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Abstract

This report is part of the research project MiReCOL (Mitigation and Remediation of CO_2 leakage) funded by the EU FP7 programme. Research activities aim at developing a handbook of corrective measures that can be considered in the event of undesired migration of CO_2 in the deep subsurface reservoirs. MiReCOL results support CO_2 storage project operators in assessing the value of specific corrective measures if the CO_2 in the storage reservoir does not behave as expected. MiReCOL focuses on corrective measures that can be taken while the CO_2 is in the deep subsurface. The general scenarios considered in MiReCOL are 1) loss of conformance in the reservoir (undesired migration of CO_2 within the reservoir), 2) natural barrier breach (CO_2 migration through faults or fractures), and 3) well barrier breach (CO_2 migration along the well bore).

This element of the MiReCOL project aims to investigate the feasibility of brine injection above a fractured cap rock or a fault at high pressure to create an inverse pressure gradient to reverse the flow direction of CO_2 plume. Research involved testing realistic reservoir and CO_2 leakage scenarios representative of the subsurface and focused on the role of controlling parameters which may affect the success or failure of the hydraulic barrier technology considered.

Using the Imperial College Saline Aquifer Model (ICSAM) chosen from the project database as the base model, two potential leakage pathways have been investigated. The potential leakage pathways include 1) an areal sink in the caprock; and 2) fault/fault zone (elongated sink). For each leakage pathway, the following key features of the storage reservoir were considered and implemented to form a number of modelling scenarios:

- Storage reservoir depth (formation pressure and temperature)

- Top of reservoir topography
- Caprock thickness/distance to the permeable layer above the storage reservoir
- Permeable layer permeability/porosity

The modelling results in terms of time-to-detection and cumulative CO_2 leakage for with/without remediation for all the scenarios are presented and the pressure gradient reversal (PGR) performances are compared. The results suggest that, for the areal sink favourable performance of PGR may be achieved when the shallow aquifer has a significantly larger permeability, whereas PGR is less well suited for a thicker caprock compared to the base case. For the case of elongated sink, the results suggest that better performance of PGR technique may be achieved in the reservoir with flatter slope or at a shallower depth than the base case.

TABLE OF CONTENTS

Page

1 INTRODUCTION AND OBJECTIVES

It has been suggested (Celia et al., 2002) that injection of brine above the caprock, at a higher pressure than the CO_2 pressure in the reservoir, would create an inverse pressure gradient to reverse the flow direction and increase the solubility of CO_2 in the saline water barrier formed, and prevent or limit leakage. Furthermore, coupled with fluid management procedures during aquifer storage (saline water extraction and re-injection above the caprock), this methodology can also be used to minimise displacement and migration of native brine, and avoid pressure build up in closed or semi-closed structures. In a more recent study, Reveillere et al. (2012) conducted a numerical study on the same phenomenon using an overly simple 3D flow model with flat layers (thus buoyancy-driven lateral migration of CO_2 was absent). They reported that this technique may efficiently stop leakage in a relatively short time or may be effectively used as a preventive measure, while continuing injecting CO_2. The effectiveness of above zone brine injection for CO_2 leakage remediation has also been investigated by Zahasky (2014).

It was thus suggested that, such a procedure could enable fast and relatively low cost mitigation action once a leakage is detected. On the other hand, the results illustrated in the literature are valid for a specific case and the methodology may have limitations which needed to be investigated further through exhaustive analysis of field based properties.

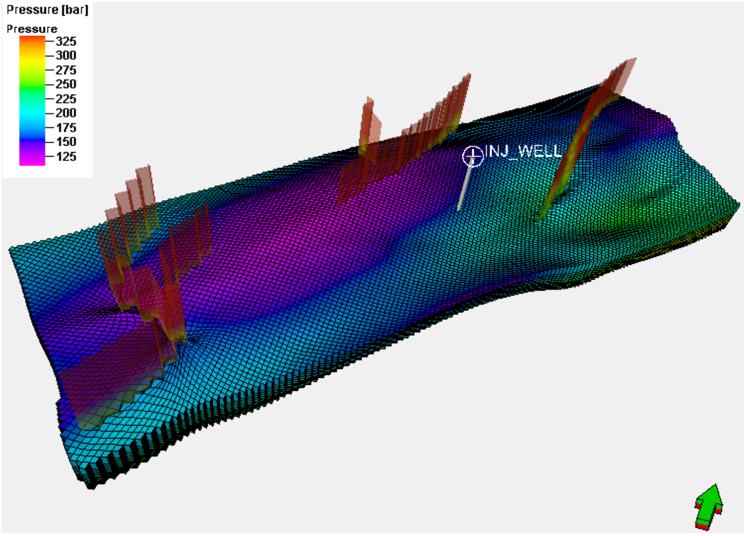
In the research reported here, the effectiveness of the pressure gradient reversal (PGR) method as a potential remediation technique for CO_2 leakage from deep saline aquifers was investigated using a realistic 3D reservoir/caprock model.

The objective of this research was to test a hydraulic barrier method to mitigate against CO_2 migration through the caprock using water injection, and specifically, to testing realistic reservoir and CO_2 leakage scenarios representative of selected models from the project database. The focus was on the role of controlling parameters which may affect the success or failure of the hydraulic barrier technology considered.

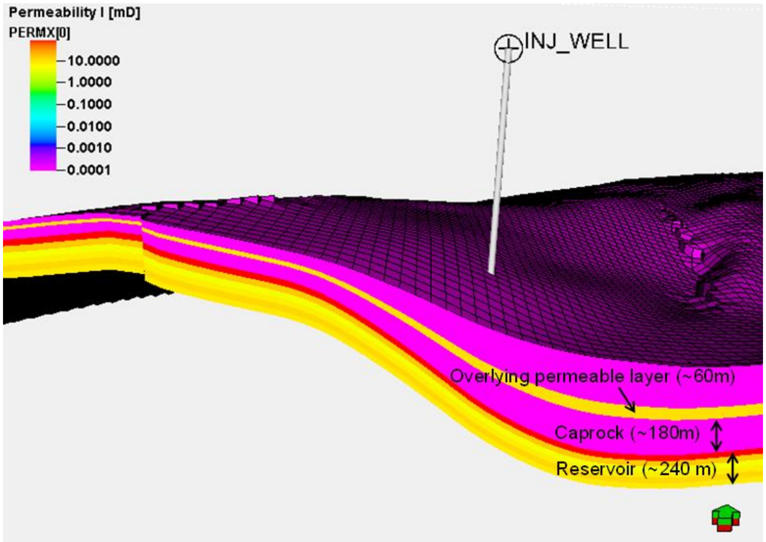
1.1 Imperial College Saline Aquifer Model

The Imperial College Saline Aquifer Model (ICSAM) has been chosen as the base model to carry out brine injection simulations. The key requirements in model selection were 1) inclusion of a caprock and 2) the presence of at least one permeability layer in the overburden formations which is suitable for brine/water injection. The ICSAM model measures 36 km x 10 km and includes several faults (Figure 1a). The model has a uniform grid block size of 200 m x 200 m in the lateral direction.

The depth of target storage formation ranges from 1,082 to 3,484 m across the model domain, dipping considerably. The injection well is located at a location where the storage reservoir is between 1,973 to 2,181 m deep. The storage reservoir, which has a thickness of approximately 240 m, consists of 6 layers of varying properties both within each layer and across the layers (Figure 1b). The overlying formation (caprock) is considered to be impermeable, except for a 60 m thick layer situated at 180 m above the reservoir, which is assigned a permeability of 10 mD in the base case scenario. The reservoir/overburden is initially at hydrostatic pressure, and the reservoir temperature is 92 ^{o}C. Figure 2 shows the gas-water relative permeability curves used for the storage reservoir and the shallow aquifer in the research. The relatively high irreducible water saturation is noted.



(a) Hydrostatic pressure distribution



(b) A close-up showing the caprock and overburden layers.

Figure 1. ICSAM reservoir/overburden model.

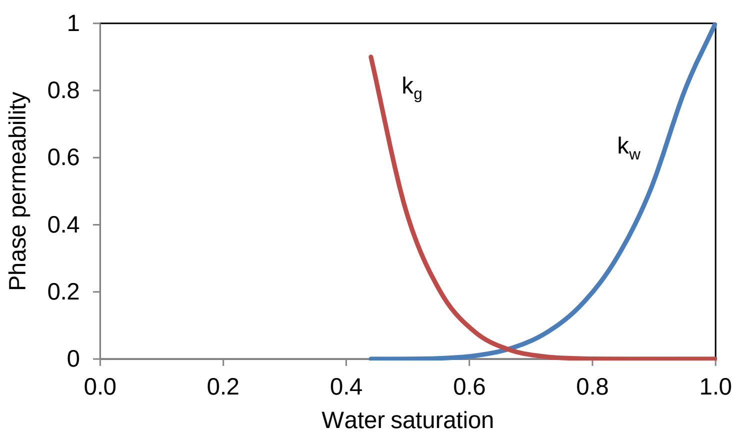


Figure 2. CO_2-water relative permeability curves used in the model.

2 TRANSIENT AND NON-TRANSIENT CO2 PLUME REGIONS AND LEAKAGE ASSESSMENT

Reservoir simulation of CO_2 injection at a rate of 1 Mt/year for 30 years was carried out to evaluate the plume migration behaviour during injection and after the termination of injection. A pore volume multiplier of 100 was used during simulations to represent the connected pore volume beyond the model domain. It was found that the plume largely stabilised at about 120 years from the start of injection. Figure 3 presents snapshots of the CO_2 plume at different stages of plume migration up dip following the formation topography.

Based upon this plume migration behaviour, the plume footprint may be broadly divided into (Figure 4):

- the transient region (where the free CO_2 largely has a limited residence time), and
- the non-transient region (where the free CO_2 residence is more or less stable),

In the transient region (Figure 4), the free mobile CO_2 represents a moving, dynamic source for potential CO_2 leakage (or migration) out of the storage reservoir if an undetected and characterised leakage zone (sink) exists along this path. Free CO_2 accumulated in the non-transient region (top of an anticline in this case), on the other hand, represents a largely stationary (or stabilised) source for potential CO_2 leakage out of the storage reservoir. This distinction has been found to have a direct bearing on the potential leakage profiles in the two regions.

In an earlier study, the potential leakage risk profiles, i.e. the total amount of leaked CO_2 through the caprock, and the leakage time periods, at various locations in both the transient and non-transient regions were computed and mapped. The leakage scenario considers one leaky block at one time iteratively. To simulate CO_2 leakage, a leakage pathway is intentionally created by assigning a permeability of between 1 and 10 mD to the column of grid blocks in the caprock between the storage reservoir and the permeable layer above (Figure 1a). During simulations, the cumulative leakage from the storage reservoir was monitored and injection is terminated when a pre-set leakage detection threshold/limit is exceeded. Based upon the findings from these early simulations, a detection threshold between 1,000 to 10,000 tonnes of CO_2 was used.

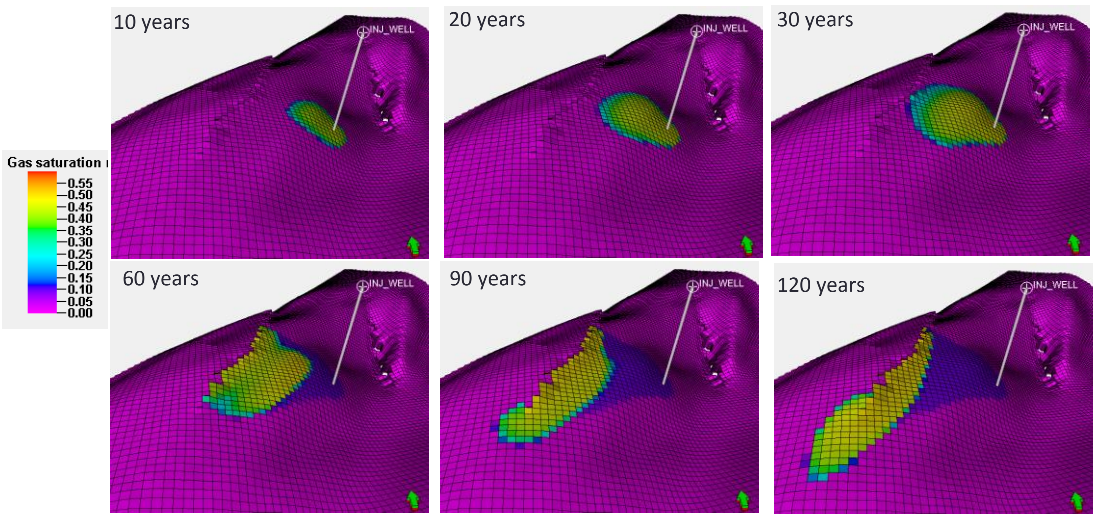


Figure 3. Simulated CO_2 plume migration in the reservoir during injection and post-injection periods.

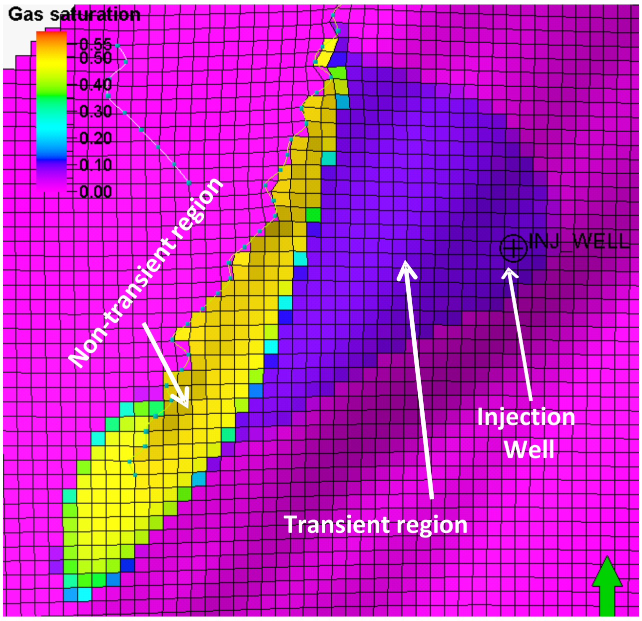


Figure 4 The CO_2 plume footprint is divided into transient and non-transient regions.

One important parameter is the time (year) it takes for the leakage to be detected during the simulation, i.e. time-to-leakage detection, referred to for simplicity as the time-to-detection (TTD). Clearly it is expected to vary spatially within the CO_2 plume footprint. Furthermore, the TTD at a given leakage location depends on the combined effect of a detection threshold applied and the leakage pathway permeability assigned (Table 1).

Table 1. Computed time-to-detection, cumulative CO_2 leakage and total leakage duration for three grid blocks marked in Figure 5 in the transient region.

	Time-to-detection (year)	Cumulative CO_2 leakage (Mt)	Total leakage duration (year)
P44	8 months	0.13	5
P43	5	0.46	20
P42	12	0.97	48

Although CO_2 injection is terminated once leakage is detected during CO_2 injection simulations, leakage is continuously monitored until its source (the free CO_2 in the storage reservoir available for leakage at that grid) is exhausted. In this way, potential leakage profile, including the total leakage duration and the cumulative CO_2 leakage, may be obtained to provide a benchmark for evaluating the effectiveness of any remediation measure. The simulation results have shown that the computed leakage profiles display very different trends in the transient and non-transient regions (Figure 5).

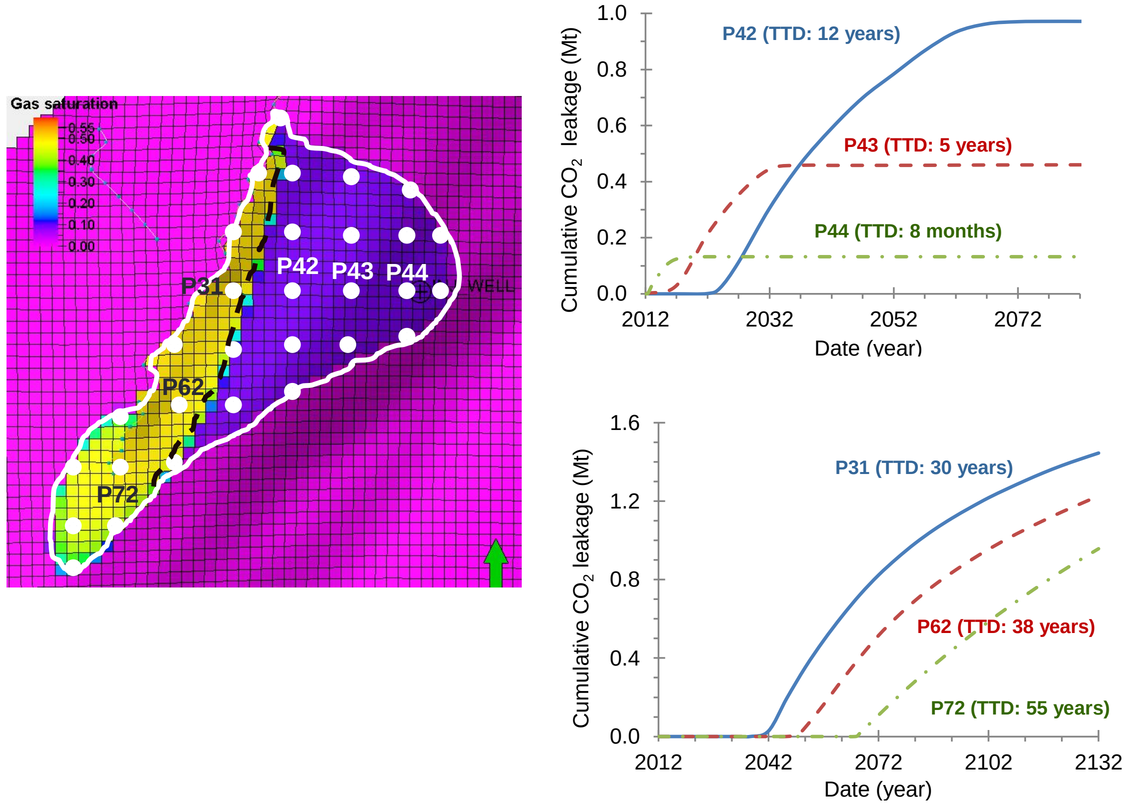


Figure 5. Computed potential CO2 leakage profiles at selected points in the transient and non-transient regions, showing distinctive region-wise trends.

Two leakage locations (grid blocks P44 and P43) in the transient source region, at a distance of 200m and 1,200 m, respectively, to the CO_2 injector were selected for conducting above-zone brine injection simulations. The focus of the injection and leakage modelling work was mainly on P44, which is much closer than P43 is to the injection well. In addition to the base case (detection threshold = 10,000 tonnes, leakage pathway permeability = 10 mD), three other cases with a lower detection threshold (1,000 tonnes) and leakage pathway permeabilities (1 mD) or both were also considered to assess the effectiveness of PGR under different conditions.

The performance of brine injection into an overlying permeable layer (Figure 6) as a potential means for leakage remediation was evaluated through reservoir simulations. In the simulations, brine was injected into the original CO_2 injection well immediately following the detection of leakage and the termination of CO_2 injection. In other words, time which would normally be required for the conversion from a CO_2 injector to a brine injector was not considered. Brine injection into the overlying permeable layer was subject to a constant bottom hole pressure limited to 1.3 times of the hydrostatic pressure to prevent fracturing the reservoir and caprock.

Varying brine injection durations (4 – 16 months) were simulated and it was found that the optimal injection duration was 12 months. The brine injection simulation results indicate that the performance of PGR is strongly affected by how early leakage is detected from the start of injection (time-to-detection), which in turns is controlled by the detection threshold, leakage pathway permeability and the distance to the injection well. The following conclusions may be drawn:

- Above-zone brine injection not only brings down the pressure difference between the storage reservoir and the overlying permeable layer, as is intended, but also the CO_2 saturation in the reservoir around the leakage block. The reduction in CO_2 leakage potential is contributed to both the factors.
- PRG is more effective the earlier the leakage is detected and the closer is the leakage location to the injection well.

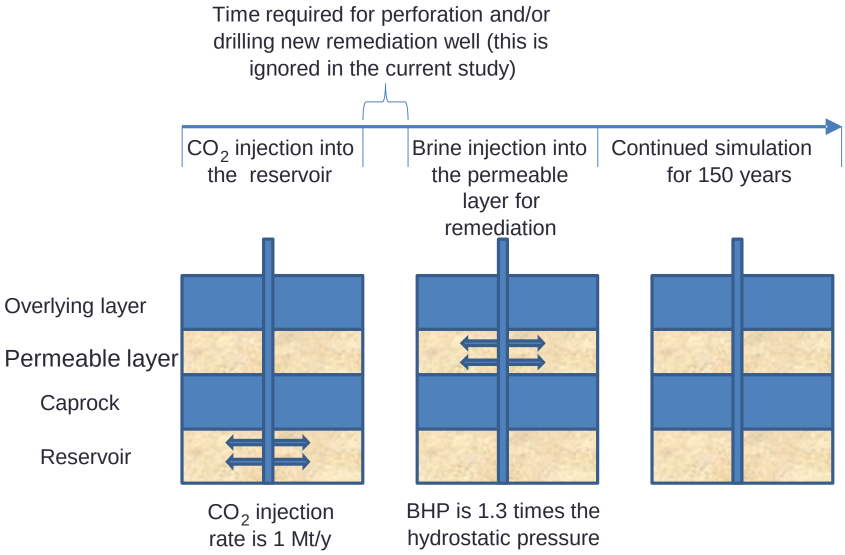


Figure 6. A schematic showing the simulation procedure for PGR method.

3 LEAKAGE REMEDIATION SCENARIO ANALYSIS

The leakage remediation model scenarios considered in the project builds upon the early leakage assessment work carried out. In addition to an areal sink, an elongated sink to represent a fault/fault zone was also considered. As before, the areal sink flow path is represented by a single column of grid cells (~200m x ~200m) across the caprock in the model, along which CO_2 in the storage reservoir can migrate to the shallow aquifer. The elongated sink at the caprock is modelled through performing local grid refinement on the selected grids to yield rectangular cells with large aspect ratio.

For each leakage pathway, the following key features of the storage reservoir are considered and implemented to form a number of modelling scenarios

- Storage reservoir depth (formation pressure and temperature)
- Top of reservoir topography
- Caprock thickness/distance to the permeable layer above the storage reservoir
- Shallow aquifer permeability/porosity

For each scenario the base reservoir model is modified accordingly for CO_2 and brine injection simulations and associated remediation performance evaluation.

3.1 CO_2 leakage and brine injection remediation scenario results

CO_2 is injected at 1 Mt/y into the injection well (Figure 1a). The leakage column permeability and leaked CO_2 detection threshold in the shallow aquifer is assumed to be 10 mD and 10,000 tonnes respectively. Following the detection of CO_2 leakage, brine is injected at a target rate of ~1 Mt/year into the overlying permeable formation (shallow aquifer, Figure 1b) through the same CO_2 injection well, subject to the BHP limit of 1.3 times the hydrostatic pressure at the injection point, for a period of 12 months. In these new and comprehensive remediation scenarios, the simulation is run for a total of 150 years.

3.1.1 Remediation of leakage through an areal sink

As discussed above for the leakage assessment simulations, grid P44 (Figure 7), which is 200m away from the injection well, is selected for conducting CO_2 leakage and subsequent brine injection simulations for the areal sink scenarios. The results for the base case scenario are presented first. Different scenarios implemented to evaluate the effects of

1) storage reservoir depth (with associated pressure and temperature variations),
2) the top of reservoir topography,
3) caprock thickness,
4) permeability and
5) porosity of the shallow aquifer

on the effectiveness of pressure gradient reversal (PGR) on CO_2 leakage remediation are then presented here.

The simulation results for each scenario include time-to-detection (TTD), cumulative leakage for without remediation and with brine injection. These are summarised in Table 2.

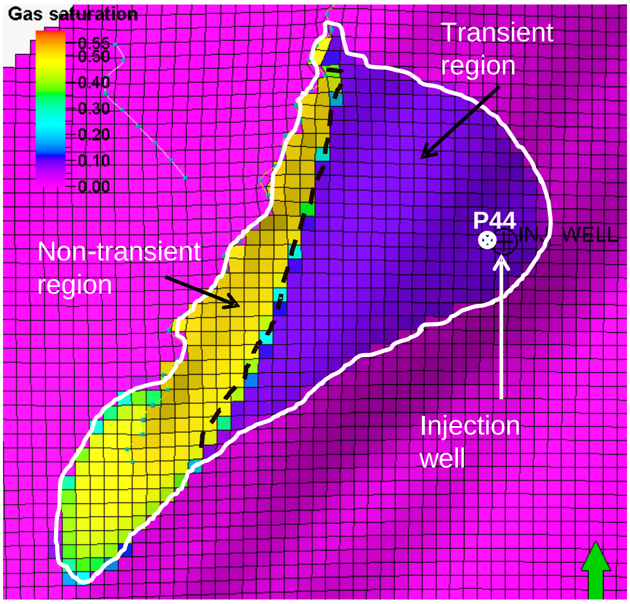


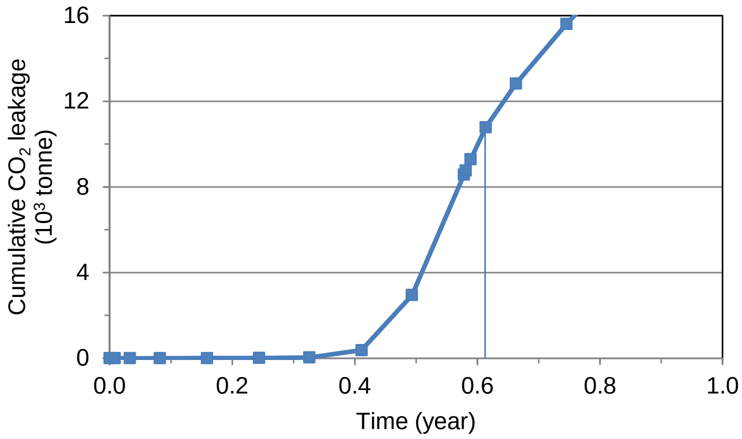
Figure 7. The CO_2 leakage location at grid 44 in transient region selected for above-zone brine injection simulations.

Table 2. Pressure gradient reversal performance for different areal sink scenarios.

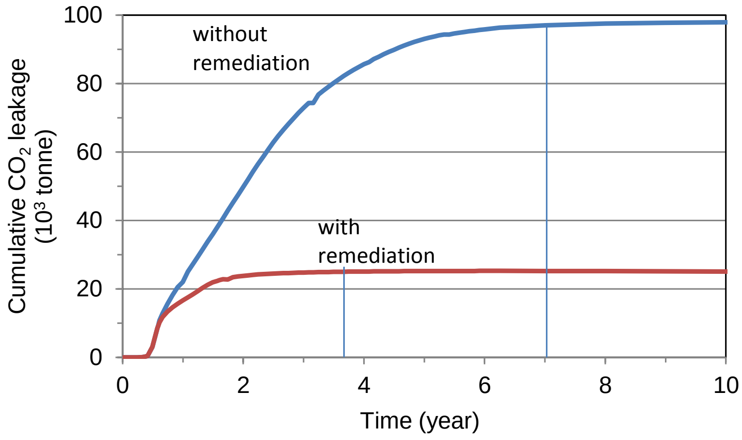
			Time-to-detection (month)	Cumulative leakage 10^3 tonne
Base Case		No remediation/ with PGR (%)	8	97/ 25 (26%)
Reservoir depth	Shallower (-350m)	No remediation/ with PGR (%)	7	80/ 26 (33%)
	Deeper (+350m)	No remediation/ with PGR (%)	9	113/ 21 (19%)
Reservoir top slope (16^o)	Gentler (7^o)	No remediation/ with PGR (%)	9	116/ 29 (25%)
	Steeper (22^o)	No remediation/ with PGR (%)	9	74/ 26 (35%)
Caprock thickness (180m)	Thinner (60m)	No remediation with PGR (%)	7	81/ 26 (32%)
	Thicker (360m)	No remediation/ with PGR (%)	10	123/ 92 (75%)
Shallow aquifer permeability (10 mD)	Lower (1mD)	No remediation/ with PGR (%)	11	60/ 30 (50%)
	Higher (100 mD)	No remediation/ with PGR (%)	7	93/ 11 (12%)
Shallow aquifer porosity (10%)	Lower (5%)	No remediation/ with PGR (%)	8	98/ 21 (21%)
	Higher (20%)	No remediation with PGR (%)	8	96/ 31 (32%)

Base case scenario

For the base case scenarios, the leakage detection threshold (10,000 tonnes) at P44 was reached in the 8th month of CO_2 injection at a rate of 1 Mt/y, as illustrated in Figure 8a. With the determination of TTD, two subsequent simulation runs were performed where CO_2 injection is terminated after 8 months, one followed by brine injection at ~1 Mt/y for a fixed period of 12 months and one without. Figure 8b presents the simulated cumulative CO_2 leakage for the two runs. The results show that the cumulative CO_2 leakage would be reduced from the bench mark 97 kt (without remediation) to 25 kt (or 26%) with brine injection, a reduction of 74%.



(a) Determination of time-to-detection



(b) cumulative CO_2 leakage

Figure 8 a) Determination of time-to-detection and b) leakage profiles with and without brine injection for the base case scenario.

Effect of storage reservoir depth (with associated pressure and temperature variations)

The reservoir formation (with a reservoir temperature 92˚C) in the base model was shifted up and down by 350 m to create a shallower (with reservoir temperature 80.75˚C) and a deeper case (with reservoir temperature 105.25˚C). As a consequence, the corresponding injection bottomhole pressure during brine injection was also limited to 189.8 and 276.9 bars respectively, compared to 232.3 bars for the base case. For the shallower/deeper case, leakage detection threshold at P44 was reached on the 7th/9th month of CO_2 injection at a rate of 1 Mt/y (Table 2). In this scenario, the cumulative CO_2 leakage would be reduced from the bench mark 80/113 kt (without remediation) to 26/21 kt (or 33%/19%) with brine injection, a reduction of 67%/81% (Table 1, Figure 9).

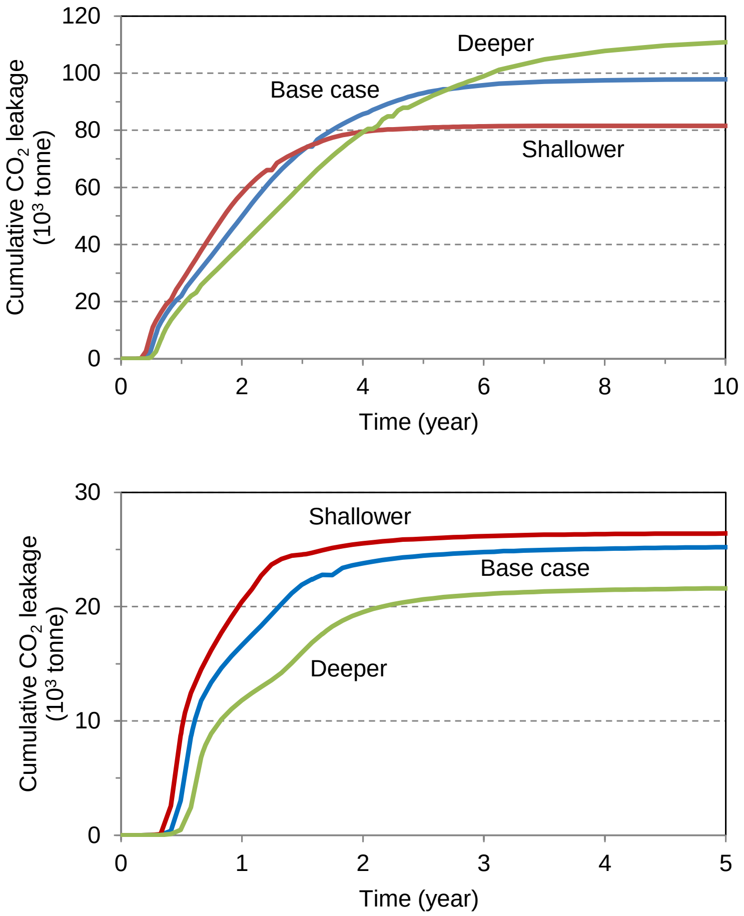


Figure 9. The effect of varying the storage formation depth on CO_2 leakage profiles without (top) and with brine injection (bottom).

Effect of storage reservoir topography

In this scenario, the reservoir top slope was varied from the base case (16˚ near the CO_2 injection well) to represent a flatter (7˚ near the CO_2 injection well) or a steeper (22˚ near the CO_2 injection well) slope. For the flatter/steeper cases, leakage detection threshold at P44 was reached on the 9th/9th month of CO_2 injection at a rate of 1 Mt/y (Table 2). Then, the cumulative CO_2 leakage would be reduced from the bench mark 116/76 kt (without remediation) to 29/26 kt (or 25%/35%) with brine injection, a reduction of 75%/65% (Table 2, Figure 10).

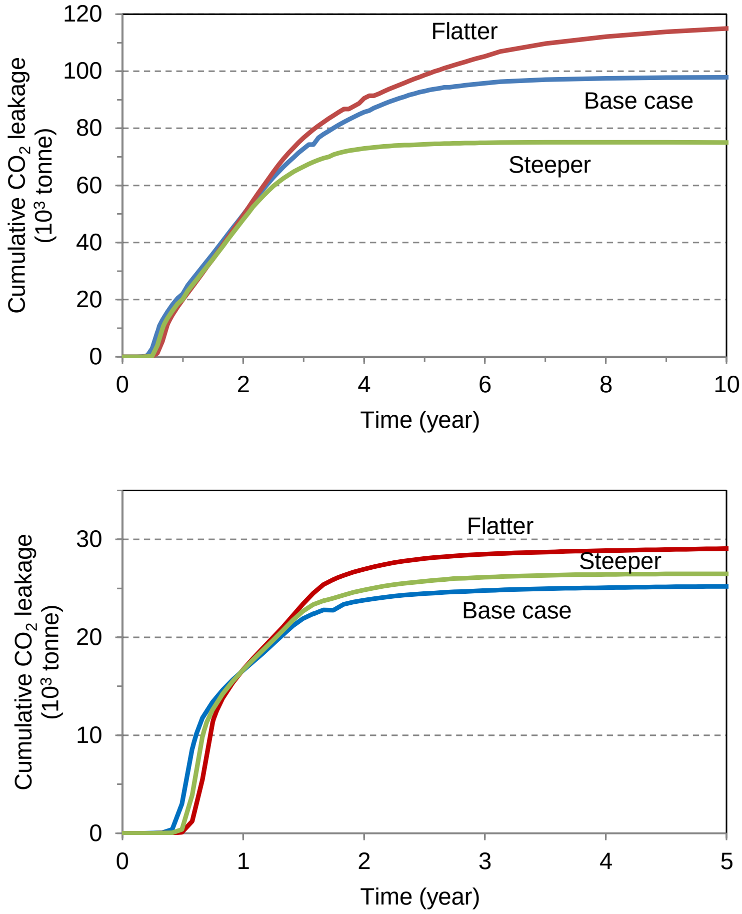
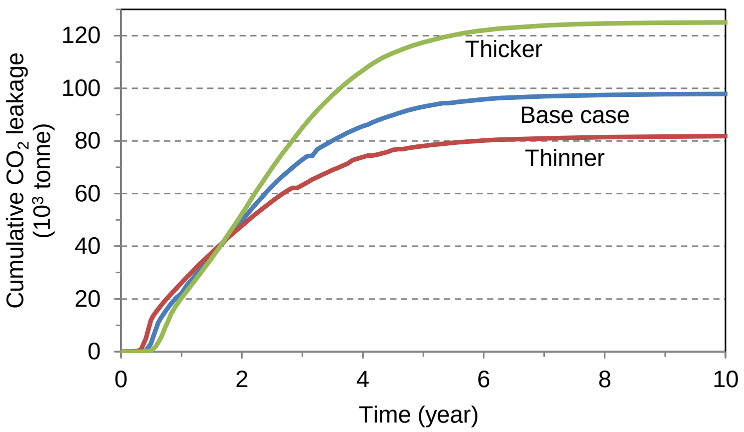


Figure 10. The effect of varying the storage reservoir topography on CO_2 leakage profiles without (top) and with brine injection (bottom).

Effect of caprock thickness

As shown in Figure 1b, the caprock thickness is 180m in the base case. For the thinner/thicker cases, it was reduced/increased to 60m/360m in the model. For the thinner/thicker cases, leakage detection threshold at P44 was reached on the 7^{th}/10^{th} month of CO_2 injection at a rate of 1 Mt/y (Table 2). For this scenario, the cumulative CO_2 leakage would be reduced from the bench mark 81/123 kt (without remediation) to 26/92 kt (or 32%/75%) with brine injection, a reduction of 68%/25% (Table 2, Figure 11).



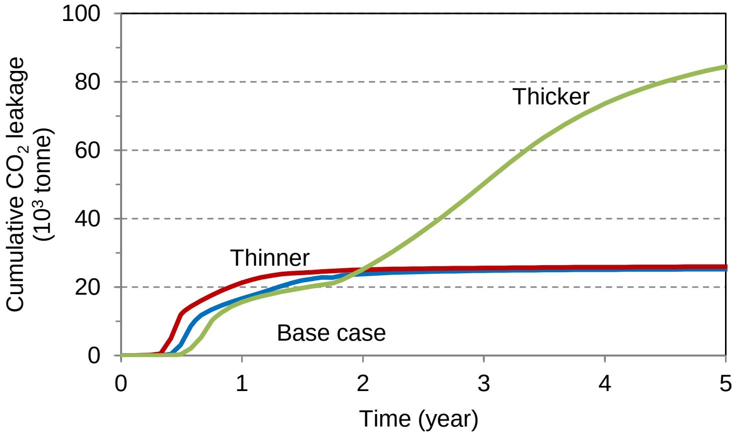


Figure 11. The effect of varying caprock thickness on CO_2 leakage profiles without (top) and with brine injection (bottom).

Effect of shallow aquifer permeability

The shallow aquifer has a permeability of 10 mD in the base case. For this scenario, the permeability was reduced/increased to 1 mD/100 mD in the model to evaluate its impact on the PGR performance. For the lower k/higher k cases, leakage detection threshold at P44 was reached on the 11th/7th month of CO_2 injection at a rate of 1 Mt/y (Table 2). The cumulative CO_2 leakage would then be reduced from the bench mark 60/93 kt (without remediation) to 30/11 kt (or 50%/12%) with brine injection, a reduction of 50%/88% (Table 2, Figure 12).

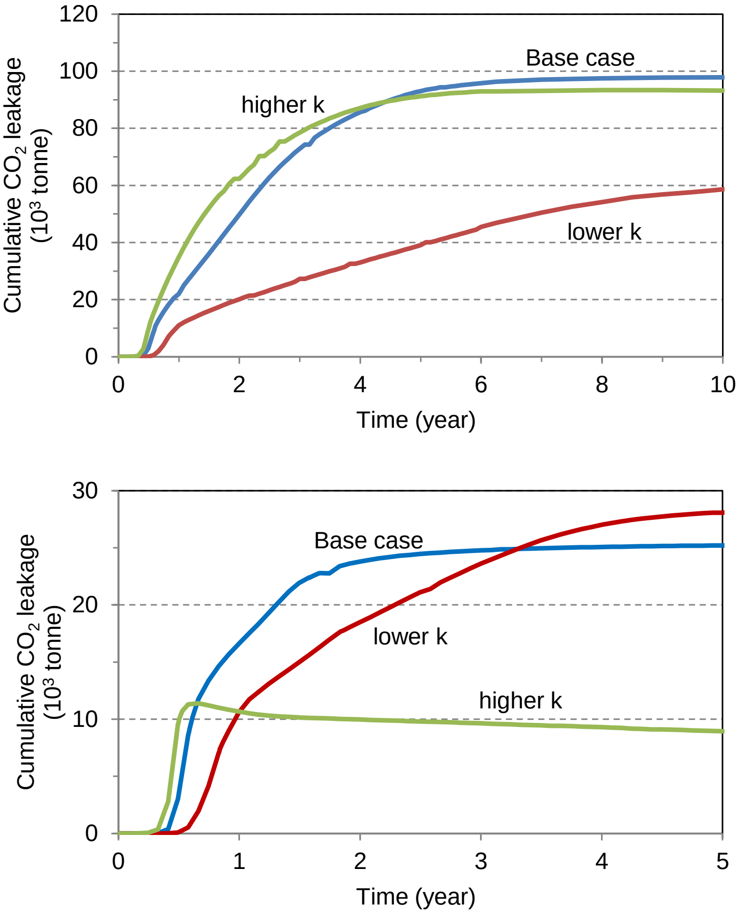
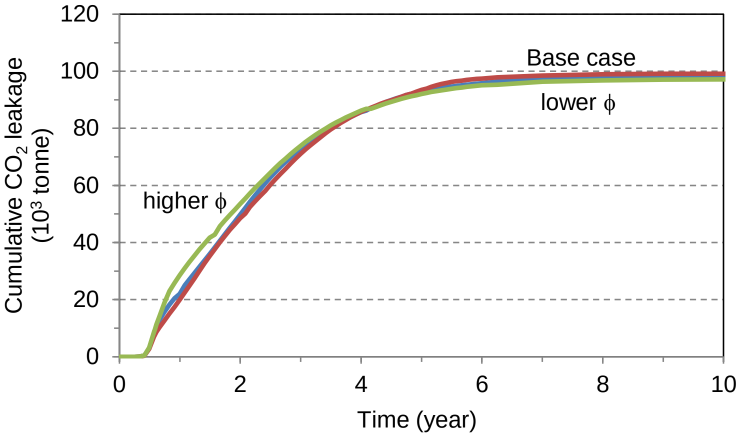


Figure 12. The effect of shallow aquifer permeability on CO_2 leakage profiles without (top) and with brine injection (bottom).

Effect of shallow aquifer porosity

In this scenario, the base case shallow aquifer porosity of 10% was reduced/increased to 5%/20 % to evaluate its impact on the PGR performance. For the lower ϕ/higher ϕ cases, leakage detection threshold at P44 was reached on the 8th/8th month (unchanged from the base case) of CO_2 injection at a rate of 1 Mt/y (Table 1). This has indicated that the cumulative CO_2 leakage would be reduced from the bench mark 98/96 kt (without remediation) to 21/31 kt (or 21%/32%) with brine injection, a reduction of 79%/68% (Table 2, Figure 13).



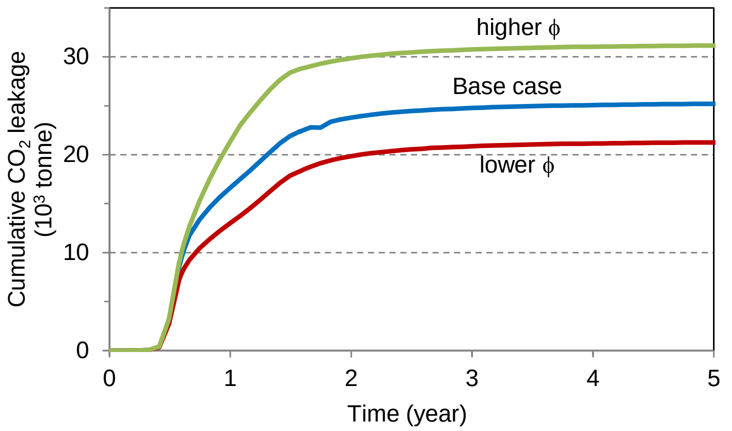


Figure 13. The effect of shallow aquifer porosity on CO_2 leakage profiles without (top) and with brine injection (bottom).

Summary of the results of areal sink scenarios

The modelling results in terms of time-to-detection, cumulative CO_2 leakage for with/without remediation for all the cases presented above are compared in Figures 14 and 15. It can be seen from Figure 14 that, for the different scenarios tested, time-to-detection (10,000 tonnes of leakage to the shallow aquifer) was between 7 to 11 months depending on the reservoir properties and the reservoir top topography selected. It was found that, the permeability of shallow aquifer has the largest impact on the detection time, increasing to 11 months from 8 months (base case and 10 mD permeability) for an order of magnitude reduction in its permeability, followed by the caprock thickness (10 months for doubling the thickness from 180m).

The results in Figure 15 suggest that favourable performance of PGR may be achieved when the shallow aquifer has a significantly larger permeability (an order of magnitude increase in permeability leads to 89% reduction in the cumulative CO_2 leakage compared to 74% for the base case permeability of 10 mD), whereas PGR is less well suited for a thicker caprock compared to the base case.

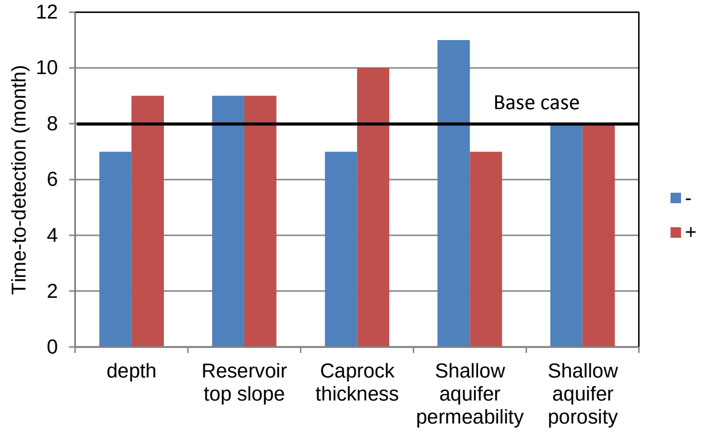


Figure 14. Comparison of time-to-detection for areal-sink scenarios (P44).

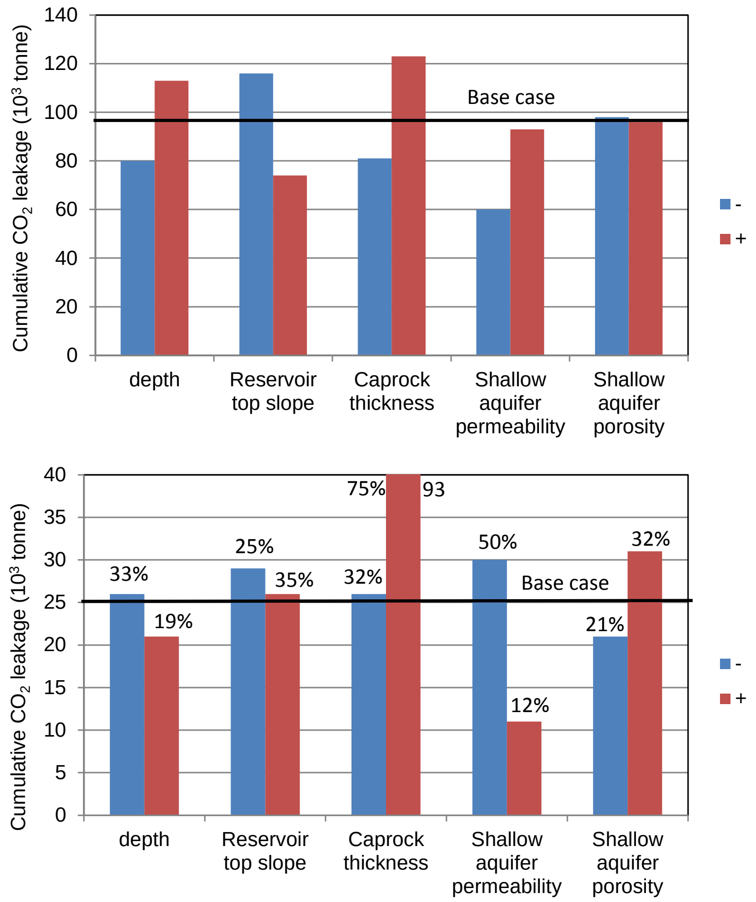


Figure 15. Comparison of cumulative CO_2 leakage for areal scenarios without (top) and with remediation (bottom).

3.1.2 Remediation of leakage through an elongated sink

An elongated sink (10m x 600m) at the location of P44 for modelling CO_2 leakage along a fault/fault zone is presented in Figure 16. The central 400m length is used as a sink. The elongated sink is assigned a vertical permeability of 100mD so that the product of leakage sink permeability and its area remains unchanged from that for the areal sink. The results for the base case scenario are presented first. Different scenarios to evaluate the effects of:

1) storage reservoir depth (with associated pressure and temperature variations),
2) the top of reservoir topography,
3) caprock thickness,
4) permeability and
5) porosity of the shallow aquifer

on the effectiveness of PGR on CO_2 leakage remediation are then presented.

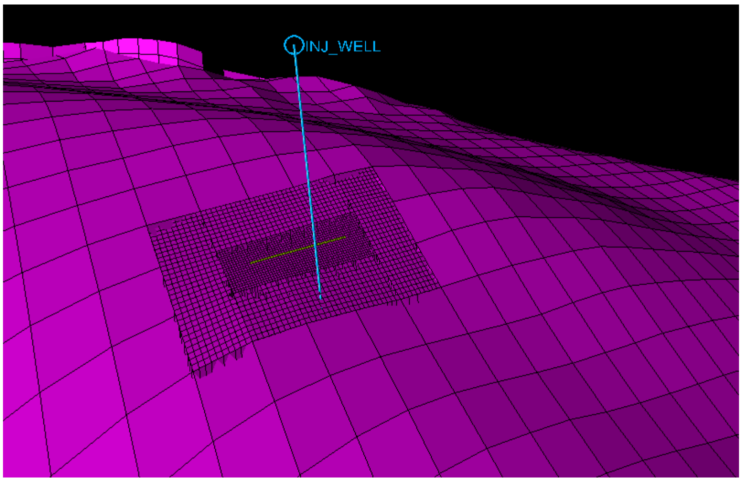


Figure 16. An elongated sink (20m x 600m) at the location of P44 for modelling CO_2 leakage along a fault/fault zone. The central 400m length is used as a sink.

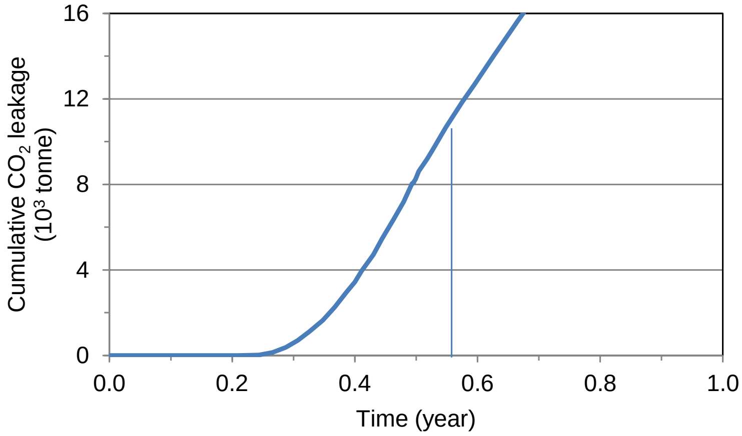
Table 3. PRG performance for different elongated sink scenarios.

			Time-to-detection (month)	Cumulative leakage 10^3 tonne
Base Case		No remediation/ with PGR (%)	7	111/46 (41%)
Reservoir depth	Shallower (-350m)	No remediation/ with PGR (%)	7	90/32 (36%)
	Deeper (+350m)	No remediation/ with PGR (%)	8	133/43 (32%)
Reservoir top slope (16^o)	Gentler (7^o)	No remediation/ with PGR (%)	10	130/30 (23%)
	Steeper (22^o)	No remediation/ with PGR (%)	9	78/36 (46%)
Caprock thickness (180m)	Thinner (60m)	No remediation with PGR (%)	9	69/33 (48%)
	Thicker (360m)	No remediation/ with PGR (%)	8	118/39 (33%)
Shallow aquifer permeability (10 mD)	Lower (1mD)	No remediation/ with PGR (%)	12	64/41 (64%)
	Higher (100 mD)	No remediation/ with PGR (%)	6	105/59 (56%)
Shallow aquifer porosity (10%)	Lower (5%)	No remediation/ with PGR (%)	7	109/45 (41%)
	Higher (20%)	No remediation with PGR (%)	7	115/47 (41%)

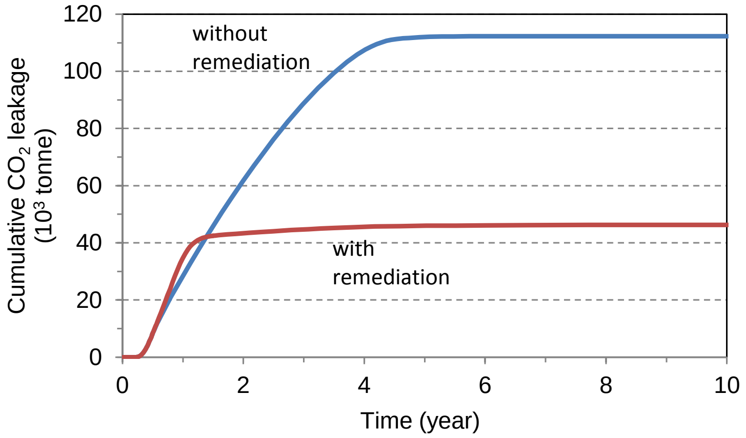
The simulation results for each scenario include time-to-detection (TTD), cumulative leakage for without remediation and with brine injection. They are summarised in Table 3.

Base case scenario

In the base case scenario, leakage detection threshold (10,000 tonnes) at the elongated sink was reached on the 7th month of CO_2 injection at a rate of 1 Mt/y, as illustrated in Figure 17a. With the determination of TTD, two subsequent simulation runs were performed where CO_2 injection is terminated after 7 months, one followed by brine injection at ~1 Mt/y for a fixed period of 12 months and one without. Figure 17b presents the simulated cumulative CO_2 leakage for the two runs. The results show that the cumulative CO_2 leakage would be reduced from the bench mark 111 kt (without remediation) to 46 kt (or 41%) with brine injection, a reduction of 59%.



(a) Determination of time-to-detection



(b) cumulative CO_2 leakage

Figure 17 a) Determination of time-to-detection and b) leakage profiles with and without brine injection for the base case scenario.

Effect of storage reservoir depth (with associated pressure and temperature variations)

The reservoir formation (with a reservoir temperature 92˚C) in the base case model was shifted up and down by 350 m to create a shallower (with reservoir temperature 80.75˚C) and a deeper case (with reservoir temperature 105.25˚C). The corresponding injection bottomhole pressure during brine injection was also limited to 189.8 and 276.9 bars respectively, compared to 232.3

bars for the base case. For the shallower/deeper case, leakage detection threshold at the elongated sink was reached on the 7th/8th month of CO_2 injection at a rate of 1 Mt/y (Table 3). The cumulative CO_2 leakage would be reduced from the bench mark 90/133 kt (without remediation) to 32/43 kt (or 36%/32%) with brine injection, a reduction of 64%/68% (Table 3, Figure 18).

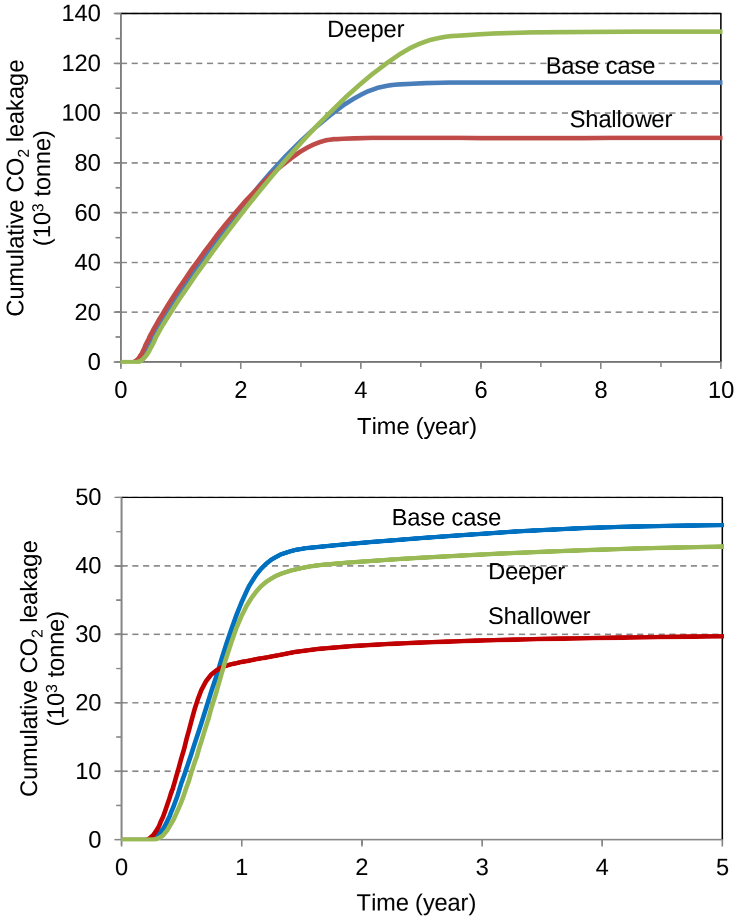
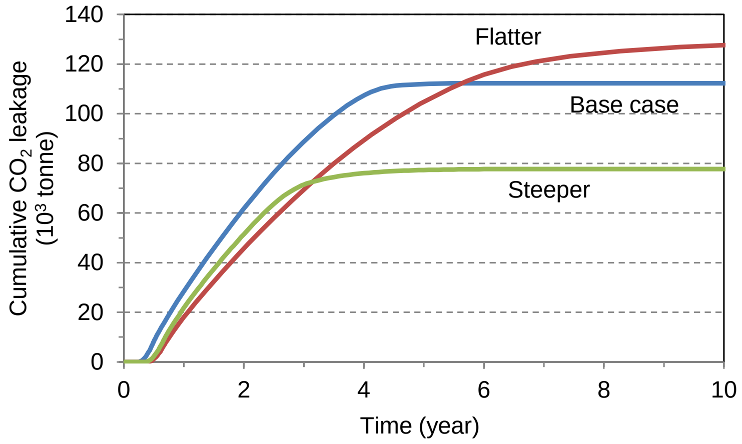


Figure 18. The effect of varying the storage formation depth on CO_2 leakage profiles without (top) and with brine injection (bottom).

Effect of storage reservoir topography

In this case the reservoir top slope was varied from the base case (16˚ near the CO_2 injection well) to represent a flatter (7˚ near the CO_2 injection well) or a steeper (22˚ near the CO_2 injection well) slope. For the flatter/steeper case, leakage detection threshold at the elongation sink was reached on the 10th/9th month of CO_2 injection at a rate of 1 Mt/y (Table 3). The cumulative CO_2 leakage would be reduced from the bench mark 130/78 kt (without remediation) to 30/36 kt (or 23%/46%) with brine injection, a reduction of 75%/64% (Table 3, Figure 19).



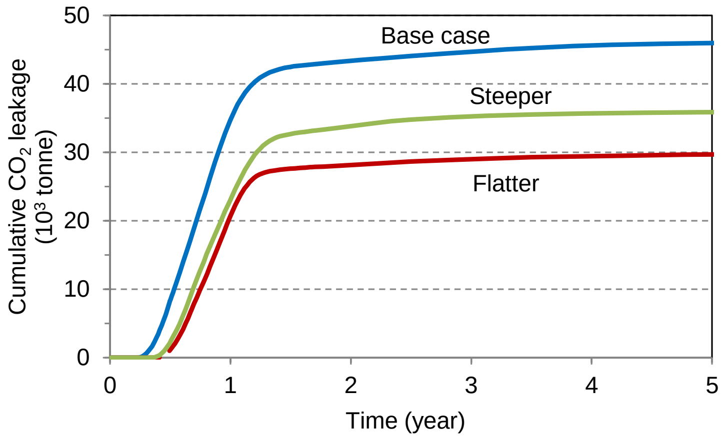


Figure 19. The effect of varying the storage reservoir topography on CO_2 leakage profiles without (top) and with brine injection (bottom).

Effect of caprock thickness

As shown in Figure 1b, the caprock thickness is 180m in the base case. For the thinner/thicker case, this was reduced/increased to 60m/360m in the model. For the thinner/thicker cases, leakage detection threshold at P44 was reached on the $9^{th}/8^{th}$ month of CO_2 injection at a rate of 1 Mt/y (Table 3). It was found that the cumulative CO_2 leakage would be reduced from the bench mark 69/118 kt (without remediation) to 33/39 kt (or 48%/33%) with brine injection, a reduction of 52%/67% (Table 3, Figure 20).

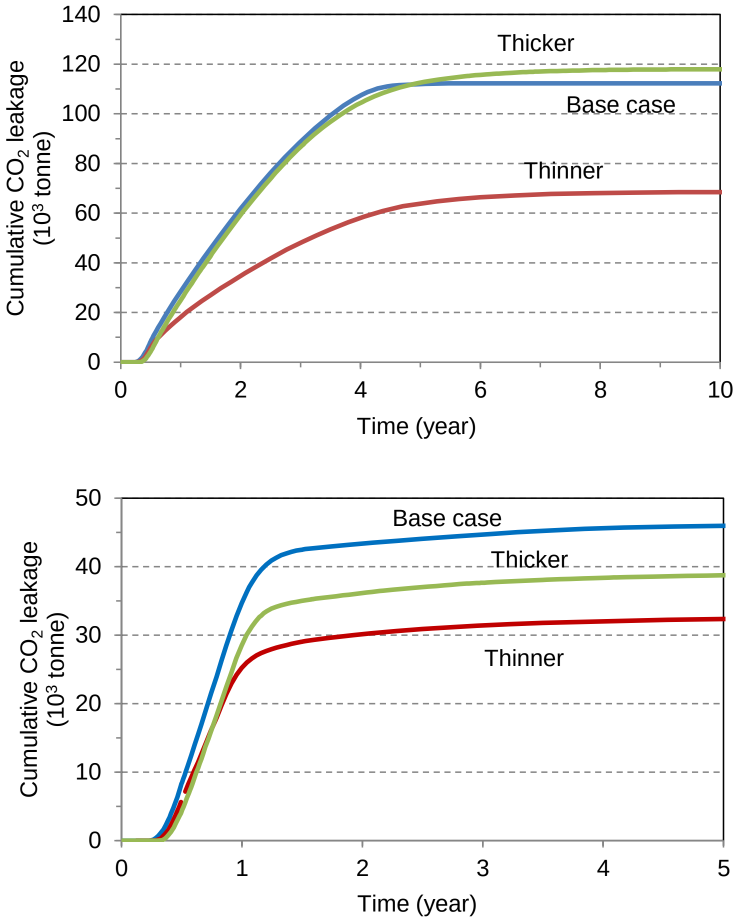


Figure 20. The effect of varying caprock thickness on CO_2 leakage profiles without (top) and with brine injection (bottom).

Effect of shallow aquifer permeability

The shallow aquifer has a permeability of 10 mD in the base case. The permeability was reduced/increased to 1 mD/100 mD in this scenario to evaluate its impact on the PGR performance. For the lower k/higher k cases, leakage detection threshold at P44 was reached on the $12^{th}/6^{th}$ month of CO_2 injection at a rate of 1 Mt/y (Table 2). In this scenario, the cumulative CO_2 leakage would be reduced from the bench mark 64/105 kt (without remediation) to 41/59 kt (or 64%/56%) with brine injection, a reduction of 36%/44%. (Table 3, Figure 21).

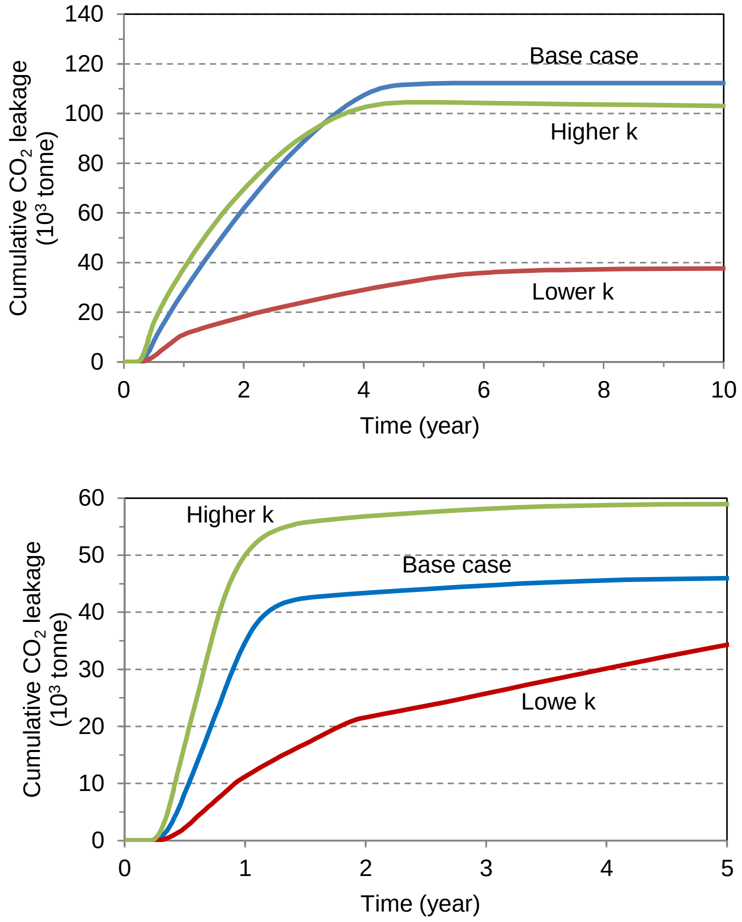


Figure 21. The effect of shallow aquifer permeability on CO_2 leakage profiles without (top) and with brine injection (bottom).

Effect of shallow aquifer porosity

The base case shallow aquifer porosity of 10% was reduced/increased to 5%/20 % to evaluate its impact on the PGR performance. For the lower ϕ/higher ϕ cases, leakage detection threshold at P44 was reached on the 7^{th}/7^{th} month (unchanged from the base case) of CO_2 injection at a rate of 1 Mt/y (Table 2). The cumulative CO_2 leakage would be reduced from the bench mark 109/115 kt (without remediation) to 45/47 kt (or 41%/41%) with brine injection, a reduction of 59%/59% (Table 3, Figure 22).

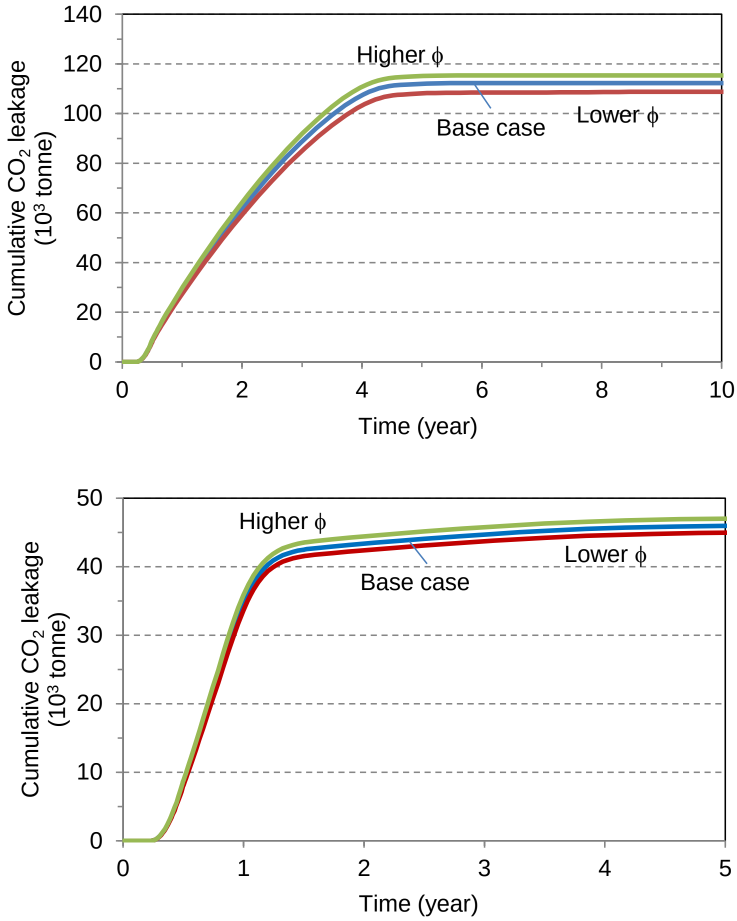


Figure 22. The effect of shallow aquifer porosity on CO_2 leakage profiles without (top) and with brine injection (bottom).

Summary of the remediation findings for the elongated sink scenarios

The modelling results in terms of time-to-detection, cumulative CO_2 leakage and the leakage period after detection with/without remediation for all the cases presented above are compared in Figures 23 and 24. It can be seen from Figure 23 that, for the different scenarios tested, time-to-detection (10,000 tonnes of leakage to the shallow aquifer) was between 7 to 12 months depending on the reservoir properties and the reservoir top topography selected. It was found that, the permeability of shallow aquifer has the largest impact on the detection time, increasing to 12 months from 8 months (base case and 10 mD permeability) for an order of magnitude reduction in its permeability, followed by the reservoir top slope (10 months for reducing it to 7^o from 16^o).

The results in Figure 24 suggest that better performance of PGR technique may be achieved in the reservoir with flatter slope (9^o reduction in the slope of the reservoir top leads to 77% reduction in the cumulative CO_2 leakage compared to 59% for the base case slope of 16^o), or at a shallower depth than the base case (65% reduction in the cumulative CO_2 leakage).

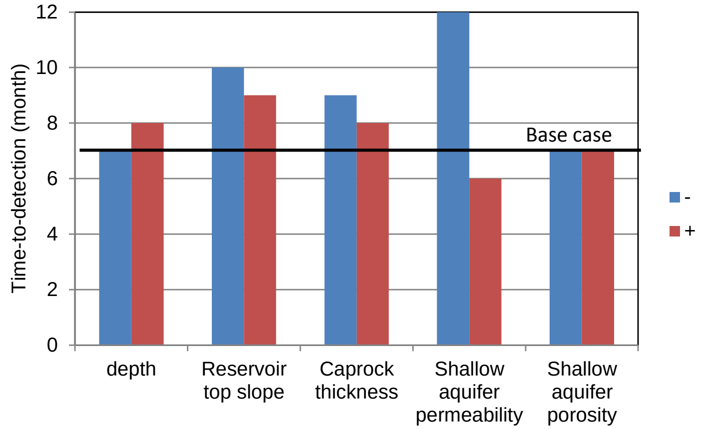


Figure 23. Comparison of time-to-detection for elongated-sink scenarios.

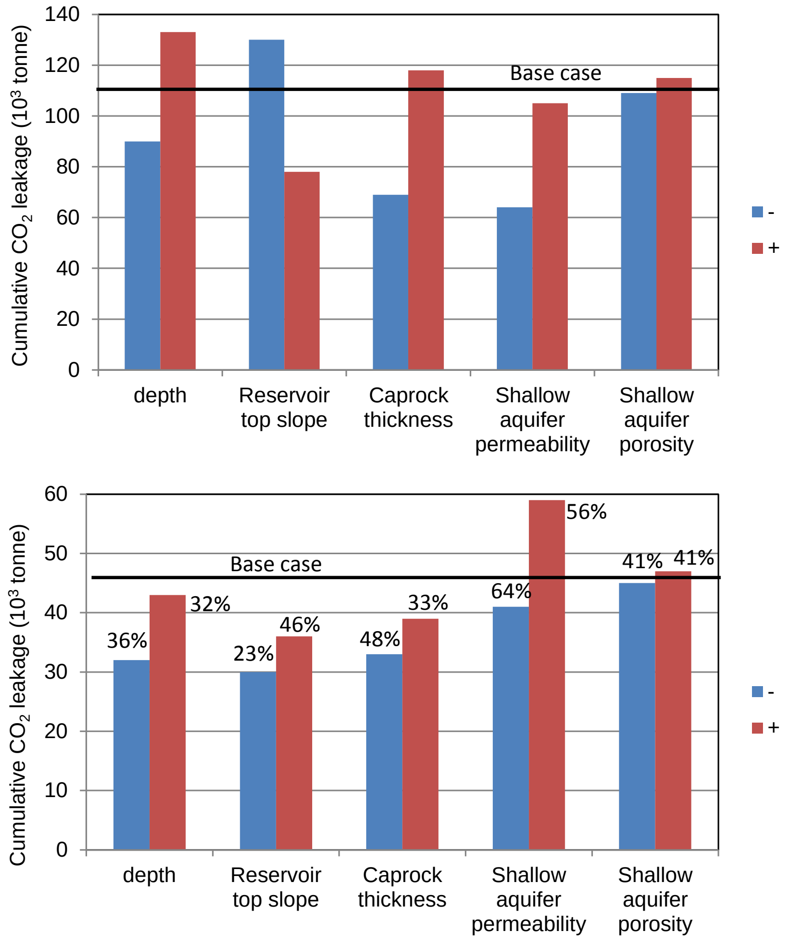


Figure 24. Comparison of cumulative CO_2 leakage for elongated scenarios without (top) and with remediation (bottom).

4 CONCLUSIONS

Injection of brine above a fractured cap rock or a fault, if maintained at a higher pressure than the CO_2 pressure in the reservoir, can create an inverse pressure gradient to reverse the flow direction of CO_2 and form a barrier to prevent or at least limit leakage. This procedure could enable fast and reasonably low cost mitigation measures once a leakage is detected, however, this technology can only be used as a temporary measure and allow for more permanent remediation techniques to be prepared and implemented with time. The efficiency of this technology relies upon continuous injection of brine above the leakage area and a number of site specific reservoir conditions represented by static and dynamic rock and fluid characteristics, geometry and position of the leakage.

Using the Imperial College Saline Aquifer Model (ICSAM) as the base model, a large number of brine injection simulations to remediate leakage scenarios have been carried out. Two potential leakage pathways have been investigated with a number of modelling scenarios for each leakage pathway. For each scenario, time-to-detection was set as 10,000 tonnes of injected CO_2 reaching the shallow aquifer. Remediation was implemnted through the injection of 1 Mt of brine over 12 months. The modelling results in terms of time-to-detection, and cumulative CO_2 leakage for with/without remediation for all the scenarios are presented and the PGR performances were compared.

The results suggest that, for the areal sink scenarios tested, time-to-detection was between 7 to 11 months depending on the reservoir properties and the reservoir top topography selected. It was found that, the permeability of shallow aquifer has the largest impact on the detection time, increasing to 11 months from 8 months (base case and 10 mD permeability) for an order of magnitude reduction in its permeability, followed by the caprock thickness (10 months for doubling the thickness from 180m). It was also found that favourable performance of PGR may be achieved when the shallow aquifer has a significantly larger permeability (an order of magnitude increase in permeability leads to 89% reduction in the cumulative CO_2 leakage compared to 74% for the base case permeability of 10 mD), whereas PGR is less well suited for a thicker caprock compared to the base case.

In the case of elongated sink scenarios, such as a fault or a fracture zone, the time-to-detection was between 7 to 12 months depending on the reservoir properties and the reservoir top topography selected. It was found that, the permeability of shallow aquifer has the largest impact on the detection time, increasing to 12 months from 8 months (base case and 10 mD permeability) for an order of magnitude reduction in its permeability, followed by the reservoir top slope (10 months for reducing it to 7^o from 16^o). Better performance of PGR technique may be achieved in a reservoir with flatter slopes (9^o reduction in the slope of the reservoir top leads to 77% reduction in the cumulative CO_2 leakage compared to 59% for the base case slope of 16^o), or at a shallower depth than the base case (65% reduction in the cumulative CO_2 leakage).

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