

A STUDY OF METHODOLOGIES AND CRITICAL PARAMETERS ASSOCIATED WITH CO₂ STORAGE ESTIMATION IN DEEP SALINE AQUIFERS

P.N.K.De Silva^a, * P.G.Ranjith^b, S.K.Choi^c and A.Haque^d

^{a,b,d}Department of Civil Engineering, Monash University, Building 60, Melbourne, Victoria, 3800, Australia.

^aE-mail: Navinda.DeSilva@eng.monash.edu.au ; ^aPhone: +61 3 9905 8901; ^aFax: +61 3 9905 4944

^{*b}E-mail: Ranjith.pg@eng.monash.edu.au ^{*b}Phone/Fax: 61-3-9905 4982

^cAustralian Commonwealth Scientific and Research Organization (CSIRO) Locked Bag 10, Clayton South VIC 3169, Australia.

Abstract

Deep saline aquifers have greater potential for carbon dioxide (CO₂) storage (around 12,000 Gt global capacity) than alternative storage media and could be adopted anywhere in the world. It is important to understand methodologies for the estimation of CO₂ storage capacities in relation to different trapping mechanisms and the extent to which critical parameters such as aquifer thickness, porosity, salinity and permeability are taken into account. Storage security will improve over time, especially as a result of mineral trapping. This paper reviews methods of estimating CO₂ storage potential from earlier studies and numerically estimates the storage potential in saline aquifers considering critical parameters such as saline aquifer and porosity.

Keywords: Saline aquifers, Trapping mechanisms, Mineral trapping

1.0 Introduction

Carbon dioxide (CO₂) is a major greenhouse gas that needs to be controlled promptly to reduce its impact on global warming. Atmospheric emissions of CO₂ are projected to increase by 2.2% globally and 3.3% in the developed countries from 2000 to 2020 due to ever-increasing human activities (Soares et al., 2006). Underground storage of greenhouse gases in deep saline aquifers has been suggested as an effective means of significantly reducing atmospheric greenhouse gases to dampen the effects of global warming. Estimates of CO₂ storage capacity in saline aquifers fall into two categories with respect to the state of storage: One assumes the CO₂ remains as a separate fluid phase and the other assumes all CO₂ dissolves in the brine. However, Bruant et al., (2002) have shown that only a small fraction of an aquifer will be filled with separate phase CO₂ due to hydrodynamic and buoyancy effects. Estimations of CO₂ storage in deep saline aquifers must account for different trapping mechanisms such as physical, solubility, residual gas, mineral and hydrodynamic.

2.0 CO₂ storage capacity

Residual gas and solubility trapping of CO₂ in saline water have been viewed as the dominant CO₂ storage mechanisms (Zhang et al., 2009). Reservoir simulation and practical experience show that the injected CO₂ will rapidly gravitate to the top of the reservoir, limiting its contact with the reservoir and thus also limiting the storage capacity of the aquifer. Figure 1 illustrates the variation of storage with time.

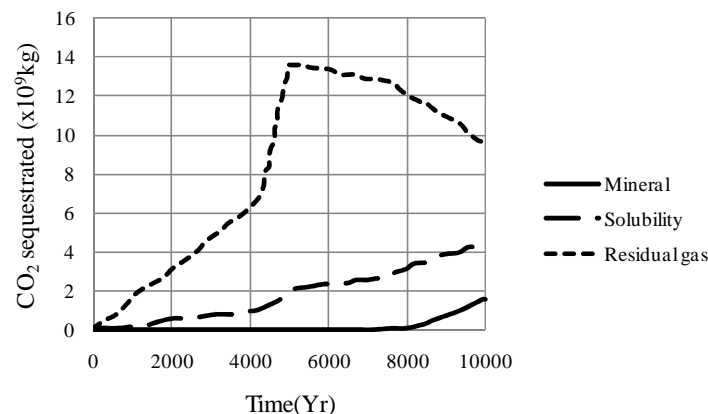


Figure 1: Comparison of time evolution of the injected carbon dioxide in different trapping mechanisms (Zhang et al., 2009).

2.1 Structural and stratigraphic trapping

Storage of CO₂ in structural and stratigraphic traps is similar to CO₂ storage in oil and gas reservoirs, the only difference being that the trap is initially saturated with water in place of hydrocarbons (Bachu et al., 2007). Theoretical storage capacity is found using the following equation;

$$M_{CO_{2t}} = Ah\phi(1 - S_{wirr})\rho(P, T) \quad \text{Equation (1)}$$

Where $M_{CO_{2t}}$ is the theoretical CO₂ storage capacity, A is the trap area, h is the average thickness, $\rho(P, T)$ is the in situ density under local pressure (P), temperature (T), ϕ is the porosity and S_{wirr} is the irreducible water saturation. Effective storage capacity is calculated using the following equation (Bachu et al., 2007);

$$M_{CO_{2e}} = C_c M_{CO_{2t}} \quad \text{Equation (2)}$$

Where $M_{CO_{2e}}$ is the effective CO₂ storage capacity and C_c is the capacity coefficient that incorporates the cumulative effects of trap heterogeneity, CO₂ buoyancy and storage efficiency. Currently, there are no values in the literature for this capacity coefficient, which is site-specific and needs to be determined through numerical simulations and laboratory studies followed by field work (Bachu et al., 2007).

2.2 Residual gas trapping

Due to the hysteretic properties of relative permeability, CO₂ is trapped at the end of injection of CO₂ as the flow is reversed (Bachu et al., 2007). This capacity can be found with the following equation;

$$M_{CO_{2e}} = \Delta V_{trap} \phi S_{CO_{2t}} \rho(P, T) \quad \text{Equation (3)}$$

Where ΔV_{trap} is the rock volume previously saturated with CO₂ that is invaded by water, $S_{CO_{2t}}$ is the trapped CO₂ saturation after flow reversal. While the porosity and relative permeability characteristics can be determined through laboratory measurements on core scale rock samples, $S_{CO_{2t}}$ and ΔV_{trap} can be determined only through numerical simulations (Bachu et al., 2007).

2.3 Solubility trapping

Solubility trapping is dependent on time and continues over long periods of time in the order of centuries (Bachu et al., 2007). CO₂ may mix with, and then dissolve in, formation water through diffusion, dispersion and convection. Theoretical storage capacity can be estimated using the following equation;

$$M_{CO_{2t}} = Ah\phi(\rho_s X_s^{CO_2} - \rho_o X_o^{CO_2}) \quad \text{Equation (4)}$$

Where A is the aquifer trap area, h is the average thickness, ρ is the density of formation water, X^{CO_2} is the carbon dioxide mass fraction in formation water and the subscripts "o" and "s" stand for initial carbon dioxide content and carbon dioxide content at saturation, respectively. The effective solubility content can be estimated using the following equation;

$$M_{CO_{2e}} = C * M_{CO_{2t}} \quad \text{Equation (5)}$$

Where C is a coefficient that includes the effect of all factors that affect the spread and dissolution of CO₂ in the whole aquifer volume under consideration.

2.4 Mineral trapping

Mineral trapping is dependent on the chemical composition of formation waters and of the rock matrix, and on temperature and pressure (Bachu et al., 2007). In addition, it depends on the contact surface (interface) between the mineral grains and the formation water containing dissolved CO₂, and on the flow rate of fluids past the interface (Bachu et al., 2007). Only local and site level numerical simulations, supported where possible with laboratory experiments and field observations, may

provide an estimate of the amount of stored CO₂ and the time-frame for CO₂ storage through mineral trapping. Previous work reveals that the CO₂ storage capacity through mineral trapping per unit of rock volume can be comparable to the storage capacity through solubility trapping, although it can take several thousand years for geochemical reactions to have a significant impact (Xu et al., 2004). Similar to residual gas and solubility trapping, as mineral trapping is a time-dependent process operating on the scale of centuries to millennia, the CO₂ storage capacity needs to be estimated for a particular point in time.

2.5 Hydrodynamic trapping

Hydrodynamic trapping differs from other trapping mechanisms as it is not based on a single, specific physical or chemical trapping mechanism, but is a combination of the mechanisms reviewed earlier, which operate simultaneously but at different rates while a plume of injected CO₂ is expanding and migrating (Bachu et al., 1994). Because hydrodynamic trapping is based on several CO₂ trapping mechanisms acting at times simultaneously and sometimes being mutually exclusive, the CO₂ storage capacity has to be evaluated at a specific point in time as the sum of the storage capacities achieved by its component trapping mechanisms (Bachu et al., 2007). Given the combination and complexity of the processes involved and of their different time scales, it is not possible to evaluate the CO₂ storage capacity at basin and regional scales except in the broadest terms by extrapolating from local-scale simulations in the relevant aquifer. Numerical simulations can provide answers for specific cases of CO₂ injection in deep saline aquifers (Bachu et al., 2007).

2.6 Combined trapping method

Nakanashi et al.(2009) propose a site-specific parameter *Sf* (“storage factor”), a ratio of immiscible CO₂ plume volume to total pore volume, to account for the combined effects of factors including trap heterogeneity, CO₂ buoyancy and sweeping efficiency. The researchers assume that the entire aquifer exists below a depth of 800 meters where CO₂ can be maintained at supercritical conditions, and no distinction is made between CO₂ stored by the various mechanisms. Further, it is assumed that injected CO₂ may be trapped for extended periods of time by a combination of trapping mechanisms (Nakanishi et al., 2009).

$$M_{CO_2} = Sf * A * h * \phi * Sg * \rho_{st} / Bg_{CO_2} \quad \text{Equation (6)}$$

Where A is the aquifer area, h is the effective aquifer thickness, so that (A x h x ϕ) represents the total pore volume within the aquifer volume under consideration. Sg is the supercritical CO₂ gas phase volume fraction in the injected CO₂ plume, assumed as 0.5 for assessment purposes. ρ_{st} is CO₂ density at standard conditions (= 1.976 kg/m³), and BgCO₂ is the CO₂ volume factor which depends on local pressure and aquifer temperature. Further it is assumed that the storage factor, Sf=0.5, for aquifer systems with limited areal extent due to predominance of CO₂ buoyancy effects and 0.25 for aquifer systems with larger areal extent(>24km²).

2.7 Method proposed by US Department of Energy

The US Department of Energy has proposed the following equation for CO₂ capacity estimation in saline aquifers (DOE 2007). Similar to earlier methods, details of the storage trapping mechanisms within a saline formation are not specified in this method. However, displacement of saline aquifer in the pore volume by immiscible CO₂ is the fundamental mechanism implicit in the calculations.

$$M_{CO_2} = Ah_g \phi_{tot} \rho E \quad \text{Equation (7)}$$

Where M_{CO₂} is the mass CO₂ storage capacity, A is the area, h_g is the gross aquifer thickness, ϕ_{tot} is the average porosity and E is the storage efficiency factor. Monte Carlo simulations estimated a range of E between 1 and 4 percent of the bulk volume of saline formations for a 15 to 85% confidence range (DOE 2007).

2.8 Storage estimation of a typical saline aquifer

Mount Simon type sandstone is used in this numerical model. The basic data for this model are listed in Table 1. The following numerical simulation using COMET3 software illustrates the saline aquifer storage estimation process. Mineral trapping and hydrodynamic trapping storage cannot be estimated using this numerical simulation procedure.

Table 1: Reservoir model set-up properties and data (Kuuskra et al.,2004)

<i>Reservoir properties /data</i>	
Thickness of aquifer layer	24 m
Area	2.6 km ²
Depth	1524 m
Pressure	1900 psia
Fracture water saturation	100%
Permeability	20 md
Fracture porosity	0.02
Water viscosity	0.73
Salinity	30000ppm
Total compressibility	9 E-06
Gas injection rate	25000 tons / year
Injection duration	25 years
Shut in period	75 years
Wellbore radius	0.1m
Temperature	39 deg cel.
No of wells	2

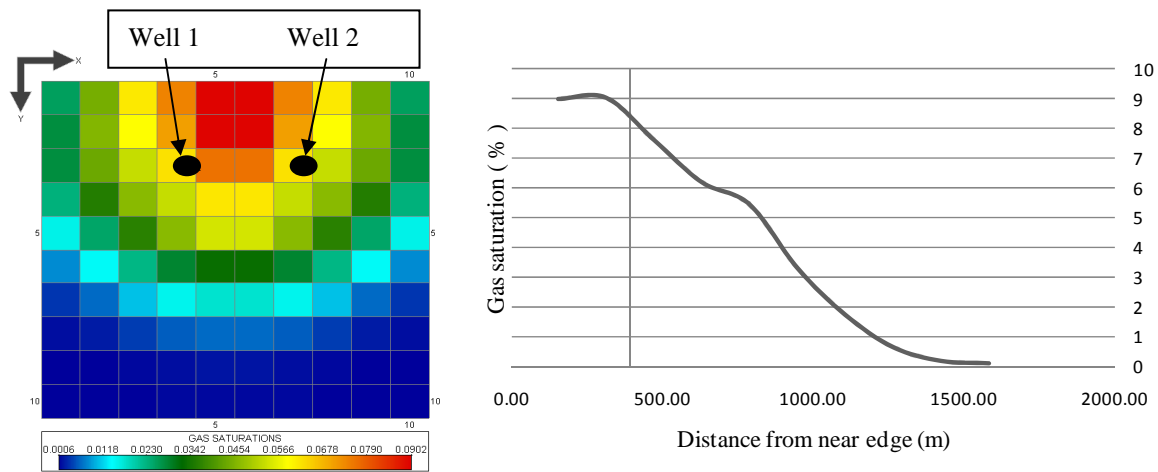


Figure 2: CO₂ gas saturation profile at 25 years and gas saturation around a well

The gas saturation levels and CO₂ contact level have been estimated under various reservoir conditions as illustrated in Figure 2 in order to estimate the storage capacity using various trapping mechanisms. Figure 3 illustrates the gas saturation level corresponding to various sand layer thicknesses from COMET3 modelling. There is a decline of gas saturation with increasing layer thickness, mainly due to the gas saturation being lowered with the reduced aquifer contact level for thicker saline aquifers.

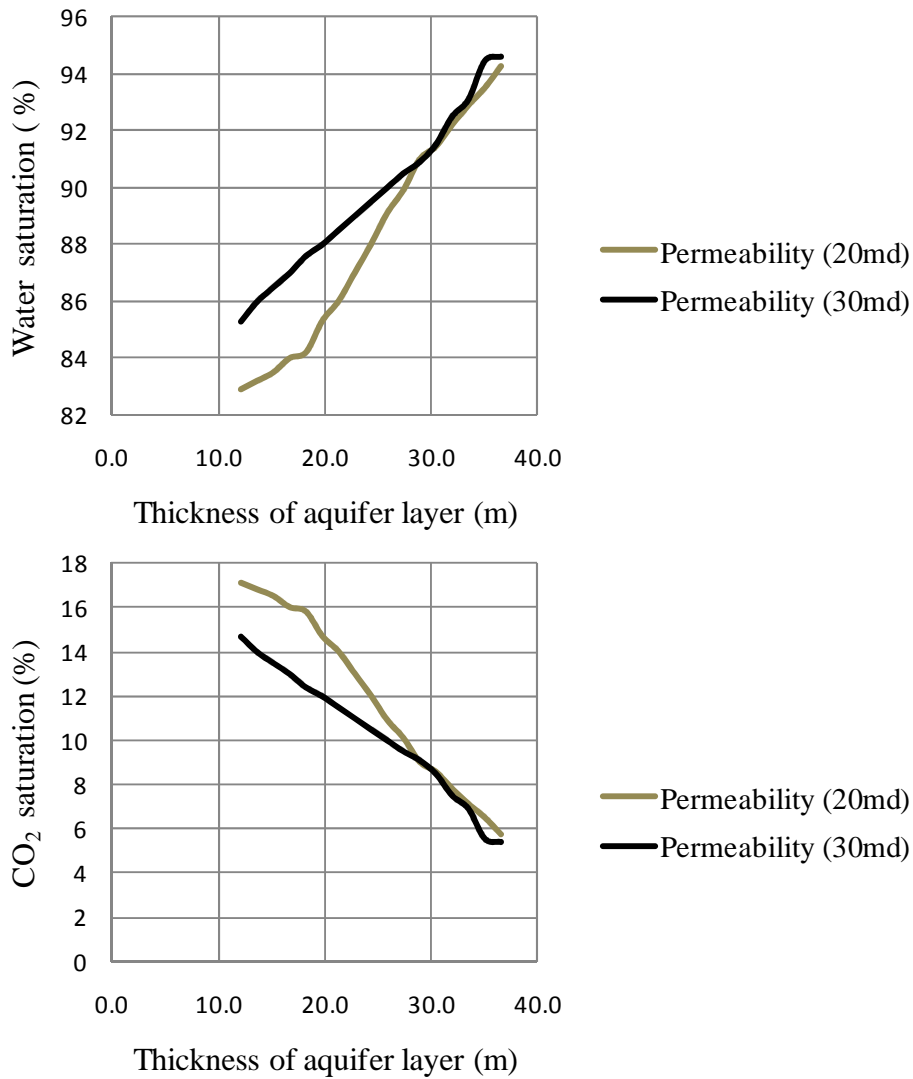


Figure 3: *CO₂ saturation variation against aquifer thickness*

Porosity is also an important parameter to be considered in terms of storage potential in a typical saline aquifer. Figure 4 illustrates the variation of CO₂ storage saturation and water saturation against porosity. Gas saturation is estimated for porosities ranging from 0.20 to 0.55. At a porosity of 0.55, gas saturation is estimated to be zero for 20md and 30md permeability levels. Porosity and CO₂ saturation show a negative relationship with the dissolution of water in saline aquifers where higher porosities have higher water saturation, and hence large dissolution of CO₂ in water levels; this is due to the interaction of parameters such as salinity level and permeability leading to higher dissolution in saline water with increasing porosity values. The storage variation is correlated to the varying gas saturation levels for structural, residual and solubility trapping mechanisms.

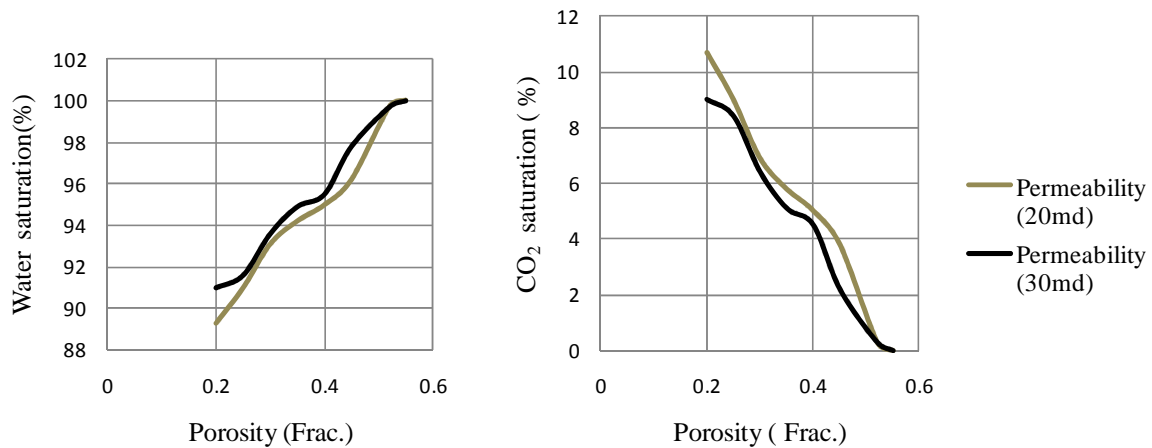


Figure 4: *CO₂ saturation, water saturation against porosity*

3.0 Discussion

Storage efficiency found in the existing research is still very conservative and generally yields values between 2 – 17% (Bradshaw et al., 2004). This may be due to inadequate consideration of the respective trapping mechanisms. Studies of the storage efficiency of an aquifer serve to identify the potential aquifers for carbon dioxide sequestration and are usually conducted in relation to site selection. However, storage efficiency is usually discussed on a site-specific scale and that there is a lack of a generic formula that can be used for a quick assessment of the storage efficiency at any random site. For the hydrodynamic trapping mechanism, there is a lack of mathematical formulae in the existing literature to estimate the storage capacity of carbon dioxide. The volume of carbon dioxide that can be stored by all the other trapping mechanisms except mineralisation can be calculated by a factor multiplied by the volume of the trap and its porosity. Since hydrodynamic trapping is a combination of the different trapping mechanisms, the storage capacity using hydrodynamic trapping might be calculated by the representative overall volume of traps and porosities, multiplied by a time-dependent factor, since hydrodynamic trapping is also time-dependent. There are studies on the effect of temperature on pressure and solubility of the aquifers individually and the subsequent effects on the storage capacity of the aquifer.

4.0 Conclusions

This paper presents a review of current methodologies adopted for the estimation of saline aquifer storage. Gas saturation level is estimated for various porosities and thickness levels of saline aquifers in order to estimate the potential CO₂ capacity. The numerical estimations found using COMET3 software has been used to estimate the CO₂ gas saturation for a specific field scenario. This methodology does not include the provision of storage by mineral trapping and hydrodynamic trapping. In order to improve the storage efficiency levels of trapping mechanisms, one needs to review the extent of storage potential especially in mineral trapping and hydrodynamic trapping.

5.0 References

- [1]. Bachu, S., Bonijoly, D., Bradshaw, J., "CO₂ storage capacity estimation: Methodology and gaps." *International Journal of Greenhouse Gas Control*, 2007; **1**(4): 430-443.
- [2]. Bachu, S., Adams, J. J., "Sequestration of CO₂ in geological media in response to climate change: capacity of deep saline aquifers to sequester CO₂ in solution." *Energy Conversion and Management*, 2003; **44**(20): 3151-3175.
- [3]. Bachu, S., Gunter, W. D., Perkins, E. H., "Aquifer disposal of CO₂: Hydrodynamic and mineral trapping." *Energy Conversion and Management*, 1994; **35**(4): 269-279.
- [4]. Bradshaw, J., Allinson, G., Bradshaw, B. E., "Australia's CO₂ geological storage potential and matching of emission sources to potential sinks, 2004;" *Energy* **29** (9-10): 1623-1631.
- [5]. Bruant, R. G., Jr, Celia, Jr. M. A., Guswa, A. J., Peters, C. A., "Peer Reviewed: Safe Storage of CO₂ in Deep Saline Aquifers." *Environmental Science & Technology*, 2002; **36**(11): 240A-245A.
- [6]. DOE (2007). "Carbon sequestration atlas of the united stated and canada." 1-90.

- [7]. Ghanbari, S., Al-Zaabi, Y., Pickup, G. E., "Simulation of CO₂ Storage In Saline Aquifers." *Chemical Engineering Research and Design*,2006;**84**(9): 764-775.
- [8]. Nakanishi, S., Mizuno, Y., Okumura, T., "Methodology of CO₂ aquifer storage capacity assessment in Japan and overview of the project." *Energy Procedia*,2009;**1**(1): 2639-2646.
- [9]. Shafeen, A., Croiset, E., Douglas, P. L., Chatzis, I. "CO₂ sequestration in Ontario, Canada. Part I: storage evaluation of potential reservoirs." *Energy Conversion and Management*,2004; **45**(17): 2645-2659.
- [10]. Soares, J. L., Oberziner, A. L. B., Jose, H. J., Rodrigues, A. E., Moreira, R. F. P. M., "Carbon Dioxide Adsorption in Brazilian Coals." *Energy & fuels*,2006;**21**(1): 209-215.
- [11]. Xu, T., Apps, J. A. , Pruess, K., "Numerical simulation of CO₂ disposal by mineral trapping in deep aquifers." *Applied Geochemistry*,2004;**19**(6): 917-936.
- Zhang, W., Li, Y., Xu, T., "Long-term variations of CO₂ trapped in different mechanisms in deep saline formations: A case study of the Songliao Basin, China." *International Journal of Greenhouse Gas Control*,2009;**3**(2): 161-180.

