Comparison of Eclipse & Updated Sedsim Models

FINAL REPORT

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Summary

This report compares the dynamic simulations run on two different reservoir static models for the Lesueur Sandstone Formation, a deep saline formation considered for the SW Hub Project. These different reservoir models were built using the Sedsim software (by CSIRO) and the Petrel software (by Schlumberger). In this report, the static model built by CSIRO is referred to as the “Sedsim model”, while the static model built by Schlumberger is referred to as the “Schlumberger (or SLB) model”. Our comparison mainly focuses on the differences in formation properties, plume shape, residually trapped CO₂, dissolved CO₂ and the cumulative amount of CO₂ injected.

First, we repaired the Sedsim static model to prevent any loss in accuracy and convergence issues when running dynamic simulations. These repairs include -

- Grid blocks above the sea-level (above the 0-m elevation mark). We solve this by using the Sedsim software to place the model at the actual formation depth, making sure that all ZCORN numbers in the GREDCL file of Eclipse simulator are positive.
- Layers in the model being too thin. We solve this by increasing the stratigraphic modelling simulation time when generating the static model using the Sedsim software.
- The presence of a large number of “inside-out” grid blocks. We deal with this by making the affected grid blocks “null blocks”.
- Grid blocks being too coarse. We solve this by setting smaller global grid block dimensions using the Sedsim software.
- Faults being improperly defined in the model. We solve this by making sure that the Non-Neighbour Connection (NNC) keyword in the Eclipse simulator used alongside the Sedsim program is working properly.

When we examine both static models we observe several main differences. These include -

- The Schlumberger (SLB) model includes the Sabina Sandstone Formation, but not the Eneabba Formation. The updated Sedsim model does not include the Sabina Sandstone Formation, but does include the Eneabba Formation.
- Similar formations in both static models start at different depths and have different thicknesses.
- The pore volume in the updated Sedsim model is 2.12 x 10¹¹ m³, while in the SLB model it is 1.74 x 10¹¹ m³.
- The average global grid block size is 251 x 250 x 18 m in the updated Sedsim model, while it is 300 x 307 x 24 m in the SLB model.
- Permeability (in all directions) is almost 10x higher in the updated Sedsim model compared to the SLB model.
- The updated Sedsim model only contains 18 faults, which are non-extensive and do not intersect as much as the 26 faults of the SLB model.

We then carry out several tests and injection designs which use almost the same parameters as our previous study (RG 133652 - Desktop design study on enhancing residual and dissolution trapping). However, there are some significant differences, such as vertical perforation intervals being reduced from 500 m to 200 m. These tests yield following results -
• The Harvey-1 well test shows that closing all faults in the updated Sedsim model leads to an increase in bottomhole pressure BHP. However, because the faults are not extensive and do not intersect with each other as much, we manage to inject the full amount of CO\(_2\) (approximately 229 Mt) in both closed and open fault cases. Since permeability is much higher and pressure dissipation is much easier in the updated Sedsim model, we end up with a funnel-shape plume. This results in a lower percentage of residually trapped CO\(_2\) (up to 3% less for closed faults). The percentage of dissolved CO\(_2\) is much lower (up to 3% less for both closed and open faults) in the Sedsim model mainly because of a smaller global grid block size and because of the higher average porosity (Taheri et. al 2012, Green & Ennis-King 2012).

• Using the Schlumberger well test location, the updated Sedsim model shows a 9% decrease and a 5% decrease, respectively, in the residual and dissolution trapping compared to the SLB model. We observe a greater amount of mobile CO\(_2\) in the Yalgorup Member for the updated Sedsim model. This is because the very low permeability layers are distributed differently in both models. In addition, we do not inject as much CO\(_2\) in the SLB model, which results in more CO\(_2\) being trapped over time.

• The capillary pressure test follows the same trend as our previous study. The percentage of CO\(_2\) residual trapping and dissolution trapping increases by about 4% (using the Brooks-Corey / Van Genuchten model) compared to the case with no capillary pressure. If the Leverett J-function is used (variable capillary pressure), the percentage of CO\(_2\) residual trapping and dissolution trapping increases by about 3% compared to the case with no capillary pressure.

• The local grid optimisation test shows a result similar to our previous study. Areal local grid refinement affects the results significantly, while vertical local grid refinement does not. In this test, we conclude that a 5x5x1 local grid refinement is optimal.

• For the optimum vertical well scenario (VWP 5) in the updated Sedsim model, we observe a lower percentage of both residual CO\(_2\) trapping (14% less) and dissolution trapping (11% less). Our optimal vertical well scenario does not trap CO\(_2\) as much as the Schlumberger well test position. This is because the wells are closer together in the Schlumberger well test compared to our VWP 5 scenario. Also, the high formation permeability and lack of extensive/intersecting fault barriers are controlling parameters.

• For our optimum horizontal well scenario in the updated Sedsim model, we also observe a lower percentage of residual CO\(_2\) trapping (14% less) and dissolution trapping (9% less) of CO\(_2\). Compared to our VWP 5 scenario, we achieve a higher percentage of residual trapping (0.6% increase) and dissolution trapping (0.4% increase) of CO\(_2\).

• For our optimum vertical well with water production scenarios in the updated Sedsim model, we also observe a lower percentage of residual CO\(_2\) trapping (9% less) and dissolution trapping (4% less). This is because the permeability is high and there is a lack of low permeability layers which create “stacked-disc” CO\(_2\) plumes, as seen with the SLB model in our previous study.

• For our optimum WAG scenario in the updated Sedsim model, we also observe a lower percentage of both residual CO\(_2\) trapping (13% less) and dissolution trapping (4% less).

• For our optimum SWAG scenario in the updated Sedsim model, we observe a lower percentage of residual CO\(_2\) trapping (7% less) but a higher percentage of dissolution trapping (13% more). The percentage of dissolved CO\(_2\) increases
significantly because the vertical permeability between the brine injector and CO$_2$ injector is good. This is unlike the SLB model where very low permeability barriers reduce the effectiveness of the SWAG engineering design.
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1. Introduction

1.1 SW Hub Project

The SW Hub Project is a government/industry partnership led by the Western Australia Department of Mines and Petroleum. The industry partners include Alcoa Australia, Griffin Energy Developments, Perdaman Chemicals and Fertilisers, Electricity Generation Corporation (Verve) and Premier Coal Limited. In 2011, the SW Hub Project achieved a national flagship status. It aims to reduce greenhouse gas emissions in Australia. The project involves capturing CO$_2$ from the exhaust gases of several industrial plants in WA, transporting it to an injection site and injecting the CO$_2$ into the Lesueur sandstone. There are 5 different injection stages during the project, these include:

- Preparation Phase
- Enabling Case
- Base Case
- Extended Case 1
- Extended Case 2

CO$_2$ injection rates are expected to change as the project progresses. They range from 0.05 million tonnes per year (Mt/yr) at the start to 6.5 Mt/yr at peak. Previous dynamic simulations conducted by Schlumberger, on the updated 2013 static model, estimate a total CO$_2$ storage of between 200 and 260 Mt (Department of Mines & Petroleum 2012, Schlumberger 2013, Baz et. al 2014). These static models were developed prior to the results of the new seismic survey shot in 2014. However, for our previous study we mainly used closed faults to mimic the data from the Fault Seal First-Order-Analysis (Langhi et. al 2013).

The storage formation is a saline aquifer in the Perth Basin and bounded by two main faults known as the Darling and Dunsborough faults. The area of interest is dominated by a NW-SE trending structural high known as the Harvey Ridge (Varma et. al 2009). This is in the shire of Harvey, north of the Kemerton Industrial Estate and south of the city of Mandurah. The formation of interest was formed in the Triassic period and is called the Lesueur Formation. It lies 1.4 - 3 km deep in the subsurface and is divided into two main members. The upper member is known as the Yalgorup Member and the lower member is known as the Wonnerup Member (Department of Mines & Petroleum 2013). There is no known proven seal for this storage formation and trapping is mainly dependent on:

- Formation heterogeneity and inter/intra-formational baffles.
- Residual and dissolution trapping is expected to be high because (a) the contact area between injected CO$_2$ and in-situ brine is larger and (b) the Lesueur Formation is thick. There is evidence of this in the current literature and from industry knowledge.

Many major faults have been interpreted in the area of interest. However, not all faults are likely to have been identified because the data coverage is poor. The new 3D seismic survey shot in 2014 would, most likely, significantly improve subsurface knowledge. One of the regional fresh water aquifers (Yarragadee Formation) is absent; while the other fresh water aquifer (Leederville Formation) is present above the area of interest (Van Gent & Stalker 2010).
1.2 Front End Stratigraphic Modelling

Front end stratigraphic modelling (also known as stratigraphic forward modelling or SFM) is based on process modelling. It utilizes the knowledge of physical processes of sedimentation to predict grain size distributions based on given information such as depositional surface shape, depositional environment and source location of sediments. This is calibrated against observations of the stratigraphy at wellbores and is an alternative to the more standard approach of using sedimentary system analogues and a stochastic approach to characterising geological uncertainty. The stratigraphy is modelled based on a general assumed understanding of certain geological processes such as:

- Erosion
- Transportation
- Deposition

The model is generated assuming that the physics and physical processes which occurred in the past also occur today. The program used to generate the new updated model is the Sedsim program. Sedsim is a 3D stratigraphic forward modelling package that consists of several computer programs that can run together or separately. Using the processes explained above, it predicts sediment distribution in a range of depositional environments and at scales ranging from meters to several kilometres. In addition, it incorporates data available from previous seismic surveys and available well data (Griffiths 2010).

There are some constraints when generating static models using the Sedsim program. These range from (Griffiths 2010):

- The software cannot model turbulent sediment deposition.
- It only has 8 grain-sizes to choose from.
- It operates only on an orthogonal grid scheme, where cells can only be shifted vertically.

The updated Sedsim model generated for this project is used to increase our understanding about the Lesueur Formation’s heterogeneity and properties. The Sedsim program generates stratigraphic static models based on several basic operations, which include (Griffiths 2010):

- Fluid flow, which uses a Lagrangian approach to simplify the Navier-Stokes equation into non-linear Ordinary Differential Equations (ODEs).
- Sediment transportation, which is based on the principle of mass conservation. Sediment moves at the same rate as a fluid element and is transported across a bathymetry, or deposited on its surface.
- Wave effects, which are used to transfer sediment exposed to the prevailing wind and wave directions and above the wave base alongshore. This is based on several parameters such as angle of incidence, transport rate, etc.
- Time sampling sensitivity, where a higher resolution of events can be modelled with smaller parametric sampling events. However, this requires more simulation time.
- Tectonic subsidence. This helps include vertical tectonic movement in the simulation.
- Compaction, which calculates porosity values as a function of effective stress and grain size.
• Isostacy, which changes stratal geometries based on a function of mantle density and flexural rigidity.
• Gravity flows. This is triggered by sediment over-steepening through tectonic movement, or the exposure of sediment because of a fall in sea-level.
• Carbonates & Organics, where SedSim is capable of modelling initial production of two types of carbonates, two types of organic material and their resultant clastic grains after erosion. This is done using Fuzzy Logic which is based on the stratigraphic modelling package ‘Fuzzim’ (Nordlund 1996)
• Aeolian processes, which causes landscape development through sediment transportation by wind energy.

1.3 Residual and Dissolution Trapping

1.3.1 Residual Trapping

In a drainage process, the non-wetting phase saturation ($S_n$) and its relative permeability increase. If any reversal occurs in the saturation distribution in such a way that $S_n$ begins to decrease, the imbibition process commences. During the imbibition process, capillarity acts together with viscous forces which helps the wetting phase flow faster in the pore system, leading to snap-off. Snap-off forces a portion of the non-wetting phase to be trapped within pore bodies and hence the relative permeability to the non-wetting phase becomes zero at a positive $S_n$. This specific $S_n$ is denoted by the residual non-wetting saturation ($S_{nr}$). The value of $S_{nr}$ depends on the non-wetting phase saturation ($S_{nh}^{hyst}$) just before imbibition starts. Note that $S_{nh}^{hyst}$ is the same for both drainage and imbibition relative permeability curves. $S_{nh}^{hyst}$ can take on a maximum value ($S_{nmax}^{hyst}$) at an irreducible wetting-phase saturation which results in a maximum $S_{nr}$. The path taken from $S_{nh}^{hyst}$ to $S_{nr}$ is known as a “scanning imbibition curve”.

Many scanning curves can be obtained and calculated using different parametric interpolation methods (Killough 1976 & Land 1968). The value of $S_{nr}$ for any given scanning curve can be calculated from equations 1 and 2 (Killough 1976 & Land 1968):

$$S_{nr} = \frac{S_{nh}^{hyst}}{1 + C \times S_{nh}^{hyst}}$$

$$C = \frac{1}{S_{nmax} - S_{nr}}$$

where $S_{nmax}$ is the maximum achievable non-wetting phase saturation and $C$ is a constant for a given type of porous rock. Figure 1.1 below shows a diagram of this process.
1.3.2 Dissolution Trapping

Contact between unsaturated CO$_2$ and water initiates mass transfer between the phases. A higher mass of CO$_2$ goes into the water phase, than the mass of water entering into the CO$_2$ phase. The water phase tends to be less mobile. This is the result of hydrodynamic flow of groundwater being very slow (displacement being only a few meters per year). As a result, CO$_2$ is dissolved and effectively “trapped” in the water phase. This trapping process takes a long time for all the CO$_2$ to be dissolved (in the magnitude of several hundred to thousand years depending on several factors). It first starts through diffusion-based dissolution and later continues through convective-mixing-based dissolution (Anchilya and Ehlig-Economides 2009, Taheri et. al. 2012, Green and Ennis-King 2012). However, since we simulate a total of 140 years, our focus will be mainly on diffusion-based dissolution.

We utilise the Spycher et al. (2003) dissolution model coupled with the Peng-Robinson equation of state for this study. Dissolution of CO$_2$ is affected mainly by three parameters: salinity, temperature and pressure. This approach relies on the “true” equilibrium constants K, rather than Henry’s Law constants typically used in chemical engineering literature. This easily allows inclusion of non-ideal aqueous solutions (such as brine solutions). At equilibrium, the following reactions, along with their respective equilibrium constants can be written as (Spycher et. al 2003) -

\[
H_2O_{(l)} \Leftrightarrow H_2O_{(g)} \quad K_{H_2O} = \frac{f_{H_2O(g)}}{a_{H_2O(l)}}
\]

\[
CO_2_{(aq)} \Leftrightarrow CO_2_{(g)} \quad K_{CO_2(g)} = \frac{f_{CO_2(g)}}{a_{CO_2(aq)}}
\]
where \( K \) is the “true” equilibrium constant which varies with temperature and pressure, \( f \) is the fugacity and \( a \) is the activity of the component in the liquid phase.

Expressing these equilibrium constants as a polynomial function of temperature (1 bar and \( H_2O \) saturation pressure above 100°C), a pressure correction, at a specific temperature, is approximated by (Spycher et. al 2003) -

\[
K(T,P) = K(T,P)_0 \exp \left( \frac{(P-P_0)\bar{V}_i}{RT} \right)
\]

Where, \( \bar{V}_i \) is the average partial molar volume of the pure condensed component \((i)\) over the pressure interval \( P_0 \) to \( P \). Here, \( P_0 \) is taken as 1 bar and at an \( H_2O \) saturation pressure above 100°C. \( \bar{V}_i \) is more sensitive to a change in temperature than in pressure and is averaged over the temperature range of interest. This allows \( K(T,P) \) values to be approximated from a single \( \bar{V}_i \) value for each component.

1.3.3 Trapping Mechanisms on a Field Scale

From the literature, we observe that different formation parameters, completion designs and injection designs affect the amount of cumulative \( CO_2 \) injected as well as residual and dissolution trapping. Some of these parameter changes and their respective effects are shown below -

- As formation pressure increases, residual and dissolution trapping of \( CO_2 \) increases. In contrast, dissolution trapping of \( CO_2 \) decreases with increasing salinity and increasing temperature (Chang et. al 1998, Spycher et. al. 2003, Sifuentes et. al. 2009, Nghiem et. al. 2009 and Takasawa et. al 2010).

- Injecting \( CO_2 \) at the bottom of a thick formation improves both trapping mechanisms. Because \( CO_2 \) is less dense than formation water, after injection it tends to migrate upwards because of gravity. The \( CO_2 \) plume travels a longer vertical distance upward through the formation, leading to more residually trapped \( CO_2 \) along the way. In addition, since we achieve a larger contact area between \( CO_2 \) and brine, there is a larger amount of \( CO_2 \) dissolution trapping (Kumar et. al 2004, Kumar & Bryant 2008 and Sifuentes et. al 2009).

- Increasing horizontal permeability leads to a greater lateral spreading of the plume, which increases dissolution trapping. The lateral velocity of the plume plays an important role in the plume shape, which affects both residual and dissolution trapping. The higher the lateral velocity, the more the residual trapping is possible because of a larger plume volume (Kumar & Bryant 2008).

- Generally, if injection rate is not constrained, longer perforation intervals result in a slight increase in the amount of dissolved \( CO_2 \). However, at a specific injection rate, decreasing the perforation interval in a vertical injection well may lead to a more uniform \( CO_2 \) plume, which results in a greater amount of residual and dissolution trapping (Sifuentes et. al 2009 and Kumar & Bryant 2008).

- Low-salinity water injection accelerates both dissolution and residual trapping. This is because water injection enhances both diffusion and imbibition. Several parameters such as (a) the brine injection rate (b) the distance between the brine injector and the \( CO_2 \) injector and (c) the perforation interval length all affect the amount of residual and dissolution trapping of \( CO_2 \) (Basbug et. al. 2005, Anchilya & Ehlig-Economides 2009, Hassanzadeh et. al. 2009 and Javaheri & Jessen 2011).
- Water production can be used to relieve formation pressure, allowing a greater amount of cumulative CO$_2$ to be injected (Anchilya & Ehlig-Economides 2009 and Javaheri & Jessen 2011).

When conducting numerical simulation of CO$_2$ storage, coarser grids lead to an overexposure of CO$_2$ injected and, as a result, over-estimate of the amount of residual trapping. In addition, for short-term simulations (as in our case of 140 years), using coarse grids leads to an over-estimation of CO$_2$ dissolution at the saturation front. Hence, increasing grid size results in a proportional increase in estimated CO$_2$ dissolution. Therefore, refining the simulation grids significantly improves the accuracy in modelling CO$_2$ injectivity and trapping mechanisms (Juanes et. al. 2006 and Green & Ennis-King 2012).

1.4 Aim of Study

Having several static model realisations of a formation takes into account a range of uncertainties. The degree of uncertainty is related to the amount of data available. This is especially the case for the South West Hub Project, where data acquisition has been limited so far. In addition, dynamic simulations carried out for the SW Hub Project so far were based on a single static model built by Schlumberger. As a result, the predictions and results generated would be limited.

Previous attempts at using the Sedsim model to run dynamic simulations using Schlumberger’s E-300 software failed to produce reliable results. This was because of the way the Sedsim output created an abrupt transition between neighbouring grids, especially those caused by improperly defined faults (non-neighbouring connections). Another problem was the very thin layers generated by Sedsim, which resulted in convergence issues for the dynamic simulation (Faeti et. al 2013).

There are two main aims for this study -

A. To repair the Sedsim static model, and conduct dynamic simulations using the E-300 compositional simulator, which we use for predicting the injection performance of the SW Hub Project.
B. To compare the dynamic simulations between the Schlumberger and updated Sedsim models.

For the dynamic simulation comparison, we focus on analysing the effects of -

- Important formation properties that could potentially affect the behaviour of the CO$_2$ plume and the state of CO$_2$ during and after injection.
- Using the Harvey-1 well placement and simulation to test both open and closed faults for both models.
- Capillary pressure and grid refinement effects on the updated Sedsim model.

In addition, we test out both models using the well positions suggested by Schlumberger (2013) and the 5 optimal scenarios previously generated and tested using the Schlumberger Model (Baz et. al 2014). We use the knowledge obtained from our previous study and compare it with the Sedsim Model based on cumulative CO$_2$ injected, trapped CO$_2$, plume behaviour and formation pressure differences. For all dynamic simulations, we use the CO2STORE keyword to activate CO$_2$ storage option and the EHYSTR keyword to activate the Killough hysteresis option.
2. Repairing the Sedsim Model

There have been several issues when trying to run newly generated Sedsim static models using Schlumberger’s E-300 software. These problems either reduce the accuracy of numerical simulation results or lead to convergence issues, which prevented us from conducting any dynamic simulations at all. Of several Sedsim static model versions received, some of the main problems encountered were -

- Grid blocks above sea-level (above the 0 m elevation mark).
- Layers in the model being too thin.
- The presence of a large number of “Inside-out” grid blocks.
- Grid blocks being too coarse.
- Faults being improperly defined in the model.

2.1 Grid Blocks above Sea-Level

The first Sedsim static model version received had almost half of the grid blocks situated above sea-level. The highest point for the static model was roughly at 1,630 m. Initially when we prepared the model for dynamic simulations, we needed to specify which fluid components were involved (in our case this is CO₂, H₂O and NaCl). After we defined these components, we initialised the reservoir, such that the highest point of the formation was at a hydrostatic pressure of 30 bars. This roughly mimicked the conditions of the Eneabba formation.

However, even when initialising the model’s pressure, the top of the reservoir filled with CO₂ gas even before injection began. This was a major cause of convergence problems and prevented us from running any valid dynamic simulations. Figure 2-1 below shows how gas accumulates at the top of the model.

![Figure 2-1: Gas accumulation at the top of the model because grid blocks are above sea-level](image)
We tried the following solutions, but these did not work either -

- Initialising the reservoir such that the highest point of the reservoir has the sea-level hydrostatic pressure conditions (30 bar).
- Making the grid blocks above sea-level “null blocks”.

The static model needed to be shifted below sea-level to mimic actual storage formation depths. Shifting the whole model below sea-level can be done using Schlumberger’s Petrel software. However, this would result in re-shaping the static model’s horizons (layers). As a result, the volume and shape of the model would be altered. The best way to solve this problem is to shift the entire model downwards using the SEDSIM software. We make sure this is done by properly by checking the GRDECL file generated by the Sedsim software. All the numbers under the ZCORN keyword of the GRDECL file should be positive. Any ZCORN numbers that are negative places the grid blocks above sea-level, which lead to convergence issues.

2.2 Thin Layers

Another problem we encounter is the very thin model layers (at times less than 1 m) and the presence of a large number of pinch-outs in the Sedsim generated static model. This causes convergence problems because the throughput is greater than 1. The throughput, in simulation terms, is defined in the following equation (Schlumberger 2009) -

\[
\text{Throughput} = \frac{\text{Volume passing through a grid block for a given time step}}{\text{Pore volume of the grid block}}
\]

When the throughput is greater than 1, the simulator needs to go through a large number of Newtonian iterations to converge onto a single solution for a particular grid block for each time step. A large number of iterations drastically increases computational simulation time, and consequently, leads to less accurate solutions and sometimes even prevents us from carrying out any dynamic simulations.

One potential solution to overcome this problem is to up-scale the layers and grid properties using Petrel. However, this introduces more uncertainty, since the total pore volume and other properties are slightly changed. The best solution to this problem is to increase the stratigraphic modelling simulation time when generating the static model using the Sedsim software. Figures 2-2 and 2-3 show the difference between two static models, one with 80,000 years of stratigraphic modelling simulation time and the other with 320,000 years.

A longer stratigraphic modelling simulation time leads to thicker and fewer layers, while a shorter stratigraphic modelling simulation time leads to thinner and more layers.
Figure 2-2: Static model generated by Sedsim after 80,000 years of stratigraphic modelling simulation time.

Figure 2-3: Static model generated by Sedsim after 320,000 years of stratigraphic modelling simulation time.
2.3 Inside-Out Grid Blocks

Inside-Out grid blocks are another issue which do not necessarily cause convergence problems, but they do lower the accuracy of the dynamic simulation results. These types of grid blocks have sides which intersect each other, resulting in a negative grid block volume. These type of grid blocks mostly arise when building a static model or when up-scaling a static model. Figure 2-4 below shows an example of the severity of inside-out grid blocks, from one of the initial updated SedSim models received.

The best solution to dealing with these types of grid blocks is to make them “null blocks”. This means making their porosity equal to zero.

Figure 2-4: An example of inside out cells in one of the updated SedSim models

2.4 Coarse Grid Blocks

From our experience with the Schlumberger model, we notice that applying local areal grid refinement has a significant effect on simulation results (cumulative CO₂ injected, residual trapping and dissolution trapping of CO₂). On the other hand, applying local vertical grid refinement around the wells does not produce any significant effects. Hence, smaller grid blocks would give more accurate results. The initial version of the updated SedSim model had global grid block dimensions of roughly 502 m x 500 m compared to the Schlumberger model, which had global grid block dimensions of roughly 300 m x 307 m. The final updated SedSim model has grid block dimensions of 251 m x 250 m. Figure 2-5 shows a comparison between the initial updated SedSim model and the final updated SedSim model.

When creating the stratigraphic model using SedSim, the best way to deal with very coarse global grid blocks is initially to set smaller global grid blocks. It is important to keep the total number of global grid blocks below roughly 1.5 million. Increasing the grid blocks beyond this number would drastically slow computational time and significantly increase the occurrence of convergence issues. It is possible to do this...
with the Petrel software. However, again it is important to make sure the total number of grids is roughly below 1.5 million.

![Comparison between final version of updated Sedsim model (left) and first version of updated Sedsim model (right)](image)

**Figure 2-5: Comparison between final version of updated Sedsim model (left) and first version of updated Sedsim model (right)**

### 2.5 Improperly Defined Faults

We noticed from the first version of the updated Sedsim model that faults tend to be improperly defined. This could result in an excessive number of defined faults. As a result, it would be very difficult to test the effects of fault transmissibility on injected CO$_2$, residual and dissolution trapping. An example of this problem is shown in Figure 2-6.

The solution to this problem is simply to make sure that the Non-Neighbour Connection (NNC) program used is working properly. This program is used alongside the Sedsim program to generate faults. Once we generate a static model, we need to check if all the faults are properly defined via the Petrel software. This process is more of an iterative or trial and error process, which we keep doing until we are sure that the faults are defined properly.
3. Methodology

3.1 Static Model Comparison

This section outlines the main differences between the two static models, which could affect the results of the dynamic simulations. Figure 3-1 shows the different formations included in each static model.

Figure 3-1: Comparison of the formations modelled in the Sedsim model (left) and SLB model (right)
Table 3-1 shows the different start and end depths of the formations included in each static model. Comparing the two static models we notice that:

- Eneabba Formation is present in the Sedsim model and not in the SLB model.
- Sabina Sandstone Formation is present in the SLB model and not in the Sedsim model.
- The Yalgorup Member starts roughly 600 m deeper in the Sedsim model compared to the SLB model.
- Thickness of the Yalgorup Member is about 600 m in the SLB model and about 300 m in the Sedsim model.
- The Wonnerup Member starts roughly 200 m deeper in the Sedsim model compared to the SLB model.
- Thickness of the Wonnerup Member in the SLB model is 200 m thicker than the Sedsim model.

**Table 3-1: Formation starting and end depths using Harvey-1 stratigraphic well as a reference.**

<table>
<thead>
<tr>
<th>Formations</th>
<th>Department of Mines &amp; Petroleum (2012)</th>
<th>Schlumberger Model</th>
<th>Sedsim Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Start depth (TVD mSS)</td>
<td>End depth (TVD mSS)</td>
<td>Start depth (TVD mSS)</td>
</tr>
<tr>
<td>Eneabba</td>
<td>226</td>
<td>680</td>
<td>N/A</td>
</tr>
<tr>
<td>Yalgorup Member</td>
<td>680</td>
<td>1340</td>
<td>680</td>
</tr>
<tr>
<td>Wonnerup Member</td>
<td>1,340</td>
<td>2,871</td>
<td>1,354</td>
</tr>
<tr>
<td>Sabina Sandstone</td>
<td>2,871</td>
<td>N/A</td>
<td>2,871</td>
</tr>
</tbody>
</table>

Figure 3-2 shows that the fault definitions for both static models differ significantly. We observe that:

- Faults in the Sedsim model do not extend laterally as much as the SLB model.
- Faults in the Sedsim model do not intersect with each other, while faults in the SLB model do intersect with each other.
- Closing all faults in the Sedsim model will not result in the same effect as the SLB model because they do not close-off entire compartments of the storage formation.
Figure 3-2: Comparison of the faults defined in the Sedsim model (left) and the faults defined in the SLB model (right)

Figure 3-3: SLB static model (Total $\Delta X = 37,833$ m, Total $\Delta Y = 35,201$ m & Total $\Delta Z = 4,888$ m)
Figures 3-3 and 3-4 clearly show the difference in shape and size of both static models. The SLB static model’s volume is approximately 3 times greater than the Sedsim static model’s volume. Table 3-2 below shows a comparison between some of the main formation properties of both static models.

Table 3-2: Comparison of the main formation properties between the SLB model and the Sedsim model

<table>
<thead>
<tr>
<th>Property</th>
<th>SLB Model</th>
<th>Sedsim Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formations Modelled</td>
<td>Yalgorup Member, Wonnerup Member, Sabina Sandstone</td>
<td>Eneabba Formation, Yalgorup Member, Wonnerup Member</td>
</tr>
<tr>
<td>Total Pore Volume</td>
<td>$1.74 \times 10^{11}$ m$^3$</td>
<td>$2.12 \times 10^{11}$ m$^3$</td>
</tr>
<tr>
<td>Number of Grids</td>
<td>$89 \times 74 \times 187$</td>
<td>$58 \times 101 \times 210$</td>
</tr>
<tr>
<td>Average X increment ($\Delta X$)</td>
<td>300 m</td>
<td>251 m</td>
</tr>
<tr>
<td>Average Y increment ($\Delta Y$)</td>
<td>307 m</td>
<td>250 m</td>
</tr>
<tr>
<td>Average Z increment ($\Delta Z$)</td>
<td>24 m</td>
<td>18 m</td>
</tr>
<tr>
<td>Average Permeability X</td>
<td>40 mD</td>
<td>479 mD</td>
</tr>
<tr>
<td>Average Permeability Y</td>
<td>40 mD</td>
<td>479 mD</td>
</tr>
<tr>
<td>Average Permeability Z</td>
<td>4 mD</td>
<td>48 mD</td>
</tr>
<tr>
<td>Number of Faults</td>
<td>26 faults</td>
<td>18 faults</td>
</tr>
</tbody>
</table>
3.2 Modifications

The starting point for our analysis is altering both dynamic models’ parameters so that they reflect the actual formation parameters. The changes are similar to those made in our previous study (Baz et. al 2014). However, we have added a few changes. These include -

- Setting the maximum bottom-hole pressure (BHP) for each well to be 90% of the formation fracture pressure (0.186 bars/m) at the well’s top most perforation. This is similar to the pressure that Schlumberger (2013) used for its maximum well BHP. We use the following equation -

\[ Z = 0.9 \times 0.186(x) \]

where \( Z \) is the maximum BHP (bars) and \( X \) is the depth of the shallowest perforation of the well (meters).

- We use the same group injection rate for all wells used in previous studies (Schlumberger 2013, Department of Mines and Petroleum 2012, Baz et. al 2014). The applied injection scheme lasts for a total of 40 years and can inject a maximum total of 231 Mt of supercritical CO\(_2\) at roughly 5.8 Mt/yr. An important point to note is that we do not focus on injecting between 200 Mt and 260 Mt for this study. This study aims to focus purely on analysing the differences between the dynamic simulations of both models. The injection rates specified are set out below -

- The Enabling Case. This case injects a total of 0.05 Mt/yr for a period of 2 years.
- The Base Case. This case injects a total of 2.5 Mt/yr for a period of 4 years.
- The Extended Case. This case injects a total of 6.5 Mt/yr for a period of 34 years.
- The Observation Phase. This period is used to observe the behaviour of the plume for 100 years after injection stops. According to Schlumberger (2013), it is during this time that the most significant plume changes take place.

- We change the aquifer salinity from the initial 19,000 ppm to 48,000 ppm. This salinity is a better reflection of the actual salinity in the formation. According to Schlumberger (2013), the salinity of the sandy sections observed by drilling Harvey-1 is between 50,000 - 60,000 ppm. However, this drops to between 20,000 - 25,000 ppm in the non-washed out shale areas. Another study by CSIRO (Stalker et. al 2013) showed that the wireline data from Harvey-1 suggested salinities of 30,000 mg/L in the Wonnerup Formation and 40,000 mg/L in the Yalgorup Formation. Since we are injecting in a mostly sandy area, with the presence of a few shale baffles, we choose a high average estimate of 48,000 ppm.

- We set all the faults’ transmissibilities specified in the model to zero. We agreed during the Technical Presentations in Perth on October 4, 2013, that all faults would be closed during simulation runs. This is because most of the main faults are not likely to be reactivated. In addition, all of the main faults possess a shale-gouge-ratio (SGR) greater than the empirical threshold (Langhi et. al. 2013).
The perforation intervals for all vertical wells are kept precisely at 200 m thick. This is unlike our previous study where we varied them between 350 m to 650 m. We do this for three main reasons. First, a perforation interval greater than 200 m is rather unrealistic and costly. Second, the aim of this project is to compare the dynamic simulation results between the two static models and not develop the field such that we inject the full amount. Third, a smaller perforation interval generally leads to enhanced residual trapping by creating a more uniformly shaped CO₂ plume (Kumar & Bryant 2008). In the study conducted by Kumar and Bryant (2008), they recommend optimising the perforation interval in order to achieve a maximum residual trapping. The well optimisation would be easy if we only use a single well, with a constant injection rate and in a homogeneous formation (as they have done). However, for all our cases, except the first Harvey-1 injection case, we have a minimum of nine wells. Taking into account pressure interference between wells would require a significant amount of time to optimise each well. In addition, we use a group injection function for all wells. A group injection function assigns a set injection rate for a specified group of wells. The injection rates for each well depend on each well’s respective BHP. Changing the perforation interval of a single well would result in different well BHP for all wells throughout the injection life. As a result, changing the perforation interval of a single well would result in different individual injection rate for all wells.

The perforation intervals for horizontal CO₂ injection wells are kept above 2,000 m. This is because Kumar & Bryant (2008) found that increasing the horizontal perforation interval reduces the lateral velocity (and spreading) of the plume, making gravitational forces more influential. This reduces the lateral contact area with brine. Their study shows that a longer horizontal perforation interval slows down the speed at which the plume migrates upwards. Furthermore, they test a vertical injection well with a set perforation interval and compare it to a horizontal well with a much larger horizontal perforation length (double and even triple the perforation length of the vertical well). The speed at which the CO₂ plume migrates upwards does not significantly decrease. However, they report that a horizontal perforation interval above 2,000 m would slow down the vertical migration of the CO₂ plume. Therefore, in order to try and slow down the vertical migration of the plume, we choose a relatively longer perforation interval.

We use the same relative permeability curves and temperature gradient used in previous studies (Evans et. al 2012, Schlumberger 2013). The relative permeability curves and geothermal gradient are shown in Appendix A, Figure 7-1 and Table 7-1 respectively. In addition, we assume that capillary pressure is negligible unless stated.

3.3 Case Descriptions

Before we analyse any of these cases, we make sure that we perform all the necessary steps to repair the Sedsim model and all the modifications mentioned in Section 3.2. Unless otherwise stated, these tests mainly study how the formation properties of both models affect CO₂ plume migration and trapping of CO₂.

3.3.1 Harvey-1 Test

Our first test involves placing a well in the same position as Harvey-1 stratigraphic well (see Figure 7-2, Appendix A). In this test we also analyse the effects of fault transmissibility for both models.
From Section 3.1, we observe that the top layers of each formation differ between the models. As a result, we apply the following algorithm when deciding the placement depth of the Harvey-1 well -

1. For the SLB model we start the perforation at layer 56 (see Figure 7-3) and perforate 200 m downwards. We do this because our previous study shows that perforating from layer 56 downwards provides optimal cumulative CO₂ injection, residual trapping and dissolution trapping (Baz et. al 2014).
2. We find the distance between the top of the Wonnerup Member and the top of the perforation interval.
3. We allocate the same distance between the top of the Wonnerup and the top perforation point of the well in the Sedsim model.
4. We make sure the wells in the Sedsim model also have a perforation interval of 200 m.

We make sure the distance between the top of Wonnerup and the top of the perforation is the same for both models. This is done to ensure that there is an equivalent distance for the CO₂ plume to migrate upwards before entering the Yalgorup Member. This makes it easier to compare since reservoir thickness is a major factor affecting the residual and dissolution trapping (Kumar & Bryant 2008, Sifuentes et. al. 2009).

3.3.2 Schlumberger Well Location Test
For the Schlumberger well location test we place 9 CO₂ injection wells at the same position as those provided in Schlumberger Report 1.1 (2013). We apply the same algorithm as the Harvey-1 Test (Section 3.3.1) for each well. We allocate the same distance between the top of the Wonnerup and the top perforation point for each well respectively in both Sedsim and SLB models. Figure 7-4, shows the position of the wells in both SLB and Sedsim models.

3.3.3 Capillary Pressure Test
As in our previous study, we test out the effects of different capillary pressure models on the updated Sedsim model’s dynamic simulation results. We use the same two capillary pressure models -

- Leverett J-Function (Satter et. al. 2008), which uses a variable capillary pressure curve.

We then compare how the results of the Sedsim dynamic simulations compare with the capillary pressure tests previously conducted on the SLB model. For a description of the capillary pressure models, refer to our previous report (Baz et. al 2014). We apply the same well locations as Section 3.3.2 (Schlumberger Well Locations) and the same algorithm as the Harvey-1 Test (Section 3.3.1) for each well. Table 3-3 shows the parameters we use for our capillary pressure study on the updated Sedsim model. For this test only, we make the perforation intervals of each well 500 m, for both the SLB and the updated Sedsim model.
Table 3-3: Parameters used for generating Brooks-Corey / Van Genuchten and J-Leverett capillary pressure curves in the Sedsim model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average permeability (k)</td>
<td>263.5 mD (average of both horizontal and vertical permeability obtained from Petrel)</td>
</tr>
<tr>
<td>Threshold capillary pressure (Pct)</td>
<td>0.046 bars, using Thomas-Katz (1968) equation.</td>
</tr>
<tr>
<td>Residual water saturation (Swr)</td>
<td>0.454 (Schlumberger 2013)</td>
</tr>
<tr>
<td>Residual gas saturation (Sgr)</td>
<td>0.370 (Schlumberger 2013)</td>
</tr>
<tr>
<td>Pore size distribution index (λ)</td>
<td>1</td>
</tr>
<tr>
<td>Van Genuchten fitting parameter (m)</td>
<td>0.4</td>
</tr>
<tr>
<td>Average porosity (Φ)</td>
<td>0.25</td>
</tr>
<tr>
<td>Constant for J-Leverett unit conversion (C)</td>
<td>0.21645</td>
</tr>
<tr>
<td>Wetting angle (θ)</td>
<td>0° (fully water-wet)</td>
</tr>
<tr>
<td>Surface tension (σ)</td>
<td>30 mN/m</td>
</tr>
</tbody>
</table>

3.3.4 Local Grid Refinement Optimisation

We try to minimise dispersion errors by applying a local grid refinement around each well. From our previous study, we notice that areal grid refinement affects the dynamic simulation results significantly, while vertical grid refinement does not affect the results much. This is especially the case for the cumulative CO₂ injected and dissolved CO₂ in the formation. Figure 3-5 shows the different refinement dimensions we use for the local grid refinement optimisation (Baz et. al. 2014). We first compare the effects of areal grid refinement (refinement in the X and Y directions) and then compare the effects of the vertical grid refinement (Z direction). For this test we apply the same well locations as Section 3.3.2 (Schlumberger Well Locations) and the same algorithm as the Harvey-1 Test (Section 3.3.1) for each well. The aim of this test is to find the optimal local grid refinement dimensions.
3.3.5 Optimum Vertical Well Scenario

For this test we apply the best vertical well scenario from our previous study (VWP 5 - Mid Upper Wonnerup, see Figure 7-3). We use the same parameters previously used in the SLB model. However, instead of a 500 m perforation, we apply a 200 m perforation in each well for both the SLB and updated Sedsim model. We apply the same algorithm as the Harvey-1 Test (Section 3.3.1) for each well and apply an areal local grid refinement of 5x5x1 (see Section 4.4). Figure 7-5 shows the position of the wells in both models.

3.3.6 Optimum Horizontal Well Scenario

We then test the best horizontal well scenario from our previous study (Horizontal Wells - Mid Upper Wonnerup, see Figure 7-3). The perforation interval of each well is roughly 2,000 m and we apply an areal local grid refinement of 5x5x1. We use the same parameters previously tested in the SLB model.

We apply the following algorithm when running our optimal horizontal well scenario -

- We take the top point in the perforation interval of a well for the SLB model (Z1).
- We apply the same algorithm as Harvey-1 Test (Section 3.3.1) for that first point (Z2) and apply it to the updated Sedsim model.
- For the second point in the SLB model, we find the depth difference compared to the first point (X).
- We locate the second point of the perforation interval in the updated Sedsim model and apply the same depth difference (X).
- Hence, the new point will be have a depth of (Z2 + X).

Applying this algorithm to the updated Sedism model allows us to mimic the exact shape of the horizontal well perforation in the SLB model. However, we do not
achieve an equivalent distance between the top of the perforation and the top of the Wonnerup Formation. We do not follow the same algorithm as the Harvey-1 Test (Section 3.3.1) because this leads to unrealistically shaped well perforation intervals (see example Figure 7-6). These irregular shaped perforation intervals are a result of different layer shapes in both the SLB and the updated SedSim models. Running the simulation with such perforation intervals leads to inaccurate results and, at times, convergence issues.

Figure 7-7 shows the position of the wells in both models.

3.3.7 Optimum Vertical Well with Water Production Scenario

Next we test the best vertical well with water production scenario (Water Production - Mid Wonnerup, see Figure 7-3). The injection well positions are exactly the same as section 3.3.5 (VWP 5), with all the perforations in both the injectors and producers set at 200 m thick. We apply the same algorithm as the Harvey-1 Test (Section 3.3.1) for both CO$_2$ injection and water production wells and apply an areal local grid refinement of $5\times5\times1$. As in our previous study, the water producers produce at a voidage rate equal to the amount of CO$_2$ injected. This is done to relieve pressure build-up in the formation during injection. We apply the same well groups, but unlike the SLB model, the SedSim model does not have defined faults which separate different voidage groups (reservoir compartments) from each other (Baz et. al 2014). The voidage groups are explained below -

- WAT$_4$ is in the same group as CO$_2$_5 & CO$_2$_11. Hence, WAT$_4$ has a target to produce the same volume of water as the volume of CO$_2$ injected by both CO$_2$_5 and CO$_2$_11.
- WAT$_1$, WAT$_2$ and WAT$_3$ are in the same group as CO$_2$_6, CO$_2$_7, CO$_2$_8, CO$_2$_10 and CO$_2$_17. Therefore, WAT$_1$, WAT$_2$ and WAT$_3$ have a target to produce the same volume of water as the volume of CO$_2$ injected by CO$_2$_6, CO$_2$_7, CO$_2$_8, CO$_2$_10 and CO$_2$_17.
- WAT$_5$ is in the same group as CO$_2$_12 & CO$_2$_16. Hence, WAT$_5$ has a target to produce the same volume of water as the volume of CO$_2$ injected by both CO$_2$_12 and CO$_2$_16.

Figure 7-8 shows the positions of both injectors and producers located in both models.

3.3.8 Optimum WAG Scenario

We also test the best Water Alternating Gas (WAG) scenario (Mid-Upper Wonnerup, see Figure 7-3). The WAG and water production well positions are exactly the same as Section 3.3.7, with all the perforations of both the injectors and producers set to 200 m thick. In addition, we apply the same algorithm as the Harvey-1 Test (Section 3.3.1) for both CO$_2$ injection and water production wells and apply an areal local grid refinement of $5\times5\times1$. We apply a similar voidage rule and grouping as in section 3.3.7. However, because we are now injecting both water and CO$_2$, the water producers produce a volume of water equivalent to the volume of CO$_2$ and water injected by the WAG wells. We keep the WAG cycle ratio at 1:1 (1 year of water injection : 1 year of CO$_2$ injection).

Figure 7-8 shows the positions of the WAG and water production wells in both models.
3.3.9 Optimum SWAG Scenario

Our final test involves our best Simultaneous Water Alternating Gas (SWAG) scenario (Mid-Upper Wonnerup, see Figure 7-3). The basis of the design is explained in a study by Anchilya and Ehlig-Economides (2009). It consists of a horizontal brine injector well located directly above a horizontal CO₂ injection well. In addition, there are two horizontal brine producers located on each side of the horizontal CO₂ injection well. We apply the same horizontal well algorithm explained in Section 3.3.6 to avoid creating unrealistic well perforation intervals, which cause convergence issues. In addition, we apply an areal local grid refinement of 5x5x1 for all wells. We use the following parameters for our study -

- CO₂ horizontal injector is at layer 55 or 56 in the SLB model (we convert this using the algorithm explained in Section 3.3.6 to the Sedsim model).
- Distance between CO₂ and brine injector = approx. 300 m.
- Distance between injector and producers = approx. 2,100 m.
- CO₂ injector perforation interval = approx. 1,800 m.
- Brine injector perforation interval = approx. 2,000 m.
- Maximum water injection rate of 171,176 m³/day. However, injection pressure is limited to 90% of the fracture pressure at the depth of perforation.

We apply a similar voidage rule as seen in section 3.3.7. However, because we are now injecting both water and CO₂, the water producers produce a volume of water equivalent to the volume of CO₂ and water injected. The voidage groups are explained below -

- WAT_3 and WAT_4 are the same group as WATINJ_2 & CO2_2. Hence, WAT_3 and WAT_4 have a target to produce the same volume of water as the volume of CO₂ and water injected by both WATINJ_2 & CO2_2.
- WAT_1 and WAT_2 are the same group as WATINJ_1 & CO2_1. Hence, WAT_1 and WAT_2 have a target to produce the same volume of water as the volume of CO₂ and water injected by both WATINJ_1 & CO2_1.
- WAT_5 and WAT_6 are the same group as WATINJ_3 & CO2_3. Hence, WAT_5 and WAT_6 have a target to produce the same volume of water as the volume of CO₂ and water injected by both WATINJ_3 & CO2_3.

Figure 7-9 shows the positions of the SWAG engineering designs in both models.

4. Results & Discussion

4.1 Harvey-1 Test

Table 4-1 shows the results of the Harvey-1 test for both SLB and Sedsim models. Open and closed faults are simulated. Harvey-1 well’s surrounding permeability, porosity and depth interval values are given in Appendix B, Figure 8-1. We observe that opening and closing the faults in the Sedsim model has no effect on the cumulative CO₂ injected. Although, the BHP of Harvey-1 in the Sedsim model increases when closing the faults, compared to opening the faults (see Appendix B, Figure 8-2), the maximum BHP is not reached. There are two main reasons -

- The high surrounding horizontal permeability.
- The faults that are not laterally extensive and do not intersect each other.
This means that pressure can easily dissipate throughout the formation with either open or closed faults in the Sedsim model. Therefore, injectivity in the Sedsim model is much higher compared to the SLB model (roughly about 5 times higher). Figure 8-3 shows the graph of injectivity vs. time.

We have a higher percentage of residually trapped CO\(_2\) in the SLB model (for either closed or open faults). This is because the Sedsim model has a very high average permeability (and high vertical permeability), which results in a “funnel shape” CO\(_2\) plume. As a result, the plume has a larger surface area to volume ratio, which results in a lower percentage of residually trapped CO\(_2\).

For both closed and open faults, the SLB model shows a higher percentage of dissolved CO\(_2\). The contrary should intuitively be true. There are two main reasons. One is that the SLB model has a lower average porosity (Taheri et. al 2012). Another reason is that the grid resolution in the Sedsim model is smaller (250 m x 250 m x 18 m) than in the SLB model (300 m x 307 m x 24 m). As a result, the SLB model overestimates the dissolved CO\(_2\) compared to the Sedsim model (Green & Ennis-King 2012).

Both models seem to have several low permeability barriers, which limit the CO\(_2\) plume from migrating upwards into the Yalgorup Member. However, because the permeability distributions and regions of low permeability are different, there is a significant difference in plume shape for both models (Appendix B, Figure 8-4). The BHP curves for the Sedsim model show a smaller pressure drop after injection (roughly 10 - 20 bars). This is because, in the Sedsim model, there is a very low permeability layer directly above the top of the perforation zone (Appendix B, Figure 8-5). As a result, CO\(_2\) accumulates at the top of the perforation, keeping pressure relatively high. This is why there is a smaller pressure drop compared to the pressure drop seen in the SLB model (roughly 60 bars). Figures 8-7, 8-9 and 8-11 show that for each case of open and closed faults, less CO\(_2\) reaches the Yalgorup Member in the Sedsim model. This is because of the very low permeability barrier directly above the top perforation.

Table 4-1: Summary of results for Harvey-1 Test (Appendix B, Figures 8-6 to 8-12)

<table>
<thead>
<tr>
<th>Model</th>
<th>Residually trapped CO(_2) (Mt)</th>
<th>Dissolved CO(_2) (Mt)</th>
<th>Mobile CO(_2) (Mt)</th>
<th>Cumulative Injected (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Closed Faults</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLB</td>
<td>74.8 (51.8%)</td>
<td>25.1 (17.3%)</td>
<td>44.6 (30.9%)</td>
<td>145</td>
</tr>
<tr>
<td>Sedsim</td>
<td>111.6 (48.6%)</td>
<td>31.4 (13.7%)</td>
<td>86.4 (37.7%)</td>
<td>229</td>
</tr>
<tr>
<td></td>
<td>Open Faults</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLB</td>
<td>111.4 (48.6%)</td>
<td>38.1 (16.6%)</td>
<td>79.9 (34.8%)</td>
<td>229</td>
</tr>
<tr>
<td>Sedsim</td>
<td>110.4 (48.2%)</td>
<td>30.9 (13.5%)</td>
<td>87.6 (38.3%)</td>
<td>229</td>
</tr>
</tbody>
</table>

4.2 Schlumberger Well Location Test

Table 4-2 shows the results of the Schlumberger Well Location Test for both SLB and Sedsim models. In addition, each well’s surrounding permeability, porosity and depth interval values are available in Appendix C, Figures 9-1 to 9-9. The SLB model shows less cumulative CO\(_2\) injection because group injectivity is roughly 10 times lower.
This is caused by lower surrounding permeability and intersecting & extensive faults that compartmentalise the reservoir.

The percentage of residually trapped CO$_2$ is higher in the SLB model for the same reason as applies in Section 4.1. A separate test conducted on the Sedsim model (results not included in this report) by lowering the average permeability by 10 times results in a more “pear-shaped” CO$_2$ plume instead of a “funnel shape” plume. As a result, a higher percentage of residually trapped CO$_2$ is achieved compared to the SLB model. This is because the surface area to volume ratio of the pear-shaped plume is lower.

We have a lower percentage of dissolved CO$_2$ in the Sedsim model because of the smaller global grid blocks and because the SLB model has a lower average porosity (Taheri et. al 2012, Green & Ennis-King 2012).

We observe a greater amount of mobile CO$_2$ in the Yalgorup Member for the Sedsim model after 100 years of observation. This is because -

- In the Sedsim model, the layers in between the top of the well perforations and the bottom of the Yalgorup Member contain several areas of high vertical permeability (see Appendix C, Figure 9-11 for an example).
- From our previous study with the SLB model (Baz et. al 2014), we observe several layers with low vertical permeability located between the top of the well perforations and the bottom of the Yalgorup.
- We inject a much lower cumulative amount of CO$_2$ in the SLB model. As a result, most of the injected CO$_2$ becomes trapped (either residual or dissolution trapping) after 100 years of observation.

Finally, the Sedsim model requires 5 times more computational simulation time compared to the SLB model (Appendix C, Figure 9-12).

**Table 4-2: Summary of results for Schlumberger Well Location Tests (Appendix C, Figures 9-13 to 9-19)**

<table>
<thead>
<tr>
<th>Model</th>
<th>Residually trapped CO$_2$ (Mt)</th>
<th>Dissolved CO$_2$ (Mt)</th>
<th>Mobile CO$_2$ (Mt)</th>
<th>Cumulative Injected (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLB</td>
<td>82.1 (54.8%)</td>
<td>42.5 (28.4%)</td>
<td>25.3 (16.9%)</td>
<td>150</td>
</tr>
<tr>
<td>Sedsim</td>
<td>103.8 (45.2%)</td>
<td>53.7 (23.4%)</td>
<td>72.0 (31.4%)</td>
<td>229</td>
</tr>
</tbody>
</table>

**4.3 Capillary Pressure Test**

Table 4-3 shows the results of the capillary pressure test for the Sedsim model. We observe similar results compared to the previous capillary pressure test conducted on the SLB model (Baz et. al 2014). Residually trapped CO$_2$ increases as capillary pressure increases because capillary pressure reduces the ability of the non-wetting fluid (CO$_2$) to pass through the wetting fluid (brine). Dissolution trapping increases because capillary forces reduce the gravity effects slightly, improving the lateral movement throughout the reservoir and exposing the CO$_2$ to a larger contact area with brine (Alkan et. al 2010). Furthermore, as in our previous report, we observe that the Van-Genuchten type curves tend to accelerate dissolution. However, this is more apparent when conducting long term simulation of more than 100 years (Li et.
The only difference from the SLB model’s capillary pressure test is that the cumulative supercritical CO\textsubscript{2} injected does not decrease. This is because the Sedsim model has high permeability, non-intersecting faults and non-extensive faults.

Table 4-3: Summary of results for capillary pressure test on Sedsim model (see figures in Appendix D)

<table>
<thead>
<tr>
<th>Model</th>
<th>Residually trapped CO\textsubscript{2} (Mt)</th>
<th>Dissolved CO\textsubscript{2} (Mt)</th>
<th>Mobile CO\textsubscript{2} (Mt)</th>
<th>Cumulative Injected (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Capillary Pressure</td>
<td>103.8 (45.2%)</td>
<td>53.7 (23.4%)</td>
<td>72.0 (31.4%)</td>
<td>229</td>
</tr>
<tr>
<td>Brooks-Corey / Van Genuchten</td>
<td>112.2 (48.9%)</td>
<td>62.1 (27.1%)</td>
<td>55.1 (24.0%)</td>
<td>229</td>
</tr>
<tr>
<td>J-Leverett</td>
<td>111.1 (48.4%)</td>
<td>60.9 (26.5%)</td>
<td>57.4 (25.0%)</td>
<td>229</td>
</tr>
</tbody>
</table>

4.4 Local Grid Refinement Optimisation

Table 4-4 shows the results of the local grid refinement optimisation for the Sedsim model. In our previous study, applying local grid refinement resulted in an increase of cumulative injected CO\textsubscript{2}. However, in the Sedsim model, the maximum amount of CO\textsubscript{2} could already be injected even before the refinement. Therefore, there is no change in the amount of cumulative injected CO\textsubscript{2}. However, residually trapped CO\textsubscript{2} increases with a higher degree of local grid refinement. This was also seen in our previous study. This is because the plume is able to spread more easily outward and eventually upwards, allowing a larger volume of CO\textsubscript{2} to be residually trapped.

In addition, larger grid blocks tend to overestimate the percentage of dissolved CO\textsubscript{2}, as we have previously seen with the SLB model. Over-estimating the dissolved CO\textsubscript{2} is a result of numerical dispersion, which comes from coarse grid blocks. This occurs mainly at the invading saturation front. For larger grid blocks, the saturation front has a larger volume of formation brine (in which CO\textsubscript{2} can dissolve). Therefore, a greater amount of CO\textsubscript{2} can dissolve (Hassanzadeh et. al 2009 and Green & Ennis-King 2012).

Again, we notice that the percentage changes in residual and dissolution trapping are more significant for the areal local grid refinement compared to the vertical local grid refinement. Furthermore, the results for the areal local grid refinement show that the change becomes insignificant after the 5x5x1 refinement. This suggests that a 5x5x1 areal local grid refinement is best for accurate simulations.
Table 4-4: Summary of results for local grid refinement optimization (see figures in Appendix E)

<table>
<thead>
<tr>
<th>Model</th>
<th>Residually trapped CO$_2$ (Mt)</th>
<th>Dissolved CO$_2$ (Mt)</th>
<th>Mobile CO$_2$ (Mt)</th>
<th>Cumulative Injected (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No refinement</td>
<td>103.8 (45.2%)</td>
<td>53.7 (23.4%)</td>
<td>72.0 (31.4%)</td>
<td>229</td>
</tr>
<tr>
<td>Areal Local Grid Refinement</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2x2x1</td>
<td>102.7 (44.8%)</td>
<td>52.3 (22.8%)</td>
<td>74.4 (32.4%)</td>
<td>229</td>
</tr>
<tr>
<td>3x3x1</td>
<td>105.5 (46.0%)</td>
<td>50.9 (22.2%)</td>
<td>73.0 (31.8%)</td>
<td>229</td>
</tr>
<tr>
<td>4x4x1</td>
<td>108.5 (47.3%)</td>
<td>50.5 (22.0%)</td>
<td>70.3 (30.6%)</td>
<td>229</td>
</tr>
<tr>
<td>5x5x1</td>
<td>110.2 (48.1%)</td>
<td>50.1 (21.9%)</td>
<td>69.0 (30.1%)</td>
<td>229</td>
</tr>
<tr>
<td>6x6x1</td>
<td>110.1 (48.0%)</td>
<td>49.9 (21.7%)</td>
<td>69.3 (30.2%)</td>
<td>229</td>
</tr>
<tr>
<td>Vertical Local Grid Refinement</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1x1x2</td>
<td>104.7 (45.6%)</td>
<td>52.8 (23.0%)</td>
<td>71.9 (31.3%)</td>
<td>229</td>
</tr>
<tr>
<td>1x1x3</td>
<td>104.9 (45.8%)</td>
<td>52.5 (22.9%)</td>
<td>71.9 (31.4%)</td>
<td>229</td>
</tr>
</tbody>
</table>

4.5 Optimum Vertical Well Scenario

Table 4-5 shows the results for the optimal vertical well scenario. In addition, each well’s surrounding permeability, porosity and depth interval are given in Appendix F, Figures 12-5 to 12-13. First, we inject a higher amount of cumulative CO$_2$ in the updated Sedsim model. This is because the permeability is much higher and there are non-extensive and non-intersecting faults (see Sections 4.1 and 4.2). Second, the VWP 5 well position gives a lower percentage of trapped CO$_2$ (both residual and dissolved CO$_2$) compared to the Schlumberger Well positions. Figures 12-1 and 12-2 show the difference in the CO$_2$ plume shape generated by the Schlumberger Well positions and VWP 5 well positions. The difference in the plume shape is caused by a combination of three different factors -

1. The close proximity of wells in the Schlumberger Well positions compared to the VWP 5 well positions.
2. The high permeability of the formation.
3. The lack of extensive fault barriers, which allows CO$_2$ plumes from different wells to connect to each other easily.

These factors enable the CO$_2$ plume to have a larger total volume (bottom circle of Figure 12-1) and connect the different parts of the plume, thus creating a larger surface area (top circle of Figure 12-2). As a result, a higher percentage of residually trapped and dissolved CO$_2$ can be achieved using the Schlumberger Well positions rather than the VWP 5 well positions.

When comparing the VWP 5 well positions for both the SLB and Sedsim model, we notice that both residually trapped and dissolved CO$_2$ are higher in the SLB model. This is because the permeability of the updated Sedsim model is much higher (almost 10x higher). This causes the CO$_2$ plume to rise up rapidly and give a small volume. In addition, because the CO$_2$ plume in the updated Sedsim model rises up quickly, the CO$_2$ has less time to diffuse into fresh brine before it accumulates under a very low permeability barrier (see Figures 12-3 and 12-4). This reduces the contact area between brine and CO$_2$ by almost half, which lowers the percentage of dissolved CO$_2$. 
Furthermore, as mentioned in the previous sections, the smaller grid size of the updated Sedsim model and lower porosity of the SLB model would lead to a higher percentage of dissolved CO\textsubscript{2}.

Table 4-5: Summary of results for optimum vertical well scenario (see figures in Appendix F)

<table>
<thead>
<tr>
<th>Model</th>
<th>Residually trapped CO\textsubscript{2} (Mt)</th>
<th>Dissolved CO\textsubscript{2} (Mt)</th>
<th>Mobile CO\textsubscript{2} (Mt)</th>
<th>Cumulative Injected (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLB (VWP 5)</td>
<td>118.1 (57.3%)</td>
<td>59.4 (28.8%)</td>
<td>28.6 (13.9%)</td>
<td>206</td>
</tr>
<tr>
<td>SedSim (SLB Test with LGR)</td>
<td>110.2 (48.1%)</td>
<td>50.1 (21.9%)</td>
<td>69.0 (30.1%)</td>
<td>229</td>
</tr>
<tr>
<td>SedSim (VWP 5)</td>
<td>100.0 (43.6%)</td>
<td>39.8 (17.4%)</td>
<td>89.5 (39.0%)</td>
<td>229</td>
</tr>
</tbody>
</table>

4.6 Optimum Horizontal Well Scenario

Table 4-6 shows the results for the optimal horizontal well scenario. Again, we inject a higher amount of CO\textsubscript{2} in the updated Sedsim model as previously explained in Sections 4.1 and 4.2. We observe a higher percentage of residually trapped CO\textsubscript{2} and dissolved CO\textsubscript{2} in the SLB model. This is again because the permeability is higher in the updated Sedsim model than in the SLB model. As a result, the plume volume is smaller (which leads to a lower percentage residual trapping) and the CO\textsubscript{2} plume migrates rapidly upwards and accumulates under a very low permeability layer (same reasoning as Section 4.5).

We notice that horizontal wells produce a higher percentage of residual and dissolution trapping. We expect this and it is similar to what we experienced in our previous study. This is because we increase the perforation interval from the 200 m vertical section to the 2,000 m horizontal section. As a result, the volume of the plume increases as well as the surface area in contact with fresh brine. Furthermore, as mentioned in previous sections, the smaller grid size of the updated Sedsim model and lower porosity of the SLB model would lead to a higher percentage of dissolved CO\textsubscript{2}.

Table 4-6: Summary of results for optimum horizontal well scenario (refer to figures in Appendix G)

<table>
<thead>
<tr>
<th>Model</th>
<th>Residually trapped CO\textsubscript{2} (Mt)</th>
<th>Dissolved CO\textsubscript{2} (Mt)</th>
<th>Mobile CO\textsubscript{2} (Mt)</th>
<th>Cumulative Injected (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLB</td>
<td>114.6 (58.1%)</td>
<td>52.1 (26.4%)</td>
<td>30.1 (13.9%)</td>
<td>197</td>
</tr>
<tr>
<td>SedSim</td>
<td>101.0 (44.2%)</td>
<td>40.7 (17.8%)</td>
<td>86.9 (38.0%)</td>
<td>229</td>
</tr>
</tbody>
</table>
4.7 Optimum Vertical Well with Water Production Well Scenario

Tables 4-7 and 4-8 show the results for the optimal vertical well with water production scenario. Each injection well’s surrounding permeability, porosity and depth intervals are given in Appendix G, Figures 14-1 to 14-9.

For the updated Sedsim model, the percentage of residually trapped CO₂ of the optimal water production scenario is lower than that of the VWP 5 well positions. Generally, this should not be the case. However, we observe this because the wells in this test are deeper in the formation, which gives different surrounding formation properties. Wells 5, 6, 7, 10, 11, 12 and 17 have a higher surrounding well permeability in this case (see Figures in Appendix 12 and 14). With VWP 5 well positions, we recall that the CO₂ plume migrates rapidly upwards because the wells have high surrounding permeability. For our water production case, since we have higher surrounding permeability, the CO₂ would migrate upwards even faster, making the CO₂ plume smaller.

The percentage of dissolved CO₂ is higher in our water production case because the updated Sedsim model decreases in porosity with depth. Figure 2-3 depicts this trend of decreasing porosity with depth. This is a result of the compaction functions generated by the Sedism program (Griffiths 2010). We recall that a lower porosity leads to a higher percentage of dissolved CO₂ (Taheri et. al 2012).

Comparing the SLB model to the Sedsim model, we can inject more CO₂ in the updated Sedsim model for the reasons previously explained in Sections 4.1 and 4.2.

We have a higher percentage of residually trapped CO₂ and dissolved CO₂ in the SLB model. This is because the permeability of the updated Sedsim model is much higher (almost 10 times higher). High permeability causes the CO₂ plume to rise up rapidly, giving a small volume. In addition, because the CO₂ plume in the updated Sedsim model rises up quickly, the plume has less time for CO₂ to diffuse into fresh brine before it accumulates under a very low permeability barrier (see Figure 12-3). This reduces the contact area between brine and CO₂ by almost half, which lowers the percentage of dissolved CO₂. Furthermore, as mentioned in the previous sections, the smaller grid size of the updated Sedsim model and lower porosity of the SLB model would lead to a higher percentage of dissolved CO₂. However, there are three additional reasons why this happens -

- From our previous study, in the SLB model, injecting CO₂ below layer 66, led to a CO₂ plume with a “stacked-disc shape”. This is because there are several low permeability layers at that depth. As a result, there is a higher contact surface area between brine and CO₂, which enhances dissolution trapping (see Figure 14-19).
- All of the water production wells (except WAT_5) in the updated Sedsim model fail to drag the CO₂ plume towards them (see Figures 14-20 and 14-21). This is because the surrounding permeability is high, which causes the CO₂ plume to migrate upwards rapidly. In contrast, all of the water production wells (except WAT_4) in the SLB model achieve this (see Figure 14-22).
- As mentioned in the previous sections, the smaller grid size of the updated Sedsim model and lower porosity of the SLB model would lead to a higher percentage of dissolved CO₂.
Table 4-7: Summary of results for optimum horizontal well scenario (see figures in Appendix H)

<table>
<thead>
<tr>
<th>Model</th>
<th>Residually trapped CO(_2) (Mt)</th>
<th>Dissolved CO(_2) (Mt)</th>
<th>Mobile CO(_2) (Mt)</th>
<th>*Net Cumulative Injected (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLB</td>
<td>78.0 (48.5%)</td>
<td>40.8 (25.4%)</td>
<td>42.1 (26.2%)</td>
<td>161</td>
</tr>
<tr>
<td>Sedsim</td>
<td>84.7 (39.4%)</td>
<td>45.5 (21.2%)</td>
<td>84.6 (39.4%)</td>
<td>215</td>
</tr>
</tbody>
</table>

*NOTE: Net cumulative CO\(_2\) injected = Cumulative CO\(_2\) injected - Cumulative CO\(_2\) produced

Table 4-8: Total CO\(_2\) produced for optimum horizontal well scenario (Figure 14-11)

<table>
<thead>
<tr>
<th>Model</th>
<th>CO(_2) produced (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLB</td>
<td>14.6</td>
</tr>
<tr>
<td>Sedsim</td>
<td>3.3</td>
</tr>
</tbody>
</table>

4.8 Optimum WAG Scenario

Tables 4-9 and 4-10 show the results for the optimal WAG scenario. Each injection well’s surrounding permeability, porosity and depth intervals are the same as those in Appendix F, Figures 12-5 to 12-13. Comparing the optimum vertical well scenario (VWP 5) and the optimum WAG scenario, there is an increase in the percentages of both residually trapped and dissolved CO\(_2\) for the WAG scenario. This is expected since we are injecting water and forcing early onset imbibition. In addition, because we are effectively dividing the CO\(_2\) plume into smaller plumes (from interrupted CO\(_2\) injection), we increase the surface area to volume ratio. These were both observed in our previous study.

Comparing the optimum WAG scenario for the SLB model and the updated Sedsim model, the SLB model has a higher percentage of residual and dissolution trapping. This is because the permeability of the updated Sedsim model is much higher (almost 10 times higher). This causes the CO\(_2\) plume to rise up rapidly, giving a small volume. In addition, because the CO\(_2\) plume in the updated Sedsim model rises up quickly, the plume has less time for CO\(_2\) to diffuse into fresh brine before it accumulates under a very low permeability barrier (see Figure 12-3). This reduces the contact area between brine and CO\(_2\) by almost half, which lowers the percentage of dissolved CO\(_2\). Furthermore, as mentioned in the previous sections, the smaller grid size of the updated Sedsim model and lower porosity of the SLB model would lead to a higher percentage of dissolved CO\(_2\).
### Table 4-9: Summary of results for optimum WAG scenario (see figures in Appendix I)

<table>
<thead>
<tr>
<th>Model</th>
<th>Residually trapped CO₂ (Mt)</th>
<th>Dissolved CO₂ (Mt)</th>
<th>Mobile CO₂ (Mt)</th>
<th>*Net Cumulative Injected (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLB</td>
<td>106.6 (57.7%)</td>
<td>61.8 (33.5%)</td>
<td>16.2 (8.8%)</td>
<td>185</td>
</tr>
<tr>
<td>Sedsim</td>
<td>101.0 (44.3%)</td>
<td>45.3 (19.9%)</td>
<td>81.8 (35.9%)</td>
<td>228</td>
</tr>
</tbody>
</table>

*NOTE: Net cumulative CO₂ injected = Cumulative CO₂ injected - Cumulative CO₂ produced

### Table 4-10: Total CO₂ produced for optimum WAG scenario (Figure 15-2)

<table>
<thead>
<tr>
<th>Model</th>
<th>CO₂ produced (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLB</td>
<td>18.5</td>
</tr>
<tr>
<td>Sedsim</td>
<td>1.1</td>
</tr>
</tbody>
</table>

### 4.9 Optimum SWAG Scenario

Tables 4-11 and 4-12 show the results for the optimal SWAG scenario. Comparing the optimum vertical well scenario (VWP 5) and the optimum SWAG scenario, there is an increase in the percentages of both residually trapped and dissolved CO₂ for the SWAG scenario. We expect these increases because of (Anchilya and Ehlig-Economides 2009) -

- Counter-current flow of CO₂ and water (water flowing downwards and the upwards migration of the CO₂ plume).
- Forced imbibition because of water injection.

When comparing the SWAG scenario for both the SLB and updated Sedsim model, we produce a much higher amount of CO₂ for the updated Sedsim model. Hence, our net cumulative injected CO₂ is much lower. This is again because of the higher permeability of the updated Sedsim model. This results in the downwards flow of water pushing the upward migrating CO₂ plume sideways, causing it to reach the water producers rapidly. As a result, once breakthrough occurs, a large amount of CO₂ would flow uninterrupted towards the water producers (see Figures 16-10 and 16-11).

The percentage of residual trapping is lower for the updated Sedsim model because it has very high permeability. This causes most of the CO₂ plume to rise up rapidly, giving a small volume. However, the percentage of dissolution trapping in the updated Sedsim model is much higher (almost double). This is because there is less restriction for counter-current flow of CO₂ and water to occur. In the updated Sedsim model the permeability is higher and there are fewer low permeability barriers. Low permeability barriers reduce the efficiency of SWAG scenarios, as we have seen in our previous study (see Figures 16-12 and 16-13).
Table 4-11: Summary of results for optimum SWAG scenario (see figures in Appendix J)

<table>
<thead>
<tr>
<th>Model</th>
<th>Residually trapped CO₂ (Mt)</th>
<th>Dissolved CO₂ (Mt)</th>
<th>Mobile CO₂ (Mt)</th>
<th>*Net Cumulative Injected (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLB</td>
<td>96.7 (52.8%)</td>
<td>35.5 (19.4%)</td>
<td>51.1 (27.9%)</td>
<td>183</td>
</tr>
<tr>
<td>Sedsim</td>
<td>70.8 (45.5%)</td>
<td>50.4 (32.4%)</td>
<td>34.4 (22.1%)</td>
<td>156</td>
</tr>
</tbody>
</table>

*NOTE: Net cumulative CO₂ injected = Cumulative CO₂ injected - Cumulative CO₂ produced

Table 4-12: Total CO₂ produced for optimum WAG scenario (Figure 16-2)

<table>
<thead>
<tr>
<th>Model</th>
<th>CO₂ produced (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLB</td>
<td>46.4</td>
</tr>
<tr>
<td>Sedsim</td>
<td>70.5</td>
</tr>
</tbody>
</table>

5. Conclusion

We have demonstrated that it is possible to use Sedsim to generate reservoir models for dynamic simulations. However, certain precautions must be taken in order to ensure smooth simulation running. These include -

- Grid blocks must be below the sea-level (below the 0-m elevation mark).
- Layers in the model must not be too thin.
- We should try to minimise the number of “inside-out” grid blocks.
- Grid blocks must not be too coarse.
- Faults must be properly defined as continuous planar surfaces and intersect with each other if it is intended.

We have observed some similarities as well as several significant differences between both SLB and Sedsim static models. The similarities include -

- The capillary pressure test shows a similar trend for both models as shown in our previous ANLEC SW Hub study and in the literature. Numerical results show that the percentage of CO₂ residual trapping and dissolution trapping increases by about 4% (using the Brooks-Corey / Van Genuchten model) compared to that with zero capillary pressure. If the Leverett J-function is used, the percentage of CO₂ residual trapping and dissolution trapping increases by about 3%, compared to that with zero capillary pressure.
- The local grid optimisation test also has similar results to our previous study and literature, where smaller grids lead to a lower CO₂ dissolution trapping. In addition, as in our previous report, areal local grid refinement affects the results significantly, while vertical local grid refinement does not. This is most likely because vertical grid refinement is already sufficient. Furthermore, we conclude that a 5x5x1 local grid refinement appears to be optimal in this case.
Some of the differences which cause considerable variations in dynamic simulation results include -

- The updated Sedsim model includes the Eneabba Formation but not the Sabina Sandstone Formation. On the other hand, the SLB model does not include the Eneabba Formation but includes the Sabina Sandstone Formation. Both Wonnerup and Yalgorup Formations have different thicknesses in both of the static models and start at different depths in each static model. Furthermore, because of the different distribution of very low permeability layers combined with the higher amount of CO$_2$ injected, more mobile CO$_2$ ends up in the Yalgorup Formation with the updated Sedsim model.

- The pore volume in the updated Sedsim model is $2.12 \times 10^{11}$ m$^3$. However, the pore volume in the SLB model is $1.74 \times 10^{11}$ m$^3$. This increases the cumulative CO$_2$ injected in the updated Sedsim model. The percentage of dissolved CO$_2$ is lower in the Sedsim model mainly because of a smaller global grid block size and because of the higher average porosity (Taheri et. al 2012, Green & Ennis-King 2012).

- The updated Sedsim model has an absolute permeability that is almost 10 times higher than the SLB model. This combined with the non-intersecting and non-extensive faults means that the full amount of CO$_2$ is injected into the formation (with either open or closed faults). In addition, because the permeability is high and pressure dissipation is easy, the plume is more funnel-shaped, rather than the optimally pear shaped plume. As a result, the percentage of residual and dissolution trapping is lower in the updated Sedsim model compared to the SLB model. We observe this for most of the cases.

- Our optimal vertical well scenario for the Sedsim model does not trap CO$_2$ as much as the Schlumberger well position. This is because (a) the wells are close together in the Schlumberger well location, (b) the permeability of the formation is high and (c) there is a lack of extensive/intersecting fault barriers in the updated Sedsim model.

- For our optimum vertical well with water production scenario, for the updated Sedsim model, the percentage of residual trapping is lower by 9% and dissolution trapping is lower by 4%. This is because the permeability is high and there are no low permeability layers that create “stacked-disc” CO$_2$ plumes, as seen in our previous study with the SLB model.

- For our optimum SWAG scenario, for the updated Sedsim model, the percentage of residually trapped CO$_2$ is 7% lower. However, but the percentage of dissolution trapping is higher by 13%. The percentage of dissolved CO$_2$ increases significantly because there is good vertical permeability between the brine injector and CO$_2$ injector. This is unlike the SLB model where very low permeability barriers reduce the effectiveness of the SWAG engineering design. As a result, the SWAG engineering design in updated Sedsim model shows potential.
6. References

- Faeli M., Baz H. & Cinar Y., 2013, “Stratigraphic forward modelling comparison with Eclipse for SW Hub”, The University of New South Wales, School of Petroleum Engineering, Sydney, Service Contract to CSIRO.


Collie Basin and the Southern Perth Basin of Western Australia”, Marine and Petroleum Geology 26, 7, 1255 - 1273.
7. Appendix A: Methodology

Figure 7-1: Relative permeability curves used for our dynamic simulation comparisons (Evans et. al 2012)

Table 7-1: Geothermal gradient used for our dynamic simulation comparisons (Schlumberger 2013)

<table>
<thead>
<tr>
<th>Depth (mSS)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>916</td>
<td>46.4</td>
</tr>
<tr>
<td>981</td>
<td>46.4</td>
</tr>
<tr>
<td>1059</td>
<td>47</td>
</tr>
<tr>
<td>1161.5</td>
<td>49.6</td>
</tr>
<tr>
<td>1221.5</td>
<td>50.3</td>
</tr>
<tr>
<td>1384</td>
<td>52.5</td>
</tr>
<tr>
<td>1406</td>
<td>53.1</td>
</tr>
<tr>
<td>1698</td>
<td>58.1</td>
</tr>
<tr>
<td>1913.5</td>
<td>60.7</td>
</tr>
<tr>
<td>2504</td>
<td>68.2</td>
</tr>
</tbody>
</table>
Figure 7-2: Position of Harvey-1 Test Well in both SLB and Sedsim models. Harvey-1 global coordinates are (385502, -6348948)

Figure 7-3: Different layers and regions in the SLB model
Figure 7-4: Position of Schlumberger Test Wells in both SLB (left) and Sedsim (right) models

Figure 7-5: Position of VWP 5 wells in both SLB (left) and Sedsim (right) models
Figure 7-6: Comparison between wells when following the algorithm in 3.3.1 (bad) and the algorithm in 3.3.6 (good) for horizontal wells. The red dot represents the shallowest depth, while the purple dot represents the deepest depth.

Figure 7-7: Position of Horizontal wells in both SLB (left) and Sedsim (right) models.
Figure 7-8: Position of wells for water production and WAG Scenarios in both SLB (left) and Sedsim (right) models

Figure 7-9: Position of wells for SWAG Scenario in both SLB (left) and Sedsim (right) models
8. Appendix B: Harvey-1 Test

Figure 8-1: Porosity, permeability and depth interval of surrounding Harvey-1 wells for both SLB model (left) and Sedsim model (right).

Figure 8-2: BHP vs. Time for Harvey-1 Tests
Figure 8-3: Injectivity vs. Time for Harvey-1 Tests

Figure 8-4: Different plume shapes which result from different permeability distribution and the different locations of low permeability layers at 140 years (open faults Harvey-1 Test)
Figure 8-5: Very low permeability layer above the top of the perforation for the Sedsim model (bottom). As a result, CO$_2$ cannot escape and there is only a small pressure drop after injection stops.

Figure 8-6: CO$_2$ mass rate vs. Time for Harvey-1 Tests.
Figure 8-7: Residually trapped CO\(_2\) vs. Time in the Yalgorup Member for Harvey-1 Tests

Figure 8-8: Residually trapped CO\(_2\) vs. Time in the Wonnerup Member for Harvey-1 Tests
Figure 8-9: Dissolved CO$_2$ vs. Time in the Yalgorup Member for Harvey-1 Tests

Figure 8-10: Dissolved CO$_2$ vs. Time in the Wonnerup Member for Harvey-1 Tests
Figure 8-11: Mobile CO₂ vs. Time in the Yalgorup Member for Harvey-1 Tests

Figure 8-12: Mobile CO₂ vs. Time in the Wonnerup Member for Harvey-1 Tests
9. Appendix C: Schlumberger Well Location Test

Figure 9-1: Porosity, permeability and depth interval of surrounding Well No.5 for both SLB model (left) and Sedsim model (right)

Figure 9-2: Porosity, permeability and depth interval of surrounding Well No.6 for both SLB model (left) and Sedsim model (right)
Figure 9-3: Porosity, permeability and depth interval of surrounding Well No.7 for both SLB model (left) and Sedsim model (right)

Figure 9-4: Porosity, permeability and depth interval of surrounding Well No.8 for both SLB model (left) and Sedsim model (right)
Figure 9-5: Porosity, permeability and depth interval of surrounding Well No. 10 for both SLB model (left) and Sedsim model (right).

Figure 9-6: Porosity, permeability and depth interval of surrounding Well No. 11 for both SLB model (left) and Sedsim model (right).
Figure 9-7: Porosity, permeability and depth interval of surrounding Well No.12 for both SLB model (left) and Sedsim model (right).

Schlumberger model:
Injection interval = 1,946 - 2,146 mSS
Average weighted $k_h = 17$ mD
Average weighted porosity = 0.16

Sedsim model:
Injection interval = 2,217 - 2,417 mSS
Average weighted $k_h = 710$ mD
Average weighted porosity = 0.14

Figure 9-8: Porosity, permeability and depth interval of surrounding Well No.16 for both SLB model (left) and Sedsim model (right).

Schlumberger model:
Injection interval = 1,815 - 2,015 mSS
Average weighted $k_h = 8$ mD
Average weighted porosity = 0.13

Sedsim model:
Injection interval = 2,078 - 2,278 mSS
Average weighted $k_h = 469$ mD
Average weighted porosity = 0.18
Figure 9-9: Porosity, permeability and depth interval of surrounding Well No.17 for both SLB model (left) and Sedsim model (right).

Figure 9-10: Group injectivity vs. Time for Schlumberger Well Position Test.
Figure 9-11: Layers between the top of the well perforations and the bottom of the Yalgorup Member in the Sedsim model.

Figure 9-12: Computational simulation time vs. Years simulated for both SLB model and Sedsim model. The SLB model is 5x faster than the Sedsim model, in terms of computational simulation time.
Figure 9-13: CO₂ mass rate vs. Time for Schlumberger Well Position Test

Figure 9-14: Residually trapped CO₂ vs. Time in the Yalgorup Member for Schlumberger Well Position Test
Figure 9-15: Residually trapped CO$_2$ vs. Time in the Wonnerup Member for Schlumberger Well Position Test

Figure 9-16: Dissolved CO$_2$ vs. Time in the Yalgorup Member for Schlumberger Well Position Test
Figure 9-17: Dissolved CO\textsubscript{2} vs. Time in the Wonnerup Member for Schlumberger Well Position Test

Figure 9-18: Mobile CO\textsubscript{2} vs. Time in the Yalgorup Member for Schlumberger Well Position Test
Figure 9-19: Mobile CO$_2$ vs. Time in the Wonnerup Member for Schlumberger Well Position Test
10. Appendix D: Capillary Pressure Test

Figure 10-1: CO₂ mass rate vs. Time for capillary pressure test

Figure 10-2: Residually trapped CO₂ vs. Time for capillary pressure test
Figure 10-3: Dissolved CO$_2$ vs. Time for capillary pressure test

Figure 10-4: Mobile CO$_2$ vs. Time for capillary pressure test
11. Appendix E: Local Grid Refinement Optimisation

Figure 11-1: CO\(_2\) mass rate vs. Time for local grid refinement optimisation

Figure 11-2: Residually trapped CO\(_2\) vs. Time in the Yalgorup Member for areal local grid refinement
Figure 11-3: Residually trapped CO$_2$ vs. Time in the Wonnerup Member for areal local grid refinement

Figure 11-4: Dissolved CO$_2$ vs. Time in the Yalgorup Member for areal local grid refinement
Figure 11-5: Dissolved CO₂ vs. Time in the Wonnerup Member for areal local grid refinement.

Figure 11-6: Mobile CO₂ vs. Time in the Yalgorup Member for areal local grid refinement.
Figure 11-7: Mobile CO$_2$ vs. Time in the Wonnerup Member for areal local grid refinement

Figure 11-8: Residually trapped CO$_2$ vs. Time in the Yalgorup Member for vertical local grid refinement
Figure 11-9: Residually trapped CO$_2$ vs. Time in the Wonnerup Member for vertical local grid refinement

Figure 11-10: Residually trapped CO$_2$ vs. Time in the Yalgorup Member for vertical local grid refinement
Figure 11-11: Residually trapped CO\textsubscript{2} vs. Time in the Wonnerup Member for vertical local grid refinement

Figure 11-12: Mobile CO\textsubscript{2} vs. Time in the Yalgorup Member for vertical local grid refinement
Figure 11-13: Mobile CO$_2$ vs. Time in the Wonnerup Member for vertical local grid refinement
12. Appendix F: Optimum Vertical Well Scenario

Figure 12-1: Arial view of the CO$_2$ plume for Schlumberger Well positions (left) and VWP 5 well positions (right) in the updated Sedsim model at 140 years. The yellow circle shows groups of wells in close proximity.
Figure 12-2: Side view of the CO$_2$ plume for Schlumberger Well Test positions (up) and VWP 5 well positions (down) in the updated Sedsim model at 140 years.
Figure 12-3: Ariel view of the CO₂ plume for optimum vertical well scenario test for SLB model (left) and Sedsim model (right) at 140 years. The high saturation seen aerially in the Sedsim model is because the CO₂ plume rises up quickly and accumulates under a low permeability barrier.
Figure 12-4: Side view of the CO$_2$ plume of optimum vertical well scenario for the updated Sedsim model (up) and SLB model (down) at 140 years.
Figure 12-5: Porosity, permeability and depth interval of surrounding Well No.5 for both SLB model (left) and SedSim model (right)

Figure 12-6: Porosity, permeability and depth interval of surrounding Well No.6 for both SLB model (left) and SedSim model (right)
Figure 12-7: Porosity, permeability and depth interval of surrounding Well No.7 for both SLB model (left) and Sedsim model (right).

**Schlumberger model:**
- Injection interval = 1,433 - 1,633 mSS
- Average weighted $k_r = 65$ mD
- Average weighted porosity = 0.16

**Sedsim model:**
- Injection interval = 1,762 - 1,962 mSS
- Average weighted $k_r = 158$ mD
- Average weighted porosity = 0.16

Figure 12-8: Porosity, permeability and depth interval of surrounding Well No.8 for both SLB model (left) and Sedsim model (right).

**Schlumberger model:**
- Injection interval = 1,748 - 1,948 mSS
- Average weighted $k_r = 30$ mD
- Average weighted porosity = 0.15

**Sedsim model:**
- Injection interval = 1,904 - 2,104 mSS
- Average weighted $k_r = 721$ mD
- Average weighted porosity = 0.23
Figure 12-9: Porosity, permeability and depth interval of surrounding Well No. 10 for both SLB model (left) and SedSim model (right)

Figure 12-10: Porosity, permeability and depth interval of surrounding Well No. 11 for both SLB model (left) and SedSim model (right)
Figure 12-11: Porosity, permeability and depth interval of surrounding Well No.12 for both SLB model (left) and Sedsim model (right).

Figure 12-12: Porosity, permeability and depth interval of surrounding Well No.16 for both SLB model (left) and Sedsim model (right).
Figure 12-13: Porosity, permeability and depth interval of surrounding Well No.17 for both SLB model (left) and Sedsim model (right).

Figure 12-14: CO₂ mass rate vs. Time for optimum vertical well scenario.
Figure 12-15: Residually trapped CO\(_2\) vs. Time in the Yalgorup Member for optimum vertical well scenario

Figure 12-16: Residually trapped CO\(_2\) vs. Time in the Wonnerup Member for optimum vertical well scenario
Figure 12-17: Dissolved CO\textsubscript{2} vs. Time in the Yalgorup Member for optimum vertical well scenario

Figure 12-18: Dissolved CO\textsubscript{2} vs. Time in the Wonnerup Member for optimum vertical well scenario
Figure 12-19: Mobile CO$_2$ vs. Time in the Yalgorup Member for optimum vertical well scenario

Figure 12-20: Mobile CO$_2$ vs. Time in the Wonnerup Member for optimum vertical well scenario
13. Appendix G: Optimum Horizontal Well Scenario

Figure 13-1: CO$_2$ mass rate vs. Time for optimum horizontal well scenario

Figure 13-2: Residually trapped CO$_2$ vs. Time in the Yalgorup Member for optimum horizontal well scenario
Figure 13-3: Residually trapped CO$_2$ vs. Time in the Wonnerup Member for optimum horizontal well scenario

Figure 13-4: Dissolved CO$_2$ vs. Time in the Yalgorup Member for optimum horizontal well scenario
Figure 13-5: Dissolved CO\textsubscript{2} vs. Time in the Wonnerup Member for optimum horizontal well scenario

Figure 13-6: Mobile CO\textsubscript{2} vs. Time in the Yalgorup Member for optimum horizontal well scenario
Figure 13-7: Mobile CO$_2$ vs. Time in the Wonnerup Member for optimum horizontal well scenario
14. Appendix H: Optimum Vertical Well with Water Production Scenario

Figure 14-1: Porosity, permeability and depth interval of surrounding Well No. 5 for both SLB model (left) and Sedsim model (right)

Figure 14-2: Porosity, permeability and depth interval of surrounding Well No. 6 for both SLB model (left) and Sedsim model (right)
Figure 14-3: Porosity, permeability and depth interval of surrounding Well No. 7 for both SLB model (left) and SedSim model (right).

Schlumberger model:
Injection interval = 1,715 - 1,915 mSS
Average weighted $k_h = 5 \text{ mD}$
Average weighted porosity = 0.13

SedSim model:
Injection interval = 2,044 - 2,244 mSS
Average weighted $k_h = 1,100 \text{ mD}$
Average weighted porosity = 0.12

Figure 14-4: Porosity, permeability and depth interval of surrounding Well No. 8 for both SLB model (left) and SedSim model (right).

Schlumberger model:
Injection interval = 1,991 - 2,191 mSS
Average weighted $k_h = 3 \text{ mD}$
Average weighted porosity = 0.12

SedSim model:
Injection interval = 2,146 - 2,346 mSS
Average weighted $k_h = 560 \text{ mD}$
Average weighted porosity = 0.17
Figure 14-5: Porosity, permeability and depth interval of surrounding Well No.10 for both SLB model (left) and SedSim model (right).

Figure 14-6: Porosity, permeability and depth interval of surrounding Well No.11 for both SLB model (left) and SedSim model (right).
Figure 14-7: Porosity, permeability and depth interval of surrounding Well No.12 for both SLB model (left) and Sedsim model (right)

Figure 14-8: Porosity, permeability and depth interval of surrounding Well No.16 for both SLB model (left) and Sedsim model (right)
Figure 14-9: Porosity, permeability and depth interval of surrounding Well No.17 for both SLB model (left) and Sedim model (right).

Figure 14-10: CO$_2$ mass rate vs. Time for optimum vertical well with water production scenario.
Figure 14-11: CO$_2$ mass rate produced vs. Time for optimum vertical well with water production scenario

Figure 14-12: Net CO$_2$ mass rate injected vs. Time for optimum vertical well with water production scenario
Figure 14-13: Residually trapped CO$_2$ vs. Time in the Yalgorup Member for optimum vertical well with water production scenario

Figure 14-14: Residually trapped CO$_2$ vs. Time in the Wonnerup Member for optimum vertical well with water production scenario
Figure 14-15: Dissolved CO$_2$ vs. Time in the Yalgorup Member for optimum vertical well with water production scenario.

Figure 14-16: Dissolved CO$_2$ vs. Time in the Wonnerup Member for optimum vertical well with water production scenario.
Figure 14-17: Mobile CO$_2$ vs. Time in the Yalgorup Member for optimum vertical well with water production scenario

Figure 14-18: Mobile CO$_2$ vs. Time in the Yalgorup Member for optimum vertical well with water production scenario
Figure 14-19: Stacked-disc plume from the SLB model at 140 years

Figure 14-20: $\text{CO}_2$ produced vs. Time for each individual water production well in the Sedsim model
Figure 14-21: An image of WAT_1 and WAT_3 at 140 years. These are two out of the four wells which failed to effectively drag the CO₂ plume towards them.

Figure 14-22: CO₂ produced vs. Time for each individual water production well in the SLB model.
15. Appendix I: Optimum WAG Scenario

Figure 15-1: CO$_2$ mass rate vs. Time for optimum WAG scenario

Figure 15-2: CO$_2$ mass rate produced vs. Time for optimum WAG scenario
Figure 15-3: Net CO₂ mass rate injected vs. Time for optimum WAG scenario

Figure 15-4: Residually trapped CO₂ vs. Time in the Yalgorup Member for optimum WAG scenario
Figure 15-5: Residually trapped CO$_2$ vs. Time in the Wonnerup Member for optimum WAG scenario

Figure 15-6: Dissolved CO$_2$ vs. Time in the Yalgorup Member for optimum WAG scenario
Figure 15-7: Dissolved CO$_2$ vs. Time in the Wonnerup Member for optimum WAG scenario

Figure 15-8: Mobile CO$_2$ vs. Time in the Yalgorup Member for optimum WAG scenario
Figure 15-9: Mobile CO$_2$ vs. Time in the Wonnerup Member for optimum WAG scenario
16. Appendix J: Optimum SWAG Scenario

Figure 16-1: CO$_2$ mass rate vs. Time for optimum SWAG scenario

Figure 16-2: CO$_2$ mass rate produced vs. Time for optimum SWAG scenario
Figure 16-3: Net CO\textsubscript{2} mass rate injected vs. Time for optimum SWAG scenario

Figure 16-4: Residually trapped CO\textsubscript{2} vs. Time in the Yalgorup Member for optimum SWAG scenario
Figure 16-5: Residually trapped CO$_2$ vs. Time in the Wonnerup Member for optimum SWAG scenario

Figure 16-6: Dissolved CO$_2$ vs. Time in the Yalgorup Member for optimum SWAG scenario
Figure 16-7: Dissolved CO$_2$ vs. Time in the Wonnerup Member for optimum SWAG scenario

Figure 16-8: Mobile CO$_2$ vs. Time in the Yalgorup Member for optimum SWAG scenario
Figure 16-9: Mobile CO$_2$ vs. Time in the Wonnerup Member for optimum SWAG scenario

Figure 16-10: CO$_2$ produced vs. Time for each individual water production well in the updated Sedsim model
Figure 16-11: CO$_2$ produced vs. Time for each individual water production well in the SLB model.

Figure 16-12: Examples of very low permeability layers (layers 51 on the left and 54 on the right) in between the horizontal CO$_2$ injector and the horizontal water injector for the SLB model. In this figure we are focusing on the injection area bounded by the faults.
Figure 16-13: Examples of high permeability layers (layers 176 on the left and 178 on the right) in between the horizontal CO$_2$ injector and the horizontal water injector for the updated Sedsim model.