Modelling of CO2 Injection in Fluvial Sedimentary Heterogeneous Reservoirs to Assess the Impact of Geological Heterogeneities on CO2 Storage Capacity and Performance

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Modelling of CO2 Injection in Fluvial Sedimentary Heterogeneous Reservoirs to assess the impact of geological heterogeneities on CO2 Storage Capacity and Performance.

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Abstract

The integration of sedimentary heterogeneity in flow simulations is still a challenging issue in reservoir engineering modelling. Yet in the CCS context, the discussion on how the heterogeneities may impact the flow performances is at the beginning. Fluvial reservoirs consist of complex heterogeneous sedimentary bodies with varying connectivity, controlled by the sedimentary history of the system. The main difficulty is to handle two different scales when evaluating the storage capacity performance of such reservoirs: (i) large scale of the pressure footprint (~10km) and (ii) small scale of the sedimentary heterogeneity (~m). This induces the generation of reservoir grids containing several 100 000 of gridblocks making the dynamic flow simulation difficult to handle. In addition to that, the high level of uncertainty requires the generation of several models to cover a large spectrum of equi-probable solution.
The present work focuses on fluvial reservoir performances using a stochastic algorithm to reproduce deterministically realistic architectural models with high resolution heterogeneities. Each geological model is split into two identical architectural models that differ in their sedimentary fill. One considers the reservoir bodies (fluvial belts) as homogeneous stacked point bar sand bodies (1st order heterogeneity, Model B), while the second type contains also flow barriers (shale oxbow lakes; 2nd order heterogeneity, Model A).
To perform the CO_2 injection two codes were used: TOUGH2-MP (integrated finite volume approach with massive parallel implementation) and 3DSL (streamline black oil simulator on a single processor). Two sets of 50 realizations were assessed (Models A and B). The streamline simulations enable quick ranking of dynamic capacity estimate at the scale of the geological model while only eight models could be conducted in a reasonable CPU time framework with TOUGH2-MP. This is explained by the high detailed characterisation of the fluid properties coupled with the flow which lowers substantially the speed of calculations.
The study reveals that heterogeneities affect the storage capacity as well as the injectivity of the well. For a reservoir formation with a typical size of 23km x 25 km x 60m, the capacities vary between 2.5 and 11Mt. The presence of oxbow lakes induces a loss of capacity that varies between 1.2Mt (23%) and 1Mt (12%) after 10 years, and 30 years, respectively.

Keywords: Fluvial reservoirs, CO_2 storage, heterogeneity, storage capacity, streamlines

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1. Introduction

The impact of the heterogeneity on the reservoir performances have always been a key topic in geosciences. The discussions cover every scale: (i) at the pore scale (micro meter), (ii) at the sedimentary structure scale (few decimetres), (iii) at the architectural elements scale (tens of meters) up to the operating field scale. In the CO_2 geological storage context, the integration of high resolution heterogeneity is still at the beginning and even more important given the fluid mobility in the reservoir. Many studies provide approximation of a gas plume evolution that migrates toward the uppermost part of the reservoir with a radial geometry. Yet the evolution of reservoir characterization and calculation capacities allow today for the study of the role of reservoir heterogeneities on CO_2 migration and storage performances. This paper is based on a PhD. (Issautier, "Impact of the sedimentary heterogeneity on the CO2 storage in deep aquifers, 2008-2011), its purpose is to study with numerical modelling approach the impact of fluvial heterogeneities on reservoir storage capacity performance. The choice of fluvial geology was related to the work performed in France on the storage facilities of the Paris Basin and to contribute to deploy large-scale CCS. The paper proposes, through dynamic reservoir simulations, to quantify the impact of high-resolution heterogeneity on storage capacities. It also proposes an analysis of the CO_2 plume migration and trapping in complex heterogeneous reservoirs. Consequently the study is at reservoir scale and the models cover a 25 km x 25 km x 60 m thick block, which is representative of the operating scale of a reservoir.

2. Workflow

2.1. Geological model

The geological models used in this study are part of a workflow devoted to estimating static storage capacities [1]. They are based on a conceptual model established on the Minjur Sandstone, Central Saudi Arabia [2], [3]. The concept involves three kinds of sedimentary objects (Figure 1): (i) sheet sandstone, (ii) multi-story meander belt and (iii) single-story meander belt; and their position in the reservoir is not random since it is controlled by the sedimentary history which can be described through sequence stratigraphy principles. The depositional scenario is considered as follows,

- The base of the reservoir consists of sheet sandstone, as a result of a low available space. This parameter favours the lateral stacking of fluvial channels represented by the sheet sandstone. Then, following a slow increase of the available space, some sinuous deposits appear (multi-story meander belt). Yet, the rivers are more prone to wander laterally to deposit the sediments and it results a compartmentalization of the meander belt;
- Then, the available space sharply increases which tends to displace the rivers far from each other when they geographically change their positions (avulsion process);
- Once the available space reaches its maximum potential, start its decrease associated to deposition of multi-story meander belts.

The scenario is then stochastically reproduced using an algorithm specifically developed for the study [1]. The so-built data set contains fifty scenarios. Each of them is split into 2 models spanning two type of heterogeneity (Figure 1&2):

- 1st order: the reservoir bodies *i.e* the fluvial belts consist of "homogeneous" stacked point bar sand bodies embedded in a shaly floodplain; Model (B)
- 2nd order: the reservoir bodies contain internal sedimentary shale heterogeneity (oxbow lakes) which compartmentalizes the reservoir; Model (A)

2.2 Reservoir grid and dynamic properties

The flow grid covers an area of 25km by 25km with a thickness of 60m. Due to CPU time and memory constraints the grid cell resolution was set to 40m x 40m x 2m leading to grids containing originally 2,500,000. The grids were then upscaled to only 850,000 cells, representing a 5 km x 5 km x 60 m field around the centre of the model; the original cell resolution remains unchanged. The cells in the rest of the model are grouped together in the X and Y directions to reach 160 m x 160 m. The vertical resolution is maintained at 2 m.

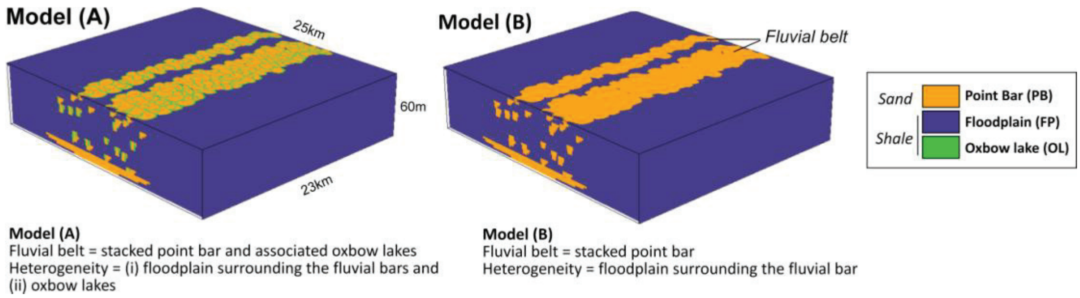

Figure1: A scenario is split into two models (A and B). They both have the exact same architecture (1st order heterogeneity *i.e* connectivity between the bodies) but a different internal sedimentary fill (2nd order heterogeneity *i.e* oxbow lakes).

The geological models were simplified with only two facies: sand and shale. For sake of simplicity, the petrophysical properties were set homogeneous within a facies, so that porosity and permeability cannot mask the 1st and 2nd heterogeneity signal on the reservoir performances. The petrophysical data (Table 1) were extracted from literature for the shale [4], except for the sand porosity/permeability data from in-house dataset.

Table 1: Petrophysical Parameters of the study

	Sand	Shale
Permeability (kh)	2.0e^{-13} m^2	1.0e^{-18} m^2
Permeability (kv)	2.0e^{-14} m^2	1.0e^{-19} m^2
Porosity (efficient)	20%	5%
Temperature	45°C	45°C
Pore compressibility	4.5e^{-10} Pa^{-1}	9e^{-10} Pa^{-1}

A unique injection well is located at the centre of the model, and CO_2 injection can only occur when the well encounters a sandy facies. Consequently, none of the models have the same amount of available “injection cells”. The injection lasts 50 years and is controlled by a seal fracturation overpressure ($\Delta P = 1.5P_{initial}$), which is a mechanical constraint to prevent a probable caprock failure. Consequently, the flow rates vary with time depending on the well’s surrounding pressure.

2.2. Uncertainty analysis

Two approaches are proposed (Figure 2); (i) comparing within each scenario, the pair of model (A and B) which provides the impact of the shale oxbow lake on the reservoir performances; (ii) comparing for all the scenarios the 50 associated models (B), which provides the impact of the connectivity between the fluvial belts on the reservoir performances.

A first calculation is realized with closed boundary conditions to avoid any CO_2 leakages in models (B) which do not contain any baffles. These simulations were carried out with TOUGH2-MP [5] on 8 scenarios only, due to heavy CPU time calculation. A specific well injectivity was implemented to TOUGH2-MP to control the injection rate with a pressure equals to 150% of the initial reservoir pressure. To complete the 50 models (A) we used the fast streamline simulator 3DSL™ [6]. Discrepancies have been noticed between the two simulators regarding the well injectivity and the productivity index model has been adjusted in 3DSL to fit TOUGH2-MP results and enable a comparison between the 8 models calculated with TOUGH2-MP and the 50 models with 3DSL.

Finally, to investigate the influence of boundary conditions we also carried out simulations with 3DSL and open boundary conditions system, but without tuning the injectivity to the TOUGH2-MP case and keeping BHP equivalent to 1.5 times the initial pressure. Consequently this last test is independent of the others and its results should not be strictly compared to the previous ones.

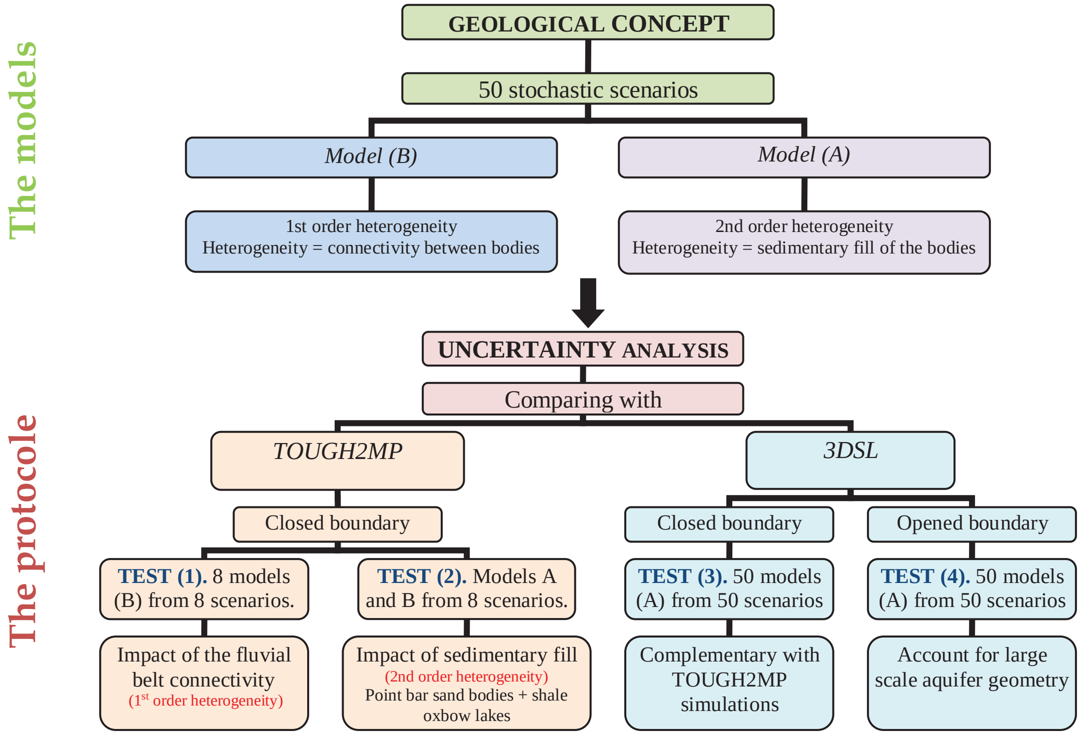

Figure 2 : Workflow established for the study: First, a geological concept is created and stochatsically reproduced with 50 scenarios. Each of them is split into two models (A and B) sharing the same architectrue but varying with internal heterogeneity. The second step is dedicated to the uncertainty analysis. Due to CPU time constrain only 8 models (B) can be run with TOUGH2-MP: (TEST 1) to study the impact of fluvial belts connectivity, (TEST 2) to study internal heterogeneity influence on reservoir performances. The utilization of 3DSL allows for an evaluation of the 50 models (TEST 3), with the influence of boundary conditions (TEST 4).

3. Results

3.1. Impact of the 1st order heterogeneity (fluvial belts connectivity) (TEST 1)

For a closed boundary conditions system the evolution of storage capacity with time is not linear (Figure 3). The first 10 years are characterized by a rapid increase in the amount of injected CO_2, which varies significantly in the different models (between 5.0 and 6.8 Mt for the eight models). Between 10 and 30 years, the injection curve shows a progressive decrease in the amount of injected CO_2, although the storage capacities still vary from one model to the next (between 7.5 and 9.0 Mt at 20 years; between 8.3 and 10.5 Mt at 30 years). Finally from 30 to 50 years, the curve begins to describe a plateau with the injected mass of gas ranging between 9.1 and 11.6 Mt. Detailed analysis of the models shows that this variance is unaffected by the number of sand facies intersected by the well, and relates to the architecture itself. In fact, the model whose well intersected the largest injecting levels (21 cells) is the one with the smallest capacity.

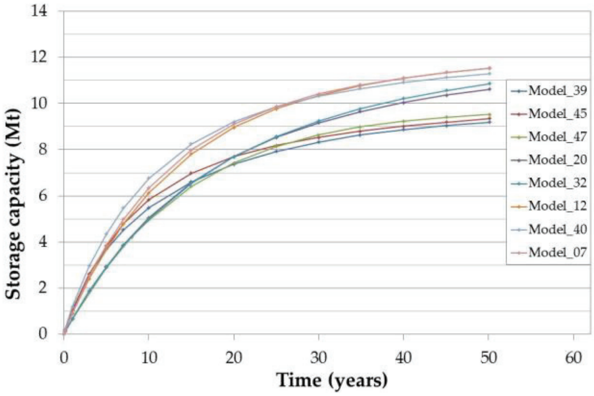

Figure 3: Storage capacities for Models (B).

Concerning the gas migration, the eight models display varying architectures and degrees of connectivity. When looking at the vertical gas migration, most of the models show the gas reaching the uppermost reservoir and spreading out over a 28 km² area (Figure 4).

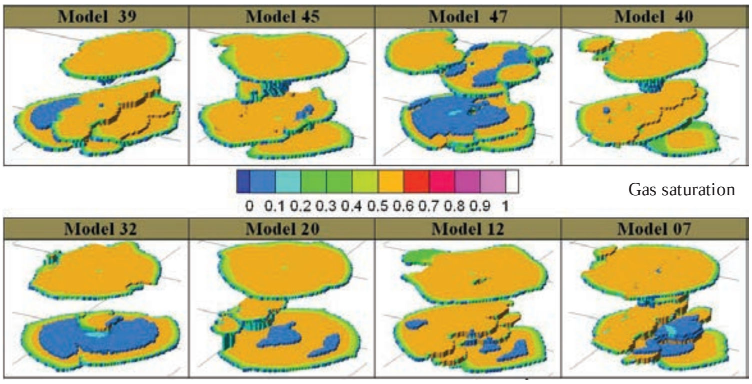

Figure 4: Saturation gas migration in the eight (B) models. The geometry of the reservoir bodies influences the gas migration as shown with models 47 and 12, for example. The radius of the gas cloud in the uppermost reservoir reaches approximately 3 km.

The plume is highly tortuous and does not follow a radial shape. Most of the models indicate two trapping areas; one at the base and the other at the top of the reservoir. The lowermost gas plume shows a broad radial extension due to the massive sandstone reservoir bodies, and only becomes tortuous when it reaches the meander belts whose boundaries are tortuous; this feature is well represented in models 40 and 07, for instance. The uppermost CO_2 gas plume is rather radial, although models 45 and 12 display a finger-like migration conditioned by the channelized shape of the meander belt. Globally, the mean saturation of the gas cloud is about 50%, although several isolated 'pools' show a very low gas saturation of 10%.

3.2. Impact of the 2nd order heterogeneity (shale oxbow lakes) (TEST 2)

The difference between the amount of CO_2 injected in the (B) and (A) models reflects the impact of the oxbow lakes on the reservoir's capacity. This 'loss of capacity' calculation was realized over the full 50 years of injection and is expressed by: $\Delta M_{CO2} = MCO2_B - MCO2_A$ where ΔM_{CO2} is the loss of capacity (in Mt), $MCO2_B$ the capacity in the (B**)** models (in Mt), and $MCO2_A$ the capacity in the (A) models (in Mt).

Figure 5 shows the loss of capacity in Mt with time for the eight models. From the beginning of the injection up to 10 years, the loss of capacity increases sharply with values at 10 years ranging between 0.7 and 2.6 Mt. Note that maximum loss of capacity is reached at varying injection times (between 15 and 20 years for the eight models) and then gently decreases to the 50 years of injection. Thus the loss of capacity is between 0.75 and 3.7 Mt after 20 years, between 0.72 and 3.8 Mt after 30 years, and between 0.6 and 3.6 Mt at 50 years.

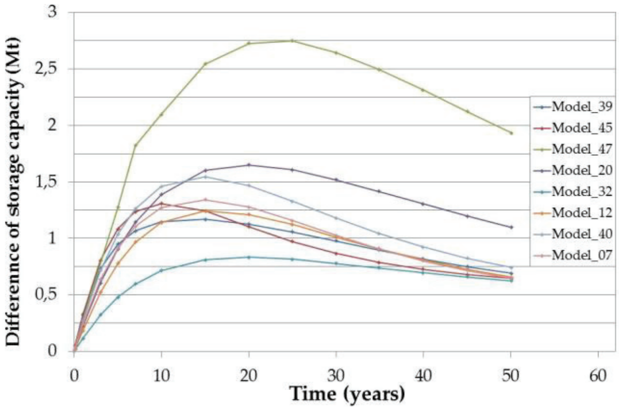

Figure 5: Loss of capacity due to oxbow lakes.

The extreme trend of model 47 is difficult to understand, since no problem occurred during the calculation and the initial conditions were the same as for the other models, as was the injection configuration at the well.

The development of the CO_2 plume through the years in the (A) models shows important differences with that of the (B) models (Figure 6). The oxbow-lake heterogeneities compartmentalize the reservoir into several porous bodies/pockets (described as point bars in sedimentology), which favours a split of the CO_2 cloud into several bodies. The amount of CO_2 reaching the uppermost reservoir is less than what we saw in the (B) models, and the CO_2 plume footprint reaches approximately 20 km^2.

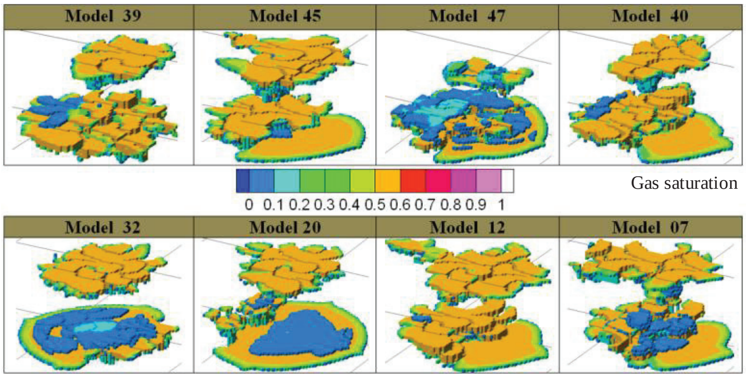

Figure 6: CO_2migration in the eight (A) models. The influence of the oxbow lakes is clearly visible, since individualized reservoir pockets (called point bars) are filled with CO_2. Some of the models show a finger-liked gas cloud indicating a migration pathway.

3.3. Storage capacity in open aquifer condition (TEST 4)

To perform the open aquifer condition, the simulator 3DSL was used, but keeping the well injectivity (productivity index) as provided in the code, therefore without fitting with the injectivity implemented with TOUGH2MP. The curves do not follow the same trend than in closed boundary conditions, since no plateau is reached after the 50 years of injection (Figure 7). The shape is nearly linear, and the final capacities spread between 2.5Mt and 11Mt and form a widespread range of values. The P50 storage capacity is roughly of 6.5Mt.

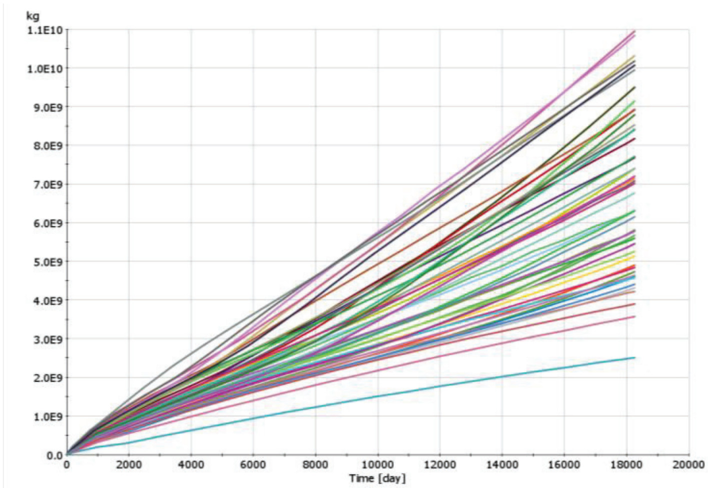

Figure 7: Storage capacity of the 50 models (A) flowed with open boundary conditions.

4. Discussion

Our results show that storage capacity, which is a major reservoir parameter that needs to be studied in any CCS operation, can be significantly impacted by heterogeneities. With respect to the 1st-order heterogeneity (homogeneous stacked point bar), the varying capacities of our eight scenarios indicate that storage capacity is strongly influenced by the connectivity between the different sand bodies; this strongly controls the amount of CO_2 that can be injected. For example storage capacities estimates for the eight models (B) ranges between 8.3 and 10.4 Mt after 30 years injection and between 9.1 and 11.5 Mt at the end of 50 years.

The differences in storage capacity between the models (A) and (B) reflect the loss of capacity due to the consideration of the shale oxbow lakes. These differences were maximal between 0 and 30 years of injection, the loss averaging approximately 1.3 Mt after 20 years and 1.0 Mt after 30 years. The difference then became smoothed toward 50 years, which is probably explained by the boundary conditions. Indeed, close boundary conditions favours a sharp pressure increase which reduces on long term the flow rate and smooth the impact of heterogeneity.

Oxbow lakes greatly increase the safety efficiency of reservoirs. Indeed, CO_2 migration in the models (A) was more difficult because of the oxbow lakes that compartmentalize the reservoir; several CO_2 pockets are observable where the CO_2 is confined by some surrounding shale baffles. The trapping due to the oxbow lakes is interesting because it decreases the amount of gas reaching the caprock, thus not only reducing possible leakages through permeability breakthrough in the caprock, but also reducing geochemical reactions. In addition, the increasing tortuosity of the gas front enhances the dissolution factor in the aquifer because it increases the exchange surface between the CO_2-depleted water and the gas plume.

Finally, the flow simulation of the 50 models (A) with open boundary conditions shows as linear trend in the gas injection related to the aquifer brine displacement. The estimated capacities spread in a wide range from 2.5 to 11Mt indicating a crucial role of both 1st and 2nd order heterogeneity. CPU time constrain is also a crucial issue for a complete uncertainty assessment. The performance of the streamline simulator 3DSL™ shows the importance of the numerical modelling technique to optimize the approach, as it enables a large computation time improvement despite the inherent assumptions.

5. Conclusion

The results of our study show that heterogeneities have a strong impact on reservoir performance. Two types of heterogeneity were considered: (i) 1st-order heterogeneities represented by fluvial belts and their connectivity (models B), and (ii) 2nd-order heterogeneities represented by (shale) oxbow lakes within the reservoir sand bodies (models A); the storage capacities are directly conditioned by both types. We have seen that the (B) models have a large variance in their storage capacities (between 9 and 11.5Mt). Yet, the figures estimated in this study are conditioned by (i) dimension and geometry of the sedimentary bodies which form the whole reservoir and (ii) boundary conditions.

Consequently magnitudes and differences of storage capacities obtained in this study should not be applied generally. In a close system, the shale oxbow lakes reduce the storage capacity by compartmentalizing reservoirs. This capacity reduction reaches 1.2 Mt (23%) at 10 years, 1.3 Mt (17%) at 20 years and 1.0 Mt (12%) at 30 years. The impact is smoothed over long term simulation due to the proximity of boundary conditions.

Conversely, the oxbow lakes play a major role in storage safety because they trap the CO_2 in isolated reservoir pools. This reduces the amount of gas able to reach the caprock and thus reduces the risk of alteration of the caprock through geochemical reactions, as well as gas leakages through permeable parts of the caprock.

For an open system, simulation of the 50 models (A) shows the crucial role of reservoir characterization since the final capacities bound between 2.5Mt and 11Mt. This wide range suggests a dramatic impact of both 1st and 2nd order heterogeneity on the reservoir performances. To summarise the influence of heterogeneity and boundary condition on our model we plot every calculations performed on models A (containing both sand point bars and shale oxbow lakes) in Figure 8 to report the storage capacity of models A with:

- TOUGH2-MP with closed boundary conditions (*TEST 2*)
- 3DSL and closed boundary conditions and injectivity adjusted to TOUGH2MP (*TEST 3*)
- 3DSL, open boundary conditions without adjusting injectivity to TOUGH2MP (*TEST 4*)

For closed system we adjusted well injectivity between 3DSL and TOUGH-MP to allow for a comparison between the 8 models calculated with TOUGH2MP and the 50 models with 3DSL, and therefore evaluate the influence of heterogeneities on the hydrodynamics of the system. Both simulators provide similar storage capacities estimates. With open boundary conditions we used 3DSL but keeping the injectivity as proposed by 3DSL (default parameters). We observe lower range of storage capacities but the ranking of the models according to their storage capacity remains globally similar. This study illustrate well the importance of estimating the influence of both the tools (and the methods) for evaluating the CO2 storage capacity along with the intrinsic geological heterogeneity of the reservoir system envisaged for large scale CO2 storage target.

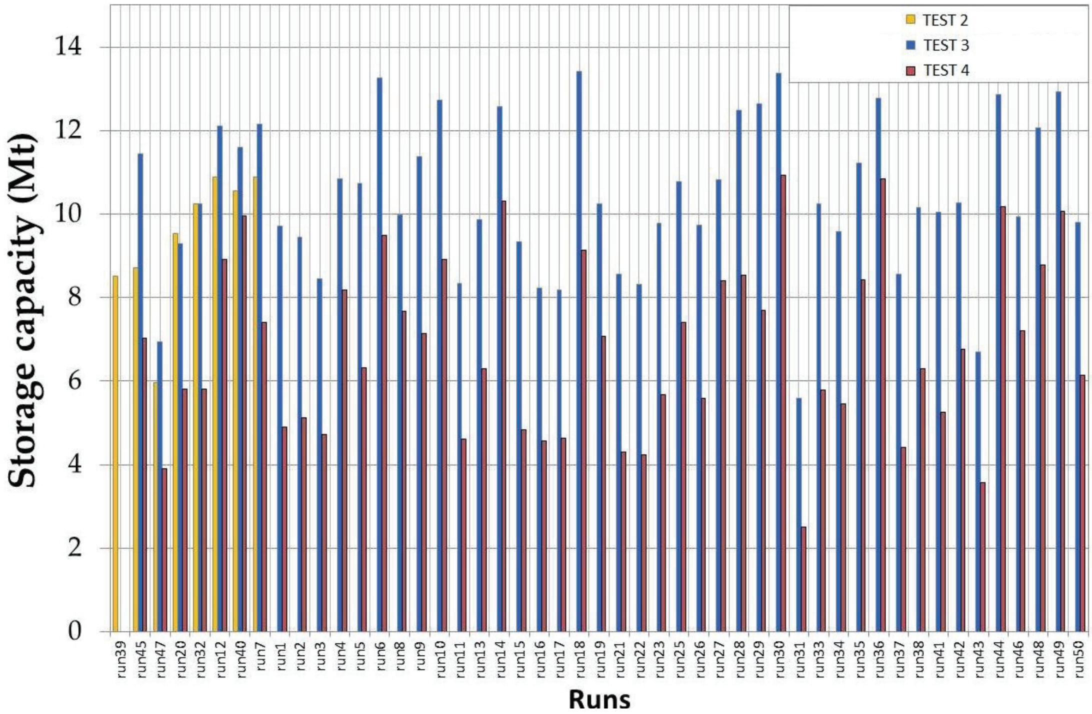

Figure 8: results of the calculations realized on the Models A with TOUGH2MP and 3DSL for varying boundary conditions and input parameters. The results show that when the input parameters are adjusted to fit between the codes, the figures are close to each other. Yet, when using default parameters, inconsistencies appear since the open boundary model has a much lower storage capacity than a close boundary model.

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