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1 Quantitative risk assessment in the early stages of a
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4
5 *Louis de Lary^a, Jean-Charles Manceau^a, Annick Loschetter^a, Jeremy Rohmer^a, Olivier Bouc^a, Isaline*
6 *Gravaud^a, Christophe Chiaberge^a, Pierre Willaume^b, Thierry Yalamas^b*

7 ^a BRGM, 3 av. C. Guillemin BP36009, F-45060 Orléans Cedex 2, France

8 ^bPHIMECA, 18/20 Boulevard de Reuilly, 75012 Paris, France

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12 Corresponding author:

13 E-mail address: l.delarydelatour@brgm.fr (L. de Lary)

14 Tel.: (+33) 2 38 64 46 24; fax: (+33) 2 38 64 36 89

15 **Abstract**

16 Methodologies for quantitative risk assessment regarding CO₂ storage operations are currently
17 scarce mostly because of the lack of experience in this field and the relatively significant
18 uncertainty degree regarding the subsurface intrinsic properties and the processes occurring
19 after the injection starts. This paper presents a practical approach designed to perform a
20 quantitative risk assessment in an uncertain context. Our approach is illustrated on a realistic
21 case study (Paris basin, France), conceived to be representative of the level of information
22 available in the early stages of a project. It follows the risk assessment principles from the
23 international standard (ISO 31000:2009), which are adapted to account for the specificities and
24 challenges of subsurface operations. After the establishment of the context of the specific case
25 study, the main risks were identified and we analysed two different risk scenarios (risk of brine

26 leakage from an abandoned well, risk of subsurface use conflict). These scenarios were
27 selected to give a comprehensive overview of different types of analysis in terms of available
28 data, modelling tools and uncertainty management methodologies. The main benefit of this
29 paper is to propose an approach, based on existing risk assessment standards, best practices and
30 analysis tools, which allows an objective quantitative risk analysis taking into account the
31 uncertainties, and therefore enables a fully informed decision-making while evaluating risk
32 acceptability.

33

34 **1 Introduction**

35 The aim of Carbon dioxide Capture and Storage (CCS) is to contribute to the limitation
36 of anthropogenic CO₂ release in the atmosphere by capturing CO₂ and storing it permanently in
37 appropriate deep (usually > 800 m) geological formations among which saline aquifers are
38 seen to provide the best world-wide geographical distribution and storage capacity.¹ As for
39 any industrial activity, the development of environmentally and healthy safe CCS must rely
40 on robust risk assessment and management on the short as well as on the long term period to
41 comply with regulatory frameworks, such as the CCS Directive in the European Union
42 (Directive 2009/31/EC).²

43 Risk management, as standardized by ISO 31000:2009,³ is a continuous and iterative loop
44 that comprises the following processes: 1) establishment of the context defining the objectives
45 of the risk management, the input parameters/data and the risk criteria used to evaluate the
46 significance of risks, 2) risk assessment that consists in the identification, analysis and evaluation
47 of risks, 3) risk treatment that aims at reducing the level of risk, 4) communication with internal
48 and external stakeholders and 5) monitoring and review of the risk management process. This
49 paper focuses on risk assessment. The specific purpose of this step, regarding the
50 ISO 31000:2009 standard is to supply information on different risks in order to allow an
51 informed decision-making regarding the level of risk and to decide whether the different risks
52 need to be treated. Basically, during risk assessment, the risks potentially relevant are selected
53 (risk identification), then their consequences on vulnerable elements and their likelihood are
54 further studied (risk analysis). The risks acceptability and the necessity for treatment are
55 finally evaluated (risk evaluation).

56 Risk assessment is particularly novel for the geological storage part of CCS, compared to the
57 surface facilities and activities (capture and transport) for which more classical industrial
58 safety practices apply. Up to now, the CO₂ geological storage experience is limited and only

59 six sites are currently in operation or at an advanced stage worldwide¹. Some experience can
60 be gained from other underground operations; but the specificities of each activity regarding
61 the risks they induce make difficult the direct transposition of the methodologies and tools to
62 deal with them.⁴ Enhanced oil recovery, consisting of injecting CO₂ to recover a larger
63 quantity of oil does not have the same primary purpose of CO₂ confinement as CCS. Natural
64 gas seasonal storage, even though it could focus on similar geological formations, is different
65 in terms of injected fluid and associated interactions with native fluids and formations, and in
66 terms of storage time scale (1 to few years for natural gas storage vs. at least centuries for CO₂
67 storage). The different context and processes are also a reason why the analogy between
68 carbon storage and nuclear waste storage should be done only with care. The lack of
69 experience can make difficult the risk identification because new risks need to be considered.
70 Besides, the consequence and likelihood analysis requires new tools and new risk criteria have
71 to be set to enable the risk evaluation.

72 In addition to the lack of experience, risk assessment is particularly challenging for CO₂
73 geological storage because safety significantly relies on the natural properties of the geological
74 storage complex and their evolution over long term time scale. In contrast with common
75 industrial risks where the engineered components of installations are well known because they
76 are the result of construction of human being and because of experience, the geological
77 reservoirs and associated features properties are: 1) inherently variable (aleatory uncertainty)
78 and 2) our knowledge of these objects is always incomplete and imprecise (epistemic
79 uncertainty).^{4,5} CO₂ storage projects therefore face a high degree of uncertainty, especially in
80 their early stages because the knowledge of the site is limited.

81 Furthermore, understanding and representing the phenomena occurring with the injection of
82 CO₂ is also complex. The behaviour of a storage site is a combination of multiple processes -
83 multiphase flow, mechanical, geochemical, thermal, biological - , occurring at different

¹<http://www.globalccsinstitute.com/projects/browse>, accessed April 1, 2014

84 spacescales- pore-scale, rock sample, near well bore, reservoir, regional - and time scales -
85 from several years to a few centuries - , and potentially coupled. These phenomena may not be
86 perfectly known and even if they are, assumptions are usually made during the models
87 construction.

88 Considering notably these elements and the nature of geological risks, suggested approaches to
89 assess risks related to CO₂ storage are mostly considered as qualitative or semi-quantitative and
90 few could be considered as quantitative.^{6-9, 34} The boundaries between methods are often quite
91 difficult to draw. From the ISO 31010:2009 standard,¹⁰ qualitative assessment uses qualitative
92 scale (such as “high”, “medium” and “low”) to define consequences, probability and the level
93 of risk. Semi-quantitative methods use numerical scales to assess the level of consequence
94 and probability and use a formula to deduce the values for the level of risk. Quantitative
95 assessment estimates values for the consequences and the associated probabilities and gives
96 values for the level of risk. Among existing approaches, uncertainties on parameters are often
97 not taken into account explicitly and the distinction between the two facets (aleatory and
98 epistemic) is rarely considered.

99 The objective of this paper is to propose an approach for preliminary quantitative risk
100 assessment and risk treatment decision support adapted to the constraints explained above and
101 based on the international standards on risk management (ISO 31000:2009). By preliminary,
102 we mean that this approach is adapted to the early stages of a project, when the site has been
103 selected but before the beginning of the injection operations. The approaches dedicated to the
104 risk assessment update, notably using monitoring data over time, are therefore out of the scope
105 of this paper. This preliminary study is characterized by a relatively high level of uncertainties
106 regarding the knowledge of the site, which gives rise to uncertainties on the predictions of the
107 storage evolution. In this paper, the approach we suggest is implemented on a realistic case

108 study (Paris basin, France), conceived to be representative of the level of information
109 available in the early stages of a project.

110 The remainder of this paper follows the different steps achieved for this implementation, in
111 accordance with the ISO 31000:2009 workflow and terminology for risk assessment: first, the
112 case study and the data available are described (section 2, establishment of the context), then
113 we explain how the risks were identified and the scenarios to analyse were deduced (section 3,
114 risk identification). In section 4 (risk analysis) we focus the assessment on two scenarios in
115 order to quantify the risks accounting for the uncertain context. These two scenarios were
116 selected to give a representative overview of different types of analysis in terms of data
117 available, modelling tools and uncertainty management methodologies. The purpose of
118 presenting the analysis of these two scenarios is to illustrate the approach we propose; the
119 results of modelling are entirely secondary. Finally, in section 5 (risk evaluation) we
120 provide elements to perform the evaluation of the risks acceptability. In each section, we
121 describe the method and then the results obtained on the case study. In the end, the application
122 of these steps shows how the challenges linked with CO₂ geological storage could be
123 accounted to perform a quantitative risk assessment of these operations and to provide
124 objective and scientific elements to the stakeholders for decision-making regarding risk
125 management.

126 **2 Establishment of the context**

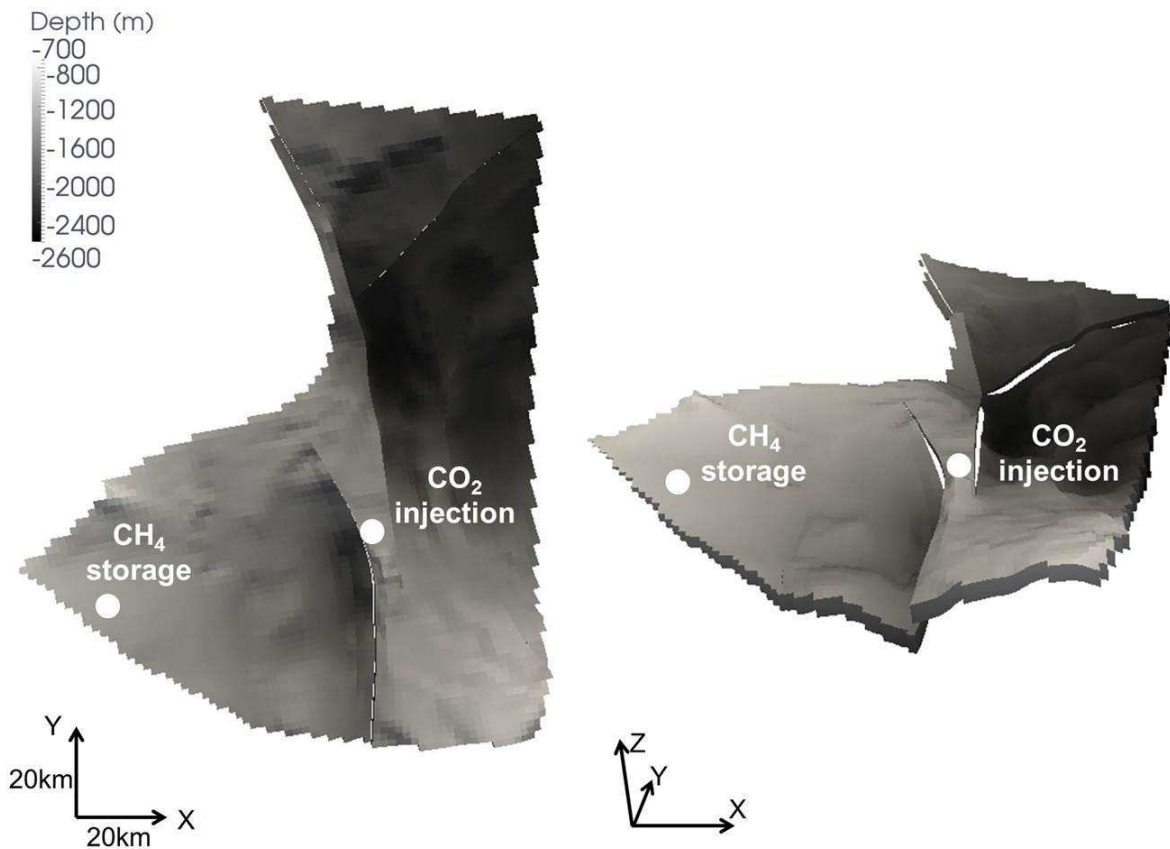
127 The establishment of the context requires the definition of the objective and the scope of the
128 risk management. The objective is here to assess the risks for the existing vulnerable
129 elements during the operations and the short term monitoring phase between the injection
130 stopping and the transfer of responsibility to the competent authority (> 20 years according to
131 the European Directive on CO₂ storage).² Long term assessment is excluded from the study.

132 Another key aspect of the establishment of the context is the gathering of existing data and
133 associated uncertainties necessary for the assessment, which comprises the geological media
134 (geological, hydrogeological and petrophysical properties), the planned operations (rate,
135 duration) and the existing vulnerable elements (populated areas, aquifers, sensitive areas at
136 ground level, other activities).

137 The case studies chosen in this paper have been the subject of previous works and have been
138 designed as an area with a good CO₂ storage potential.^{11,12} No CO₂ storage has been performed
139 nor actually planned in this region, but these previous studies provide enough raw data to
140 consider this site as a realistic case study. The considered area is located in the Paris Basin,
141 which is the largest onshore sedimentary basin in France covering a large surface
142 (110,000 km²) in the North of France.¹³ The central part of the Basin is filled with about
143 3000 m of sediments.

144 The methodology used for the storage formation and injection point selection in previous
145 studies was based on a screening phase that integrated the geological, environmental and legal
146 constraints.¹⁴ Decision was supported by a Geographical Information System (GIS) compiling
147 the data about geology, other subsurface activities, faults, deep wells, deep aquifers, density
148 of population, sensitive ecological areas, seismic hazard and industrial activities, thus
149 enabling the delimitation of exclusion zones using criteria related to risks, costs, operation and
150 conflicts of interests. The selected saline aquifer is the lower Triassic (Keuper) sandstone

151 reservoir formation (see Figure 1). At the selected injection point (see



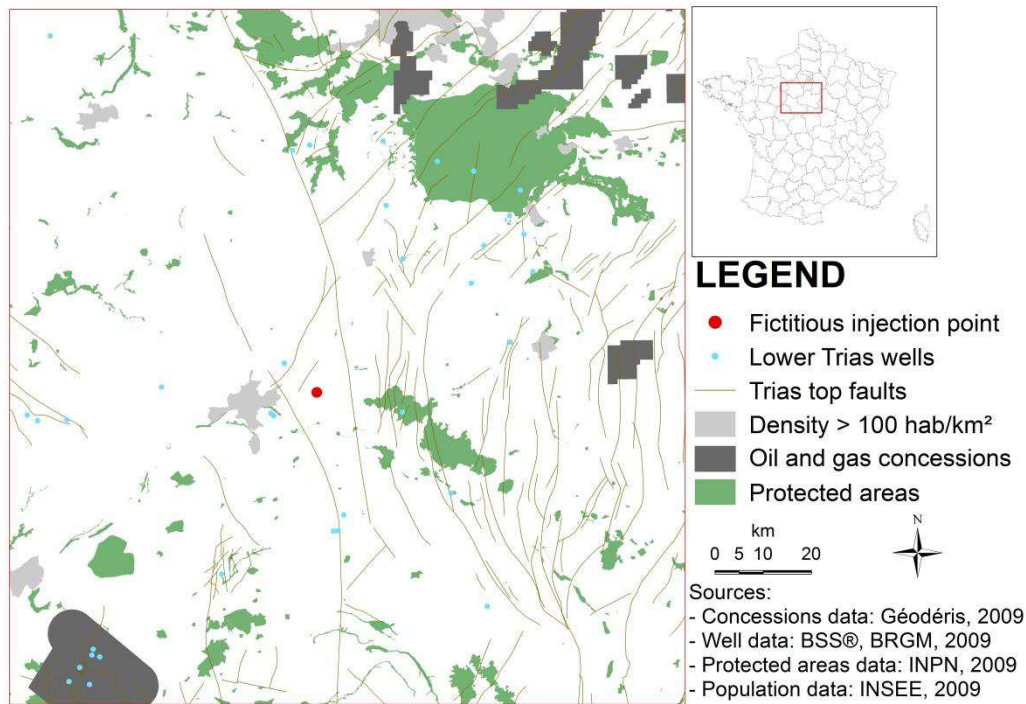
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153 Figure 3), the formation is ca. 60 m thick and ca. 1600 m deep. Two major faults are located
154 near the chosen injection point. In the Paris basin, plugged wells are considered as well
155 localized. However, for some of them, very little information is available about their
156 characteristics. Regarding the operations, the fictitious injection characteristics were taken as
157 equal to those accounted in the previous studies:¹⁴ the injection rate is about 2 MtCO₂/year
158 during 30 years.

159 The Albian aquifer located about 1000 m above the target reservoir is among the main
160 vulnerable elements of the region.¹⁵ Due to the geological confinement this aquifer is
161 naturally protected from any sort of pollution from the soil surface and it has drinking water
162 quality. This resource is thus reserved mainly for emergency supply of the Paris region in case
163 of pollution of other sources or for the supply of some industrial activities requiring high and
164 constant water quality. The other underground activities targeting the lower Triassic aquifer

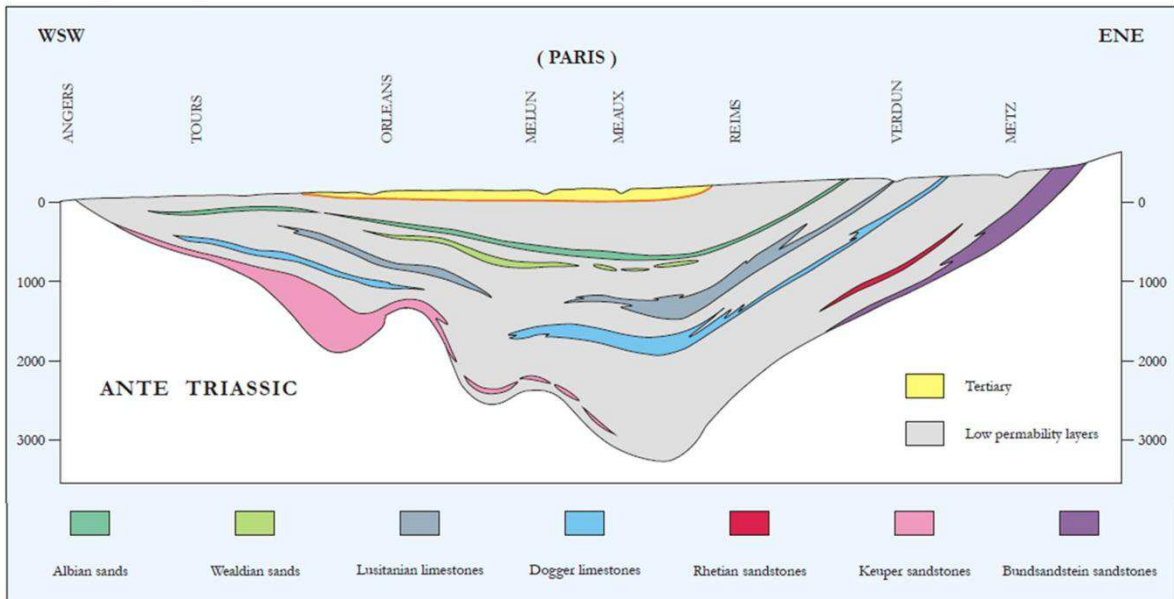
165 formations are some hydrocarbon exploitation and natural gas storage operations. At ground
166 level, the existing stakes, in this low density population area, are mainly some sensitive
167 ecological areas, and activities such as agriculture or forestry.

168 As a summary,



169

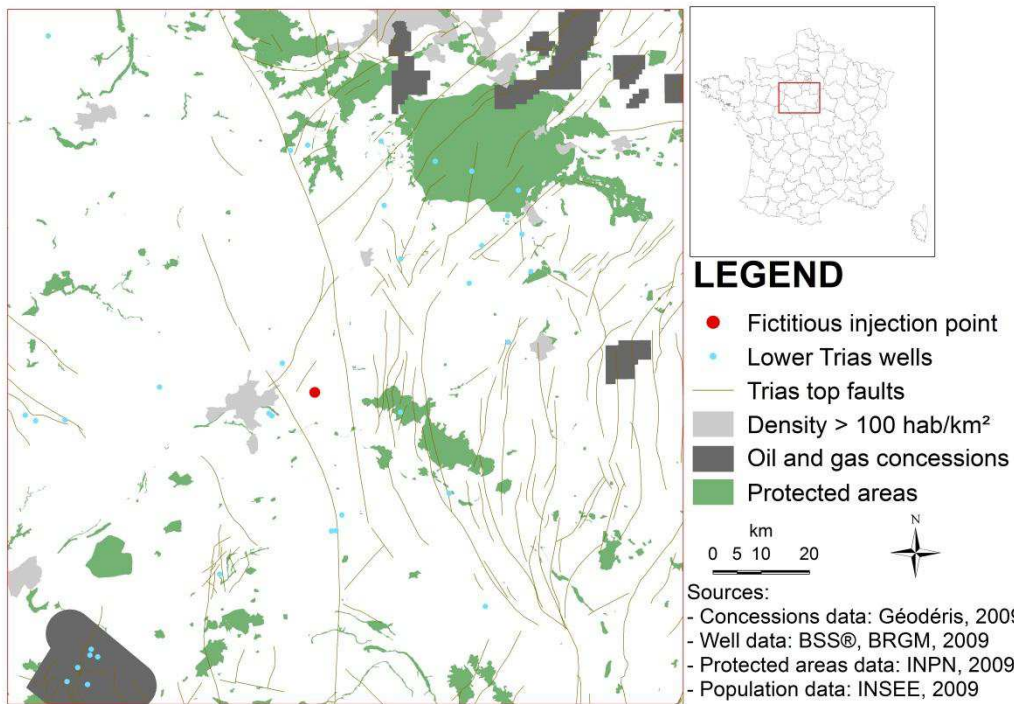
170 Figure 2 recaps the key elements highlighted in the establishment of the context.



171

172
173

Figure 1: Schematic cross-section of the main aquifer units on a WSW-ENE transect of the Paris basin (adapted from ^{12,16}).



174

175
176

Figure 2 : Position of the fictitious injection well, faults, wells, other underground exploitations and protected areas in the studied area.

177 **3 Risk identification**

178 By definition, risk identification is a systematic inventory and description of risks and of their
179 causes and consequences. Numerous approaches have been developed in many fields; we
180 adopt in this study a systematic team approach, where a panel of experts with different skills is
181 guided through a systematic process and identifies the risks specific to the injection project
182 from a predefined set of risks scenarios. Rather similar approaches have been proposed by
183 several authors.^{6,17,18} For the expert team work, bow-tie trees (or diagrams) were used as a
184 supporting tool. They are a graphical representation of the risk events together with their
185 initiating events, the outcome events until the potential impact they can lead to. Each path
186 from an initiating event to an impact event is called a risk scenario. Two different steps were
187 necessary, 1) the elaboration of generic bow-tie trees, and 2) the risk identification consisting
188 in the selection and adaptation of the relevant scenarios to the chosen site.

189 The elaboration of generic trees for CO₂ storage in saline aquifers was based on a list of main
190 risk events and a list of impacts from Bouc et al.¹⁹. The diagrams were established by a panel
191 of experts in the following fields: risk management, CO₂ storage, geology, hydrogeology,
192 multiphase flow, reservoirs, geomechanics, geochemistry, numerical simulation of subsurface
193 phenomenon, wells, and impacts in the field of CCS. Starting from each of the main events,
194 the experts panel was asked to determine iteratively all the possible causes (bottom-up
195 approach) up to primary causes and all the possible consequences (top-down approach) down
196 to the impacts. In order to check that all the possible primary causes were considered
197 exhaustively, an analysis of failure inspired from the FMEA (Failure Modes and Effects
198 Analysis) was carried out. Results were synthesized on several bow-tie trees separated between
199 the events occurring near the wellbores and those concerning more generally the geological
200 medium. Two main phases were distinguished: operational phase and post operation.

201 Diagrams were designed with the finest level of details in order to be used as a basis for
202 identification at any step of a project.

203 The risk identification on the specific case study of this paper implies the adaptation of the
204 generic bow-tie trees to the chosen site, and the selection of relevant risk scenarios to be
205 further analysed. Based on the generic diagrams from step 1, another group of experts (with
206 specific knowledge on the case study in addition to similar skills as the above-mentioned
207 group) systematically discussed all the events of each tree. Those considered unrealistic or
208 impossible due to the site condition were removed from the trees. Among the remaining
209 events, the experts were asked to discuss the priority of analysis for the events leading to the
210 same consequence. A simplification of the generic diagrams was sometimes necessary
211 when the details level of the diagrams was considered too important regarding the objective of
212 our study (preliminary quantitative risk assessment). This approach resulted *in fine* in a wide
213 number of possible scenarios due to numerous possible combinations of causes, main events
214 and consequences. Therefore, the final step of the identification was to build from all the
215 scenarios a representative list of conservative scenarios. The conservative scenarios were
216 defined as the scenarios that should represent an upper bound of the risk level. They were
217 established from the discussions on the priority on each event and doing conservative
218 hypotheses. The main purpose of this last step was to end-up the identification process with a
219 manageable number of scenarios to analyse.

220 Applying this approach on the potential CO₂ storage site, the work of the expert panel
221 resulted in the following conservative scenarios to be analysed:

- 222 1- Flow modification in the CO₂ storage geological formation and subsequent potential
223 (pressure) impacts on other subsurface activities;
- 224 2- Native fluid migration through abandoned wells and potential impacts on overlying
225 aquifers quality;

- 226 3- Loss of mechanical integrity in the reservoir leading potentially to induced seismicity
227 on other subsurface structures (on wells notably);
- 228 4- Loss of mechanical integrity of the caprock leading potentially to migration risk
229 scenarios;
- 230 5- Fluid (native or injected) migration through the caprock (higher permeability areas or
231 fractures/faults) with potential impacts on overlying aquifers.

232 A comprehensive risk analysis should focus on the five scenarios. Only the analyses of
233 scenarios 1 and 2 are presented in this paper. These two risk scenarios were chosen to provide a
234 representative overview on the different types of analysis that could be performed, with
235 different choices in terms of quantification (modelling) tools and uncertainty management
236 methodologies.

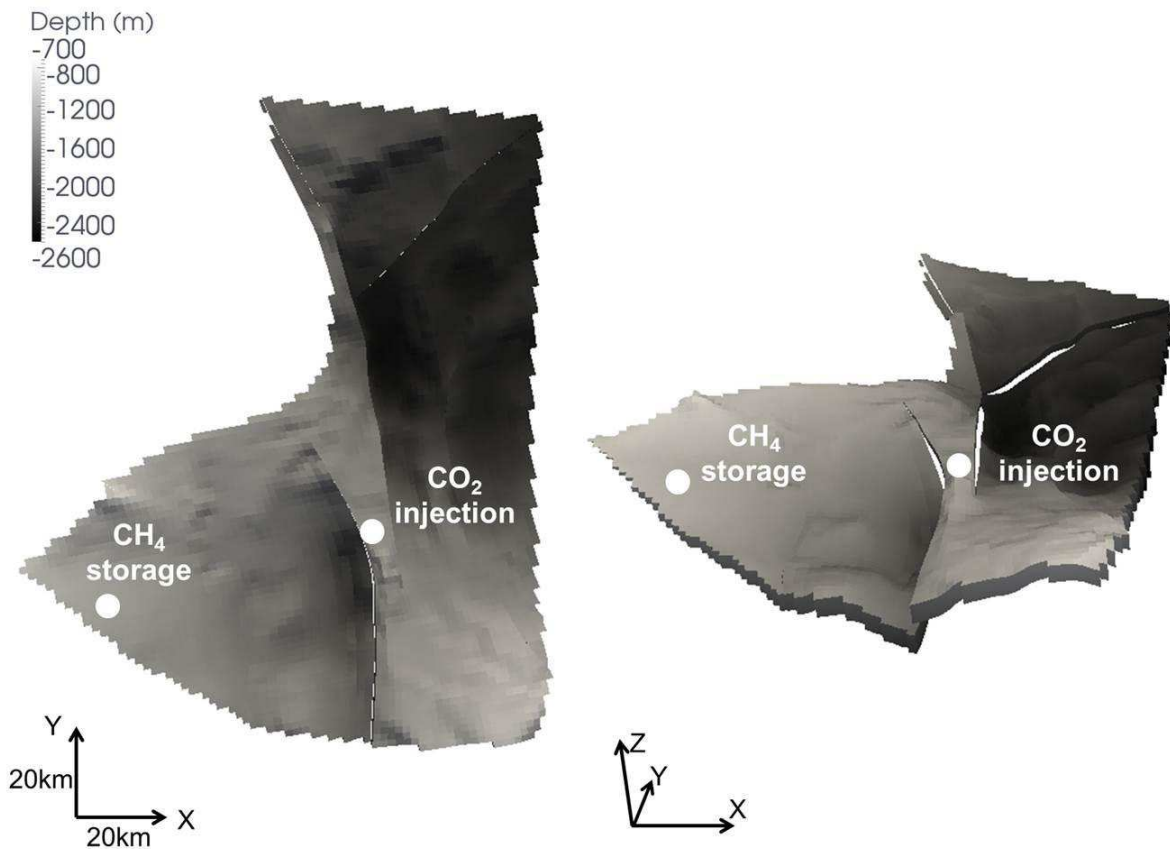
237 **4 Risk analysis**

238 **4.1 Scenario 1: *Flow modification in the storage formation and potential*** 239 ***pressure impacts on others subsurface activities***

240 **4.1.1 Presentation of the scenario and choices for risks quantification**

241 During the experts workshops, it was decided that the potential impacts of the over
242 pressurization of the CO₂ storage on the subsurface activities targeting the same aquifer
243 formation (oil concessions and gas storage operations) should be further analysed and
244 quantified. In this paper, we propose to consider a fictitious seasonal gas storage field that
245 would be located in the close surrounding of the contemplated injection point (ca. 60 km

246 South West of the injection point, see

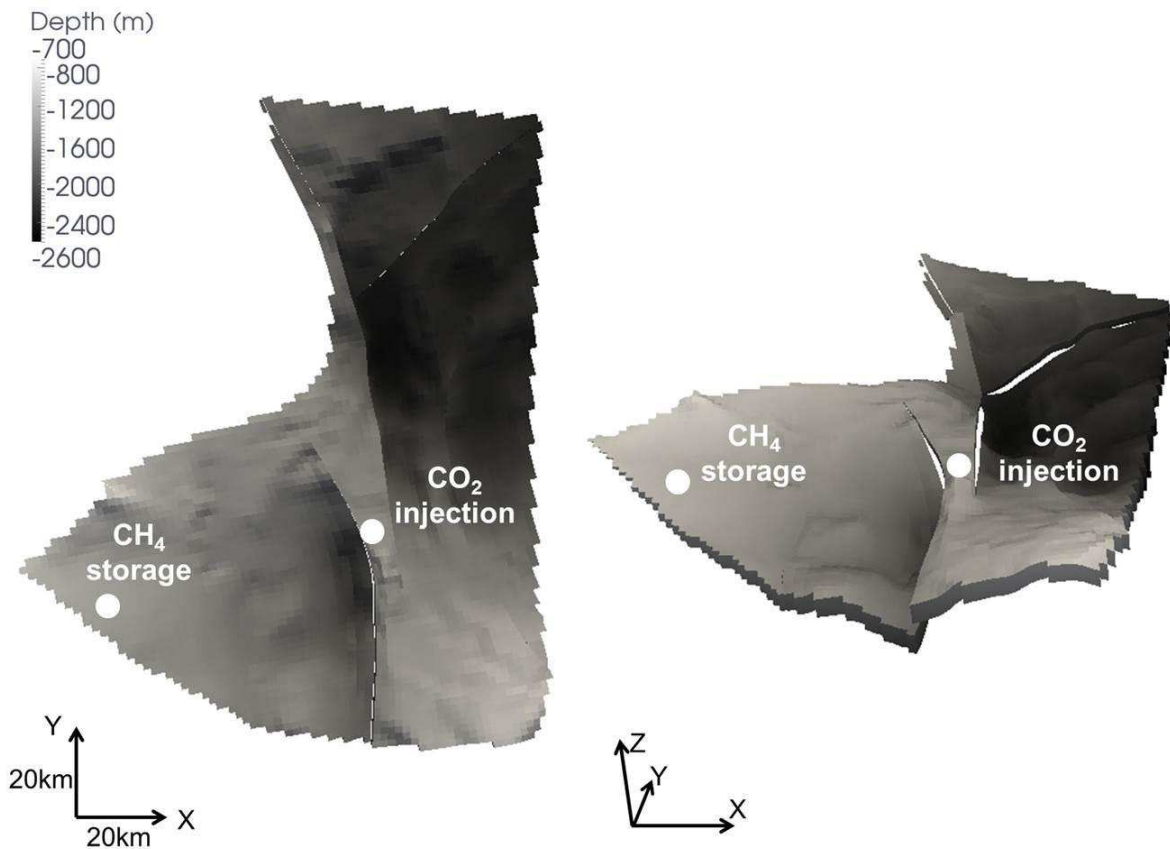


247

248 Figure 3). We consider that in this storage field ca. 0.4 Mt of gas (CH₄) is injected each
249 summer and the same amount is withdrawn during each winter. Simulations were run for
250 30 years after 6 years of reservoir filling designed to set up the cushion gas (i.e. the amount of
251 gas that remains permanently in the aquifer to allow the storage operations).

252 For the quantification of the pressure impacts of the CO₂ injection on the natural gas storage
253 operations, large-scale numerical 3D flow modelling was conducted. A geological model of
254 the formation was built using Petrel©. The dynamic modelling simulations were performed
255 with the multiphase flow transport simulator TOUGH2 combined with its module EOS7C
256 accounting for the properties of CO₂-CH₄-brine mixture.^{20,21} The final model is made of

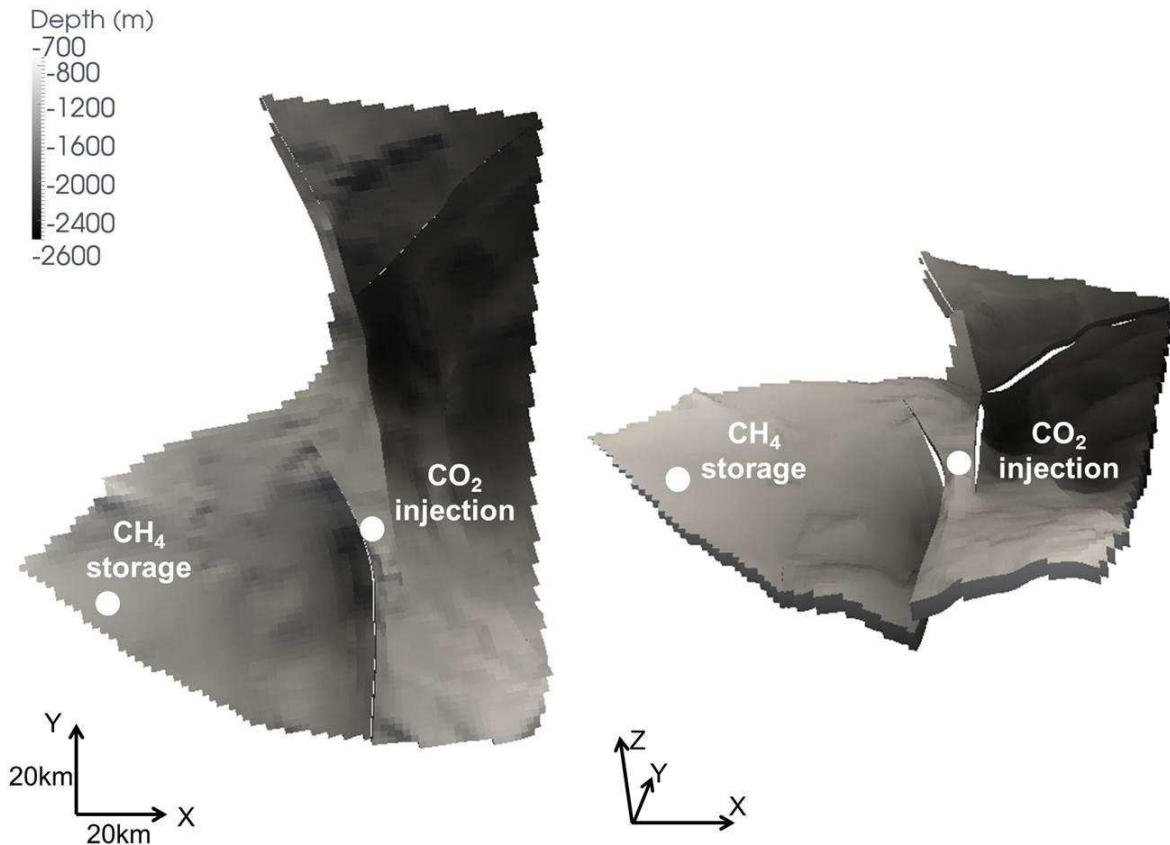
257 29,586 cells; its geometry is detailed on



258

259 Figure 3. The natural gas storage and CO₂ injection operations were simulated by constant CH₄
260 injection/extraction rate (0.4 Mt/y injected and extracted during 30 years) and CO₂ injection
261 rate (2 Mt/y during 30 years). The pressure impact on the CH₄ storage caused by the CO₂
262 injection operations was assessed through the overpressure induced by the CO₂ storage
263 operations in comparison with the CH₄ storage-only situation. As indicators of this pressure
264 impact, we chose:

- 265 - Indicator 1: the average relative overpressure (in %) due to the CO₂ injection within
266 the 5 bars pressure footprint of the CH₄ storage;
- 267 - Indicator 2: the average relative overpressure (in %) due to the CO₂ injection within
268 the 1 bar pressure footprint of the CH₄ storage.



269

270 **Figure 3: Two views (2D top view on the left, 3D perspective view on the right) of the static model of the**
 271 **geological formation of interest used in the flow simulations for scenario 1 quantification – the vertical**
 272 **scale is exaggerated in the perspective view**

273 4.1.2 Representation of available information

274 A probability distribution for porosity and permeability was established from the available
 275 data set at several wells reaching the formation (the spatial variability of porosity and
 276 permeability was however not considered in the simulations). Due to the lack of data, expert
 277 knowledge elicitation was used to determine a probability distribution for the pore
 278 compressibility (pore compressibility is the fractional change of pore volume of rock with a
 279 unit change in internal pressure). The multiphase flow parameters (relative permeability and
 280 capillary pressure) both for the CO₂/brine CH₄/brine systems in sandstones are more difficult
 281 to characterize and generally few data can be found in the literature. They were thus
 282 considered fixed in this study.

283 The choices made for the main uncertain input parameters are summarised in Table 1.

284 Table 1: Uncertain input parameters considered for scenario 1 simulation.

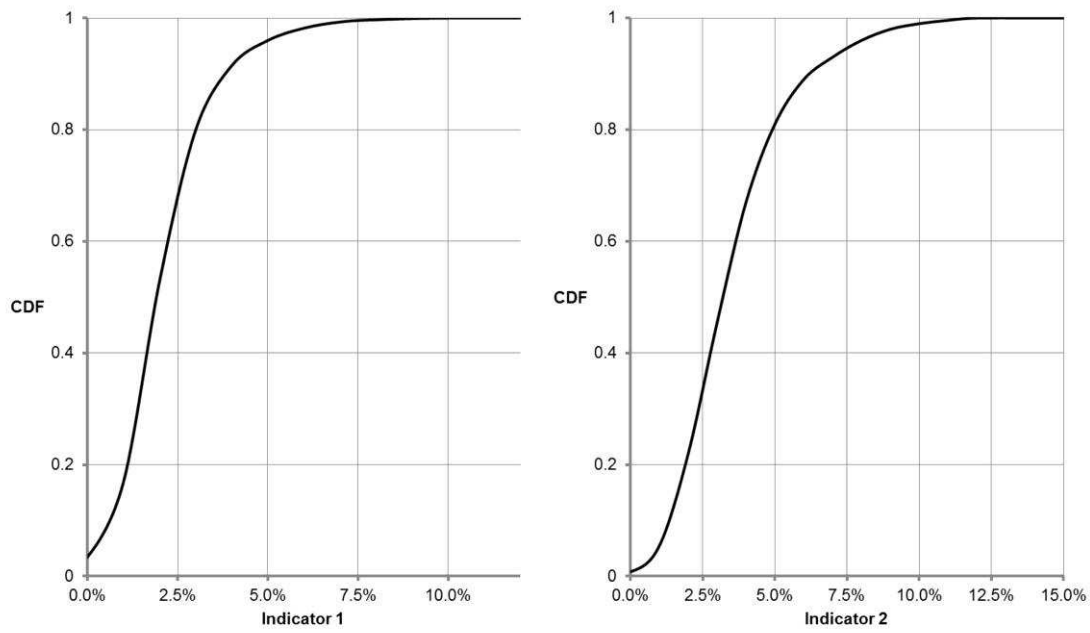
Parameters	Source of information	Representation mode	Values
Porosity (-)	Measurements (after Martin (2009) ³³)	Probabilistic distribution	Normal distribution (mean: 0.165; standard deviation: 0.053)
Permeability (m ²)	Measurements (after Martin (2009) ³³)	Probabilistic distribution	Log-normal distribution (mean: -28.4; standard deviation: 0.9)
Pore compressibility (Pa ⁻¹)	Expert opinion	Probabilistic distribution	Uniform law (support: 1.10 ⁻¹⁰ - 9.10 ⁻¹⁰)

285

286 4.1.3 Uncertainty propagation

287 A Monte-Carlo approach was chosen to analyse the effects of parameter uncertainties on the
 288 outcomes of the flow modelling. Given the number of parameters, 10,000 simulations would
 289 be necessary for this analysis. This large number of direct simulations was not feasible in
 290 practice since the simulator used for this study is computationally intensive (up to one day for
 291 one simulation). A metamodel(a surface response) was thus developed from the physical
 292 model and the Monte Carlo simulations were performed on this analytical model. The model
 293 approximation was built from 100 simulations with the physical model and using polynomial
 294 chaos expansion.²² It was validated through a cross-validation procedure. The Monte Carlo

295 analysis with the metamodel was achieved using the Open Turns tool².

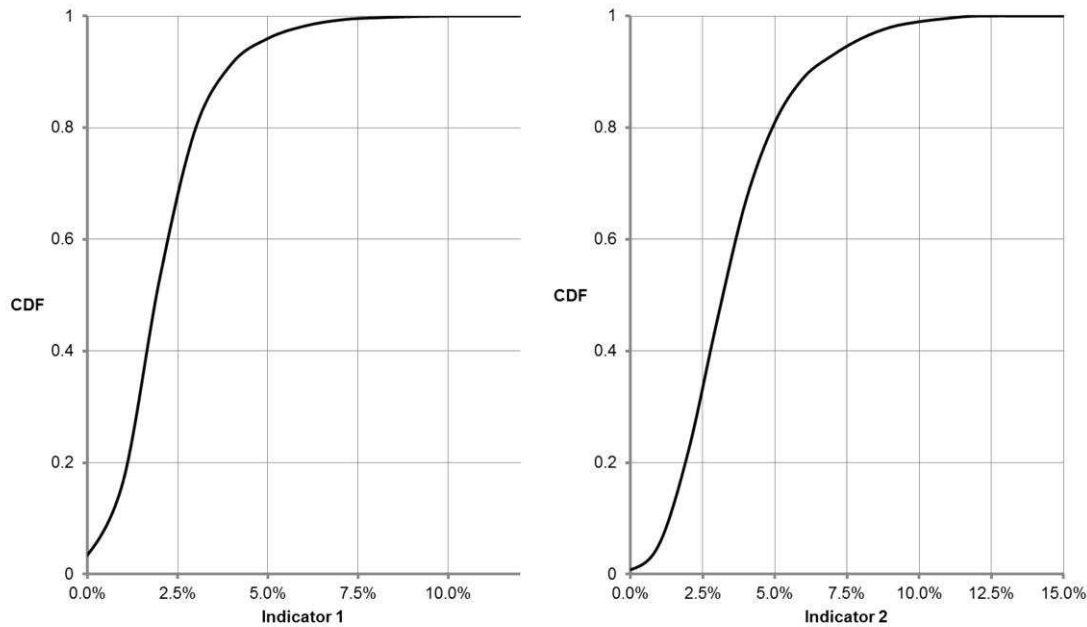


296

297 Figure 4 provides the cumulative probability distribution for the two different indicators

298 considered.

²<http://www.openturns.org/>



299

300 **Figure 4: Uncertainty propagation results: Cumulative probability density function (CDF). On left the**
 301 **average relative overpressure due the CO₂ injection within the 5 bars pressure footprint of the CH₄**
 302 **storage (indicator 1); on right the average relative overpressure due the CO₂ injection within the 1 bar**
 303 **pressure footprint of the CH₄ storage (indicator 2)**

304 4.1.4 Sensitivity analysis

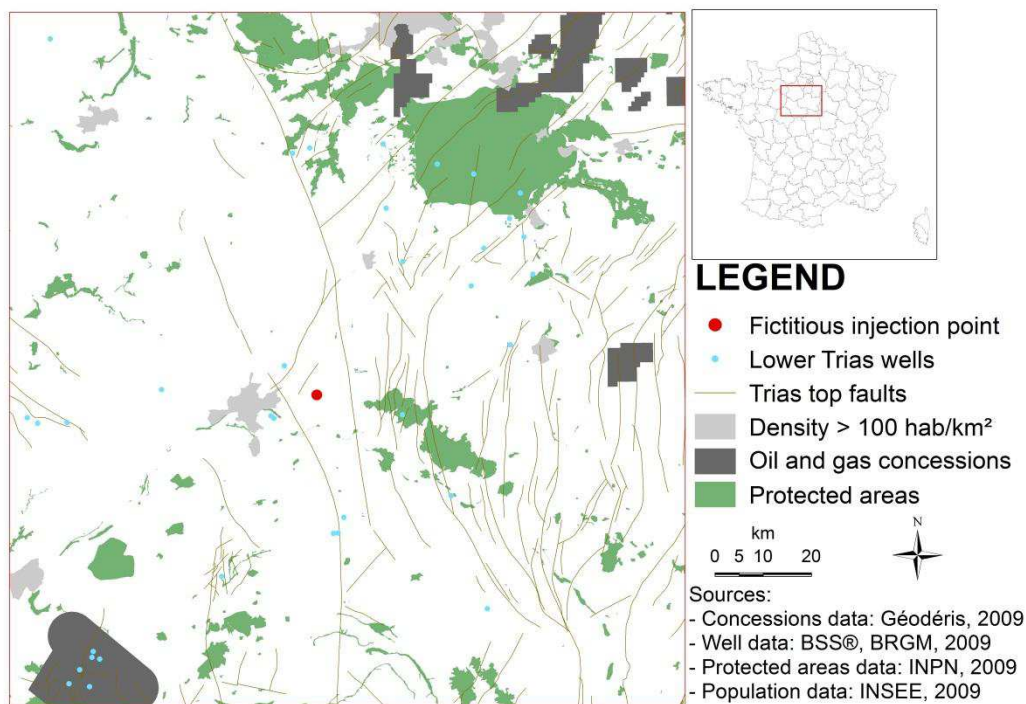
305 A global sensitivity analysis was performed on the three input parameters considered
 306 uncertain in the analysis (porosity, intrinsic permeability and compressibility) in order to
 307 determine which uncertainty has the greatest influence on the values of indicators. The
 308 analysis is based on the calculation of Sobol' indices,²³ which were evaluated directly using
 309 the chaos coefficients from the metamodels. The sensitivity analysis outcomes for the two
 310 indicators are relatively similar: the porosity appears to be the most significant parameter for
 311 the pressure impact (normalized Sobol' indice of 50 % for indicator 1 and 63 % for indicator
 312 2). For compressibility, the normalized Sobol' indices equal respectively 25 % and 26 %, and
 313 for the permeability 12 % and 4 %. This analysis is of first importance in a risk management
 314 perspective since diminishing the uncertainty level of the most important input parameters
 315 may change the overall risk level. In our specific case, if we consider that porosity and
 316 permeability are relatively well known, improving the probability distribution of the
 317 compressibility with for instance new measurements through laboratory or *in situ*

318 measurements would certainly lead to a more specific probability distribution assessment and
319 therefore to a more precise analysis of the risk level.

320 **4.2 Scenario 2: Native fluid migration through abandoned well**

321 **4.2.1 Presentation of the scenario and choices for the risks quantification**

322 This scenario focuses on the risk of brine leakage through an abandoned well that could
323 potentially reach the Albian aquifer and impact its quality. According to the expert workshop
324 held for the risks identification, several abandoned wells, close enough to the injection point
325 and reaching the formation targeted for the CO₂ injection, justify this analysis (see



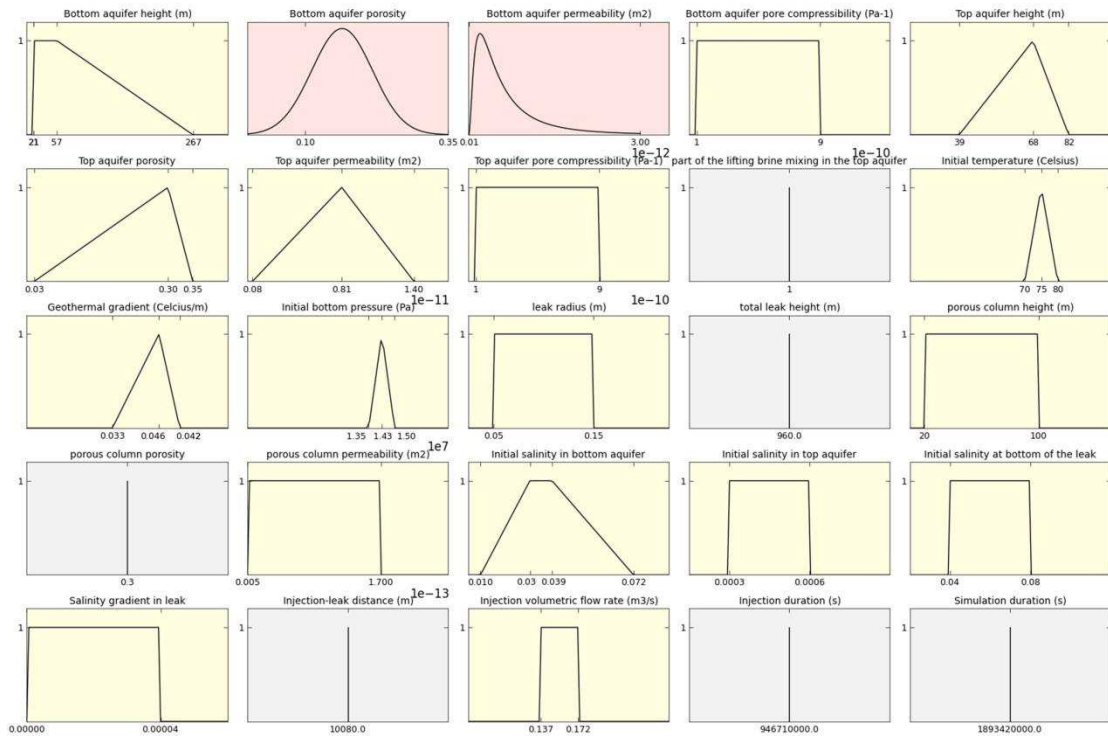
326
327 Figure 2). In the following, we present the analysis performed for the abandoned well the
328 closest to the injection point (distance of ca. 10 km). Because of the risk identification stage
329 results, the possible existence of a non-mapped well during site characterization is not
330 considered here. The risks are analysed during the injection stage (30 years) and during
331 30 additional years after the end of the injection.

332 A semi-analytical model (SAMBA) is used to quantify the potential brine migration that could
333 occur through the abandoned well.²⁴ This model has been developed to estimate saline brine
334 intrusion due to an existing connection (e.g. abandoned well with poor integrity) between one
335 deep saline aquifer over-pressurized by a CO₂ injection and another overlying aquifer. The
336 particularity of this model isto take into account the density difference between lifting and
337 lifted brines during the migration. Despite its apparent simplicity, this model requires 25
338 different input parameters.²⁴This model enables the quantification of the leaking volume of
339 brine, which has been chosen as indicator of the brine leakage impact for the analysis and
340 evaluation of this scenario.

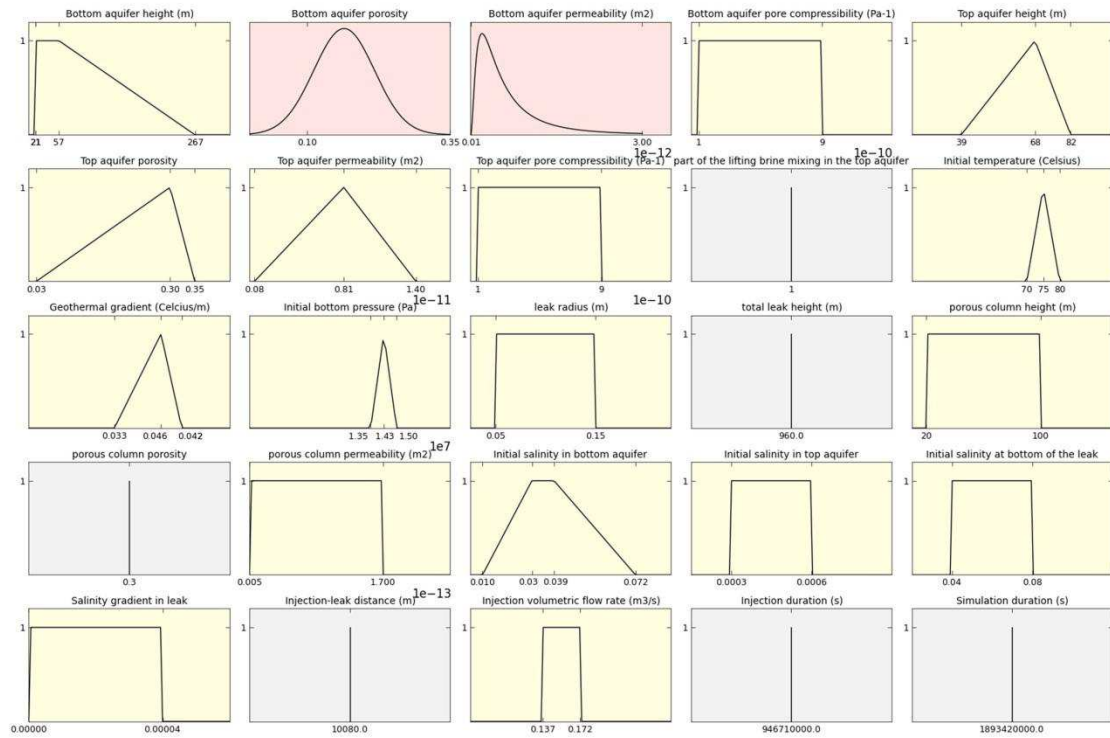
341 **4.2.2 Representation of available information**

342 As mentioned in the scenario 1 analysis section, the reservoir properties (porosity and
343 permeability) can be represented by a probabilistic distribution function estimated with the
344 different measurements values at disposal.However, most of the other input parameters are
345 characterized by high epistemic uncertainties. The available information, especially
346 concerning the well integrity, is incomplete, imprecise or vague. In such cases, the knowledge
347 of experts has been shown to be very useful to compensate the lack of observations.
348 Typically, an expert (or a panel of experts) is asked to choose, within the probabilistic
349 framework, the characteristics of the distribution (percentiles, mode, mean, median, etc.) and
350 the mathematical form of the distribution (e.g., Gaussian, uniform, triangular, etc.), which is
351 either theoretically known or (and it is the most usual case) supposedly chosen to best
352 represent the available information. This expert knowledge elicitation was done for the
353 compressibility in scenario 1 analysis. But, as outlined by Dubois and Prade,²⁵ the probability
354 may be too rich to be currently supplied by individuals as the identification of the probability
355 distribution requires more information than what an expert is able to supply, which is often
356 restricted to the 0.5 and 0.95 fractiles. Therefore, alternative formal frameworks to deal with

357 epistemic uncertainties have been proposed in the literature (see a review by Dubois and
 358 Guyonnet²⁶). In the present work and for this specific scenario, we propose to use the
 359 possibility representation of information (e.g., Baudrit et Dubois²⁷ and references therein) and
 360 therefore represent with possibility distributions the input parameters with high epistemic
 361 uncertainties. As a summary,



362
 363 Figure 5 recalls the mode of representation chosen for the 25 input parameters needed for the
 364 simulations (2 represented by probability distributions, 6 by fixed values, and 17 by
 365 possibility distributions).



366

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368

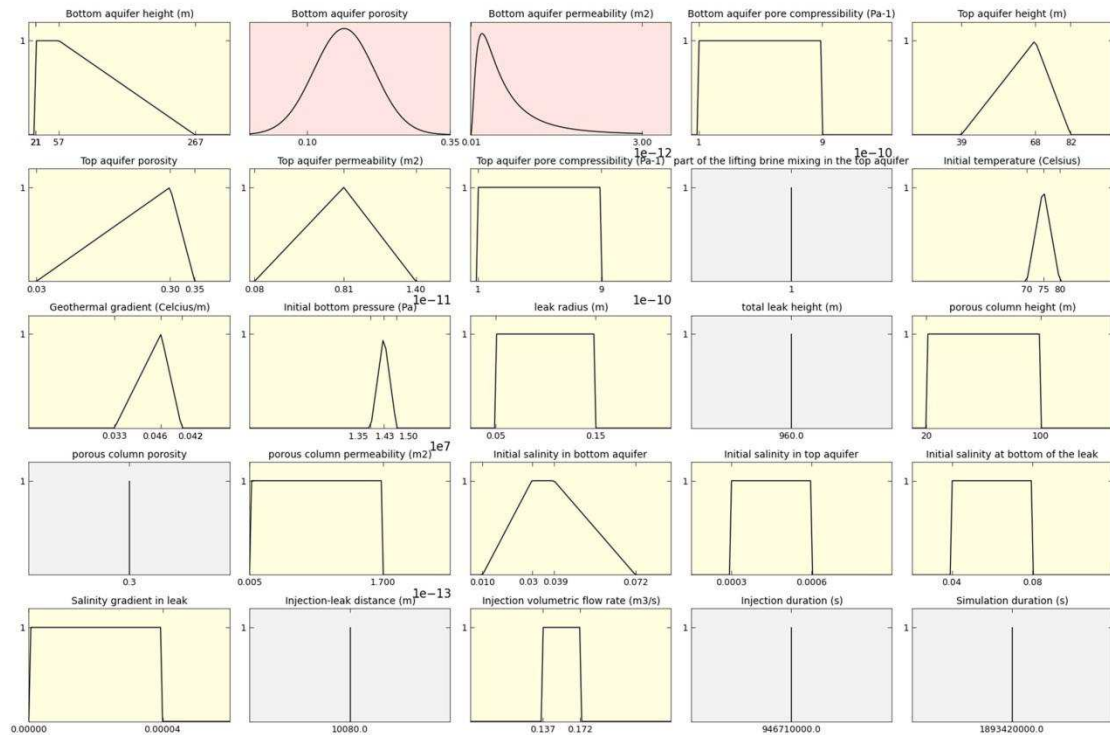
Figure 5 : Representation of information concerning the 25 parameters of the SAMBA model (grey: fixed value; yellow: possibility distribution; red: probability distribution)

369 **4.2.3 Uncertainty propagation**

370 For propagating these possibility and probability representations through the model, we resort
371 to the independent Random Set propagation method.²⁸This framework enables to jointly
372 propagate possibility and probability distributions. It assumes independence between all
373 parameters and all sources of information. A convergence study showed that
374 4,000 simulations is a good compromise between time computation (about 1 hour for
375 4,000 simulations) and precision ($\pm 2\%$). In order to compare the results with a pure
376 probabilistic treatment of the problem (as done for scenario 1 analysis), we performed the
377 uncertainty propagation using Monte Carlo analysis based on probability distributions for all
378 the input parameters (intervals were taken as uniform distributions).

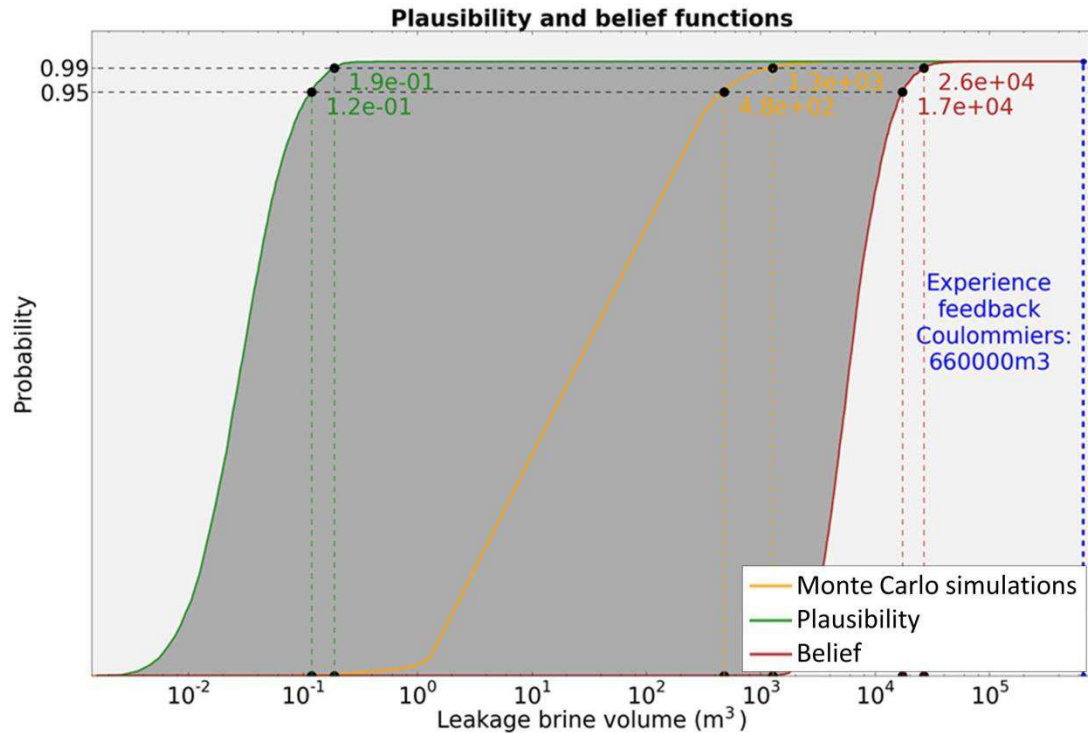
379 The results of the uncertainty propagation step can be summarized, as proposed by Baudrit et
380 al.,²⁸ within the formal framework of evidence theory in the form of two cumulative
381 distribution functions (CDFs) bounding all the possible ones: a plausibility curve that
382 corresponds to the situation for which the uncertainties drive to the most optimistic result; a
383 belief function that corresponds on the contrary to the most unfavourable curve based on
384 available data. The only known information concerning the true CDF is that it belongs to the

385 area between both curves. It can be seen on



386

387 Figure 5 that if the choice of assigning a uniform probability distribution to possible values
 388 when confronted to ignorance is made (Monte Carlo approach), the results of simulations
 389 are bounded between both curves. However, Monte Carlo results give a false impression of
 390 confidence in the outcomes of propagation analysis by providing a unique probability value,
 391 but without enabling to quantify the effect of the lack of knowledge (epistemic uncertainty).



392

393 **Figure 6 : Plausibility and belief functions obtained for the indicator *brine leaking volume*, and comparison**
 394 **with Monte Carlo simulations (the experience feedback indicated on this figure is detailed in section 5.2)**

395 **4.2.4 Sensitivity analysis on uncertainties**

396 The uncertainty on the results can be estimated with the area between both curves, which is
 397 mainly dependent on epistemic uncertainty. It is thus possible to carry out a sensitivity
 398 analysis as in Ferson and Tucker.²⁹ Instead of varying the investigated parameter as in anone-
 399 at-a-time sensitivity analysis,³⁰ it consists in fixingthe investigated parameter to its reference
 400 value, while keeping the same representation mode for all the other parameters. The area
 401 between plausibility and belief obtained after fixinga parameter enables to quantify the
 402 uncertainty decrease that can be expected if data gathering gives evidence that this parameter
 403 is equal to its reference value with no uncertainty.

404 The result of this sensitivity analysis on the brine leakage scenario shows that the area
 405 decrease is more important for the following parameters: porous column permeability (91 %),
 406 porous column height (60 %), leak surface (55 %), bottom aquifer permeability (25 %). Note
 407 that these results should be interpreted cautiously since the area decrease depends on the

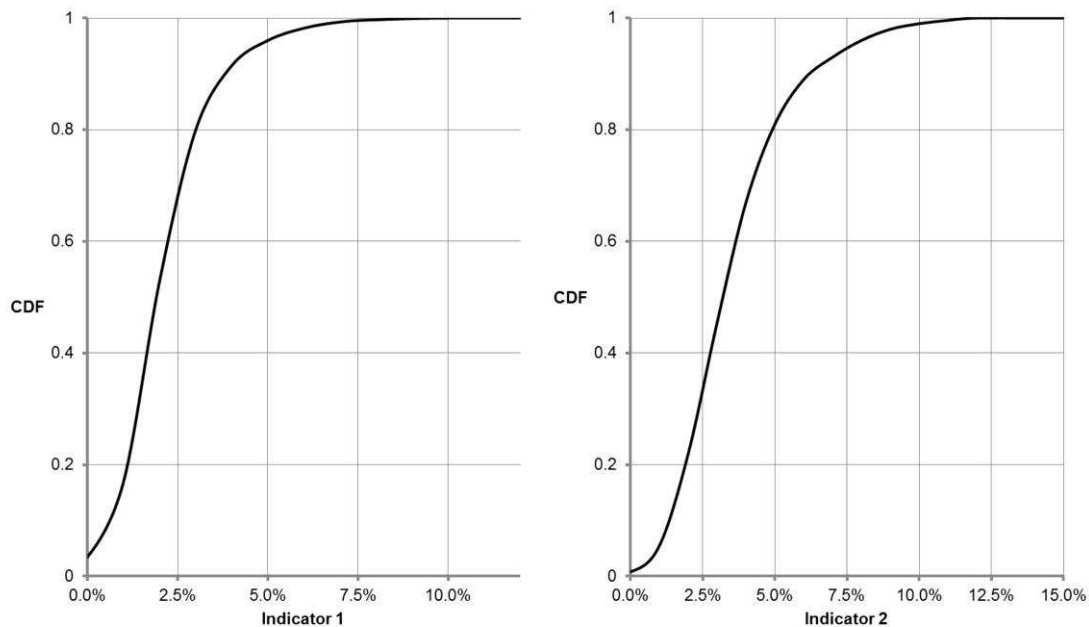
408 reference value to which the parameter is fixed. The interest of such an analysis is to establish
409 priorities in data gathering: it is indeed not worth spending a lot of effort for acquiring data on
410 a parameter whose epistemic uncertainty has no real influence on results.

411 **5 Risk evaluation**

412 As recalled in the introductory section, the risk evaluation consists in comparing the risk
413 analysis results against the acceptability targets. Risk criteria should theoretically be defined
414 beforehand and recalled in the establishment of the context. In this paper they are discussed in
415 this section on risk evaluation for clarity purposes. It is important to note that no standardized
416 criteria are currently available for CO₂ storage risks specifically.³¹ In practice, risk criteria may
417 be set in order to respect the environmental regulations in place but also according to other
418 stakeholders expectations and demands (e.g. other users of a similar geologic formation, local
419 population). In this paper, the storage site is fictitious and thus, the stakeholders concerns
420 cannot be discussed and accounted for. Therefore, in the following subsections, rather than
421 discussing the acceptability of the two risks scenarios, we discuss how the results of the risk
422 analysis could be used in a real situation in order to enable a fully informed decision-making.

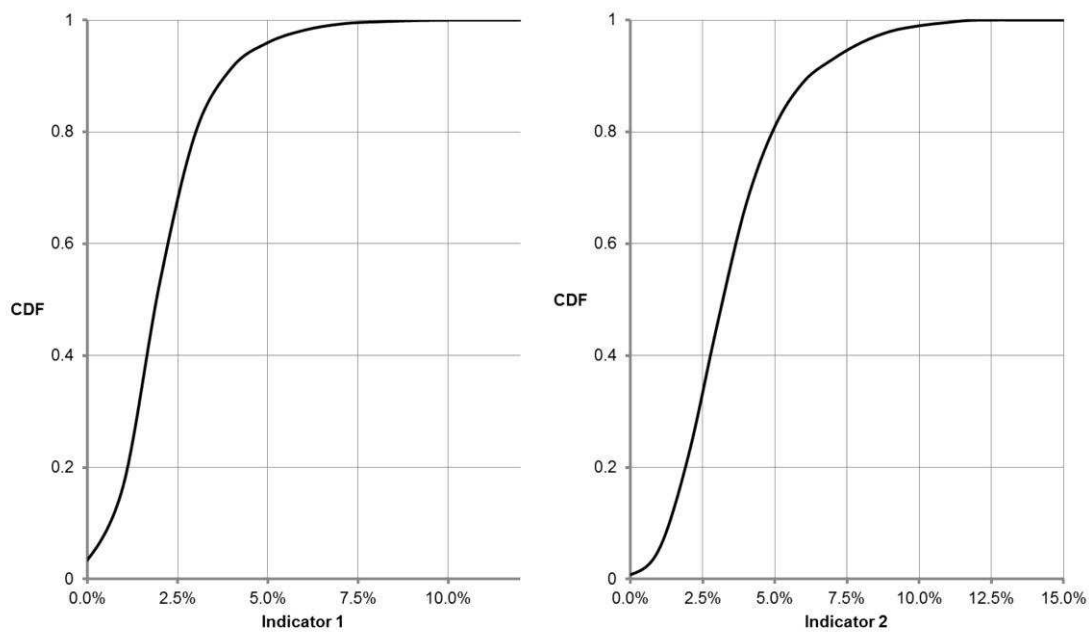
423 **5.1 Scenario 1: Flow modification in the storage formation and potential**
424 **pressure impacts on others subsurface activities**

425 As shown on



426
427 Figure 4, the distributions of the two indicators are different and the pressure impact is higher
428 in the 1 bar footprint of the CH₄ storage than in the 5 bars footprint. This is explained, in our
429 case, by the fact that the 1 bar footprint of the natural gas storage goes very close to the CO₂
430 storage injection. The 5 bars footprint therefore gives more localized information of the
431 overpressure at the gas storage site and in that sense appeared to be the best indicator to assess
432 the local disruption at the CH₄ storage site. However, establishing one criterion relatively to
433 this indicator to evaluate the acceptability of this perturbation is difficult because it is strongly
434 dependent on the vulnerability of the gas storage to pressure changes. The risk criterion is
435 likely to be defined after discussions between the different users of the geological formation
436 and the regulators. If, after assessment, an impact in pressure until X % is found unable to
437 compromise the natural gas storage operations (due for example to the safety margins in these
438 operations), the stakeholders may for instance establish the following risk criterion: the risk

439 generated by the CO₂ storage operations is considered acceptable if there is at least a 99%
 440 confidence level that the pressure impact in the 5 bars CH₄ storage footprint is lower than
 441 X %. The treatment of this risk scenario should be decided with respect to that criterion.
 442 For the sake of illustration in our study, let us arbitrarily consider a value X = 5 % (without
 443 any consideration of the relevance of this value). The associated level of confidence is 96 %,
 444 meaning that the risk level would be close to acceptability (see on



445
 446 Figure 4). In such a case, the decided risk treatment might be the performance of another
 447 analysis to quantify the pressure impacts with more precision (through for instance model
 448 improvement). An additional characterization of the poorly known but influential input
 449 parameters (outcomes of the global uncertainty analysis) would be another way to reduce the
 450 uncertainties on the risk level. Alternatively, with X = 1 % the project would not be acceptable
 451 and it would be necessary to lower the level of risk rather by modifying the injection pattern
 452 and/or setting mitigation measures.

453 **5.2 Scenario 2: Native fluid migration through abandoned well**

454 Similarly to the former scenario, no firm regulatory criterion has been found regarding the
455 volume of brine leakage. Instead, an experience feedback study of brine leakage in the Paris
456 Basin was carried out in order to define acceptability thresholds. To our knowledge, the only
457 reference is a brine leakage from a geothermal well (high salinity) near Coulommiers in the
458 Paris Basin.³² A leakage of 660,000 m³ is reported, with no significant incidence on drinking
459 water supplies. The context of this leakage is obviously likely to be different than the one of
460 our study and therefore the comparison with this value should be cautious. In a conservative
461 approach, let us assume that the situation may be considered acceptable if there is at least 99%
462 confidence that the leakage volume is lower than the experience feedback value. As shown
463 on Figure 6, the most unfavourable leakage value is more than two orders of magnitude lower
464 than the chosen experience feedback. Thus, the situation would be considered acceptable with
465 the considered criterion. The results obtained with Monte Carlo simulations would give the
466 same evaluation outcomes. However, the possibilistic treatment of uncertainties nuances the
467 Monte-Carlo results, by clearly indicating the level of epistemic uncertainties. Using a
468 different risk criterion (brine volume comprised between 1300 and 26000 m³ with a degree of
469 confidence of 99 %), the Monte-Carlo-based approach would have directly led to a decision
470 (acceptability), while the possibility approach would have suggested to make additional
471 studies or take additional safeguards, as it does not exclude a leakage volume in excess of the
472 evaluation criterion. This highlights the importance of choices in the mathematical tools for
473 representing the lack of knowledge especially in the early phases of the CO₂ storage project,
474 where few data is available.

475 **6 Summary and Conclusions**

476 In the present paper, we describe a new approach for performing a quantitative risk
477 assessment of CO₂ geological storage operations. Compared to existing methodologies in the
478 CO₂ geological storage domain that are mostly qualitative or semi-quantitative, our approach
479 has been designed in order to provide quantitative elements to evaluate the risks acceptability.
480 This approach is based on the international standards regarding risk management practices,
481 which are applied to the subsurface and to CO₂ geological storage operations. Our approach is
482 presented on a case study, conceived to be representative of the level of information available
483 at an early stage of a project. The application of the different steps of the methodology shows
484 how the challenges linked with CO₂ storage risks assessment could be faced: in particular, our
485 approach proposes a detailed assessment and representation of the partial knowledge of the
486 geological medium in terms of intrinsic properties and processes. The complexity and number
487 of processes and mechanisms impose a strong effort of risk identification combining generic
488 risk database and experts knowledge in numerous domains in order to come up with
489 representative risk scenarios to be analysed. A quantitative analysis of these scenarios is
490 relevant only if it is accompanied by a comprehensive uncertainties management framework
491 including data collection and description, uncertainty representation and propagation. In this
492 study the analysis has been performed using different kinds of modelling tools associated with
493 different ways of dealing with uncertainties, which highlights the importance of a proper
494 combination between risk quantification and uncertainty management tools. The risk
495 evaluation stage has been carried out by assuming risk acceptability criteria, but in real-case
496 application, this would require a deeper joint analysis between stakeholders (operators,
497 regulators).

498 In the end, it has been shown that the proposed approach can lead to the risk scenarios
499 selection and quantification in a transparent way, i.e. without introducing subjectivity prior to

500 the risks acceptability evaluation. The implemented approach also appears to be flexible to
501 different tools and contexts regarding the available data. The results of this approach could
502 therefore be used, in different situations, as a scientific basis for discussion between
503 stakeholders for decision-making and as arguments for prioritizing additional characterization
504 and quantification (modelling), if required. In addition, the results constitute important
505 information for achieving the next stages of the risk management process, including the set-up
506 of risk monitoring or treatment measures. Such quantitative approach could also help in the
507 risk communication as it gives a clear picture of the risk related to CO₂ storage project with
508 the associated uncertainties, thus contributing to the confidence and acceptance of a project.

509

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516

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