Geologic Disposal of Carbon Dioxide as a Climate Change Mitigation Strategy: State-of-the-Art of Risk Assessment (RA) Methods

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A. GhirianandM. Fall

University of Ottawa, Ontario, Canada

Abstract

This paper offers a state-of-the-art review and analysis of the main risk assessment (RA) methodologies for the geologic storage of carbon dioxide as well as assesses their strength and weakness. It is shown that each deep geological disposal (DGD) of carbon dioxideDGD-CO_2 site project needs its own specific risk assessment strategy which is normally based on the available knowledge and technology of the project operators. Qualitative RA methods are more applicable in preliminary assessment and site selection and characterization where there is a lack of geologic data and elevated uncertainties. However, quantitative risk assessment approaches along with complex modeling and simulation are normally adopted for the advanced assessments. All the studied RA methods eventually lead to a risk assessment conclusion required for current or future monitoring plan and risk mitigation strategy.

Keywords: Deep geological disposal, CO_2, Risk assessment, Climate Change

Résumé

Ce document présente une revue et une analyse des principales méthodes actuelles d'évaluation du risque ayant trait au stockage géologique du dioxyde de carbone ainsi qu'une étude de leurs forces et faiblesses. Il est démontré que chaque projet de site de stockage géologique en profondeurde dioxyde de carbone (DGD-CO_2) nécessite une stratégie d'évaluation du risque qui lui est propre, celle-ci étant normalement basée sur les connaissances et la technologie des exploitants du projet. Les méthodes qualitatives conviennent plutôt au stade préliminaire de l'évaluation, de la sélection et de la caractérisation d'un site,où il y aun manque de données géologiques et une existence de fortes incertitudes. Cependant, on utilise normalement des méthodes quantitatives en parallèle avec une modélisation et une simulation complexes pour les évaluations poussées. Toutes les méthodes étudiées débouchent sur une conclusion utile à la mise en place actuelle ou future d'un plan de surveillance et d'une stratégie d'atténuation des risques.

Mots clés : Stockage géologique profond, CO_2, Évaluation du risque, Changement climatique

1. Introduction

It is now broadly accepted that large scale diminutions in carbon dioxide (CO_2) emissions are needed during this century to significantly reduce the extent of climate change modification. There is an international consensus that the deep geological disposal of carbon dioxide is one the best options to significantly reduce atmospheric concentrations of CO_2. In the past decade, many studies have been conducted to investigate the possible risks and uncertainties related to short and long-term disposal of CO_2 for the geologic sequestration purposes. Several qualitative and quantitative risk assessment methodologies have been developed to establish standardized risk assessment methods. Many projects around the world have tried different RA approaches adapted to deep geological disposal (DGD) of carbon dioxide (DGD-CO_2). However, currently there is no generic method to evaluate the risk and/or uncertainty of DGD-CO_2projects. The objective of the present paper is to offer a state-of-the-art review and analysis of the main risk assessment (RA) methodologies for the geologic storage of carbon dioxide.

2. Risk assessment methods for geological disposal of CO_2

Risk analysis consists of several steps including risk assessment, risk management and risk communication (Korre and Durucan, 2009). Risk assessment for geologic sequestration consists of determining the risks (*risksource assessment*), identifying the probability of the occurrence of (*exposure assessment*), and the magnitude of loss from individual risk events (*effectsassessment*), and combining the exposure-effect information to produce qualitative or quantitative measures of risk (*risk characterization*). The outcomes of riskassessments combined with effects of social, political, and techno-economic parameters are employed to prioritize, monitor, control and mitigate risks(NETL, 2011).Risk Assessment (RA) methods can be conducted by two approaches: qualitative and quantitative.Qualitative risk assessment methods are normally performed when the detailed data, knowledge, time and expertise are not available and mostly provide the description of the risk level (Condor et al., 2011). It can be employed at the early stages of a geological sequestration (GS) project to aid in site screening, selection, communicating project aspects to the public, and helping regulators in permitting projects (NETL, 2011). Quantitative risk methods in contrast, are applicable in a geologic sequestrationsystem when there is a low level of uncertainty (Condor et al., 2011). Furthermore, it can be used for long-term assessment when more detailed site characterization and modeling data are available to estimate the potential risk in human health and environmental risks (NETL, 2011). In the following section twelve worldwide currently used RA methods by the industry and academic institutes are discussed and efforts have been made to describe the methodology and highlight the important features.

2.1 Vulnerability evaluation framework (VEF)

U.S. Environmental Protection Agency (EPA) developed this qualitative RA method to systematically determine conditions that could increase or decrease the vulnerability to adverse impacts in a sequestration system. It’s a conceptual framework to aid the regulators and technical experts to highlight the areas with elevated potential riskin order to conduct design evaluation, specific risk assessment, monitoring, and management (EPA, 2008;Bacanskas et al., 2009).In this framework, only the well-understood vulnerabilities can be included in the assessment, and uncertainties beyond the available knowledge and experiences may need more monitoring and management in order to reduce the level of uncertainties and increase the accuracy of evaluation (EPA). In this model the potential impact categories are identified, and a series of decision-support flowcharts are provided in order to systematically organize and assess the attributes and impacts. The conceptual VEF method has three main componentscomprising (1)Geologic sequestration system and geologic attributes consists of confining system and injection zone and their associated geologic attributes; (2)Special area of evaluation includes unanticipated migration/leakage and pressure changes; and (3)Potential impacts categories and receptorsare identified, including human health and welfare, atmosphere, ecosystems, groundwater and surface water, and the geosphere(EPA, 2008).

After establishing the flowcharts the different level of vulnerabilities, including low or elevated vulnerability, can be assigned to each attribute. Special attention should be paid to attributes with elevated vulnerability, and actions should be taken to minimize those vulnerabilities by the developed monitoring program and mitigation plan. However, attributes with high vulnerability would not mean the high vulnerability of the entire GS system (EPA, 2008).

2.2 Structured what-if technique (SWIFT)

The SWIFT is a flexible and high-level qualitative risk identification approach to identify the potential hazards and uncertainties in a GS system. It was developed byNorwegian Petroleum Directorate(DNV) for qualitative hazard identification. In this method a series of questions such as "How could…?" or "what-ifs…?" are asked to find the potential risk and hazard related to GS system. Also, it's a self-stand method or can be used in conjunction with other method like FMEA (Card et al., 2012).

The risk assessment is conducted by organizing some workshops including a group of experts and stakeholders with the intimate and comprehensive knowledge about the studied system. Then, by making different checklists,brainstorming meeting and structured discussion groups, the categories under discussion are structured and bring to the attention of the workshop. The keywords in the checklists can beoriginated from the Quintessa online database of Features, Events and Processes (FEP's) that is specifically designed for CO_2 storage risk assessment.The studied categories can bestorage reservoir, sealing layers (caprocks), vadose zone, groundwater, wells, fault/fracture zones and atmosphere(Sollie et al., 2011).The associated risk to each studied categories are identified in a qualitative manner, considering the activity from a top-down perspective starting with systems or operations, rather than individual features, events or processes (Aarnes et al. 2009).

2.3 Features, events and processes (FEPs)

In this qualitative RA method the specific risk features, events, and processes (FEPs) which contribute to or prevent the unplanned CO_2leakage/migration from the injection zone are identified (NETL, 2011). For example, features include the physical parameters that can influence the GS system, such as caprocksand reservoir hydrogeological characteristics, leaky wellbores or faults. Events are the processes that can influence the evolution of the system over a short timescale such as earthquake, well-blowouts, injection pressure increase. Processes arethe dynamic interactions between the Features which can take place in different time scale such groundwater quality alteration due to CO_2 injection (Lewicki et al., 2007; Walke et al., 2011).

There are two basic approaches to generate a conceptual model by using the FEP method include bottom-up and top-down. In top-down approach, important FEPs are determined and categorized to createscenarios; while, in bottom-up approach, a detailed site characterizations are employed to identify all the possible FEPs. By using these approaches the conceptual model of the GS system can be developed step by step to from a conceptual model for further numerical analysis (Walke et al., 2011)

Since the future possible evolution in the studied geologic system cannot be predicted precisely, different possible scenarios for possible changes of the system should be developed. Typically, FEP analysis and scenario development are performed using expert inputs. During the risk assessment, the project experts identify possible leakage, potential receptors, and specific consequences. After identification of specific FEPs and development of a risk registry for the studied site, a list of potential consequences should also be identified and associated with the FEPs. The most critical consequences could be the contamination of underground water, unplanned migration of CO_2 into hydrocarbon resources or long-term CO_2 emission into the atmosphere (NETL, 2011).

2.4 Multi-criteria assessment (MCA)

It's anassessment framework which includes several non-monetary evaluation techniques and is conducted in two roundsof interview. In the first round interview, various CO_2 storage alternatives are scored against a set of evaluation criteria in order to assess each candidate siteindependently. For this purpose differentexpertsassign weights to rank the relative importance of each criterion.The list of criteria is prepared based on the main purpose of the storage projects through a process of iteration. Then the criteria are categorized in different groups to make a summary of the views and preferences of the participants. The examples of criteria are storage capacity, leakage and migration potential, monitoring and etc.

During a second round of interviews, assessment is conducted by using a set of criteria relating specifically to the scenarios.Someexamples of scenarios are reservoir performance, costs, infrastructure change, environmental impacts and etc. Then final scenarios were scored under this set of appraisal criteria.Since MCA emphasizes on participant judgments, the way of scoring and weighting is important (Gough and Shackley, 2006).

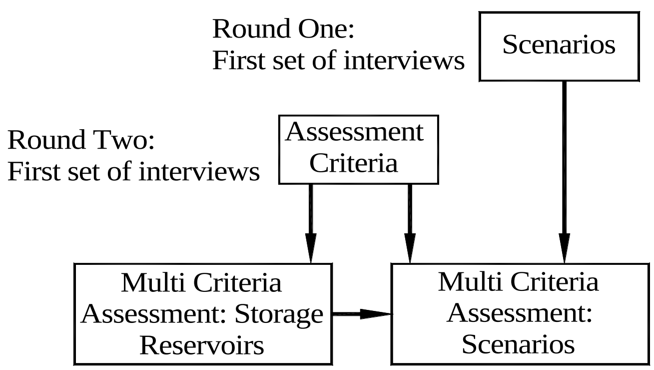

Figure 1. The multi-criteria assessment conceptal model (Gough and Shackley, 2006)

2.5 Method organized for a systematic analysis risk (MOSAR)

As discussed in Cherkaoui and Lopez (2009), MOSAR is used to assess the potential risks of a GS system and then identify the preventive measures to neutralize them.Itcan cover wide range of application since it takes different aspects (e.g., technical aspects, site morphology and geology, politics, economic and social) into consideration.It consists of two steps (A and B) where the system is divided intodifferent under-systems. For example, a GS system can be defined in five under-systems comprising injection plant, injection wells, injection zone, sealing layer or caprocks, and faults and fractures. Then, each under-system is considered as an independent source of danger, but connected to each other. Subsequently risks scenarios can be developed between the under-systems which finally form the event trees (Cherkaoui and Lopez, 2009). It can be done by defining the originator eventsandconsequence events for each under-system. For example, for injection wells as an under-system, reservoir property changes or high injection pressure can be two originator events for two consequences of CO_2 leaks and wells breaks, respectively. Several links can be established between different originatorsconsequences within an under-system and then can be developed between the under-systems to create different scenarios. Then, all the possible scenariosare put in a “Gravity times Probability” grid in order to form a hierarchy system (event trees) (Cherkaoui and Lopez, 2009). Next, the low-risk (acceptable) and elevated risk (unacceptable) are identified and preventive measures are developed to neutralize the unacceptablescenarios and insure the risks prevention (Figure 2).With MOSAR method all the scenarios can be concentrated in an acceptable area in order to reduce the risk. So, the protection and prevention measures can be improved and new mitigation plans can be built (Cherkaoui and Lopez, 2009).

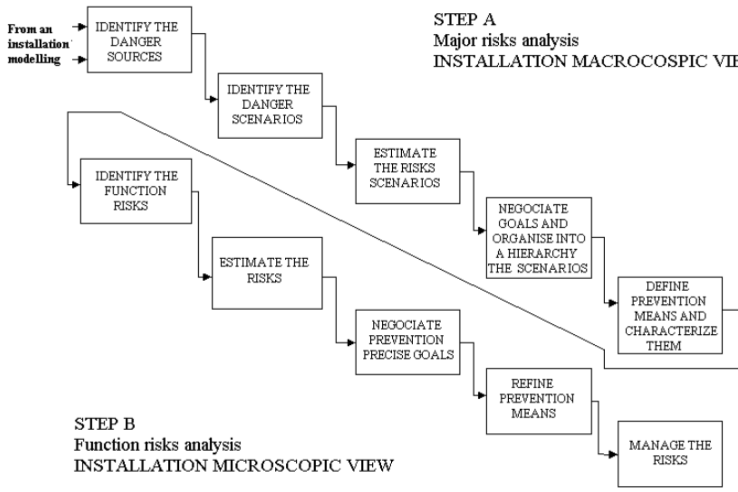

Figure 2. MOSAR conceptual model (Cherkaoui and Lopez, 2009)

2.6 RISQUE method

Geological Disposal of Carbon Dioxide (GEODISC) is a research program of the Australian petroleum cooperative research centre that developed the RISQUE (Risk Identification and Strategy using Quantitative Evaluation) method. It’s a quantitative approach to conduct risk assessment in terms of the probability of risk events occurrence and their consequences by using an expert panel judgment and experience.Potential injection project are assessed against six key performance indicators, including: containment, effectiveness, self-funding potential, wider community benefits, community safety, and community amenity (KPIs)(Bowden and Rigg, 2004). Risk assessment is conducted through five stages. In the first stage the initial criteria against which the risk is to be assessed is established. In stage two, by using an expert panel, the key risk events are identified through adiagrammatic event tree risk model. In stage three, the risk analysis comprising likelihood and consequences of each risk event are performed by using the Monte Carlo simulation. In stage four, the risk management strategy is developed, and based on the results of risk analysis performed in pervious stage the action plan to treat the key risk events is defined. Finally in the last stage,the best alternatives for CO_2 injection site are screened and selected.Figure 3 shows a typical plot that produce during the RISQUE risk assessment(Bowden and Rigg, 2004).Among all the KPIs, containment and effectiveness as reservoir performance are much more important. Containment is the ability of the reservoir to contain most of the injected CO_2 and effectiveness is the ability of the reservoir to receive the planned CO_2injection volumes. Some factors such as reduced injectivity, inadequate source, poor public perception of other projects, and regulatory change could reduce the effectiveness of GSC project (Bowden and Rigg, 2004).

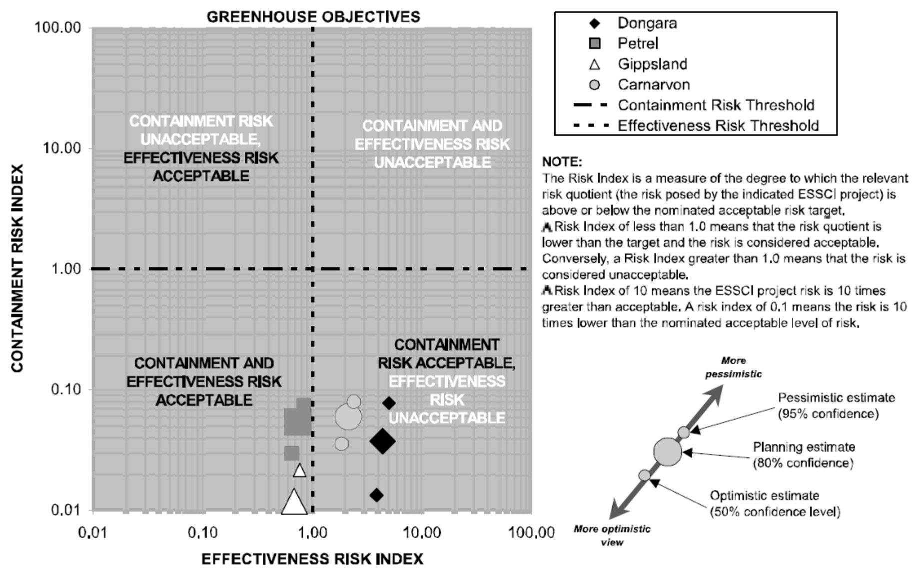

Figure 3. Example of CO2 site storage performance with respect to containment and effectiveness risk by using RISQUE method (Bowden and Rigg, 2004)

2.7 Evidence support logic (ESL)

As stated in Egan (2008) and Metcalfe et al. (2009), ESL was developed to ensure that there is comprehensive coverage of relevant factors and uncertainties by identifying all the potential relevant evidences and evaluation of those evidences. ESL includes three main stages. (1) Development of a decision tree in the form of ahierarchical logical hypothesis model (connection of the main hypothesis to the related information through the intermediate hypothesis). It includes all the evidences that are relevant to the performance assessment of a GS site, evaluation of the possible FEPs that may affect the system and the data and information required for the judgment and identification of the interaction between FEPs. (2) In this stage, the logical model and identification of sources of evidence are quantified either tosupport thehypothesis orto reject them.For example, each item of qualitative or quantitative information is mapped into two values of 0 to 1 representing evidence for and against (Figure 4). (3) In this stage, the evidence values are propagated logically through the event treesfrom the lowest level of the hierarchy to the top level hypothesis to assess the uncertainty. For example, if the evidence of atrue hypothesis is presented by pT (where p isprobability) and the evidence of afalse hypothesis is presented by pF, then uncertainty U = 1-pT-pF. To facilitate the assessment of this systematic model, TESLA software has been developed by Quintessa based on the ESL method. The main advantage of ESL is that it can distinguish between the poor data qualityand unknown data quality (Egan, 2008; Metcalfe et al. 2009).

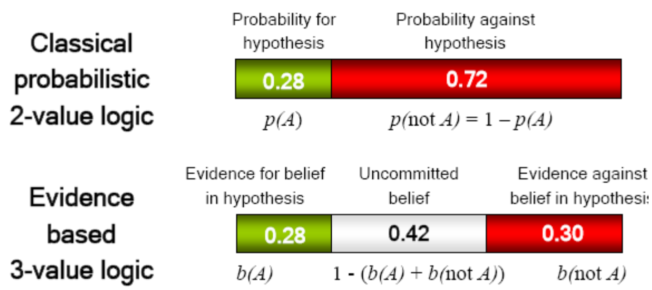

Figure 4. Example of classical two-value probabilistic analysis compared with three-value interval analysis (Egan, 2008)

2.8 Certificating framework approach (CFA)

The CF approach is a simple and transparent method that divides a GS system down into its fundamental components, including CO_2 (or brine) source, conduits for leakage, and compartments where impacts may occur.The purpose of the CF is to evaluate the degree to which a geological carbon storage site is expected to be 'safe' for human and environment and 'effective' in terms of containing effectively the most of the injected CO_2. In this method, it is assumed that surface operation related to CO_2 storage is well known and the focus is only on geologic storage(Oldenburg et al., 2009). Also, CFA assumes that the wells and faults are the main potential leakage pathways in the geological carbon storage projects.For quantification of risk, the system is divided into five compartments which are the regions containing vulnerable entities(Oldenburg et al., 2009). These compartments can be subsurface (hydrocarbon reservoirs or underground sources of drinking water) or at surface (local sites where leakage occurs), and distant sites (Figure 5).The CFA evaluates the CO_2 leakage risk for each compartment to determine the effective trapping threshold which should be less than a threshold determined by regulators and insurers. The methodtakes into account both the probability and impact of CO_2 leakage. The methodestimates the probability of intersection of the CO_2 (or brine) source with conduits as well as the probability of intersection of CO_2 plume anda compartment. The resultant of both likelihoods is the probability of the studied leakage scenario (Oldenburg et al., 2009).

2.9 Performance and risk (P&R) assessment for well integrity

It's a quantitative risk-based methodwhich was developed by Schlumberger and OXAND to assess the performance and risk associated to well integrity with respect to CO_2 leakage (Meyer et al., 2009).A risk is usually characterized by the combination of the severity of an adverse situation and the probability of the situation of occurring. In P&R framework the three major steps of risk assessment are: (1) to collect available data and identify the degradation processes; (2) to identify risks and quantify their associated adverse impacts through modeling and (3) to mitigate the risks by adopting one or more options for decreasing risks and implementing those targeted actions (Meyer et al., 2009).With the risk mitigation plan the operator can decide to take best action(s) to reduce the adverse impacts of the risk: preventive (design) or corrective (remediation) actions, or monitoring (Figure 6).

Well materials ageing (e.g., cement leaching by fluids formation, casing corrosion and etc.) and uncertainties of the system are integrated and then introduced to a CO_2 flow model in order to assess CO_2 migration along the wellbore over long term. Tools like Design of Experiments are efficiently used to identify the main parameters that could impact the well. The numerical modeling is employed to assess CO_2 migration along the wellbore and to quantify the possible leakage to the different in-risk impartments for various well integrity conditions (i.e., scenarios built from uncertainties related to geometry, cement quality, ageing kinetics and etc.)(Meyer et al., 2009; Le Guen et al. 2008). Then, CO_2 migration through various pathways is obtained and each point of interest (surface, underground water, etc.) evaluated in terms of potential adverse impacts.Results of all the scenarios' assessment are gathered to identify the risk levels (i.e. frequency level and severity level) associated to the well integrity. Information is then introduced into a risk mapping model and an acceptable risk level can be obtained for each compartment (environment, health & safety, economics and etc.). Based on the risk sources, recommendations are proposed in order to treat/mitigate the risks to the acceptable level (Le Guen et al. 2008).

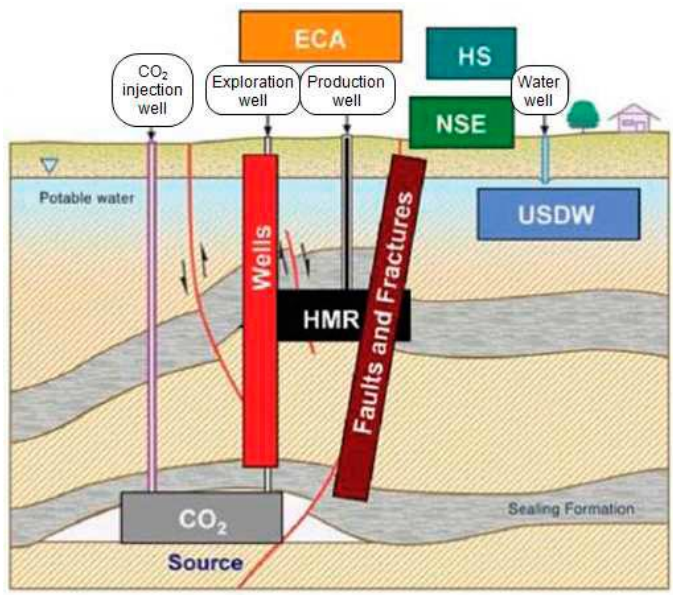

Figure 5. Typical cross section with CFA source and compartments. ECA (Atmosphere); HS (Health and safety); NSE (Near-surface environment); USDW (Underground Water); HMR (Hydrocarbon resources)(Oldenburg et al., 2009)

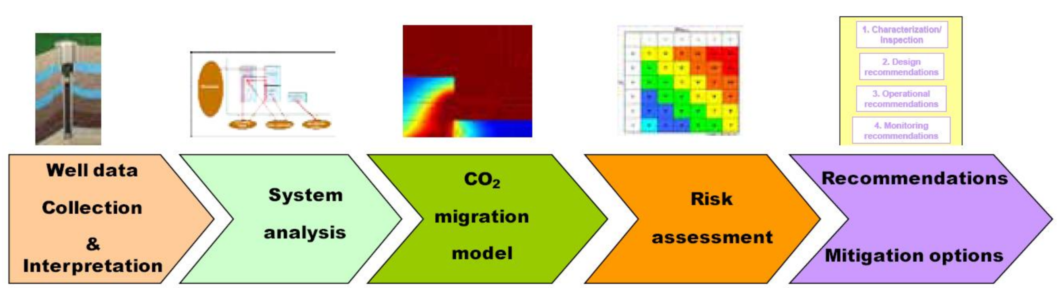

Figure 6. Well integrity performance and risk workflow(Meyer et al., 2009)

2.10 System modeling approach (SMA)

It's a probabilistic simulation approach for performance assessment of geologic sequestration of CO_2. Los Alamos National Laboratory (LANL) developed a computational system-level model named as CO_2-PENS (Predicting Engineered Natural Systems) to perform probabilistic simulations of CO_2 capture, transport, and injection in different geologic reservoirs. In addition, the long term fate of CO_2leakage/migration out of the injected reservoir can be simulated(Stauffer et al. 2009).

The model links together many different process-levels that describe the entire CO_2 sequestration pathway, starting from CO_2capture at surface and injection into the storage reservoir. The CO_2 migration from different conduits such as leaking wellbores, faults/fractures and unsealed caprocks along with mineral formation and dissolution, and atmospheric mixing are simulated(Stauffer et al. 2009). Then,complex interactions between uncertainties are solved to determine the performance of the studied geological sequestration system. It can be done by coupling processes simulation of the probability distributions of each uncertain variable. The combined risk is then used to calculate the overall risk along with the effects of uncertainties on overall risk of the GS project (Stauffer et al. 2009).

2.11 Screening and ranking framework (SRF)

The SRF approach is typically used forpreliminary screening and rankingof a large number of geological carbon storagesitesbased on the HSE (health, safety and environment) risk. This method can be applied to multiple sites with limited data. It's a fast and consistent method to identify the bestcandidate sites, which later are subjected to more detailed site characterization and quantitative risk assessment analyses as discussed in Oldenburg (2008).Three levels of entrapment are assumed in this method,including primary sealing(if leakage occurs through wells and faults), secondary sealing (dispersion of CO_2 plume) and attenuation potential (mixing in atmosphere or ground or surface water).Then, potential of containment/attenuation characteristics of the GS site is assessed to score each characteristic along with the associated uncertainty(Oldenburg, 2008).

It's a dynamic model in which the properties of attributes which have approximate quantities could eventually be measured or modeled with additional site characterization information. Therefore, arbitrary uncertainty can be assigned to the properties of the attributes to evaluate and rank multiple sites relative to each other (Oldenburg, 2008).

2.12 Carbon Storage Scenario Identification Framework (CASSIF)

As explaineed in Yavuz et al. (2009), CASSIF is based on the three main CO_2leakage scenarios (well, fault and seal) where the relevant risk factors can be identified in order to conduct the risk assessment. The main framework of the method is presented in Figure 1, which includes: (1) risk questionnaire creation (FEPQuest), (2) FEP pre-selecting(FEPMan),and (3) workshop.

In the first step, questionnaires should be filled by the experts to obtain the preliminary overview of all the potential risk factors. The questionnaires include about 40 questions to obtain all the required site information such as storage geology, geometry, accessibility, etc. By evaluating the questionnaire the important FEPs can be highlighted and knowledge gaps can be identified along with a summary of the site details. Then, most important FEPs with elevated uncertainties are selected through the FEPMan for more discussion during the workshop. Eventually, the results of the FEOQuest and FEPMan are used for workshop preparation to create potential risk factors and possible scenarios. Three areas of discussion groups normally set during the workshop: (1) well containment, (2) seal containment and (3) fault containment. The results of the workshop describe the possible weaknesses of the studied site based on the FEP based scenarios. The level of the details depends on the requirement for a specific site. Many options can be obtained from the results such as the mitigation strategy and risk evaluation (Yavuz et al., 2009).

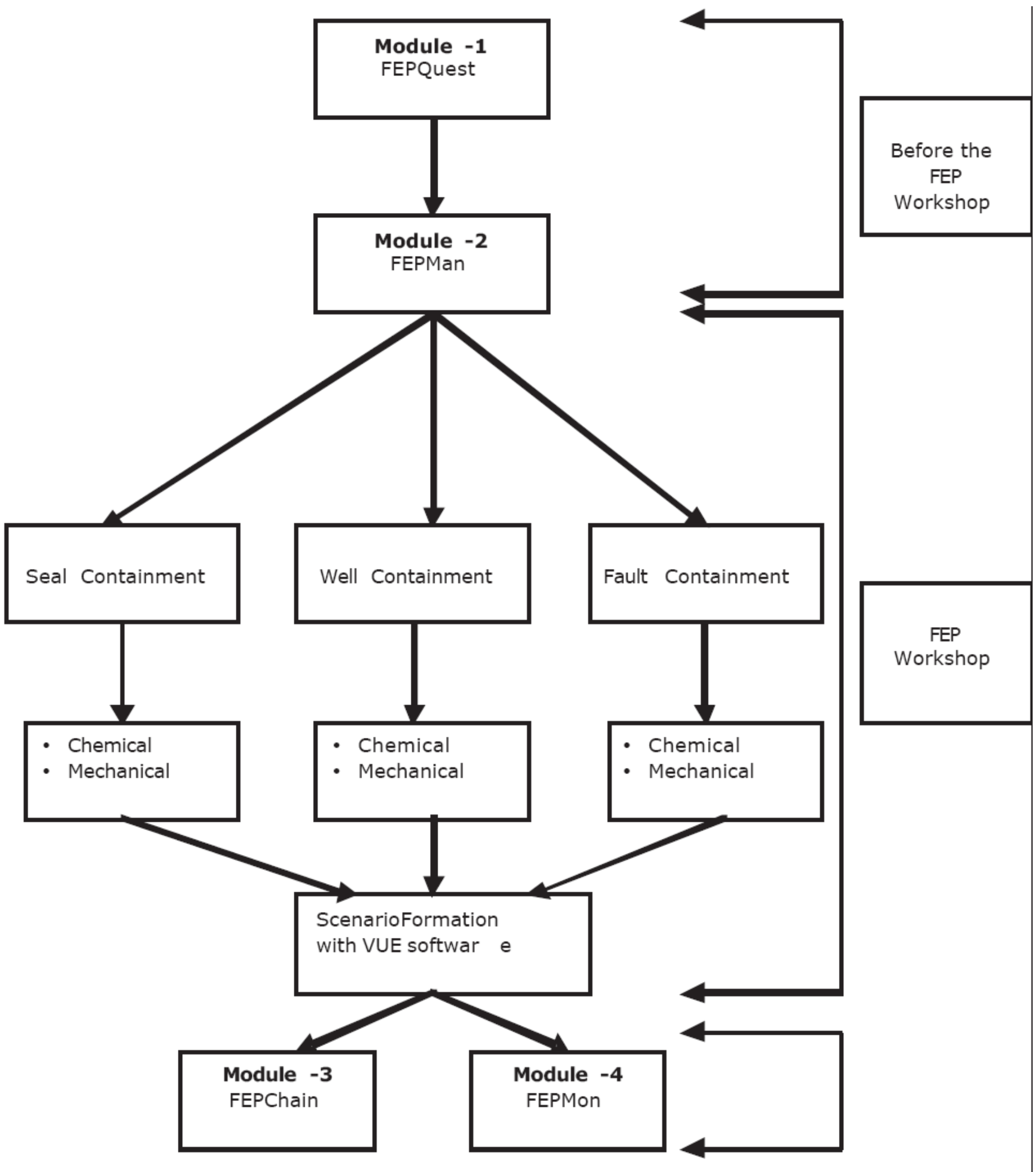

Figure 7. conceptual model of CASSIF(Yavuz et al., 2009)

3. Conclusion

A summary of state-of-the-art of risk assessment (RA) methodsis presented in this paper. Typically two main types ofmethods, including qualitative and quantitative methods, are available for risk assessment. The applications of these methods dependon the stage of thegeological carbon sequestration (GCS) project,includingearly stage with limited available data, or detailed and comprehensive risk assessment for long-term fate of geologically stored CO_2.

RA method can be used as a tool for screening and ranking the different GCS projects for site selection purposes, hazard identification, identify the potential consequence of adverse impacts during the event of the CO_2 leakage, and proposing mitigation and monitoring plan.

In spite of the differences in stages, processes and methodology, there are some similarities in the process of risk assessment which include creating FEP data base, building different possible scenarios, performing risk assessment and consequence analysis and eventually establishing necessary mitigation and treatment plan.

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