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Impact of Background Flow on CO_2 Plume Movement and Trapping in Saline Aquifer

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Summary

To achieve effective long-term CO_2 storage in saline aquifers, it is essential to understand and monitor CO_2 distribution and trapping mechanisms, which are significantly influenced by groundwater flow. This study investigates the impact of background flow velocity and direction on CO_2 plume behavior and different trapping mechanisms (residual and solubility) using numerical analysis. The results of simulation show that in the flat (0° dip) model, increasing background flow velocity significantly extends the plume migration distance, enhancing both solubility and residual trapping through a larger CO2-water contact area and increased pore space occupation. The analysis is further extended to a dipping aquifer scenario to assess the role of groundwater flow direction. In the co-current flow case, where water and CO_2 move in the same direction, the plume attains its maximum lateral extension, resulting in the highest storage efficiency. Conversely, in the counter-current flow scenario, where CO_2 and water move in opposite directions, lower CO_2 trapping is observed because, particularly at high velocity, the drag force exerted by water overcomes buoyancy force and limits further plume extension.

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Introduction

Underground CO_2 storage is a key strategy for mitigating greenhouse gas emissions by permanently sequestering CO_2 in deep geological formations. Among the various storage options, saline aquifers are considered the most favourable due to their widespread availability and substantial storage capacity (Celia et al., 2015). Many of these aquifers are dynamic and exhibit slow groundwater flow, with velocity less than 1 km/year (Harter, 2003).

When CO_2 is injected into a saline aquifer, it rises toward the caprock due to the density and viscosity differences between the injected CO_2 and formation water, assuming no vertical barriers are present. Over time, CO_2 plume spreads laterally under the influence of buoyancy and background flow (Awag et al., 2023). During its migration, CO_2 is subject to several trapping mechanisms that occur on different timescales. Initially, as the injected CO_2 rises up, it can be trapped beneath impermeable caprock, which is known as structural trapping**.** As the plume continues to spread, water begins to displace the trailing part of the plume through imbibition process, which immobilizes a portion of the CO_2 in the pore spaces, leading to residual trapping. Additionally, over the time, CO_2 gradually dissolves into the brine (solubility trapping), and in the long term, reacts chemically with rock minerals to form stable precipitates in a process known as mineral trapping (Kelemen et al., 2019).

To effectively assess the storage efficiency, and potential risks on CO_2 leakage in the subsurface, it is essential to monitor plume migration and quantify the contributions of different trapping mechanisms over time, particularly after injection has ceased (Awag et al., 2024). The primary objective of this study is to investigate the impact of various background flow velocities on plume migration and on the efficiency of solubility and residual trapping mechanisms through numerical simulation. Additionally, recognizing that many aquifers exhibit dip angles typically ranging from 1° to 3° (Jing et al., 2021), the second stage of this study introduces a dip angle model. We further analyse how different groundwater flow directions (co-current and counter-current) influence plume distribution and the amount of trapped CO_2.

Methodology and Model Description

A two-dimensional (2D) homogeneous flat model (0° dip) is developed using the CMG-GEM (2024.10) compositional simulator to investigate CO_2 migration and trapping mechanisms under different background flow conditions. The reservoir is initially saturated with brine at a salinity of 200000 mg /l. The relative permeability data are derived from typical aquifer sandstone, and a maximum gas saturation (Sgr=0.3) is applied in the hysteresis to model residual trapping. CO_2 dissolution into the brine is modelled using Henry's law under isothermal conditions, while mineral trapping and other geochemical reactions are not included in this study . Key aquifer parameters and rock properties used in the model are summarized in Table 1.

Table 1. *A summary of model properties.*

Parameter	**Value**	**Unit**
Reservoir size (I×J×K)	20000×500×50	m
Number of grids (I×J×K)	4000×1×50	-
Initial Reservoir Pressure	120	bar
Reservoir Temperature	80	˚C
Reference Depth	1200	m
Thickness	1	m
Horizontal Permeability (I,J)	100	mD
Vertical Permeability (K)	10	mD
Porosity	0.13	-

CO_2 Injection Rate	150000	m^3/day

To evaluate the effect of background flow without artificially over-pressurizing the reservoir, vertical water injection and production wells are placed at the left and right boundaries of the model, respectively, operating at equal rates (Figure 1). Three different background flow velocities are examined based on data taken from Forties aquifer, in the North Sea: 0 m/year (no-flow condition), 0.04 m/year (low background flow velocity), and 0.4 m/year (high background flow velocity) (Goater et al., 2013). Additionally, a vertical CO_2 injection well is positioned 6000 m from the water injection well, injecting supercritical CO_2 at a constant rate for 15 years. The system is then monitored for an additional 100 years to analyse the post-injection plume behaviour. The length of reservoir is set sufficiently large to ensure that the injected CO_2 plume does not reach the model boundaries within the simulation timeframe.

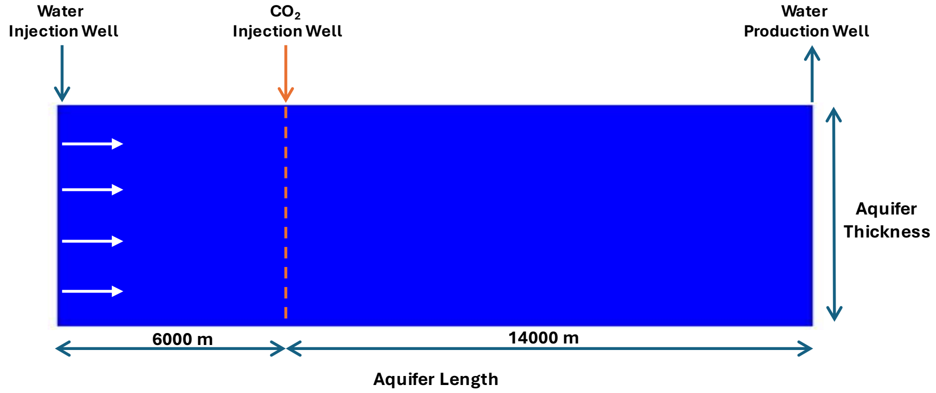

Figure 1. *Schematic view of aquifer model with background water flow.*

Dip angle Model. In addition to the flat model, dip angle variation is incorporated for both low and high background velocity cases to evaluate the influence of aquifer slope on CO_2 and water migration. The aquifer is tilted downward from left to right at a 2° dip angle. In this titled configuration, two different flow scenarios emerge depending on the relative movement of water and CO_2: co-current flow and counter-current flow. To examine the impact of both flow types on CO_2 plume migration and trapping, separate models are built by altering the positions of the injection and production wells. In the co-current scenario, the water injection well is placed at the right boundary (downdip), causing both CO_2 and water to move updip in the same direction. Conversely, in the counter-current scenario, the water injection well is located at the left boundary (updip), leading water to flow downdip while CO_2, driven by buoyancy, migrates updip, resulting opposing flow directions.

Results and Discussions

In this section, we present the impact of background flow (both velocity and direction) on CO_2 distribution, as well as on the solubility and residual trapping mechanisms based on simulation outputs. We first examine how varying background flow velocities affect the plume shape and migration distance in flat reservoir model. Figure 1 illustrates the extent of the plume along both the reservoir length and thickness for three different flow velocities. The results show that as the background velocity increases, the leading edge of the CO_2 plume migrates more rapidly, resulting in a larger plume extension. This expansion of plume enhances the contact area between CO_2 and water, thereby promoting greater CO_2 dissolution. Additionally, the continuous influx of unsaturated water driven by the background flow further accelerates dissolution of CO_2. In contrast, under static (no-flow) conditions, the dissolution process eventually stabilizes once the water near the injection well becomes fully saturated with CO_2.

Furthermore, higher background flow significantly increases residual trapping. As the moving water pushes the plume farther away from the injection zone, it forces CO_2 into new pore spaces. This process increases residual trapping efficiency by reducing the mobile fraction of the plume. thereby increasing residual trapping by reducing the mobile fraction of the plume. Table 2 summarizes the fraction of the injected CO_2 trapped by solubility and residual trapping mechanisms for the various background flow conditions.

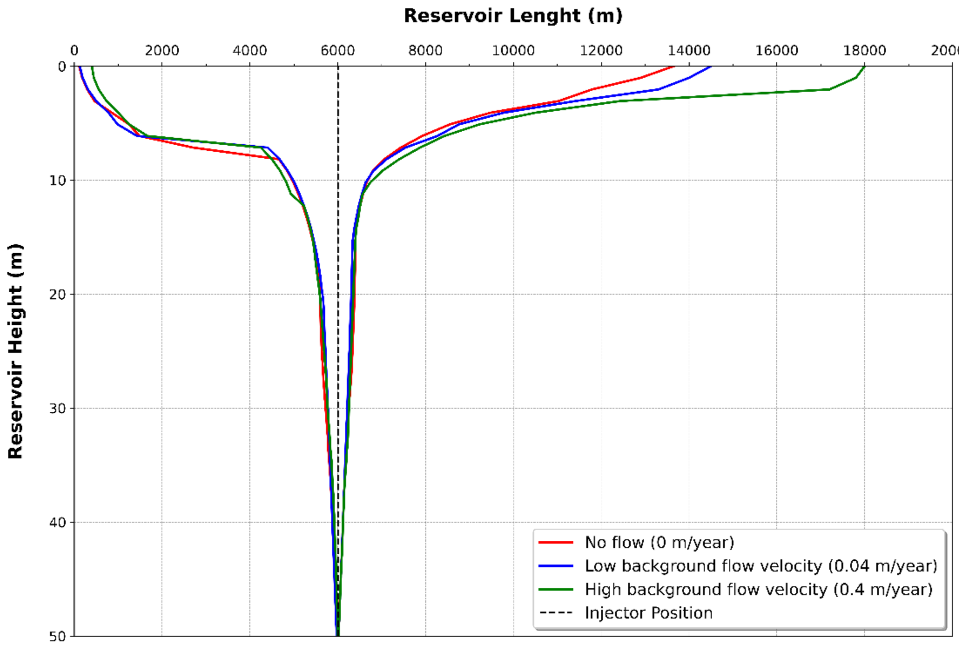

***Figure 2**. The spatial distribution of CO_2 plume for different background flow velocities at the end of 100 years post-injection, based on the gas saturation profile (Sg > 0.05).*

In the second stage of our analysis, we investigate how the direction of groundwater flow in a dipping aquifer influences CO_2 plume behaviour under various background flow velocities. Table 2 compares these findings with results from a flat reservoir model, focusing on plume extension (from the leading to the trailing edge) and trapping efficiency. In the co-current flow scenario, where water displaces CO_2 from the trailing edge and both fluids move in the same direction, the combined influence of background flow and buoyancy force drives the plume to migrate the greatest distance. Specifically, at high groundwater velocity, this results the largest plume extension, which is associated with the highest residual trapping (due to increased pore space occupation) and solubility trapping (as the greater contact area between CO_2 and water promotes dissolution). By contrast, in the counter-current flow scenario,

***Table 2.** Impact of background flow velocity and direction on CO_2 trapping mechanisms and lateral extent of plume at the end of 100 years post-injection.*

Velocity (m/year) and direction of background flow	**Fraction of residual trapping**	**Fraction of solubility trapping**	**Plume extension (km)**
Flat Model: 0 m/year	0.22	0.07	**~13,4**
Flat Model: 0.04 m/year	0.26	0.08	**~14,1**
Flat Model: 0.4 m/year	0.42	0.12	**~17,6**
Co-Current: 0.04 m/year	0.35	0.09	**~14,5**
Co-Current: 0.4 m/year	0.50	0.12	**~18,1**
Counter-current: 0.04 m/year	0.30	0.09	**~14,2**
Counter-current: 0.4 m/year	0.23	0.08	**~10,8**

the plume's distribution strongly depends on the velocity of background flow. At low velocity, buoyancy force remains dominant, allowing the plume to continue moving updip. However, at high velocity, the drag force exerted by the water eventually overcomes buoyancy, causing the plume to reverse direction and migrate downdip under the influence of background flow. As a result CO_2 re-enters previously trapped pore spaces, which limits further plume extension and restricts additional residual and solubility trapping. Consequently, residual trapping is significantly lower in the counter-current flow scenario (especially in high background flow velocity) compared to the co-current flow scenario (Table 2).

Conclusions

In this study, we develop both flat (0° dip) and dipping aquifer models to examine how injected CO_2 spreads and is trapped in the subsurface under various groundwater flow conditions. Our numerical simulations reveal that the efficiency of CO_2 storage process is strongly dependent on background flow dynamics. The results indicate that while background flow generally enhances solubility and residual trapping by increasing plume migration distance, its impact differs depending on the flow direction. In the co-current flow scenario, where CO_2 and water move in the same direction, higher background velocity promotes greater trapping efficiency due to increased pore space occupation and a larger CO_2–water contact area. However, in the counter-current flow scenario, particularly at high velocity, background flow can negatively impact trapping by reversing plume movement direction, limiting further residual and solubility trapping.

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