

Report of modifications

This is a report of the revisions in the PhD thesis ‘Geological Storage of CO₂: Sensitivity and Risk Analysis’ to address the first review comments. In this report, we cover the issues and concerns mentioned in the first review comments. In addition to addressing the review comments, a detailed literature review is added to the thesis. Moreover, the English has been improved.

The received comments can be divided in five parts. We first quote the reviewers comments in bold italic font. Corresponding answers follow the quoted comments.

1 The geological setup

‘...throughout the Thesis, the reader never learns what the internal depositional architecture of the model is.

‘The SAIGUP model contains varied depositional features, delta-front lobes, beaches, prograding / aggrading sequences, faults, etc. It also has a structural dip, which is not clearly explained. Some cartoons of this are provided, but no proper cross-sections or maps to judge how the various lithofacies elements fit together. The native grid resolution of the SAIGUP model is not stated, and nor what degree of upscaling was required to produce the input for the flow modelling, if so.

To improve the presentation of geological description, the structure of (initially) Section 1.4 is changed dramatically. The Subsection ‘Uncertainty’ is moved to separate section, i.e., Section 1.4 ‘Uncertainty sources’. Section 1.5 is now titled ‘Geological modelling’. An entire subsection 1.5.1 ‘Geological description’ is added that includes a literature review and positioning of the research in the context. This section starts by describing the architecture of sedimentary shallow-marine basins and the rock types in the geological setup. For example, in paragraph 6 of Section 1.5.1 we see:

“Depositional environment varies from fluvial to marine systems. The texture and degree of sandiness of beach deposits are functions of the shore profile, typically consisting of a gently sloping formation layering in a transition from near shore to deep offshore. Deposits range from sandy, coarse grain structure near the shore, to muddy, burrowed, fine grained sand in the lower offshore. High energy near the shore that is a result of interplay between wave, fluvial, and tidal forces, filters out the larger grains in the deposition.”

Figure 1.4 is added that explains the heterogeneities in fluvial and beach depositions. Then the suitable heterogeneity types with regard to CO₂ storage are discussed. Paragraph 9 of Section 1.5.1 reads:

“In theory, we prefer a medium that allows for more lateral movement to overcome the buoyancy bypassing of the flow. Heterogeneity in the vertical direction, such as shale inter-bed barriers can serve for enhancing the lateral flow and disperse the flow in the lateral direction. Structural heterogeneities can have a similar impact. In addition, splitting a large plume into smaller plumes lowers the risk of leakage of huge CO₂ amounts via potential breakings in the integrity of the sealing barriers or abandoned wells.

...”

Section 1.5.1 proceeds by discussing examples from the literature that determines the novelty of the work in using large scale of realistic geological variations for sensitivity analysis; Section 1.5.1, paragraph 11 :

“...A case study from the Texas Gulf Coast [37] investigates the sequestration capacity and efficiency in accordance to the geological heterogeneity. The study performs a site-scale assessment of brine aquifers for geological CO₂ sequestration. Injection is considered in the Frio formation which is a sandstone-rich, high quality rock, overlain by thick, regionally extensive shale in the upper Texas Gulf Coast. Migration of CO₂ during injection (20 years), and post-injection (40 years) is studied in different geological realizations. The heterogeneity represented by stochastic modelling of geological sediments. Structural heterogeneity is modelled by layers dip angle and faults at different locations. Six models are made based on regional available geological information...”

In addition, examples of pilot projects are given in the text that describes the practicality of such kind of research within industry.

In Section 1.5.2, detailed discussions on the SAIGUP geological modelling procedure and upscaling methods are given. Paragraphs 3, 5-7 are added to this section. Table 1.1 is added to the text to provide the fine and coarse grid information. Figures 1.5 to 1.9 are added to Section 1.5.2 to support the discussion in the text regarding the sedimentology and structure of SAIGUP models. As an example from the text, we see in paragraph 6, Section 1.5.2:

“On the last step, the fine populated grid is mapped on to the coarse grid that is to be used for the flow solver. Since the grid size in the fine model is too expensive computationally for flow simulations, the lateral dimension is doubled in each cell while every four layers are lumped into one layer in the vertical direction. Figure 1.10 shows the top view of lateral transmissibility in logarithmic scale for four consecutive layers of a selected case, and their corresponding upscaled layer in the coarse grid. Table 1.1 shows the grid specifications in the coarse and fine SAIGUP models.

...”

Moreover, an example of SAIGUP geological realization available to download is given in the text. Last paragraph in Section 1.5.2 reads:

“For more information about the geological modeling, see the special issue of the Petroleum Geosciences that is devoted to the SAIGUP study [47]. One selected realization of the SAIGUP models is available for download [65] and this model is used as an example in MATLAB Reservoir Simulation Toolbox (MRST) [67].”

2 The flow equations

‘A substantial section then follows on the theoretical basis for flow in porous media and on the aPC statistical analysis. The former distils fairly standard published texts and is not innovative; it is also difficult to see what it really adds to the rest of the Thesis, because the modelling actually uses the proprietary ECLIPSE flow simulator that is essentially treated as a black-box.’

The beginning of Section 1.6 is modified to explicitly mention that the set of discussed flow equations are used in the flow solver employed for the study:

“...Solution to this type of equations is implemented in the ECLIPSE black-oil simulator that we use to model the flow...”

It is a convention in the Department of mathematics, University of Bergen that any relevant equation used in the study should be mentioned in the report.

‘It is not stated which simulator version, ~ I E100 or E300, and which specific options were employed in the simulations.’

‘Information on the implemented boundary conditions and selected input parameters is given, yet hardly an adequate description on the ECLIPSE model set up or specific options and keywords used in the simulation of CO2 storage.’

Now, it is explicitly mentioned in Section 1.6 that ECLIPSE Black-Oil is used for the study. Section 1.6.2 is added that describes the ECLIPSE E100 models used in the study and provides the important parts of the ECLIPSE input files. This includes the physical models (PVT tables) used in the simulation.

‘A short section on vertical averaging is interesting and quite clear, but again does not seem to be relevant because, so far as we could tell, vertical averaging was not used in the simulations.’

This section is removed from the thesis, as it was not directly related to the main research area of the thesis.

3 The flow model

‘It is not made clear what the grid structure of the reservoir flow model is until Paper V (Table I).’

The grid information is now discussed in detail in Section 1.5.2 and it is provided in Table 1.1. In addition, Paper I is modified to provide the model specifications in detail.

‘The size of the model is also a cause for concern.’

‘In terms of the methodology, there are issues with the resolution of the model, boundary conditions, model induced artefacts, and sensitivity to key parameters.’

‘... the pressure and saturation fields interact strongly with the model ' boundaries.’

Section 1.8.2 is expanded to discuss the size limitations in SAIGUP models. In the first paragraph, the issue is described:

“...In some storage sites, the lateral extent that the CO2 travels can go to hundreds of kilometers. This makes our study limited in the spatial domain around the injector. For the same reason, in the temporal scale, we are more focused on injection and early migration time. We examine a number of injection scenarios to study the spatial distribution of CO2 in the medium during injection and early migration periods.”

This is also discussed in Section 1.10.2, paragraph 2:

“First limitation is the SAIGUP model size. CO2 storage studies require large models that can cover the CO2 spatial traveling extents within aquifers. Hence, our study is limited to the domain around the

injector. Yet, many cases in our study suffer from volumes of injected CO₂ lost via open boundaries. While this can be used as an indication for vertical versus lateral transmissibility, the study can be improved by using larger models. In some parts of our study, realizations are compared at a time after injection that the same amount of injected CO₂ exists in the domain (e.g., the cases compared at 15 years of injection in the pressure study)..."

The model size impact on the pressure results is discussed in paragraph 2, Section 1.8.2:

"Pressure study is essential for injection operations. A detailed pressure study requires larger scales than what are used here. We choose open boundaries for the model to compensate for the actual large extents of a typical storage location (Figure 1.27). The choice of open boundary is not valid in domains that are bounded by structural seals. In fact, for the close and semi-close domains the pressure is a main control on the storage capacity along with other parameters. The results of our pressure study can change significantly by choosing different boundary conditions...."

On the same issue, we see in paragraph 2, Section 1.10.2:

"The pressure behavior is very sensitive to the way the boundaries are defined. In reality, there are different systems of aquifers. Some of them are large with huge pore-volumes. To model these aquifers, we can use smaller models with open boundaries. However, some aquifers are medium and small in size. To model these aquifers, we can assume semi-close and close boundaries."

Then, an approach is suggested to minimize the size effect based on the actual condition of the aquifer under study:

"For any aquifer system, we can define the boundary by exaggerating the pore volume of the cells on the boundaries of the model. The transmissibilities of the boundary cells can be also modified to represent the size of the aquifer system. This controls the amount of pressure relaxation in the medium through the boundaries. If CO₂ exists in the boundaries, relative permeability functions at the boundary can be modified in addition to the transmissibilities."

The way we model the boundary is then explained:

"The open boundaries in our study are considered to be fully open. This makes the pressure to relax through the boundaries and mainly, the results of our pressure study are influenced by this choice. While we have observed a considerable number of cases with extreme pressures due to heterogeneity effects, the pressures reported in our study are moderate compared to models with not fully opened boundaries. The sensitivity analysis is based on comparing cases for their pressure values. Therefore, the outcome of sensitivity analysis should be valid regardless of the boundary choices. "

And finally, the IGEMS study is introduced that is a continuation of our study considering larger model size to investigate the flow of the injected CO₂ in the aquifer. Paragraphs 7 and 8 in Section 1.10.2 say:

"The size limitation in the SAIGUP models resulted in an extension to the current study in a project, which is called IGEMS [68]. The IGEMS models have larger size compared to the SAIGUP models. The CO₂ storage due to structural trapping in the SAIGUP models is limited to a major fault that allows for most of the injected CO₂ to accumulate under the cap-rock. This is not sufficient for studying the

effect of variations in the top-surface topography on the CO₂ movement in the medium. The IGEMS study has focused on the structural trapping due to deformations in the top-surface morphology and faults. The results show that the structural trapping can be important in the amount of storage due to structural trapping and it can control the speed of plume migrating under the top sealing cap-rock.”

‘Thus, for example, many of the realisations suffer substantial loss of CO₂ out of the model. This can lead to major artefacts, whereby for instance, some models show reduced leakage risk because most of the CO₂ has left the model and has no impact on the leakage point.’

As mentioned in addressing the previous comments, detailed discussions on the SAIGUP size effect are added in the thesis. We agree that the size limitation induce artefacts to some extents. However, we believe that most of our flow study and results are valid and valuable in demonstrating the impact of heterogeneity on the CO₂ flow behavior.

For the particular example that is mentioned here, leakage risk is defined only on the part of the cap-rock that is within the model. This definition is only used to present the method. This is discussed in the last paragraph in Section 2.2, comments on paper I. In addition, the re-entrance of the exited CO₂ is considered in our modeling. Therefore, if a considerable CO₂ volume returns into the domain and reaches the cap-rock by travelling upward, it can contribute to the risk of leakage.

‘In another example of boundary-induced effects, it is suggested (Paper II, page 6) that CO₂ flux out of the open boundaries near the injection point could be used as a proxy for volumetric sweep efficiency. In fact, the dominant effect is just the relative difficulty in forcing CO₂ up-dip into the interior of the model compared with driving it down-dip through the nearby open boundary.’

As the reviewers suggest, the out-flux measure is highly sensitive to the heterogeneities in the dip direction connected to the boundary. Therefore, it is decided not to consider the out-flux rate as a measure. It is removed from the list of responses in Section 1.8.3 and in the summary of paper I. However, the detailed discussions regarding out-flux through boundaries and dynamics of flow in the medium remain in the text, both in the introduction part and paper I.

‘More generally, it is difficult to assess the degree to which the results will have wider generic application or are model-specific. In particular it is difficult to assess how robust the results are and to what degree model deficiencies (size of model, boundary conditions, and internal grid resolution) are influencing the results — our intuitive feeling is that model artefacts are significant.’

In addition to the parts added in the beginning of Section 1.8.2, Section 1.10.2 is added to discuss the limitations of our study, how the results are influenced, and what the general approaches for more generic conclusions are. It is discussed that due to relaxations at the open boundaries, the pressure values in our study are lower than pressures than can be simulated in a larger model. In addition to the size effect that is already discussed in the current document, paragraph 9 in Section 1.10.2 says:

“In the vertical scale the SAIGUP models can be improved by using a higher grid resolution. Variation in the vertical direction exists in considerably smaller scales than the lateral direction. In particular, this is more crucial for long-term migration of CO₂ where a thin plume of CO₂ migrates beneath a sealing layer due to buoyancy forces.”

And next follows:

“Another issue to be mentioned is the assumption for geological uncertainties that are used in the stochastic analysis. We consider near uniform distributions for the probabilities of uncertain parameter values. While there is no loss of generality, there are too comments that could improve our analysis:

- In general, the uncertainty probability can be different than uniform distribution. These information are very case dependent and can change from one location to another.
- One advantage of the aPC method is the flexibility to apply for arbitrary forms of uncertainty data. Choosing various distributions for the geological parameters would be more demonstrative of the aPC method strength.”

Then, a general workflow for sensitivity, uncertainty, and risk analysis is discussed.

‘The model outputs depend crucially on the detailed interaction between the injected CO₂ and the geological complexity within the model for example whether the CO₂ plume encounters low permeability rocks in the vicinity of the wellbore, or whether high permeability pathways are available to enable plume migration away from the injection well. Surprisingly, however, only one injection well location or well completion is tested, so we do not get any feel for how robust the results are with respect to well position and injection strategy. This is a key issue for CO₂ storage — to know the possible effects and impacts of well placements in 'different reservoir environments.'

A discussion is added in the comments on paper I, Section 2.2:

“Within one geological realization, injection location can dramatically impact the injectivity of the well. In fact, this is an uncertain parameter in the CO₂ storage operations. Choosing to inject in the river channels or in the permeable homogeneous parts near the shore will enhance the injectivity and the CO₂ sweep efficiency in the medium. On the other hand, injecting in locations with low permeabilities and pore-volumes can significantly increase the injection pressure, while limiting the transport of CO₂ in the medium. Studying the impact of injection location can be performed by injecting in many different points in one realization and comparing the corresponding flow responses. However, this will considerably increase the number of detailed simulations in the study.

For the allowed time, we limited our study to a fixed point by injecting via one well in the flank part of the SAIGUP models. This location is selected after qualitative analysis of a detailed study on a homogeneous case. There, we aimed to fulfill the criterion of maximizing the CO₂ storage capacity via increasing the vertical travel path toward the structural trap location under the cap-rock. One mitigating strategy for minimizing the effect of injection location can be to inject via several wells in different locations in the medium.”

‘A similar argument can be extended to the leakage risk scenarios. Results computed are computed for a single spatial leakage probability function, but it is not clear how robust these results are. Moving the central leakage point with respect to depositional lobes or fault locations might radically change the outputs.

In addition to the discussion in paper I and III, this issue is also mentioned in the comments on paper I, Section 2.2, last paragraph:

“We use a leakage probability over the cap-rock that can dramatically influence the calculated leakage risk. We take this assumption to simplify the way we introduce the method.”

4 Issues regarding papers and work conclusions

‘Papers I and II are outlines of conference presentations based on preliminary modelling and analysis. They are not well written, with exceptionally poorly labelled and captioned diagrams and very rudimentary explanations of the results. Papers III and IV comprise manuscripts submitted for publication in main-stream journals. They essentially repeat, but expand on the results in I and II and are much better written and presented. There is a high level of duplication between papers I and II, and papers III and IV.’

The first two papers are excluded from the thesis and moved to appendix A. One more paper that was prepared during the PhD studies is added to the appendix.

It is important to mention that the first two papers are written in the start of the PhD program, and we can observe a progress trend of improvement in the later papers. Also, the reason paper III accepted for publication before the rest of papers is that it is submitted earlier than the rest.

‘The first four papers all suffer from a significant presentational defect in that the SAIGUP static model and also the flow simulations based upon it are treated as opaque ‘black-boxes’, which the reader is not able to evaluate or even able to reproduce based on the provided information.’

Literature review and model setup sections are added to paper I. For example, we see in Paragraph 3 of the section ‘literature review’:

“Over the last two decades, there have been several modelling studies related to the storage of CO₂ in the subsurface. There are a number of studies in the literature that are concerned about geological modeling and its importance in the process of CO₂ storage modeling. Most of them are case study practices related to a specific site locations (for example, [18]), or pilot projects (In Salah [31], Ketzin [14], and Johansen [12]).

...”

In Paragraph 5, section ‘Modeling setup’, we see:

“The start point of geological modeling is the pair of sedimentary heterogeneity matrices changing in different levels of heterogeneity in lateral and vertical directions. Structural heterogeneity is also considered by variations of the fault orientations, intensity, and the transmissibility across the fault. The focus has been on the following considerations during the modeling:

- *Enough overlap in the geological parameter variations exist between realizations to allow for quantitative assessment of the contribution of each factor.*
- *Although models are synthetic, each realization should be complex enough to represent a plausible geology suitable for realistic flow modeling.*
- *A large number of realizations can be used for sensitivity analysis.*

...”

Table 1 and Figures 1 and 2 are added to paper I to support the discussion in the text. In addition, an extensive discussion section is added in the introduction of the thesis, as discussed earlier (Section 1.5.1 and 1.5.2).

‘We do have concerns in assessing how much of this work the Candidate carried out himself. He did run the multiple (162) flow simulations and presented the results, and on Paper IV he is sole author, but these elements of work are not particularly innovative and he does not show deep insights in the interpretation and application of his results. Paper V is more original, but it is not clear what input the candidate has made to this.’

After discussions with the advisers, a subsection added to the summary of papers I and III in Section 2.2 to clearly mention what the candidate contribution to each part of the work was.

For paper I:

“The idea of using realizations from the SAIGUP project to study how variations in geological parameters impact the injection and early-stage migration of CO₂ was first suggested by the main supervisor of this thesis. The conceptual design of the injection scenario, as well as the measured reservoir responses were developed jointly with the co-authors of the paper. The candidate was solely responsible for working out the details of the simulation setup, developing a work-flow, performing simulations, post-processing results, and developing the first analysis of the results. The candidate then collaborated with the co-authors to refine the analysis and write the paper.”

And for paper III:

“The study was a joint work between the candidate and the co-authors on the following steps:

- Defining the problem.*
- Designing the simulation scenarios.*
- Designing the work-flow.*
- Integrating the aPC MATLAB code into the work-flow.*
- Performing the runs and processing the results.*
- Performing the global sensitivity analysis.*
- Performing the risk assessment.*
- Analyzing the results and preparing plots.*
- Writing the report.*

The candidate had a solid and major contribution in every step, and in particular, integrating the aPC code into the work-flow, running the simulations, performing the sensitivity and risk analysis, and processing the results. The report has gone through extensive reviews.”

5 Specific comments and issues

‘... without seeing into the black-box - (for example to see how plume and pressure distribution with time might vary with a given parameter), it is impossible to properly understand the processes and how the fluids in the model interact with the flow property architecture...’

About four cases are selected for a thorough flow discussions. The report of heterogeneities and flow responses is given in Section 1.8.3 and in paper I. Two cases are described in Table 1.4. A discussion on the flow analysis is given at the end of Section 1.8.3, starting by Paragraph 11:

“Results are discussed by comparing all cases in plots. However, the conclusions are made based on detailed flow study in some picked cases. For example, Figures 1.31 to 1.35 show the rock properties and CO₂ distribution in the domain at end of injection and end of simulation in two different cases. The heterogeneity description of the selected cases, called A and B, is given in Table 1.4.

...”

Figures 1.31 to 1.35 are added to show the heterogeneities and simulation responses in cross sections. In addition, CO₂ plume evolution and pressure development in the medium for selected cases are shown in Figures 1.36 and 1.37.

Moreover, paper I is equipped with a detailed discussion on flow analysis with supporting Figures 6, 7, and 8:

“...However, after injection stops, many cases have small negative fluxes, which means that a small volume of CO₂ reenters the domain. Once again, we observe that cases with low aggradation angle stand out from the rest. In these cases, the injected plume is almost entirely confined to the bottom of the model because of poor vertical communication (See Figures 6, 7 and 8)....”

‘A good example of this is the result (Paper III, Figure 7), that the sensitivity of reservoir pressure to the direction of progradation actually switches polarity at the end of the injection phase. This is a rather radical result that is difficult to visualise without seeing details from the model on how the pressure field interacts with the geological architecture.’

A discussion is added to Paper I that describes the change in sensitivity sign before and after the injection. This discussion makes it clear how the results of sensitivity analysis should be used:

“The discussed results are based on an overall trend and should be used carefully when a generic conclusion is expected. For example, pressure sensitivity values with respect to progradation dip direction are based on only two points, i.e., average of all values for cases with up-dip progradation and average of cases with down-dip direction. In Figure 13, we see that the progradation sensitivity changes polarity before and after injection operation. Squeezing the information of about 80 cases in one point makes it more difficult to make a general conclusion from this result. Figure 14 shows that some cases do not follow the trend shown in Figure 13. Albeit, there is a slight increase in the center level of pressure values from Figure 14-a to 14-b, while the level is decreasing when we compare Figure 14-c to 14-d.”

Meisam Ashraf,

Trondheim, October 2013