way as to minimise these biases. During this project there was limited opportunities for such group elicitation, however regular group elicitation exercises would improve the risk assessment method by helping to ensure that the individual experts become more aware of the impact of bias on their perception and assessment of risk, with the feedback from such sessions helping to increase their awareness of how and why their perception of risk changes throughout a project. Though experts are asked to provide explanations of why they assess the scores as they do when completing the assessments individually, in practice they do not always provide complete information and such meetings also provide an opportunity for the risk analyst to discuss in detail with the experts their reasoning for assessments of the best-guess and lower and upper bound scores of the likelihood and severity. By documenting both the perception of risk and the experts' reasoning for their scores, in particular for those FEPs that are rated as high risk and where significant changes in scores occur between assessments, it is possible to track and understand the rationale behind the assessments, thus providing greater confidence in the results.

7. Conclusion

Identifying areas of risk is vital to the success of any CCS project. This assessment of two distinct geological storage sites shows that for the majority of areas of potential risk, experts perceived the level to be moderate or low. Where perception of risk was high, uncertainty in key information tended to be an important influence. Work in the subsurface is inherently uncertain and it will never be possible to 'prove' in advance of CO_2 injection that a store meets all the requirements for storage and hence that it is risk free. However, unless uncertainty can be brought to within some acceptable limit, perception of risk, particularly the upper bound, is likely to remain high in any future CCS reservoir evaluation project. By careful selection of data acquisition activities and explicitly considering areas of high risk, uncertainty can be reduced in key areas at an early stage of a project using relatively inexpensive techniques. This allows decisions to be made on the potential suitability of a site for storage, and on the value of investing in more expensive, but more detailed site evaluation.

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