

Specific Sequestration Volumes: A Useful Tool for CO₂ Storage Capacity Assessment

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INTRODUCTION

The problems and processes of sequestering CO₂ in geologic formations must be analyzed from several viewpoints. There are several well constrained aspects to the process of CO₂ sequestration, such as the number of point sources, the mass of CO₂ emitted by the point sources, and the pipelines that will have to be built to move the CO₂ from the point source to the sequestration site (Fig. 1). However, the typical approach to CO₂ sequestration assessments involves estimating the sequestration capacity of a geologic formation, i.e. the volume or mass of CO₂ that can be stored in a geologic formation, such as saline reservoirs, coal beds, or petroleum reservoirs (Hendriks and Blok, 1993; van der Meer, 1995, 1996; Bachu et al., 1994; Law and Bachu, 1996; Ennis-King and Paterson, 2001). One recent study took a different view of CO₂ sequestration assessments; Bachu (2001) proposed considering the subsurface space of geologic formations in terms of CO₂ phase relations, categorizing regions within the stratigraphic units of Alberta where CO₂ would be gas, liquid, or a supercritical fluid, based on measured temperatures and pressures.

The approach outlined in this paper differs from previous work in that here we calculate the sequestration volumes, i.e. the amount of geologic formation needed to sequester a given mass of CO₂, by converting the mass of CO₂ emitted by point sources into volumes of geologic formations needed to sequester CO₂ based on realistic geologic conditions. The term of specific sequestration volume (SSV) is defined herein as the factors necessary to convert the mass of CO₂ emissions to geologic storage volume. If CO₂ emissions are recalculated as units of specific volume, i.e. volume per unit mass, then the volumes of geologic reservoirs necessary to store CO₂ emissions from large point sources can be estimated. The SSV's, as defined in this study, can be reported in units of cubic meters, cubic feet, and petroleum barrels to establish a framework that fits reference volumes common to ground-water hydrogeology and the oil and gas industry. In this paper, we convert the mass of CO₂ emitted annually by a single 1100 megawatt power plant into volumes of geological formations needed for sequestration over annual and decadal intervals.

METHODS

A few assumptions are necessary to determine SSV's. For this study, all calculations were performed assuming temperature and pressure conditions of 60°C and 150 bars, which are reasonable values for reservoir depths ranging from 1.5 to 2 kilometers. Two geologic settings were considered as follows: (1) a coal bed; and (2) a sandstone with 10 percent porosity and residual water saturation ranging from 0 to 100 percent. Furthermore, values for the CO₂ sequestration density and SSV for one hundred percent pore space at 60°C and 150 bars were calculated; either of these values can serve as an end member to compare with the hypothetical geologic sequestration settings presented in this paper.

A. Calculation of SSV for Coal Bed

The coal sorption values used in this study are from Krooss et al. (2002), who report CO₂ sorption isotherms at 40, 60, and 80°C, from 1 to 200 bars, on three coal samples of varying rank (High-volatile B bituminous; Medium volatile bituminous, and Low volatile bituminous). The data in Krooss et al. (2002) are the only reported CO₂ isotherms for coal that reach pressures greater than 120 bars. For this study, the coal samples with the highest (31 cm³/g) and lowest (14 cm³/g) sorption values at 60°C and 150 bars were considered to represent a maximum and minimum sequestration capacity for coal. The sorption values from Krooss et al. (2002) are given in cubic centimeters of CO₂ per gram of coal at 15°C and 1 atm (1.01325 bars). The volume of CO₂ was converted to a unit mass using the density of CO₂ (1.86 kg/m³) at 15°C and 1.01325 bars (Krooss et al., 2002). The mass of coal was converted to a volume using an

approximate density for bituminous coal (1300 kg/m^3 , van Krevelen, 1993), as Krooss et al. (2002) do not report density of the coal samples investigated. The highest and lowest CO_2 storage capacities for the coal samples, based on the high and low sorption values, are shown in Table 1.

B. Calculation of SSV for Aqueous Fluids and Reservoirs

The GEOFLUIDS solubility model (<http://geotherm.ucsd.edu/geofluids/>), which is the online version of the model reported in Duan et al. (1995), was used to calculate the solubility of CO_2 both in pure H_2O and in a 4m NaCl solution. A 4 molal (m) NaCl solution ($\sim 190,000$ TDS) was chosen for this study to represent a natural brine. Solubilities for more complex brines can be calculated from the measurements of Rosenbauer and Koksalan (this volume).

The GEOFLUIDS model determines the mole fraction of CO_2 , H_2O , and NaCl in the solution as well as the density of the resultant solution. Based on the model, the solubility of CO_2 in pure water is 0.018 mole fraction CO_2 with a solution density of 0.938 g/cm^3 and the solubility of CO_2 in the 4m NaCl solution (0.066 mole fraction NaCl) is 0.01 mole fraction CO_2 with a solution density of 1.077 g/cm^3 . These mole fractions were multiplied by their molar masses, and summed for the total mass of the solution. The mass of CO_2 per mass of the solution was converted to mass of CO_2 per volume of solution using the density values. The CO_2 storage capacities of the model solutions are shown in Table 1.

The storage capacities for the solutions (Table 1) were used to calculate the storage capacities of a sandstone with ten percent porosity and residual water saturations ranging from zero to one hundred percent. Residual water saturation is defined as the volume fraction of water occupying the pore space; the remaining pore volume is filled with free phase CO_2 . Free phase CO_2 at 60°C and 150 bars has a density of 604 kg/m^3 (Span and Wagner, 1996; Lemmon et al., 2003); this value was used to determine how much CO_2 is stored in the pore space not occupied by residual water saturation. The CO_2 sequestration capacities for five, fifty, seventy-five, and one hundred percent residual water saturations are shown in Table 1. As the residual water saturation increases, the sequestration capacity decreases, due to the significantly higher density of free-phase CO_2 relative to dissolved CO_2 at these temperature and pressure conditions (Fig. 2). Injecting CO_2 into a reservoir will displace some residual water, leading to a relatively high sequestration capacity. When the reservoir returns to one hundred percent residual water saturation, i.e. the CO_2 dissolves completely, relatively less CO_2 can be stored in the same volume. Therefore, as the CO_2 completely dissolves, an identical mass of CO_2 will occupy a larger volume of the reservoir.

RESULTS

A. Saline Formations and Coal Beds

The SSV's in Table 1 can be used to convert the reported masses of CO_2 emitted by point sources into subsurface storage volumes. As an example, we have chosen to convert the mass of CO_2 emissions from the 1100 megawatt capacity Laramie River 2&3 coal-fired power plant in Wyoming. According to the U.S. EPA EGRID98 database (<http://www.epa.gov/airmarkets/egrid/index.html>), this power plant operated at eighty-five percent of capacity in 1998 and emitted approximately 8.7 million metric tons (tonnes) of CO_2 . This mass was then multiplied by the respective SSV to calculate the subsurface volume, in cubic meters, necessary to sequester the CO_2 in each scenario listed (Table 1). Therefore, a sandstone with ten percent porosity and a 4m NaCl solution occupying seventy-five percent of the pore space has an SSV of 60 cubic meters per tonne of CO_2 (Table 1). Based on the 8.7 million tonnes of CO_2 emitted by the power plant, 5.19×10^8 cubic meters of the sandstone aquifer will be needed to sequester the annual CO_2 emissions (Table 1).

The sequestration volumes shown in Table 1 represent the amount of subsurface space needed to sequester the annual CO_2 emissions from the Laramie River 2&3 power plant in the hypothetical geological settings described in this paper. However, for sequestration to be a viable mitigation option, the CO_2 emissions will have to be injected into geologic formations for the life of the power plant and sequestered for very long periods ($>10,000$ years). To gauge the subsurface volume necessary to sequester CO_2 emitted through time, sequestration volumes for the Laramie River 2&3 plant have been calculated for CO_2 emissions over 10-year, 50-year, 100-year, and 200-year intervals (Fig. 3) assuming a constant rate of CO_2 emission at 1998 levels (<http://www.epa.gov/airmarkets/egrid/index.html>).

Volumes in cubic meters are also shown in hectare-meters and acre-feet (Table 1 and Figs. 4&5). The units of hectare-meters represent the area, in hectares, needed to sequester a given mass of CO₂ if the target formation was one meter thick (10,000 m³ = 1 hectare-meter). The units of acre-feet represent the area, in acres, needed to sequester a given mass of CO₂ if the target formation was one foot thick (1233 m³ = 1 acre-foot). These units allow for the visualization of the areas that would be affected by CO₂ sequestration as they can be plotted on a map for relative size comparisons. For example, if the target formation was a one meter thick sandstone with fifty percent residual saturation of a 4m NaCl solution, then sequestering ten years of CO₂ emissions from the power plant would occupy an area of 278,000 hectares (Figure 4c), an area is slightly larger than the state of Rhode Island. However, the sequestration targets would likely have thicknesses greater than one meter, making the area affected much smaller.

Over time, the injected CO₂ will dissolve in the fluids present in a saline reservoir. If all the CO₂ dissolves, i.e. the mass of CO₂ injected does not exceed solubility, and assuming no mineral sequestration, then the volume calculated for one hundred percent residual water saturation will be the final sequestration volume. If the sequestration target was a one hundred meter thick sandstone aquifer with 100% residual saturation of a 4m NaCl brine, then the final sequestration areas would cover approximately 40,000 hectares for ten years of CO₂ emissions and 800,000 hectares for two hundred years of CO₂ emissions (Figure 4c). For comparison, the state of Connecticut covers ~1,250,000 hectares.

If the sequestration target was a ten meter thick highly adsorptive coal, then the area occupied by the CO₂ emitted by the Laramie River 2&3 power plant over ten years would cover slightly more than 11,000 hectares (Figure 4a). If CO₂ was sequestered over two hundred years in this same scenario, the area occupied by CO₂ would cover 232,000 hectares, which is slightly smaller than the state of Rhode Island. Coal bed sequestration targets will likely be less than ten meters thick, thereby increasing the area needed for sequestration.

B. Comparison of Power Plant CO₂ Emissions to Petroleum Field Sizes

One measure of reservoir volume is barrels of oil equivalent (BOE). There are 6.29 barrels per cubic meter; therefore, to create an SSV to convert mass of CO₂ emissions to barrels, the cubic meter SSV for one hundred percent space (Table 1) is multiplied by 6.29. The mass of CO₂ emissions from the Laramie River 2&3 power plant were converted to million barrels of oil equivalent (MMBOE) for 1, 10, 50, 100, and 200 years intervals and compared to correlative petroleum field class sizes (NRG Associates, 2001) (Table 2). The emissions from this power plant reported as MMBOE at 60°C and 150 bars (Table 2) are equivalent to a petroleum field size class of 13 (512 to 1024 MMBOE) at the 10-year interval (910 MMBOE) and a petroleum field size class of 16 (4096 to 8192 MMBOE) by the 50-year interval (4550 MMBOE). At the two hundred year interval, the barrels of CO₂ sequestered from the Laramie River 2&3 plant equivalent would equal a class 18 field-size (Table 2), which encompasses volumes ranging from 16,384 to 32,768 million barrels of oil equivalent (NRG Associates, 2001).

DISCUSSION

According to the EGRID98 database, there are 169 power plants in the United States that have capacities of 1100 megawatts or greater but only 64 power plants that emitted more than 8.7 million metric tons of CO₂. Sequestration volumes computed for each of these plants large power plants will be within an order of magnitude of the Laramie River 2&3, illustrating that significant rock volumes will be needed to sequester CO₂ emissions over long time periods.

Emission intervals of greater than 50 years likely extend not only beyond the life of the Laramie River 2&3 power plant, but beyond the life of any current power plant. However, as long as the electrical infrastructure in the United States is primarily powered by fossil fuels, there will be large masses, and consequently volumes, of CO₂ to sequester. Furthermore, even if there is a move to a hydrogen-based economy, the energy source to produce the hydrogen will likely come from natural gas or coal for the foreseeable future, which also creates a large mass of CO₂ that will need to be sequestered. Therefore, for this study we have calculated up to two hundred years of emissions from this one power plant not because we think this particular plant will be in service 200 years from now, but because the need to inject CO₂ into geologic reservoirs will likely persist for the next few centuries.

One interesting result from the present study is that coal beds will sequester a much larger mass of CO₂ per cubic meter than the hypothetical saline reservoir discussed above (Table 1a and 1c and Fig.

3a and 3c). If the porosity of the sandstone was greater than 10%, then, obviously, the mass of CO₂ that could be sequestered would increase per the same volume of sandstone. However, the SSV of saline fluids is greater than that of coal by a factor of ~1.5 to 3 (Table 1a). Therefore, at the temperature and pressure assumed for this study, coal has the ability to sequester a greater mass of CO₂ per unit volume than 4m NaCl brine. These results indicate that unmineable coal beds make an attractive sequestration target simply from the viewpoint of CO₂ storage capacity, even before factoring in the value of coal bed methane that would be produced by the injection of CO₂.

Petroleum reservoirs make attractive sequestration targets for several reasons. The volumes have been well characterized by calculating the known reserves of petroleum fields. Furthermore, there is a proven seal that has kept the petroleum in place over geologic time and the geologic characteristics of the reservoir rock are typically well understood. Finally, the infrastructure is in place, in the form of operating injection and extraction wells, to begin injecting CO₂ into the traps. There are only 128 petroleum fields in the United States that are a 13 field size or larger (NRG Associates, 2001), which is the relative petroleum field size of the CO₂ emitted by the Laramie River 2&3 power plant (Table 2). There are 64 power plants that emitted more than 8.7 million metric tons of CO₂, which is greater than the capacity of the Laramie River 2&3 power plant. The equivalent field-class size for the CO₂ emitted by the power plant over a 200 year interval is 18, which is the maximum petroleum field size designation on the NRG associates (2001) scale. Only four fields in the United States are defined as a size class 18, the maximum petroleum field size designation on the NRG Associates (2001) scale. Sequestering the entire mass of CO₂ emissions from even an individual point source in individual petroleum traps will be a difficult for long periods of time. However, in the near term, i.e. over the next few decades, petroleum traps are attractive sequestration targets due to their proven volumes and seals as well as having the infrastructure in place to inject CO₂ into the trap (Burruss et al., this volume).

CONCLUSIONS

This study analyzed the concept of CO₂ sequestration volumes from the perspective of CO₂ produced by point sources rather than assessing the total subsurface volume available for geologic sequestration. The SSV values reported herein can be modified to fit any sequestration target, so that sequestration volumes can be estimated for any given point source and geologic sequestration scenario. The volumes to be occupied by sequestering all of the CO₂ emitted by power plants will be substantial. However, determining the volume necessary to sequester the CO₂ emissions from point sources is an important frame of reference for CO₂ sequestration assessments.

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TABLE AND FIGURE CAPTIONS

Table 1. CO₂ sequestration densities, SSV's and sequestration volumes. A. Values for 100% space, coal, and aqueous solutions. B. Sandstone with 10% porosity and various residual pure water saturation percentages. C. Sandstone with 10% porosity and various residual 4m NaCl solution saturation percentages.

Table 2. Tonnes of CO₂ emitted by the Laramie River 2&3 power plant over 1, 10, 50, 100, and 200 year intervals, the relative volume of CO₂ in millions of barrels of oil equivalent (MMBOE) of CO₂ at 60°C and 150 bars, and the corresponding field-size classes.

Figure 1. Breakdown of geologic sequestration of CO₂ from production to storage, illustrating the well constrained steps of the process.

Figure 2. This plot illustrates the CO₂ sequestration capacity of a sandstone with 10% porosity as a function of percent residual water saturation. The residual waters considered here are pure H₂O and a 4m NaCl solution. The capacity values are in kilograms of CO₂ per cubic meter of sandstone.

Figure 3. These plots represent the cubic meters of reservoir volume that would be needed to inject the CO₂ emissions from the Laramie River 2&3 power plant over 200 years. A. Volumes in cubic meters needed for 100% space and coal seams. B. Cubic meters of sandstone with 10% porosity and varying amounts of residual pure water saturation. C. Cubic meters of sandstone with 10% porosity and varying amounts of residual 4m NaCl solution saturation.

Figure 4. These plots represent the hectare-meters of reservoir volume that would be needed to inject the CO₂ emissions from the Laramie River 2&3 power plant over 200 years. A. Volumes in hectare-meters needed for 100% space and coal seams. B. Hectare-meters of sandstone with 10% porosity and varying amounts of residual pure water saturation. C. Hectare-meters of sandstone with 10% porosity and varying amounts of residual 4m NaCl solution saturation.

Figure 5. These plots represent the acre-feet of reservoir volume that would be needed to inject the CO₂ emissions from the Laramie River 2&3 power plant over 200 years. A. Volumes in acre-feet needed for 100% space and coal seams. B. Acre-feet of sandstone with 10% porosity and varying amounts of residual pure water saturation. C. Acre-feet of sandstone with 10% porosity and varying amounts of residual 4m NaCl solution saturation.

Table 1.
A.

Setting	Sequestration capacity (kg CO ₂ /m ³)	SSV (m ³ /tonne CO ₂)	Power plant sequestration volumes ^a		
			m ³	Hectare-m	Acre-ft
100% space	604	1.7	1.44x10 ⁷	1.44x10 ³	1.17x10 ⁴
Coal, high sorption ^b	75	13	1.16x10 ⁸	1.16x10 ⁴	9.41x10 ⁴
Coal, low sorption ^b	34	29	2.56x10 ⁸	2.56x10 ⁴	2.08x10 ⁵
pure H ₂ O	41	24	2.10x10 ⁸	2.10x10 ⁴	1.72x10 ⁵
4m NaCl	22	45	3.95x10 ⁸	3.95x10 ⁴	3.21x10 ⁵

B.

Residual pure water saturation	Sequestration capacity (kg CO ₂ /m ³)	SSV (m ³ /tonne CO ₂)	Power plant sequestration volumes ^a		
			m ³	Hectare-m	Acre-ft
5%	58	17	1.50x10 ⁸	1.50x10 ⁴	1.23x10 ⁵
50%	32	31	2.70x10 ⁸	2.70x10 ⁴	2.19x10 ⁵
75%	18	55	4.80x10 ⁸	4.08x10 ⁴	3.88x10 ⁵
100%	4.1	244	2.10x10 ⁹	2.10x10 ⁵	1.72x10 ⁶

C.

Residual 4m NaCl saturation	Sequestration capacity (kg CO ₂ /m ³)	SSV (m ³ /tonne CO ₂)	Power plant sequestration volumes ^a		
			m ³	Hectare-m	Acre-ft
5%	57	17	1.50x10 ⁸	1.50x10 ⁴	1.23x10 ⁵
50%	31	32	2.80x10 ⁸	2.80x10 ⁴	2.25x10 ⁵
75%	17	60	5.20x10 ⁸	5.20x10 ⁴	4.21x10 ⁵
100%	2.2	455	3.95x10 ⁹	3.95x10 ⁵	3.21x10 ⁶

^a Based on 8.7 million tonnes of CO₂ emitted by Laramie River 2&3 plant in 1998.

^b Coal values are derived from Krooss et al. (2002). The high and low sorption coals refer to the maximum and minimum sorption values reported by Krooss et al. (2002) at 60°C and 150 bars.

Table 2.

Years	Tonnes CO ₂	MMBOE	Field-Size Class ^a
1	8.70x10 ⁶	91	10
10	8.70x10 ⁷	910	13
50	4.35x10 ⁸	4550	16
100	8.70x10 ⁸	9100	17
200	1.74x10 ¹⁰	18200	18

^a Based on classification scale reported in NRG Associates (2001).

Economic incentives
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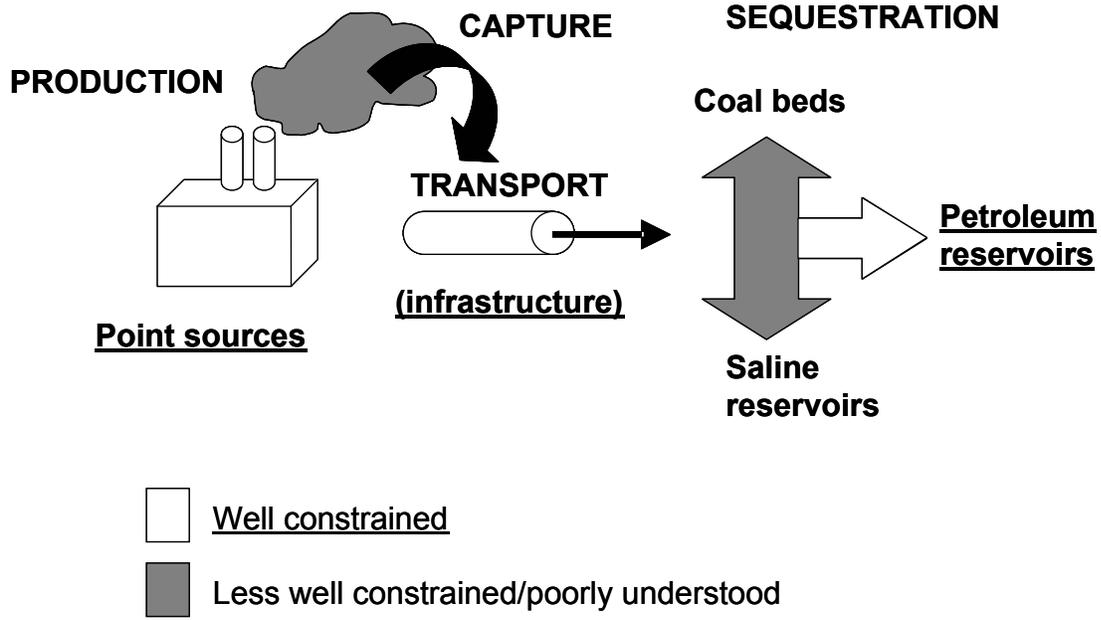


Figure 1

Mass of CO₂ per cubic meter of sandstone with 10% porosity

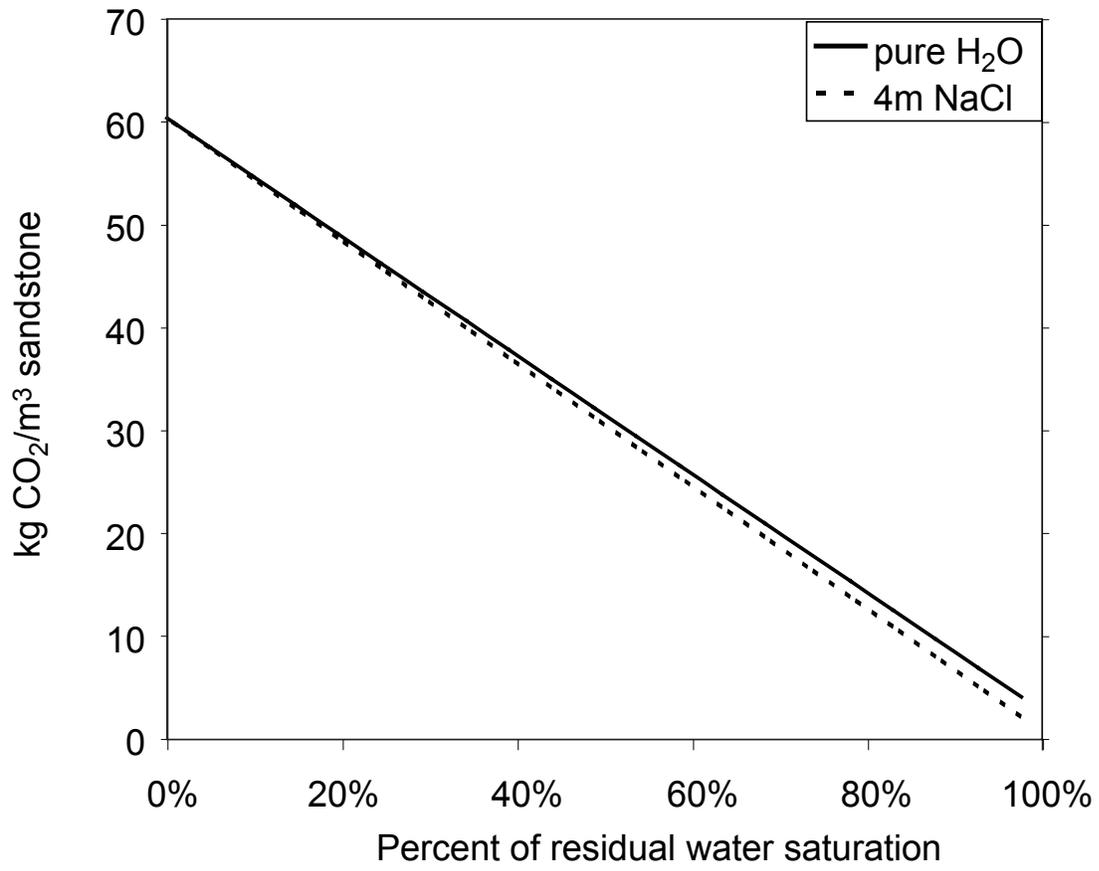
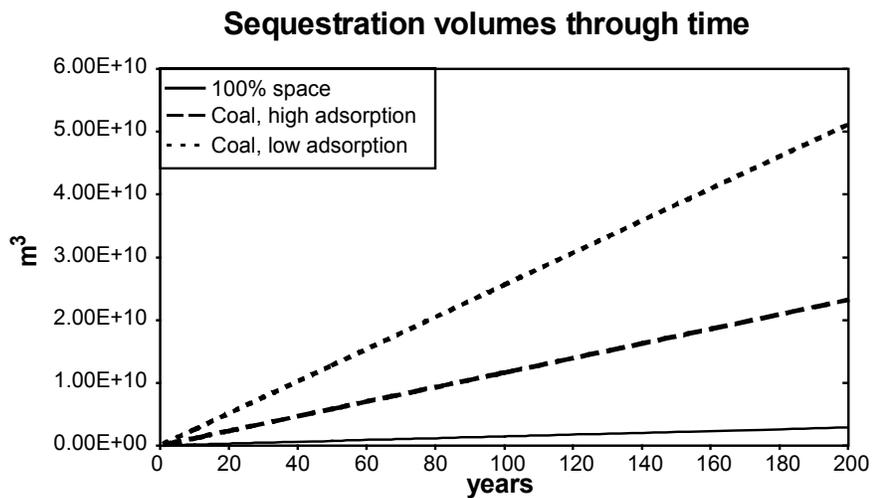
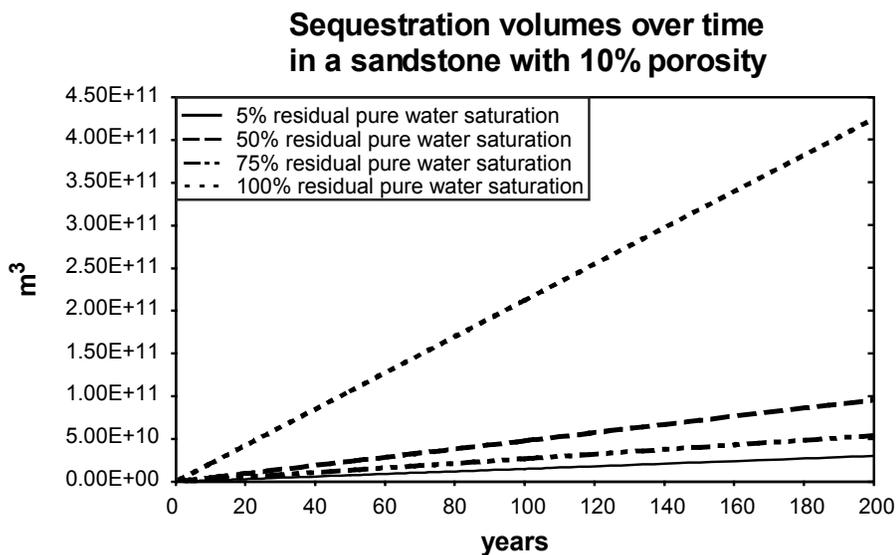


Figure 2

A.



B.



C.

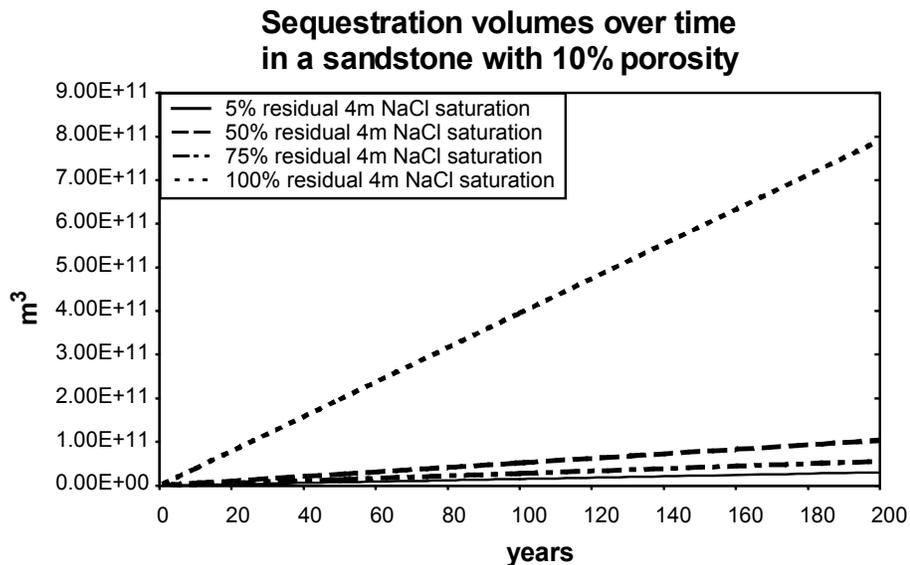
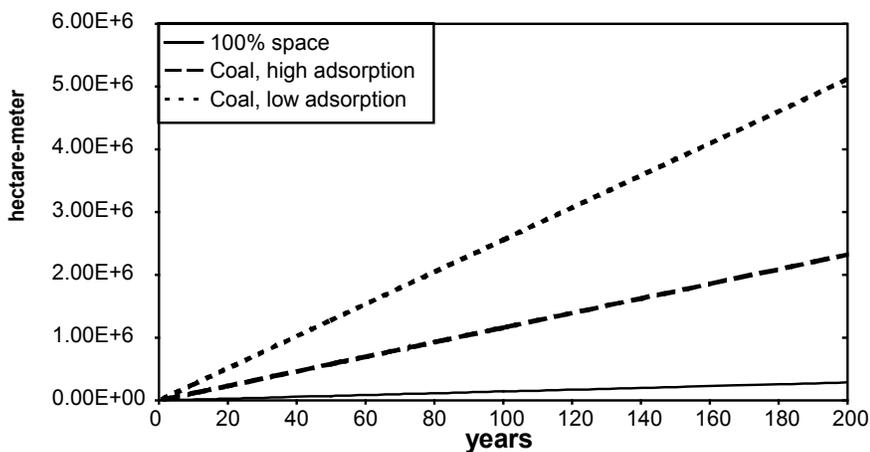


Figure 3

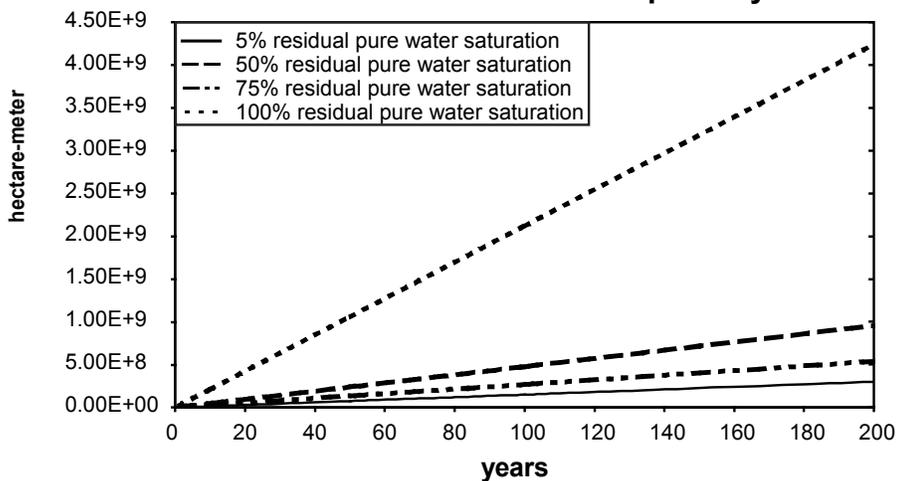
A.

Sequestration volumes through time



B.

Sequestration volumes over time in a sandstone with 10% porosity



C.

Sequestration volumes over time in a sandstone with 10% porosity

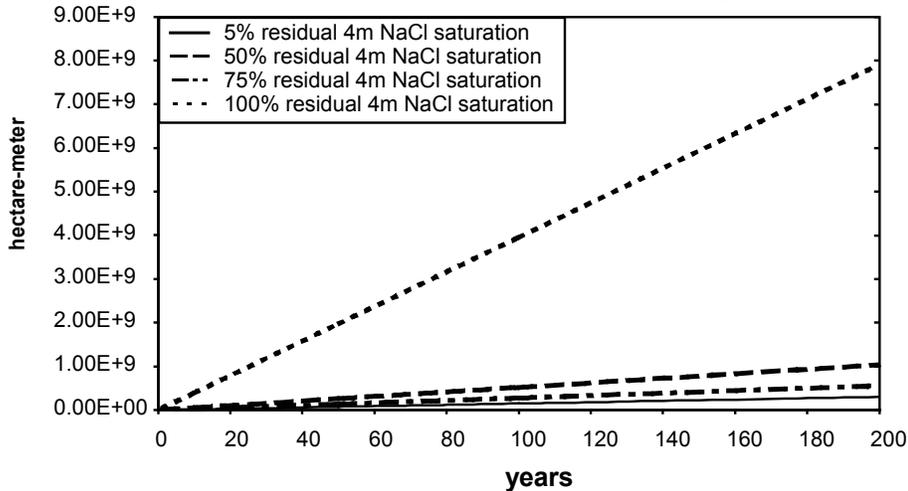
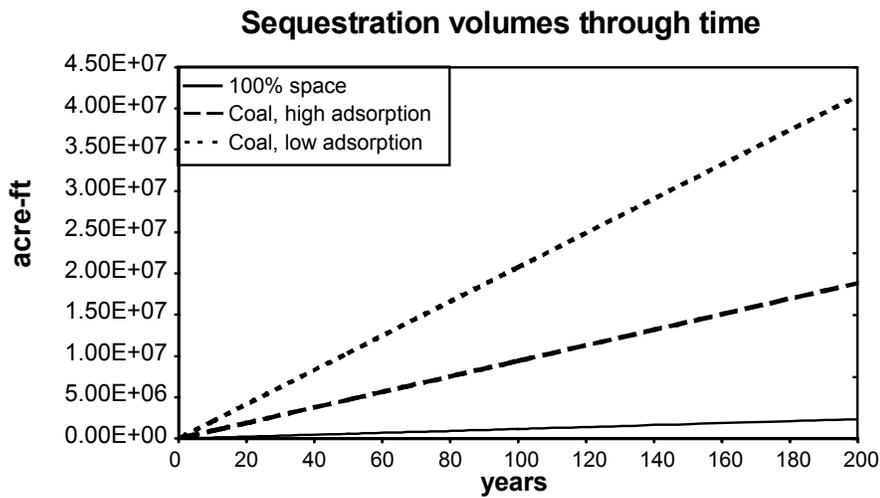
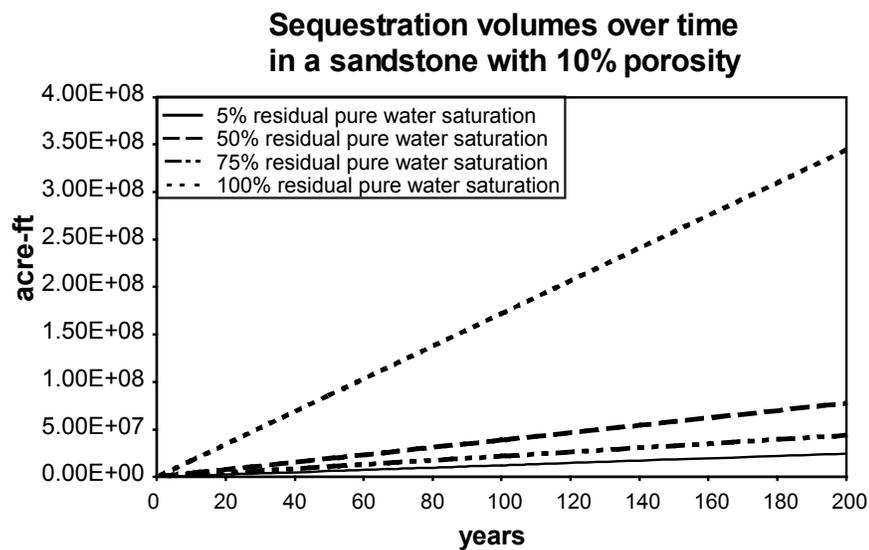


Figure 4

A.



B.



C.

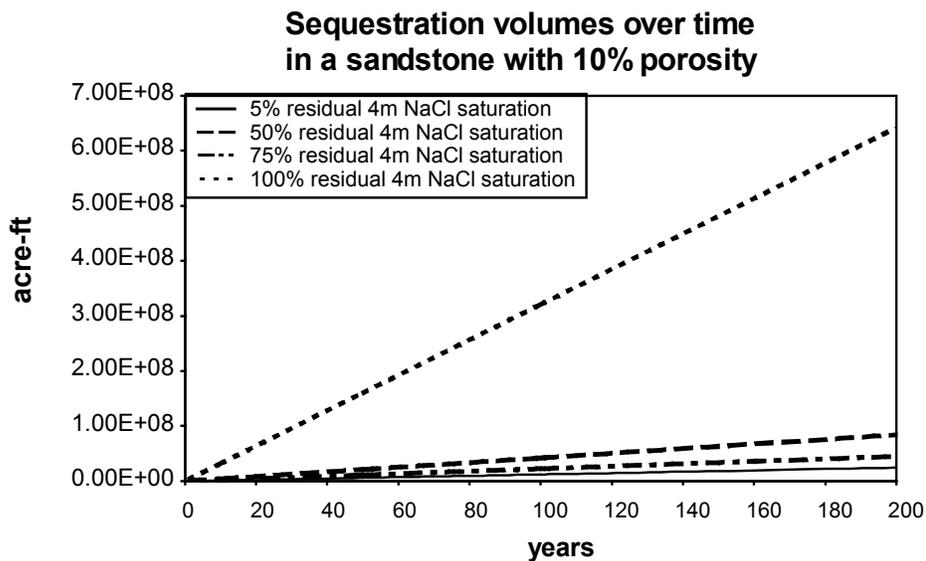


Figure 5