Security Assessment on Geological Storage of CO_2: Application to Hontomin Site

Antonio Hurtado, Sonsoles Eguilior, and Fernando Recreo

Abstract The safety and risk assessment of CO_2 storage in geological formations requires a robust and iterative methodology based on an objective assessment, which shall provide an analysis and assessment of potential risks to health, safety and environment. The application of this methodology from the initial stages of the project will facilitate achieving its objectives. The results of the methodology should be twofold: the quality of the site from the point of view of the risks and the associated uncertainties. In the early stages of a project involving scarcely known natural systems, the methodology should take into account the unavoidable uncertainties in the available information and its impact on the risks, through a formalized quantification of those. In these phases the models used are mainly qualitative. As the project progresses and more information is available, the risk assessment methodology should allow gradual and continuous transition from qualitative data based models to quantitative ones.

Taking all these into account, in this work are presented the methodologies commonly used, based on those developed and fine-tuning for the past 20 or 30 years to the study of Deep Geological Repositories of high-level nuclear wastes, as well as the development carried out to estimate the risks of Hontomín Technological Development Plant, implemented under the formalism of Bayesian Networks (BNs).

1 Introduction

Two major challenges for engineering, applied to geology is the development of projects in a complex and uncertain environments. All projects in environments of significant complexity and uncertainty have a higher probability that a combination of variables that generates the materialisation of the risk occurs, defining risk as distribution functions of potential harm or loss associated with an activity

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developed in an environment of uncertainty. It is always opposed to the achievement of the project goals.

Like the great majority of human activities, capture and geological storage of carbon dioxide (CCS) emissions is subject to risks. In fact this technology has a risk level similar to any other type of industrial activity and particularly those related to the oil and gas industry, for which there are specific regulatory frameworks. With regard to the CCS, the problem is reduced mainly to provide satisfactory answers to the questions concerning whether the CO_2 can leak and, if so, what would be the consequences for the environment, health and safety [1]. Stress should be laid on the importance of adequate response to these issues, among other reasons, for their influence on public acceptance of this technology, which being a key element for the implementation of CCS on a large scale [2]. The precise location of a safe storage site, able to sequester CO_2 for long time periods and with minimal risk is essential to gain public acceptance to the application of this technology.

The long-term safety and risk management associated with the Geological Storage of CO_2 should be considered as part of an ongoing and iterative process throughout the project lifecycle. Based on appropriate methodologies, it should establish a robust and reliable framework for identifying, assessing and managing the risks and uncertainties at each stages of the project, including: (i) the identification and initial selection of suitable geological formations; (ii) their characterization; (iii) project development activities; (iv) the operational period; (v) the closure operations in the preliminary stage of transferring facility control; and finally, (vi) the transfer of responsibilities. During all the stages risk management shall aim to improve the knowledge of the system and its risks to support achievement of the project objectives. As outlined in the Guide 1 for the implementation of the European CCS Directive [3, 4] the environmentally safe management of geological storage of CO_2 should be a key objective that must be present at all the stages. Today a broad range of methodologies and approaches are available. It will be necessary to reflect, learn and take into account the skills and limitations of each, so as to make the most of each approach at the different stages of project development [5].

The risk estimation takes into account the whole of the risk pathway from hazard identification to the unwanted consequences and will never be perfect or definitive. The intrinsic nature of the project prevents this to be an achievable goal. However this should not be considered as an obstacle, because, in reality, no risk assessment is perfect or definitive. The aim is not to achieve these levels of perfection but to provide a management support tool to reduce the chances of the emergence of circumstances that may cause the project does not meet the expectations previously established throughout the project development.

2 Geological Storage of CO_2 – Risk Assessment and Analysis

In the case of CCS projects, risks include first of all, those arising from the operation of surface facilities with associated impacts on safety, health and the environment during all phases of capture, pipeline transport (or others) and injection processes. They are similar to those associated with any other engineering project and its evaluation is a common practice in diverse industries such as oil and gas industries. Validated methods are available for quantitative risk assessment that are directly applicable and tools that have been used in other industrial processes. As estimates of probabilities and consequences are directly based on the experience, confidence in the assessment of these risks turns out to be high, but usually not free from bias. The reason for this is that such estimates introduce a type of "over confidence" bias known as "hindsight bias". This is manifested in the fact that, while reporting on the occurrence of an event, you tend to assign a higher posterior probability than the initially assigned to make the prediction. Thus, when reporting on a given fact it tends to be seen as inevitable, i.e., a joint influence of the observed data and previous theories is observed [6]. This means that, as a side effect, is obtained a reduction about the surprised results or events, which is especially important in the evaluation of scientific papers [7] taken as the basis for assigning events probabilities.

Along with the above, in the geological storage of CO_2 there are long-term risks associated with CO_2 leakage from storage or movements induced by it. These can be summarized as local risks associated with effects on the environment or health of the population, and global risks associated with the release of CO_2 into the atmosphere and the impact of such release in the processes of climate change that are trying to avoid the CCS [8].

In general, it is observed that the methodologies proposed for the evaluation of long-term risks arising from geological CO_2 storage (GCS) are based on those that have been developing and adjusting for the past 20 or 30 years during the study of deep geological repositories of high level nuclear waste. Geological storage of CO_2 shares with that field of knowledge the large periods of time and large spatial areas involved [9]. This brings implicit the high level of uncertainty, both associated with the natural environment and the future evolution. Both must be considered in risk analysis to be carried out.

The matters mentioned in the foregoing paragraphs require the identification of all the relevant issues from the point of view of safety in geological storage of CO_2, with the purpose to feed such projects in the future. This should include:

1. The risks identified that actually occurred and its causes;
2. Determine those that we will be able to describe as generic ones and therefore that could affect similar projects;
3. Identify those unique aspects;

4. The issue of risks that did not materialize also must be addressed, as well as the different reasons for that;
5. Determine which risk management measures were effective and determine those that were ineffective;
6. Determine all potential sources of bias and uncertainties.

3 Common Methodologies for Risk Analysis and Assessment

As stated earlier, a key activity in the risk analysis and assessment is to develop and/or adapt methodologies and tools to assess risks to health, safety and environment. That assessment would help to guide the development of monitoring tools that will enable in early detection and remediation. As geological storage of CO_2 is a relatively new research area, new methods are being proposed to perform risk analysis and assessments and there is no well – established method for this purpose [10].

The methodologies developed for CO_2 long-term storage risk assessments are essentially based on the determination of the storage formation potential for retaining CO_2 overtime and, therefore, attempt to determine the long term behaviour of CO_2 initially injected into the formation. These methodologies use systems analysis structured processes to organize and streamline the procedure leading to the definition of scenarios and reduce the role of subjective judgments in determine these. The development of a wide range of risks and the mechanisms that underlie them provides a good basis for a systematic assessment of the risks.

The Risk Analysis and Assessment Methodologies are generally classified into two groups: qualitative and quantitative. When there is a lack of data and/or specific knowledge, a qualitative risk assessment may be sufficiently effective. Among the most common qualitative methods are: Method of FEP (Features, Events and Processes) and scenarios [11], a systematic approach for identifying all relevant system elements from the point of view of its future evolution and subsequent identification of possible scenarios for the evolution thereof; Vulnerability Assessment Framework (VEF) [12], a regulatory and technical framework to systematically identify those conditions that could increase the potential for adverse impacts; and screening and ranking framework (SRF) developed to evaluate potential geologic carbon dioxide (CO_2) storage sites on the basis of health, safety and environmental (HSE) risks arising from possible CO_2 leakage [13].

Quantitative methods are used at a certain level of knowledge about the system under study, where the level of uncertainty is relatively low. Two main types of methods belong to this group: Deterministic Risk Assessment (DRA) [14] and Probabilistic Risk Assessment (PRA) [14, 15].

DRA provides an estimate of risk associated with a specific set of values of the parameters of the models. Therefore, it does not explicitly deal with uncertainty in parameter values. With respect to the values of the parameters used in the models, the best estimate of each parameter has to be taken, performing a single or a few of execution of the model. Often conservative values of the parameters are used to lead to an overestimation of risks, but as the relationship between values and the risk does not have to be monotonous, this overestimation may not be valid or unusable from the point of view of risk management. DRA allows the use of more detailed calculation models. The calculation time may be longer because it does not require a very large number of executions. On the other hand, this also means that both temporal and spatial discretization can be thinner.

Deterministic assessments can also be applied only to a particular aspect of the system, using more sophisticated and detailed partial models. These aspects will be addressed throughout the entire process of assessment of CO_2 storage with more or less detailed models. Sometimes these studies are called Performance Assessment [16].

As mentioned above, uncertainties are not treated in the deterministic risk assessment. However, it is a useful approximation to determine trends and to learn about the behaviour of the system due to the individual variation of the parameters. When the input parameters are well known, DRA gives very precise and accurate results.

PRA provides a probability distribution of the risk connected with the uncertainty in all or some of the values of the parameters. Usually it is associated with the use of Monte Carlo methods where probability density functions are used to describe the possible range of variation in the parameters of the model describing the system. Multiple simulations are performed, each with a set of parameter values that are randomly selected from the probability distribution functions. The result is, in turn, a probability distribution function that evaluates the risk and the uncertainty of the model parameters. Lately alternative methodologies are being developed based on Bayesian [17, 18] or intervals [19] statistics.

Something important in assessing long-term risks of geological storage of CO_2 and related to uncertainty is the identification of the possible scenarios of system evolution. The methodology for developing scenarios is the procedure for identification and description of those that could influence the behaviour of the geological storage during the evaluation period. The need to perform a scenario development in behaviour and risk assessments arises from the fact that it is virtually impossible to accurately predict the evolution of the system over a long period. The scenario development phase aims to achieve a set of scenarios that describe the behaviour of the system overtime to provide a reasonably complete picture of the evolutionary paths of the system. These scenarios broadly define the context to perform the steps of modelling and the analysis of consequences. This is because the potential long-term behaviour in the geological environment should be assessed and the possible migration pathways and mechanisms should be defined. And all this depends on the scenario under consideration [20].

Among the systematic methodologies for developing scenarios, the scenario analysis approach, which includes analysis of FEP, can be mentioned. It was successfully applied in the field of radioactive waste disposal to assess the problem of long-term behaviour of radioactive waste in the geological environment [21]. In addition it is the approach taken, for example, in the Weyburn Project in the part of performance evaluation and safety of the geological storage of CO_2 [22].

Each scenario may be considered a set of FEP and their interactions. The scenarios in turn are the starting points for the selection and development of physical–mathematical models. Details of the resolution of the various storage components of a model can vary significantly depending on the primary objectives of the evaluation, and the treatment of the uncertainties. The main disadvantages of this method are that it requires a lot of specific information of the site under consideration and that consumes a significant amount of resolution time.

A significant amount of information, much of it from the expert judgment (EJ) should be used. Therefore it is important that the methodology includes a plan of documentation designed to collect all the process and the justification for the performed scenarios selection, always looking for a maximization of traceability and transparency.

In this context, the generation of databases of international FEPs have proved a valuable asset in the field of radioactive waste storage as well as a useful tool for auditing lists of FEPs. In the framework of the European programs and in regard with the Weyburn research projects, QUINTESSA [23] developed a database of generic FEP for CCS, which includes the FEPs related to long-term safety and storage behaviour after CO_2 injection and sealing of injection wells. In this database the FEPs associated with the injection phase that may affect the long-term behaviour of the geological storage are included. This database was inspired on the FEP database NEA/OECD [24]. Currently it includes about 200 FEPs sorted into categories, with their description, references, links to other databases, etc., and has the potential to serve as a "knowledge base" for the geological storage of CO_2.

The most important applications of the FEPs analysis and scenarios are [24]:

- Encouraging extensive discussions among members of the evaluation team and independent experts during the identification of relevant FEPs.
- Providing a source of information that can be used for the development activities of scenarios and models.
- Providing a framework to store information about FEPs and whether or not they are included in the evaluation models.
- Operating as a tool to audit the models used in the evaluation to ensure that all relevant processes are included, or help in specifying the future needs in developing models or data acquisition.

The various options that have been presented above are not the only ones that have been used in the field of CO_2 capture and storage [10].

Therefore, quantitative techniques can be subsumed under the DRA or PRA headings, although they may differ in the simulation codes used and/or in the stochastic approach. In the same way, there is a wide range of qualitative techniques that systematize information from EJ and that focus on different aspects of risk management (stakeholder communication, conceptual framework for regulators, hazard identification, evaluation of alternatives in multiple objective, etc.). Thus, in the initial stages, where qualitative methods are most suitable, it will be necessary to take into account the objectives pursued in the project to choose the methodology that best suits them.

4 Application of Methodologies to the Hontomín Technological Development Plant

One aspect to consider within the *Compostilla* (OXYCFB300) project was the construction of the facilities of a CO_2 storage pilot plant. For this, the first phase required the identification and initial selection of geological formations accomplishing certain requirements of suitability, among which highlights the fulfilment of the safety, health and environment criteria during the storage time [25].

The first step for evaluating the long-term safety related to the geological storage of CO_2 was conducted during the site selection process. Specific research [5] was required since no enough detailed information for the site to make an analysis of scenarios and assigning probabilities in order to perform a probabilistic analysis was available.

A method of selection and classification of formations (SCF) which evaluates the potential of possible geological storage of CO_2 was used for the first stage. The method is based on the analysis of risks to health, safety and environment (HSE) derived from potential CO_2 leaks [26].

The methodology is designed in such a way so that it can be applied at sites with limited data. The necessary data of general character are mainly based on the expert opinion and will be a function of the degree of characterization available for sites.

The methodology considers uncertainty as input and output values of the same, because of the fact that a lack of data is an expected condition in most processes of site selection, especially in the early stages. The overall uncertainty in this context is broadly defined and includes both uncertainty in the parameters (e.g., the degree of knowledge of a particular property) and variability (e.g., the degree of variability that has a certain property). The overall uncertainty reflects the confidence of the evaluator wherein the site characteristics are well known. Therefore, the methodology enables in comparing the sites, taking into account both the HSE risk expectation and the estimation of the level of knowledge of the risk.

4.1 Areas of Study and Results

The methodology described above was applied to three location areas as potential sites for the pilot plant named *Huérmeces*, *Huidobro* and *Leva*. These areas are located in the western part of the so-called “Cantabrian Basin” and the regional scheme of the study area can be seen in Fig. 1.

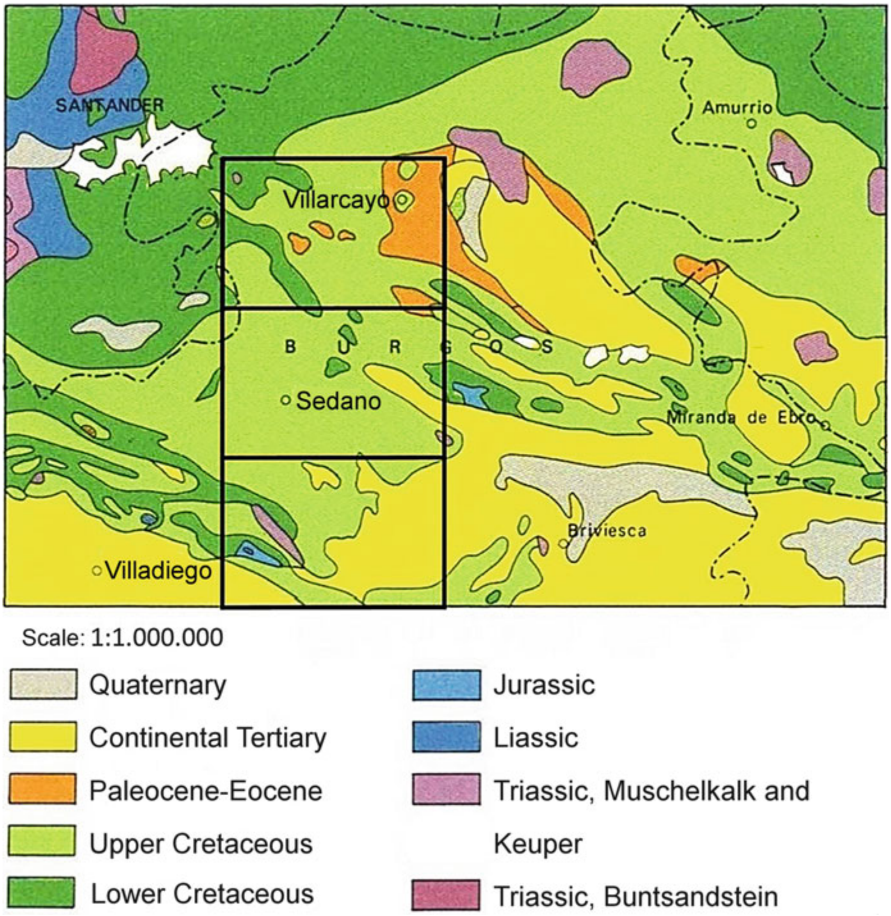

Fig. 1 Regional localization of the three areas studied (*Leva* (*up*), *Huidobro* (*middle*), *Huérmeces* (*down*) (Modified from Ref. [27])

The main benefit of the applied methodology is that it formally expresses knowledge and uncertainties associated with the assessment, which in future iterations could be reviewed and modified if new data becomes available. The system supports a wide degree of versatility, allowing the evaluator to assign different weights depending on the relative importance for the risk of the properties defined for evaluation. Since this would make the direct comparison among areas much more complex, therefore in the present work, weights assigned to the various properties were considered to be the same for all locations under study. However, the transparency of the system and its simplicity allows any reviewer to alter the assigned weights and further analyses to compare the effects of these changes on the response of the site.

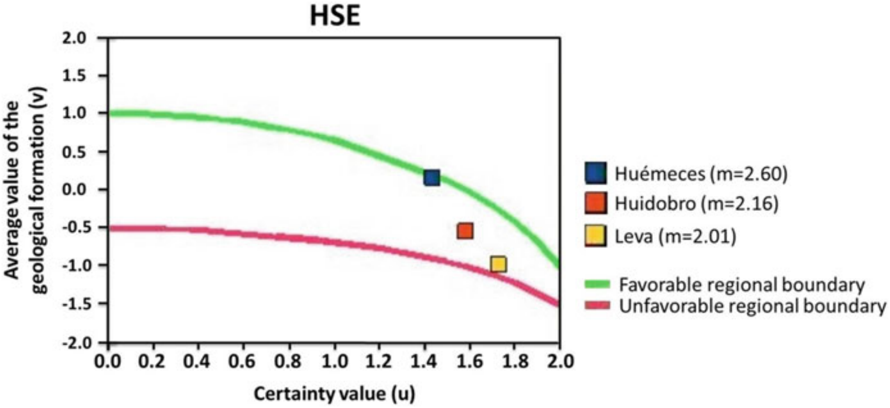

Fig. 2 Final evaluation of study areas

The methodology has allowed establishing an order that quantifies the relative suitability of a potential pilot site for CO_2 injection with respect to the other candidates. A summary of the results of the methodology applied to the locations is illustrated in Fig. 2. Of the three areas studied, *Huérmeces* is the one with the best results in the relative evaluation of the considered characteristics, with an average magnitude for the formation of 2.60 (the magnitude is the distance between the point and the origin), mainly associated with the certainty in the knowledge of the properties of the formation, since the magnitude of its "average value of the formation" evaluator index is only slightly positive (0.17). The other two formations share a high level of certainty, although mean values in both of them are negative ones (*Huidobro*,-0.54; *Leva*,-0.97) and therefore are at an evident disadvantage as compared to the former one as potential sites for an injection pilot plant. Table 1 shows the final assessment of the areas and the summary of the results is expressed.

The storage formation probably better qualified in the area of *Huérmeces* (*Hontomín* Anticline sector) is the Clastic Lias Unit, a limestone level inter bedded with limestone and dolomite levels, 114, 92 and 62 m thick at boreholes *Hontomín*-1, *Hontomín*-2 and *Hontomín*-3, respectively, to which is attributed a medium permeability value and constitutes a deep saline aquifer at hydrostatic pressure with a slow flux. In the borehole *Hontomín*-3, the storage formation is situated between 1238 and 1300 m depth, and the existence of a fault at a depth of 1259 m that causes total temporary loss of drilling fluid has been identified, which could compromise the tightness of it.

So, the finally selected site called *Hontomín* offers the following strong points:

- Primary containment: includes the storage level and the primary seal, expressing the target formation having a potential to contain CO_2 in the long term. An average attributes value of 0.67 in a range of 2.00 (excellent)/−2.00 (inadvisable) is obtained, which puts it above the "good performance" curve, with an

Table 1 Summary of the main results

	Prim. Cont.		Sec. Cont.		Atten. Pot.		Formation		
	Value	Cert.*	Value	Cert.*	Value	Cert.*	Value	Cert.*	Magnitude
Huermeces	0.67	1.84	0.18	1.12	−0.35	1.34	0.17	1.43	2.60
Huidobro	0.50	1.47	−2.00	2.00	−0.11	1.28	−0.54	1.58	2.16
Leva	−0.82	1.78	−2.00	2.00	−0.10	1.40	−0.97	1.73	2.01

*Cert. – certainty degree

average certainty degree of 1.84 out of a maximum 2.00, based on the borehole data at a reasonably well known level.

- Secondary containment: expresses the potential of an additional containment in case of leakage in the target formation. It is rated with an average of attributes of 0.18, slightly below the "good performance" curve, with an average certainty degree of 1.12.
- Potential of attenuation: expresses the ability of the site, including the overburden above the secondary seal, to mitigate or disperse any eventual leakage of CO_2 in the case of successive failure of the primary and secondary containment (multiple barrier concept). The resulting valuation is low, with an average value of −0.35, above the trace of the "unfavourable behaviour" curve, being −2.00 for an inadvisable site, and with a certainty degree of 1.34 on 2.00.

4.2 Risk Assessment Through a Methodology Based on Bayesian Networks

To advance in the risk assessment of the site selected in the previous phase, a methodology based on Bayesian networks (BN) has been developed [17]. The Bayesian point of view provides tools to cope with the resolution of problems in complex systems that require quantifying uncertainty by estimating a probability. It interprets probability as a measure of subjective belief as long as the axioms of probability are not violated and is accompanied by the Bayes Theorem as an updating rule of probability values as a function of new observations.

The Bayesian point of view allows a combination of quantitative probabilistic data from, for example, calculation models and/or databases, with qualitative estimates of probability coming from, for example, a EJ This allows a transition from some initial qualitative models to final quantitative models going through intermediate steps combining both types of probability estimates.

The development of models based on BNs for a description of these systems is not an easy task. However, it represents an attractive tool of making connections between different elements, because of the simplicity of its maintenance and because it allows taking decisions under uncertainty. Furthermore, this methodology given its conceptual development, allows the realization of fundamental activities in risk analysis of any CO_2 geological storage project, such as mathematical analysis (areas of maximum and minimum variation, zones of stability, etc.) or sensitivity analysis to estimate both the impact of different variables on the uncertainties of the system, and the level of uncertainty of different conceptual models, fundamental questions for the treatment of these uncertainties.

The application of this methodology for estimating the probability of risk of leakage in an GCS means modelling of a complex system, as illustrated in Fig. 3, where the global dependency graph between risk variables from an GCS are shown.

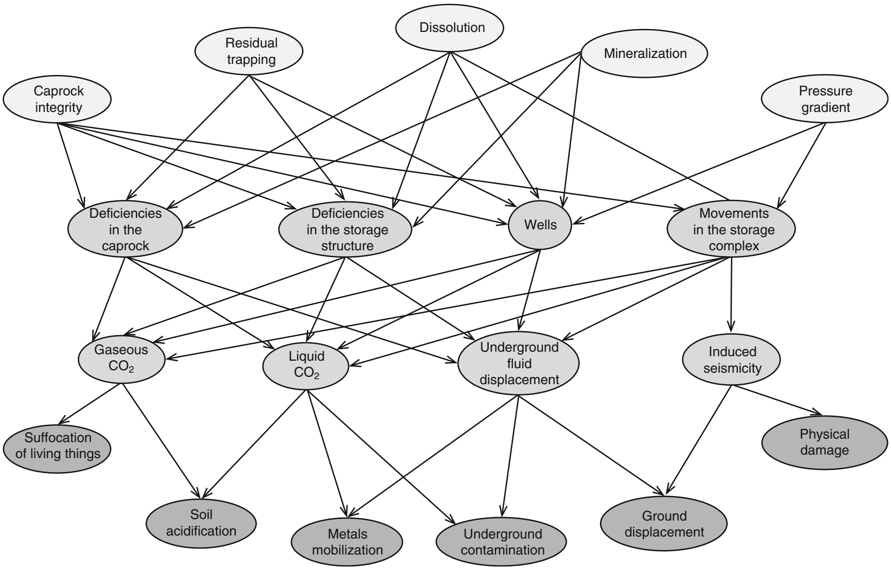

Fig. 3 Global dependency graph between risk variables derived from geological storage of CO_2

This BN model is oriented towards estimating the probability of system leakage. Its application in the early stages of the project implies that there will be a significant shortage of data. To overcome this situation, the model must be supplied with qualitative information, for example, from EJ to assess the initial conditions and offering the best answer.

This initial state of the assessment problem must be overcome gradually depending on the progress of the characterization studies and generation of modelling based on a gradual replacement of qualitative estimates by physical/chemical-mathematical models.

4.2.1 Implementation and Results

The model was applied to the *Huérmeces* area to be tested. Previously this area was the subject of an assessment of Selection and Classification of Formations (SCF) type, based on the analysis of possible CO_2 leakage resulting from the HSE methodology [26] and discussed above.

To this end, the proposed methodology applies the same criteria as in SCF. Thus the qualitative probability was coded on a scale from "0" (CO_2 leakage probability equal to 1) to "4" (no chance of leaking CO_2); and the degree of certainty was coded from "0" (weakly assumption based on objective data) to "2" (accurate measurement). This was because it is considered that including more levels only brings greater subjectivity to the evaluation given the level of information available. For practical purposes, it was decided to decouple the edaphic capacity of attenuation of potential leakages from the other sub-systems due to the lack of information thereof.

The model identifies CO_2 leakage scenarios, prepared from [28–30]. Namely:

- CO_2 leakage through wells.
- CO_2 leakage due to the fracturing of the caprock by over-pressurization.
- CO_2 leakage through the pore system of the caprock, either by overpressure or by the presence of an undetected zone of high permeability.
- CO_2 leakage through a fault.
- Brine migration from the geological formation.

It should be noted that there are significant differences between the two methodologies. The SCF methodology provides relative comparisons between sites but does not include relations between parameters, simulations or assignment of probabilities. It makes impossible to carry out quantitative safety assessments.

Figure 4 shows an example of a BN from the probability model risk of leakage in geological storage of CO_2 applied to the *Huérmeces* study area. It was applied a colour code to display quickly the system information that is known and the influence of different variables (listed in the Table 2) on the estimated probability of the leakage risk value:

- Red indicates that the value of the probability of risk of leakage of the generic variable Vi is greater than 0.5. That is: $P\ (Vi) > 0.5$. The value of this variable may have been initially provided by the method of EJ in the case of a "root" variable, or it may have been derived from the application of the BN inference rules for the variables other than the root ones.
- In a similar way, the green colour indicates that $P(Vi) < 0.5$
- Finally, the blue colour indicates that $P\ (Vi) = 0.5$. This value is justified by the lack of information on this root node generic variable Vi. In the event that a variable Vi satisfies exactly that $P\ (Vi) = 0.5$, either derived from the application of EJ or by applying the BN rules of inference, the chosen colour was red.

Given the colour code it is easy to distinguish the variables that provide information to the model. Since this methodology takes into account uncertainties, the value of the estimation is given as a range of values, between an upper and a lower one. An approximate figure of 80 % is achieved in the BN that determines the upper range. And about two thirds of them provide information for CO_2 leakage. Such information should be supplemented by sensitivity analyses that indicate the relative importance of each of the variables in the contribution to the total uncertainty of the system, which is influenced by both the value itself as the network position of the variable and its associated dependencies.

For the study area, the estimated qualitative probability range of leakage risk is between 0.33 and 0.66, expressed in arbitrary units (au), with an associated dispersion value of the results of $d = 0.65$ (see Fig. 5). Given the conditions set out above, after eliminating the influence of the model variables related to the edaphic capacity

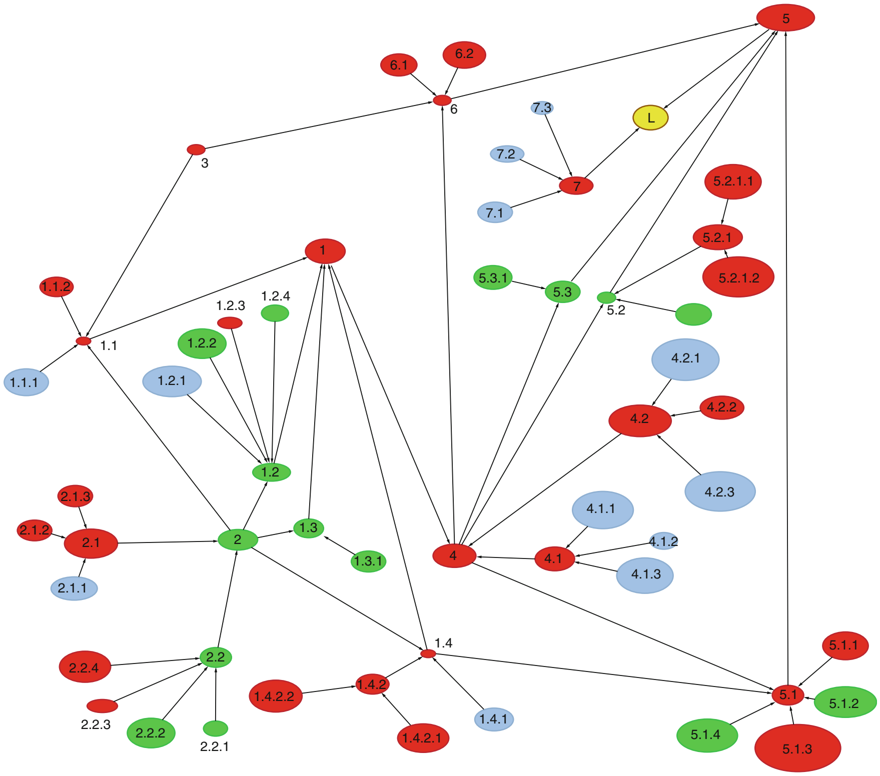

Fig. 4 Example of a Bayesian network from the leakage probability model risk in CO_2 geological storage applied to the Huérmeces study area

of attenuation of potential leakages, the probability range obtained is $p \in [0.41 - 0056]$ au, with a value of $d = 0.31$.

Comparing these results with those obtained in the evaluation of the same area using the methodology SCF [31] is consistent. Both methodologies conclude that the study area is qualified as an intermediate level of goodness for the geological storage of CO_2. Also similar resulting values are obtained in regard to the estimation of uncertainties.

To introduce statistical calculations, the model has been implemented in GoldSim [32] high-level programming language for the resolution of complex dynamic systems. This implementation allows to obtain the qualitative functions of probability (density or cumulative) of the storage subsystem (or primary), its convolution with the secondary containment subsystem (or secondary), and the probability function of the edaphic dispersion subsystem decoupled from previous ones. From these functions the estimation of the qualitative probability of global leakage risk is obtained. This is shown in Fig. 6.

Table 2 List of Fig. 4 codes

1 – Leakage in the primary containment system	1.1 – Geological fault in primary containment	1.1.1 – Presence of tectonic fault	
		1.1.2 – Permeability of the geological fault	
	1.2 – Caprock	1.2.1 – Injectivity of the storage geological formation	
		1.2.2 – Demonstrated sealing	
		1.2.3 – Thickness	
		1.2.4 – Permeability	
	1.3 – Structural leakage	1.3.1 – Lateral continuity	
	1.4 – Wells	1.4.1 – Number of active wells	
		1.4.2 – Abandoned wells	1.4.2.1 – Number of Abandoned wells
			1.4.2.2 – Permeability
2 – Extent of the CO_2 plume	2.1 – Geological environment conditions	2.1.1 – Geothermal gradient	
		2.1.2 – Hydrology	
		2.1.3 – Pressure gradient	
	2.2 – Storage geological formation	2.2.1 – Depth	
		2.2.2 – Porosity	
		2.2.3 – Pore fluid	
		2.2.4 – Permeability	
3 – Tectonics			
4 – Extent of the CO_2 plume in the secondary containment	4.1 – Permeable geological formations	4.1.1 – Permeability	
		4.1.2 – Pore fluid	
		4.1.3 – Porosity	
	4.2 – conditions of the geological environment	4.2.1 – Geothermal gradient	
		4.2.2 – Pressure gradient	
		4.2.3 – Hydrology	
5 – Leakage in secondary containment	5.1 – Seal geological formation	5.1.1 – Thickness	
		5.1.2 – Depth	

(continued)

Table 2 (continued)

		5.1.3 – Demonstrated sealing	
		5.1.4 – Permeability	
	5.2 – Wells	5.2.1 – Abandoned shallow wells	5.2.1.1 – Number of abandoned shallow wells
			5.2.1.2 – Permeability
		5.2.2 – Number of active wells	
	5.3 – Structural cause leakage	5.3.1 – Lateral continuity	
6 – Secondary containment fault	6.1 – Permeability		
	6.2 – Tectonic fault		
7 – Soil dispersion	7.1 – Permeability		
	7.2 – Thickness		
	7.3 – Landuse		
L-Leakage			

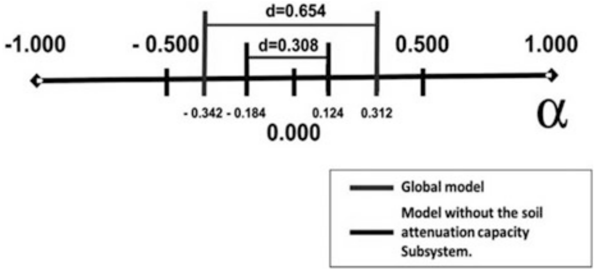

Fig. 5 Graphical representation of the results (range and dispersion) of qualitative probability estimation of risk of leakage of CO_2 in the *Huérmeces* study area for geological storage of CO_2, applied to the global system as well as the storage and secondary containment subsystems

The simplified results of the partial sensitivity analysis developed are reflected in Fig. 7. This is a partial analysis given that the influence of edaphic dispersion subsystem is not taken into account. Comparing the importance of the input parameters on the results leads to the conclusion in a clear manner about the domain of the secondary subsystem in contributing to the system uncertainty. This in turn leads to the conclusion about the importance of improving knowledge of this part of the system in order to reduce the uncertainties associated with these estimates.

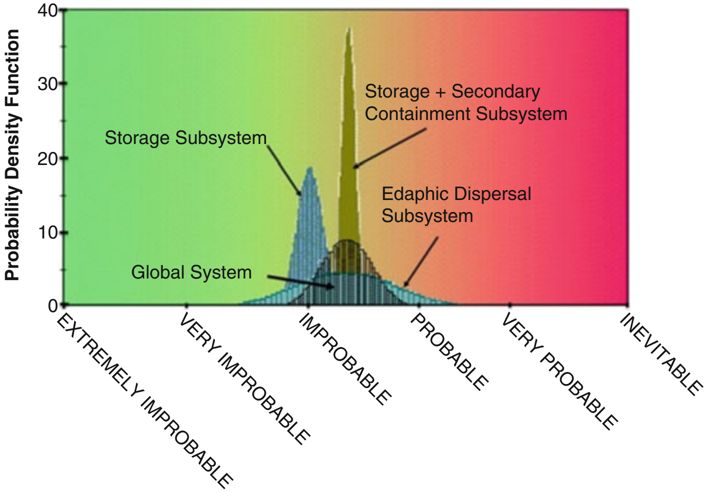

Fig. 6 Qualitative density probability functions from the stochastic model of leakage risk by applying to the Huérmeces study site

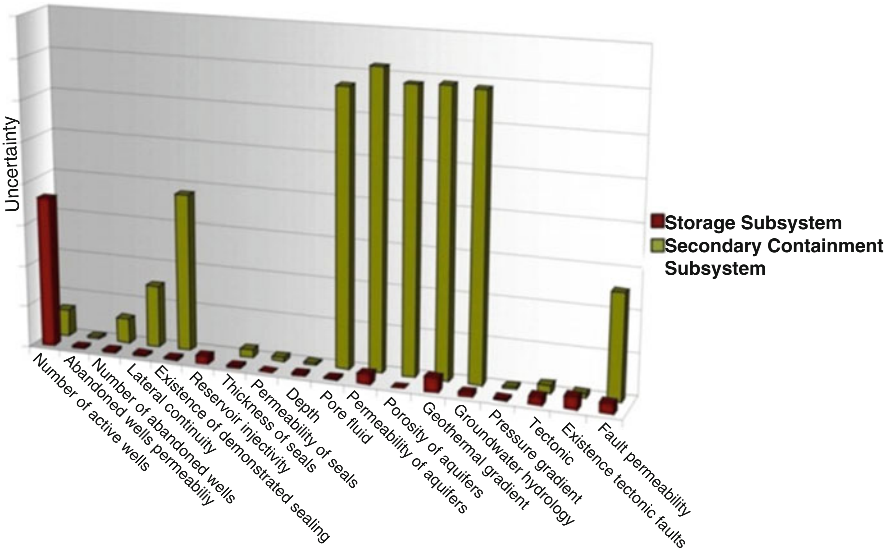

Fig. 7 Partial sensitivity analysis from the qualitative probability of leakage risk applied to the Huérmeces study site

5 Conclusions

The intention of this paper has been to show that it is possible to provide new information with a dimension of risk management from existing data, by selecting and developing appropriate methodologies, from the early stages of the project and under the current terms offered by this technology of CO_2 geological storage.

The safety analysis and risk assessment, based on appropriate methodologies should be able to assess the risk associated with geological storage of CO_2. All the approaches provide valuable elements. The choice of the appropriate methodology depends on the state of the project, the available data and objectives. Taking into account the above, it has been necessary to reflect, learn and consider the positive aspects of each approach and its limitations to get the best part out of the various approaches to the task of risk control. In our opinion a key issue in the development of such projects is that whatever the main risk assessment methodology is applied, it is necessary to include an assessment of the uncertainties associated with the process in order to facilitate the subsequent decision making.

One of the major constraints to overcome to the development of the studies, as we have reported here, is that there is currently no standardized method or combination of methods to assess the risk for these projects. This is in spite of the fact that since the capture and storage of CO_2 was proposed as a mitigation option to reduce anthropogenic emissions of CO_2 there have been many attempts to study potential long-term risks of CO_2 storage in geological formations and various projects worldwide have tried different industrial-like methods adapted to the geological storage of CO_2.

The lacks of data, especially in the early stages, and the level of uncertainty associated with project development have made it impossible for us the application or adaptation of quantitative risk assessment methods from industrial methods. It can be concluded that these methodological approaches are not a convenient starting point in the current development of these projects. Therefore it has been necessary to develop both a specific framework and a qualitative method that allows for a gradual introduction of quantitative methods from qualitative data as the most appropriate methodological approach suitable for ongoing projects.

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