Screening and ranking framework (SRF) for geologic CO_2 storage site selection on the basis of HSE risk

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Abstract A screening and ranking framework (SRF) has been developed to evaluate potential geologic carbon dioxide (CO_2) storage sites on the basis of health, safety, and environmental (HSE) risk arising from CO_2 leakage. The approach is based on the assumption that CO_2 leakage risk is dependent on three basic characteristics of a geologic CO_2 storage site: (1) the potential for primary containment by the target formation; (2) the potential for secondary containment if the primary formation leaks; and (3) the potential for attenuation and dispersion of leaking CO_2 if the primary formation leaks and secondary containment fails. The framework is implemented in a spreadsheet in which users enter numerical scores representing expert opinions or published information along with estimates of uncertainty. Applications to three sites in California demonstrate the approach. Refinements and extensions are possible through the use of more detailed data or model results in place of property proxies.

Keywords: Screening, Ranking, Geologic CO_2 Storage, Site Selection, HSE

Introduction

In order to reduce the possibility that carbon dioxide (CO_2) storage projects will result in health, safety, and environmental (HSE) impacts due to CO_2 leakage and seepage, it is essential that sites be chosen to minimize HSE risk. This is particularly important for early pilot studies for which leakage and seepage for any reason could be perceived as a failure of the general approach of geologic CO_2 storage. Apart from site-specific operational choices once a given CO_2 injection project is underway, the best way to avoid unintended leakage and seepage is to choose a good site at the outset. To this end, a spreadsheet-based Screening and Ranking Framework (SRF) for evaluating multiple sites on the basis of their potential for HSE risk due to CO_2 leakage and seepage has been developed (Oldenburg 2005). Some key terminology used in the HSE SRF is presented in Table 1.

Background and Motivation

Existing approaches to risk assessment of fluids injected into geologic formations include the Features, Events, and Processes (FEP) scenario approach (e.g., Savage et al. 2004; Wildenborg et al. 2005), Probabilistic Risk Assessment (PRA) (e.g., Rish 2005), and related approaches (e.g., Bowden and Rigg 2004). In the FEP/scenario approach, a comprehensive list of FEPs is developed and codified in a database that is then used to define scenarios for leakage and seepage, or any other performance-affecting event. Modeling is then used to evaluate the consequences of that scenario in terms of CO_2 impact due to long-term high concentrations at key receptors. The performance-affecting FEPs may have subjective probabilities associated with them, and from the product of consequence as simulated in the scenario and probability as assigned to the FEPs, risk can be calculated. In the probabilistic approach of Rish (2005) developed for Class I hazardous waste injection wells, probabilities of events and distributions of properties are input and the likelihood of various detrimental events is calculated. Bowden and Rigg (2004) invoke a quantitative probabilistic approach that involves innovative risk measures applied to key performance indicators. This approach is applicable to screening and ranking of multiple sites, while the FEP and PRA approaches are most applicable to risk assessment of a single site. However, the Bowden and Rigg (2004) approach involves a level of detail (e.g., an expert panel) beyond what is likely going to be practical for initial screening and ranking of numerous sites.

The SRF approach presented here is aimed at an early screening and ranking stage of site selection. In the early stages, there are likely to be numerous sites up for evaluation, as there are numerous objectives of geologic CO_2 storage. For example, the various objectives of proximity to CO_2 source, proximity to existing pipelines, compatible current land use, favorable geologic structure, etc., will not all be met at any one site, resulting in numerous sites put forward for evaluation that all have strengths but also weaknesses. At this early stage, site characterization data will be sparse or non-existent, and time and money will not be available for in-depth site characterization. What is needed for screening and ranking of a large number of sites on the basis of HSE risk is a quick, inexpensive, and consistent framework to identify a small number of the better candidate sites, for which more in-depth site characterization and risk assessment analyses can be undertaken with more detailed and quantitative approaches. As more data become available, additional criteria and selection frameworks may be applied, such as those evaluating injectivity and capacity.

SRF Approach

Theory and Design

The HSE impacts of CO_2 that are of concern are caused by high concentrations of CO_2 in the near-surface environment where humans, plants, and other living things reside. For example, if a large flow rate of gas with a high concentration of CO_2 occurs over a small area, the resulting large flux of CO_2 can cause persistent high CO_2 concentrations in soil gas which in turn can lead to root respiration limitations and corresponding plant stress or death (Farrar et al. 1995; Qi et al. 1994). In aquifers, high CO_2 concentrations can in some circumstances lead to leaching of heavy metals that could adversely affect water quality (Wang and Jaffe 2005). In the above-ground environment or in basements and houses, high CO_2 concentrations in air can lead to health effects ranging from dizziness to death in humans and other animals (Benson et al. 2002).

There is a wide variety of recognized potential pathways for leakage from deep geological formations to the near-surface environment, e.g., abandoned wells and permeable fault zones. However, for nearly every leakage pathway, there is also potential for secondary entrapment at higher levels in the system. In addition, CO_2 leakage along any of the pathways involves the potential for attenuation or dispersion of a CO_2 plume during migration. To minimize HSE effects, it is necessary that injected CO_2 either (1) does not leak from the storage formation, (2) is secondarily trapped if leakage does occur, or (3) is attenuated or dispersed if leakage occurs (e.g., by mixing in the atmosphere, or by uptake and mixing by groundwater or surface water) and if there is ineffective secondary entrapment.

With this understanding, the HSE SRF was developed to evaluate three basic characteristics of a geologic CO_2 storage site:

(1) Potential of the target formation for long-term containment of CO_2;
(2) Potential for secondary containment if the primary target site leaks; and
(3) Potential of the site to attenuate and/or disperse leaking CO_2 if the primary formation leaks and secondary containment fails.

The SRF is implemented in a spreadsheet designed to evaluate these three basic characteristics through user input of Property values, which define Attributes, which define the Characteristics, as shown in Table 2. The spreadsheet does simple arithmetic and averaging to produce a score for each basic characteristic along with the associated uncertainty. The values and properties entered by the user combine to represent proxies for site characterization data and model analyses that may not be available, as shown in the far-right column of Table 2. For example, there is a Primary Containment attribute called Primary Seal for which lithology is a proxy for permeability and porosity. The idea here is that permeability and porosity may not have been measured but that the known lithology of the seal provides a fair representation of these properties. This proxy could be replaced at a later stage of site study or operation by data or model results that represent seal effectiveness in more detail, e.g., by quantitative prediction of CO_2 flux. In this way, the SRF can be extended and updated as site characterization occurs to include more quantitative measures of performance.

The SRF relies on input by a user who either already knows something about the sites, has opinions about the sites based on general information, or who has gained knowledge about them from published reports, maps, and papers. The expected users of the SRF are geoscientists and/or hydrologists with some general knowledge of the sites and/or access to limited published information about the sites in reference books or maps. It is expected that one user or group of users will evaluate all of the candidate sites in a given screening or ranking exercise, thereby ensuring a measure of consistency in each assessment. Simplicity and transparency are key design features of the SRF spreadsheet.

Although the SRF was developed based on experience with geology and CO_2 storage rather than with the formality of decision analysis, the approach falls loosely under the category of multi-attribute utility theory (Keeney 1980; Keeney and Raiffa 1976). The three scores that are evaluated for each site are proxies for combinations of impact and likelihood (i.e., risk) of leakage, secondary entrapment, and attenuation. The assessment made in the framework is based on four classes of information: (1) site characteristics which are defined by (2) attributes, which are defined by (3) properties which are defined by (4) values input by the user.

Spreadsheet

The SRF is implemented in a spreadsheet with three simple worksheets (one for evaluation of each of the three basic characteristics) and a summary page. There are three categories of entries. First, the user can control the importance of a given property through the specification of weighting factors for each of the *j* properties of each attribute. The weighting factors (w_j) are normalized by the spreadsheet as

$$\sum_j w_j = 1 \tag{1}$$

so any arbitrary scale can be used. The weighting option allows the user great latitude in applying his/her judgment to the evaluation. For example, if the user feels strongly that caprock seal thickness is the overriding property controlling leakage and seepage, then a large number can be assigned for the weight of that property and the caprock thickness value will dominate the assessment of the attribute Primary Seal. An example of the Primary Containment worksheet is shown in Figure 1, in which light blue cells are those expecting user input. The two other worksheets (Secondary Containment, and Attenuation Potential) are similar but with appropriate cells for the respective properties as given in Table 2. As shown in Figure 1, the weight of the seal thickness property is assigned a value of 10 out of a total of 21 making approximately one-half of the weight of the primary seal attribute and its uncertainty rest on the seal thickness value. For comparing sites in the process of screening or ranking, the use of different weighting factors for the properties of different sites should be carefully considered. In the example cases presented below, constant weighting factors are used for consistency.

The second step of the SRF spreadsheet is to assign a numerical value a_j to the properties based on suggestions in pop-up comments in the spreadsheet. Examples of property values can be seen in Figure 1 for the Rio Vista case. The numerical values are chosen as integers ranging from –2 (poor) to +2 (excellent) with 0 considered neutral (neither good nor bad). Broad ranges of values are offered for various conditions in the pop-up comments to guide the user in selecting an integer between –2 and +2. Real numbers can also be used in cases when the user feels it is warranted.

The third thing the user does is enter a value for the confidence with which each property is known (2 is very certain, 0.1 is highly uncertain). This confidence information will be carried along and plotted with attribute assessments for each of the three characteristics.

From this user input, a variety of averaged quantities is generated by the spreadsheet. The fundamental calculation the spreadsheet does is to add up the weighted property assessments and average them across the attributes to arrive at a score for each of the three fundamental characteristics. This is done for each of the *j* properties shown in Table 2, and then averaged over the *i* attributes. There are three attributes (primary seal, depth, and reservoir) for Primary Containment, two attributes (secondary seal, shallower seals) for Secondary Containment, and four attributes (surface characteristics, groundwater hydrology, existing wells, and faults) for Attenuation Potential. Thus, $i = 3$ for Primary Containment, $i = 2$ for Secondary Containment, and $i = 4$ for Attenuation Potential (see Table 2)). For site *n*, the score (*S*) for each characteristic is an average over the *i* attributes of the weighting factors (*w*) and values (*a*) of the *j* properties which can be written as

$$S_n = \frac{1}{i}\sum_{1}^{i}\left[\sum_{j} w_j a_j\right]_i \qquad (2).$$

For site *n*, the overall qualitative measure of confidence (*C*) for each characteristic is an average over the *i* attributes and *j* properties and values is averaged over the *i* attributes as follows,

$$C_n = \frac{1}{i}\sum_{1}^{i}\left[\frac{1}{j}\sum_{j} c_j\right]_i \qquad (3)$$

where c_j is the confidence with which each property is known. It is important to emphasize that the relative assessments of different sites are not necessarily linearly related to their relative physical behaviors. For example, a site that scores a 1.5 for the primary containment characteristic does not necessarily leak 50% less than a site that scores 1.0 for primary containment. In fact, such sites could be orders of magnitude different in their ability to contain CO_2. The assessment scores simply represent relative rankings of the sites without indicating absolute performance.

Additional Points

The SRF is designed so that it can be applied to multiple sites with limited data. Many of the properties and values of attributes that the user will input into the SRF spreadsheet are actually proxies for uncertain and undetermined quantities that could eventually be measured or modeled with additional site characterization effort. However, because of the lack of data that will be the norm for most site-selection processes, uncertainty has been made a fundamental input and output of the SRF that is kept separate from the scores for the characteristics. Uncertainty in the SRF is defined broadly and includes parameter uncertainty (e.g., how well-known a given property is) and variability (e.g., how variable a given property is).

The methods behind the SRF differ from other approaches such as the Features, Events, and Processes (FEP) scenario approach (e.g., Savage et al., 2004; Wildenborg et al. 2005), and the probabilistic approach (e.g., Rish 2005). The FEP/scenario approach is laborious at the site-selection stage and requires significant site-specific information to be carried out effectively. The Probabilistic Risk Assessment (PRA) approach (Rish 2005) is similar to the FEP/scenario approach and makes use of a Failure Modes and Effects Analysis (FMEA) coupled to event and fault tree development. Estimating the frequency of occurrence of very rare events makes these approaches difficult to apply. Furthermore, these quantitative approaches rely on accurate distributions of properties, something that will be difficult at best to estimate for multiple sites especially during the early phases of site selection. The approach of Bowden and Rigg (2004) is preferred for screening and ranking over FEP and PRA, but still appears to demand more information and expense than will be available at the level of screening more than a few sites.

In summary, the SRF spreadsheet was designed to provide a qualitative and independent assessment of each of the three basic characteristics through an evaluation of the properties of their various attributes. In the SRF approach, there is no modeling and simulation nor are probabilities assigned. The rationale behind the SRF is that detailed site-characterization information, especially for pilot CO_2 injections, is not expected to be sufficient to undertake a FEP/scenario analysis at the site-screening stage, nor to assign probabilities for a probabilistic analysis. Instead the SRF uses qualitative pieces of information, for example as gleaned from general reports or an expert’s knowledge of an area, as proxies for potential FEPs and consequences combined. By this approach, the analysis is greatly simplified and includes explicitly the level of confidence that the user assigns to the assessments as a primary output. In short, the SRF is designed to answer the question, “From a choice of several potential sites, and based on existing information, which site has the lowest HSE risk?”

Screening and Ranking Framework Examples

Rio Vista Gas Field

The Rio Vista Gas Field is located in the Sacramento Basin of California, approximately 75 km northeast of San Francisco. In production since 1936 from reservoirs in an elongated dome-shaped structure extending over a 12 km by 15 km area, the majority of gas has come from the Domengine sands in fault traps at a depth of approximately 4500 ft (1400 m) with sealing by the Nortonville shale. Details of the field can be found in Burroughs (1976) and Johnson (1990). Information from these published sources along with our general knowledge allowed us to fill in values in the SRF spreadsheet assuming it would be used as a geologic CO_2 storage site. As shown in the Summary worksheet and attribute graph for Rio Vista of Figure 2, the high attribute score reflects the very effective primary containment expected at Rio Vista. Secondary containment is not expected to be very effective as sealing formations above the Nortonville shale are largely absent. However, the attenuation potential is excellent at Rio Vista due largely to steady winds and flat topography. As shown in Figure 2, confidence in the attribute assessments is quite high for subsurface and surface characteristics at Rio Vista due to its long history of gas production. The high score and certainty suggest that Rio Vista Gas Field is a good candidate for geologic CO_2 storage. The colored curves on the attribute graphs are arbitrary functions that separate poor, fair, and good regions of the graph. The concave-down shape of these curves indicates that increasing certainty in site attributes improves the score of a site even if attribute assessment stays the same. This is consistent with the idea that if even if the attributes of a site do not change as you learn more about it, the site becomes more desirable because the more you know about a site, even if it is more knowledge about deficiencies, the better you can engineer around the deficiencies.

Ventura Oil Field

The Ventura Oil Field taps reservoirs in young folds and fault traps in marine sediments of the tectonically active coastal area northwest of Ventura, California. The primary structure is the Ventura Anticline, a dramatic fold that is visible in outcrops in the deeply incised canyons of the area. Natural oil seeps and tar are widely found in the area. Using geological information from published references (Sylvester and Brown 1988; Harden 1997) and our own knowledge of the site, we assigned values in the SRF appropriate for the Ventura Oil Field. As shown in Figure 2, the Ventura Oil Field ranks lower than the Rio Vista Gas Field. The oil accumulations at Ventura indicate that good traps exist, but the evidence of widespread oil seepage along with the lack of significant natural gas accumulation suggest that pathways to the surface also exist. As for secondary containment, some of the oil reservoirs in the area are quite shallow, suggesting that secondary containment may occur, however there is a high degree of uncertainty, and variability especially in light of the abundant seepage. As for attenuation potential, the Ventura area is highly dissected with steep canyons that do not promote dispersion of seeping CO_2. There is also considerable population to the southeast that could be exposed to seeping CO_2. Therefore, attenuation potential is also judged worse at Ventura than at Rio Vista.

Mammoth Mountain

The SRF was also applied to a naturally leaking site for verification purposes. Mammoth Mountain, California, is a 200,000 year-old dormant volcano with active springs, geothermal anomalies, and CO_2 seepage that has killed native trees and also skiers who fell into enclosed depressions in the snow. For this purely academic analysis of the potential HSE effects of deliberate CO_2 injection, we assume the area under consideration is comparable to Rio Vista and Ventura in terms of size by considering the entire Mammoth Mountain area. Using published information from (Farrar et al. 1995; Sorey et al. 1999) we filled in values and properties of the SRF spreadsheet. Many of the properties are given the lowest values because they simply do not apply at Mammoth Mountain. For example, as evidenced by the extensive seepage, we have concluded that there is no effective seal present, and therefore scored those properties with the lowest values. Other properties are not very well known and we scored them accordingly. As shown in Figure 2 (right-hand side), the Mammoth Mountain site scored badly as expected in primary and secondary containment. The site does better on attenuation potential because it is fairly windy and the population is relatively sparse. Nevertheless, the SRF spreadsheet demonstrates that Mammoth Mountain would not be a good place to store anthropogenic CO_2 in the subsurface.

Discussion

The preceding demonstration of the SRF cannot formally be called a validation since no one has injected CO_2 into any of these sites and evaluated the three basic characteristics directly. Nevertheless, the results are consistent with our general knowledge and expectation of these three sites. The benefit of the SRF is that this knowledge and expectation is now formally expressed in a way that others can review, criticize, revise, or affirm. There is a large degree of arbitrariness introduced in the SRF by allowing the user to weight the importance of various site properties. In the above examples, the weighting factors were the same for all three analyses. In the case that weighting factors are changed for the various sites under comparison, it will be more difficult to defend direct comparisons. Nevertheless, the transparency of the system and simplicity will allow a critic or reviewer to alter the weighting functions and do the analysis again to compare the effect. Group efforts with multiple people evaluating the same sites may prove especially useful because this would tend to capture a large range of opinions while simultaneously bringing uniformity to comparisons between the different sites. As with any tool, misuse is of course possible and the SRF assumes an underlying integrity of the users. Because of the transparency and simplicity of the approach, there is little possibility to hide abuses.

Extensions of the framework are possible. First, as more data become available, distributions rather than single values could be input by the user where such distributions are known. This would add a component of variability to the outcome, and potentially better represent the range of performance of a site rather than a worst-case, best-case, or average performance. In addition, proxy scores for site properties such as lithology could be replaced by measurements or modeling results of permeability and porosity during a more detailed site characterization phase.

Conclusions

A framework for screening and ranking candidate sites for geologic CO_2 storage on the basis of HSE risk has been developed to evaluate three basic characteristics of a geologic CO_2 storage site. The framework allows users to arbitrarily weight and assign uncertainty to the properties of the attributes of the basic characteristics to evaluate and rank two or more sites relative to each other. We emphasize that this is a screening and ranking risk assessment tool intended to guide the selection of the most promising sites for which more detailed risk assessment would be carried out at a later stage of the project. Example applications of the framework show that comparative evaluations of prospective sites with limited characterization data can be accomplished based on potential for CO_2 leakage and seepage and related HSE risk. Testing and further development of the SRF are underway.

Acknowledgments

This paper benefitted from the helpful comments of two anonymous reviewers and guest editors Jens Birkholzer and Chin-Fu Tsang. Earlier drafts were reviewed by Thomas E. McKone and Marcelo J. Lippmann (LBNL). I thank Larry Myer and Sally Benson (LBNL) for support and encouragement. This work was supported in part by WESTCARB through the Assistant Secretary for Fossil Energy, Office of Coal and Power Systems, through the National Energy Technologies Laboratory (NETL), and by Lawrence Berkeley National Laboratory under Department of Energy Contract No. DE-AC03-76SF00098.

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Figure Captions

Figure 1. Example worksheet from the SRF spreadsheet for the characteristic Primary Containment.

Figure 2. Summary SRF worksheet and three graphs for the example sites.

Tables

Table 1. Terminology related to CO_2 HSE screening and ranking framework.

Term	Definition
Leakage	Migration in the subsurface away from the primary containment formation.
Seepage	Migration across a boundary such as the ground surface or into surface water.
Near-surface	Plus or minus 10 m from the ground surface.
Flux	Transport per unit area per unit time (e.g., kg m^{-2} s^{-1}).
Flow	Transport per unit time (e.g., kg s^{-1})
Plume	Large relatively concentrated volume of CO_2 either in the subsurface or above ground.
Impact	Consequences or effects of a given high CO_2 concentration on health, safety, and the environment.
Risk	Product of probability of occurrence of an event and its impact.

Table 2. Characteristics, attributes, properties, and proxies.

Characteristics	Attributes (*i*)	Properties (*j*)	Proxy for..
Potential for primary containment	Primary seal	Thickness	Likely sealing effectiveness
		Lithology	Permeability, porosity
		Demonstrated sealing	Leakage potential
		Lateral continuity	Integrity and spillpoint
	Depth	Distance below surface	Density of CO_2 in reservoir
	Reservoir	Lithology	Likely storage effectiveness
		Permeability and porosity	Injectivity, capacity
		Thickness	Areal extent of injected plume
		Fracture or primary porosity	Migration potential
		Pore fluid	Injectivity, displacement
		Pressure	Capacity, tendency to fracture
		Tectonics	Induced fracturing, seismicity
		Hydrology	Transport by groundwater
		Deep wells	Likelihood of well pathways
		Fault permeability	Likelihood of fault pathways
Potential for secondary containment	Secondary seal	Thickness	Likely sealing effectiveness
		Lithology	Permeability, porosity
		Demonstrated sealing	Leakage potential
		Lateral continuity	Integrity and spillpoint
		Depth	Density of CO_2
	Shallower seals	Thickness	Likely sealing effectiveness
		Lithology	Permeability, porosity
		Lateral continuity	Integrity and spillpoint
		Evidence of seepage	Effectiveness of all seals
Attenuation Potential	Surface characteristics	Topography	CO_2 plume spreading
		Wind	Plume dispersion
		Climate	Plume dispersion
		Land use	Tendency for exposure
		Population	Tendency for exposure
		Surface water	Form of seepage
	Groundwater hydrology	Regional flow	Dispersion/dissolution
		Pressure	Solubility
		Geochemistry	Solubility
		Salinity	Solubility
	Existing wells	Deep wells	Direct pathway from depth
		Shallow wells	Direct pathway
		Abandoned wells	Direct pathway, poorly known
		Disposal wells	New fluids, disturbance
	Faults	Tectonic faults	Large permeable fault zones
		Normal faults	Seal short-circuiting
		Strike-slip faults	Permeable fault zones
		Fault permeability	Travel time