CONFERENCE PROCEEDINGS

The Impact of Boundary Conditions on CO_2 Capacity Estimation in Aquifers

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Introduction

The boundary conditions of an aquifer determine the extent to which fluids (including formation water and CO_2) and pressure can be transferred into adjacent geological formations, either laterally or vertically. Aquifer boundaries can be faults, lithological boundaries, formation pinch-outs, salt walls, or outcrop. In many cases compliance with regulations preventing CO_2 storage influencing areas outside artificial boundaries defined by non-geological criteria (international boundaries; license limits) may be necessary. A bounded aquifer is not necessarily a closed aquifer.

The identification of an aquifer's boundary conditions determines how CO_2 storage capacity is estimated in the earliest screening and characterization stages. There are different static capacity estimation methods in use for closed systems and open systems. The method used has a significant impact on the final capacity estimate.

The recent EU Directive (2009/31/EC) stated that where more than one storage site within a single "hydraulic unit" (bounded aquifer volume) is being considered, the characterization process should account for potential pressure interactions. The pressure interplay of multiple sites (or even the pressure footprint of just one site) is heavily influenced by boundary conditions.

Static Capacity Estimation

Static capacity estimation methods take the basic form:

$$M_{CO2} = A\ h\ \Phi\ E\ \rho_{CO2} \qquad \text{equation 1}$$

Where M_{CO2} is the capacity as mass of CO_2; A and h are the aquifer area and thickness respectively; Φ is the porosity: E is an efficiency factor; and ρ_{CO2} is the density of CO_2 under aquifer conditions.

A closed system is taken to be an aquifer bounded laterally and vertically by barriers to flow and pressure communication. Capacity is obtained by increasing the pressure of the reservoir, resulting in compression of the formation water and expansion of the rock's pore volume. The efficiency factor takes the form:

$$E = \Delta p\ (\beta_p + \beta_w) \qquad \text{equation 2}$$

Where β_w and β_p are the compressibility of the formation water and rock compressibility respectively; and Δp is the maximum allowable pressure increase.

One of the simplifications inherent in the method is that pressure increase is distributed evenly throughout the aquifer. Maximum allowable pressure increase is typically an estimate based on a percentage of the average lithostatic pressure. The term β_p is typically a simplification of a complex dataset; poro-elastic expansion is a dynamic process and its magnitude depends on pressure, rate of pressurization, and the rock's pressure and diagenetic history (Freeze and Cherry, 1979).

Typically an open system is closed vertically (i.e. the caprock is very low permeability) but open laterally. For an open system, CO_2 injection may be into an aquifer so large that it is considered infinite, or an aquifer with an outcropping boundary. Static estimates assume that capacity is generated by displacing water out of the aquifer (or elsewhere in an "infinite" aquifer) and any increase in the pressure of the system is disregarded.

In open systems the efficiency factor E is a complex function that aims to account for the number of suitable trapping structures, reservoir net-to-gross, effective porosity, buoyancy effects, capillary trapping, and displacement efficiency. The DOE (2008) performed Monte Carlo simulations for ranges of those parameters to produce estimates for E, arriving at a range of 1–4%.

Case Study: The Bunter Sandstone Formation

The Lower Triassic Bunter Sandstone Formation extends across the UK sector of the southern North Sea (Fig.1), exposed onshore in Eastern England as the Sherwood Sandstone Group. The Bunter is composed of permeable (100–700 mD) and porous (20–25%) sandstones, mostly fine but locally medium to coarse (Cameron et al., 1992). The depth to the top surface of the Bunter is variable due to halokinesis in the underlying Permian evaporites generating dome structures in the overlying sediments.

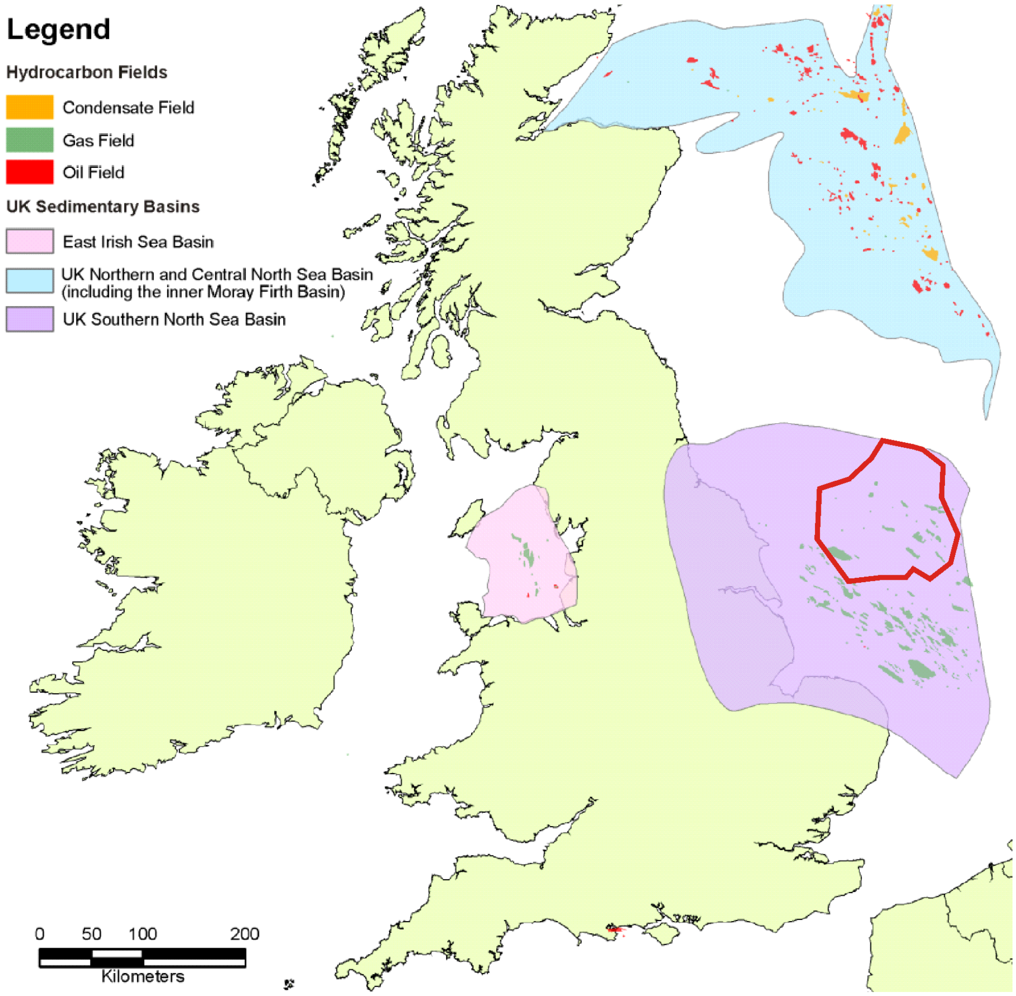


Fig.1: Map of the British Isles showing major sedimentary basins. The Bunter Sandstone formation is located within the Southern North Sea Basin. The area outlined in red is the specific section of the aquifer used in this study.

The Bunter Sandstone hosts a number of natural gas fields (e.g. Esmond, Forbes, Gordon) which indicate potential for CO_2 storage. The Bunter is sealed beneath by the Bunter Shale and Zechstein salts, and above by the Haisborough Group, which includes mudstones, dolomites, and evaporites.

This study focused on a limited area of the Bunter Formation offshore in the southern North Sea. Within this area are a number of structures formed by movement of the underlying Zechstein Salt. The formation boundary is defined by presumed permeability barriers: salt walls that cut the formation to the east and south, by the Dowsing Fault Zone/ Central Fracture Zone to the west, and by the depositional limit of the sandstone to the north and east. Within the study area the Bunter Sandstone ranges from 400–3000 m depth, with an average porosity of 20% and a permeability of 100 mD. The pore space is calculated to be 350 km^3. The average salinity is 130,000 ppm NaCl equivalent; temperature gradient is 35°C/km; hydrostatic pressure gradient is assumed to be 10.67 kPa/m; and the lithostatic gradient 22.5 kPa/m. At these conditions, the average density of CO_2 within the reservoir would be 700 kg/m^3.

The static capacity of this bounded aquifer can be assessed in three ways: by treating it as a closed system, an open system, or by treating each structural closure (trap) as an independent open system. For the closed system scenario, the maximum allowable pressure increase is set to 9.25 MPa (75% of the average lithostatic pressure), with CO_2 density set to 800 kg/m^3 to account for the higher pressure; and β_p to 4.5×10^{-10} Pa^{-1}. For the regional open system estimation, E was set at 2% and CO_2 density at 700 kg/m^3. For the assessment on a structure-by-structure basis, ten structural closures were identified, with E set to 40% in each, based on a dynamic simulation of injection into one Bunter structure (Brook et al., 2003).

Table 1: Results of static capacity estimations for a subset of the Bunter Sandstone formation.

Scenario	Closed Aquifer	Open Aquifer	Open Traps
Capacity (Mt CO_2)	2200	4900	4865

The similar results given by the two open system methods indicates that 2% is a valid regional assessment if the aquifer is open. In aquifers with fewer obvious structures, there will be a discrepancy between the regional and "traps" type of assessment, e.g. the relatively flat upper surface of the Utsira aquifer (northern North Sea) means that only 0.3% of the pore volume is available for simple buoyancy trapping beneath the topseal (Chadwick et al., 2002). The 2% efficiency factor is valid for the Bunter, but may need to be adjusted depending on the aquifer under investigation to avoid overly optimistic or pessimistic capacity estimates.

The contrast between the closed system capacity and the "traps" capacity shows the need for a regional assessment – if the identified boundaries of the aquifer are pressure and flow barriers, then there is a significant impact on the number of traps that can be fully exploited. In this case the Bunter cannot be considered to be an "infinite aquifer". Accounting for the boundary conditions of the aquifer (albeit with the conservative assumption that they are perfect seals) has reduced the capacity estimate by 50%.

Dynamic Models

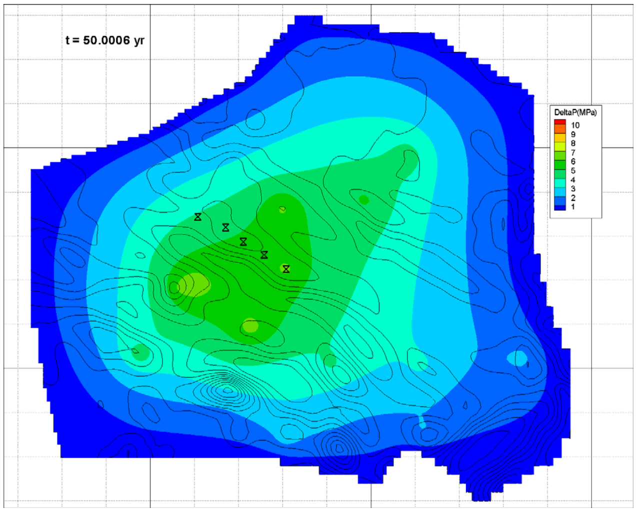
The case study aquifer was used in TOUGH2 simulations to determine whether the static estimates accurately represent the impact of boundary conditions on capacity, and to determine any potential issues relating to a heterogeneous pressure distribution (the static methods assume a uniform distribution).

In the model setup, 12 wells (including the 10 structures used for the static estimate) were used to inject a total of 33 Mt CO_2 per year, for 50 years (1650 Mt CO_2). The overburden was set at 500 m thick, with a permeability of 10^{-25} m^2. In the open system, there is a pressure increase associated with injection, but it does not exceed the prescribed limit (9.25 MPa; 75% of average lithostatic; Fig. 2a). The pressure footprints of individual wells overlap to generate higher pressures where they are closely spaced (a factor not accounted for in the static methodology). Rather than considering the pressure increase as an absolute value, the relative pressure (i.e. the pore fluid pressure expressed as a percentage of the lithostatic pressure, for a given point) indicates that shallower (400 m) structures exceed the prescribed 75% lithostatic limit, despite being remote from the injection wells (Fig. 2b).

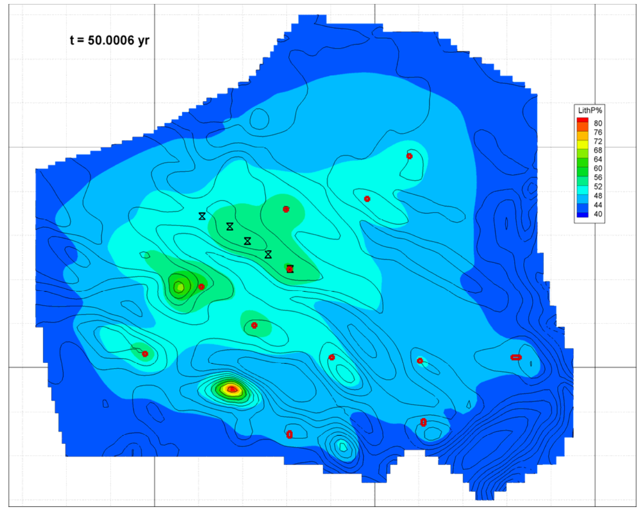
The closed system is the same as the open system, but with closed boundaries laterally. The pressure increase is higher for both average pressures and near-well pressures (Fig. 2c). Again, where wells are closely spaced the overlap of pressure footprints leads to higher pressures. For one well, the pressure increase approaches the 9.25 MPa limit. Expressing pressure as a percentage of lithostatic pressure, again the shallower structures show pressure increase in excess of 75% lithostatic, as well as at the injector (Fig. 2d).

A final simulation was run with the overburden permeability increased to 10^{-17} m^2 (0.01 mD) to account for permeability heterogeneity in the caprock such as faults and fractures. A low permeability overburden can still retain CO_2 provided that the capillary entry pressure is not exceeded, and that faults are not found in the areas of CO_2 accumulation. With a permeable caprock and closed lateral boundaries (Fig. 2e), the pressure build-up more closely resembles that of the open system. As with the open system, the pressure increase does not reach the 9.25 MPa limit, but the 75% of lithostatic pressure limit is exceeded in the shallowest parts of the aquifer.

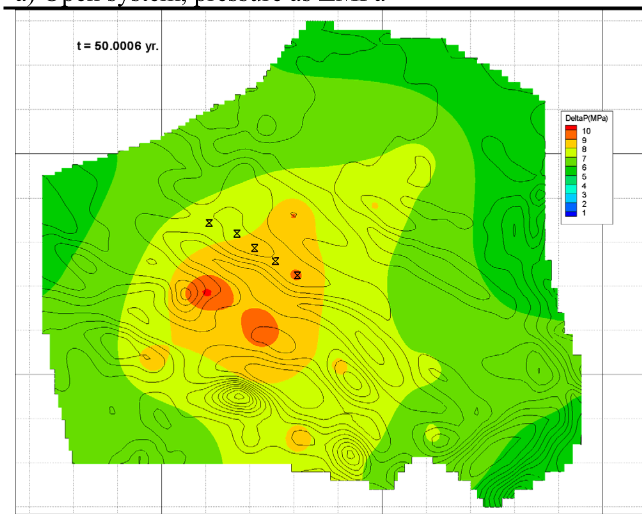
In summary, the dynamic models confirm that a general pressure increase is to be expected in closed aquifers; capacity is unlikely to be limited by the *average* pressure increase, but by near well pressure increase or by pressure increase at shallow points within the reservoir. Treating the caprock as permeable to the displaced formation water leads to significantly lower pressures and higher capacities – assuming an aquifer is completely closed is a conservative assumption. For shallow areas of aquifers, the difference between hydrostatic and lithostatic pressure is smaller, and hence those shallow points are more likely to reach pressure limits. Injection models indicate that this is the case for both open and closed systems, and so even aquifers with open boundaries require a regional assessment with regards to pressure evolution.



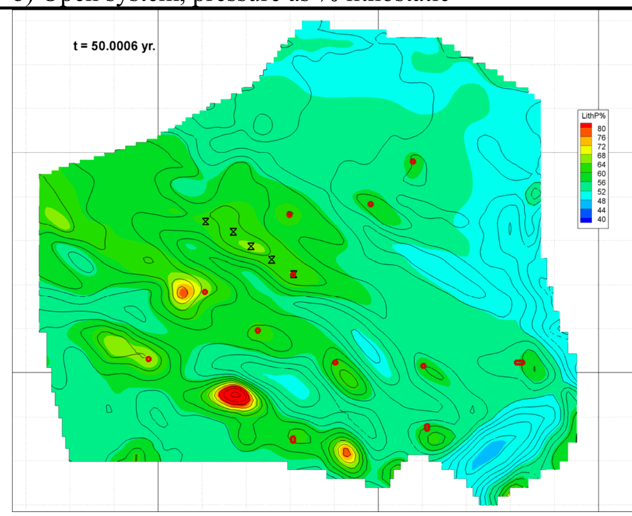
a) Open system, pressure as ΔMPa



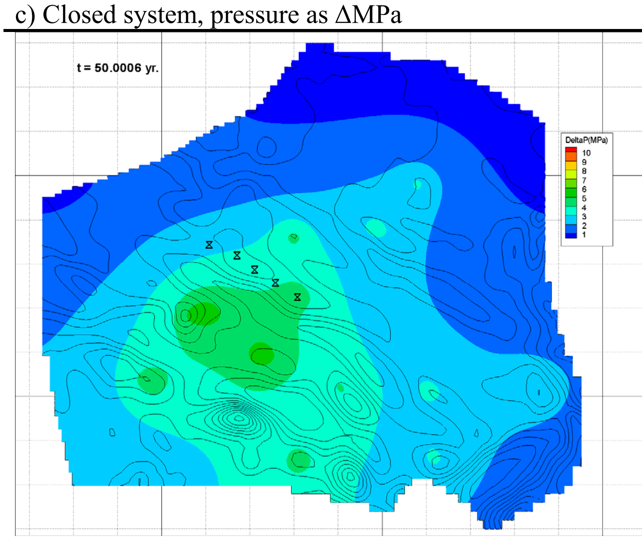
b) Open system, pressure as % lithostatic



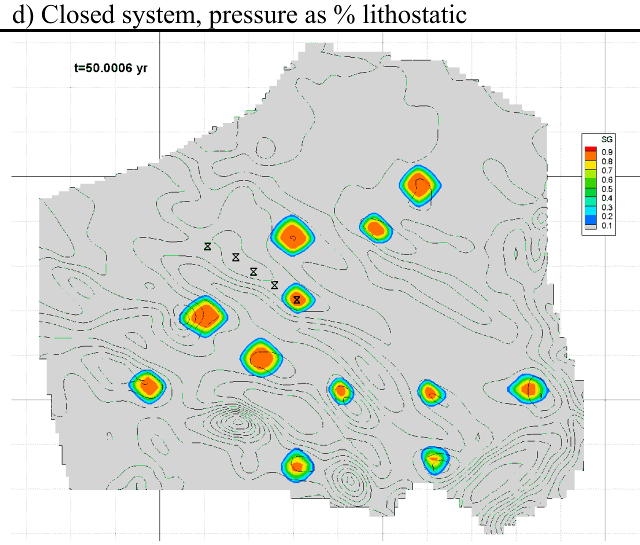
c) Closed system, pressure as ΔMPa



d) Closed system, pressure as % lithostatic



e) Closed system with low permeability overburden, pressure as ΔMPa



f) CO_2 saturation around injection wells

Fig. 2: Results of injection models. Simulations show 12 wells injecting (in total) 33 Mt CO_2 per year, for fifty years. Well locations visible in lower right hand model (CO_2saturation plot). Closed system shows higher ΔMPa than open and permeable-overburden systems. The shallow point in the aquifer is vulnerable to pressure increase when viewed as % lithostatic, depsite being unused for injection (compare lower right hand figure).

Summary

The boundary conditions of an aquifer have a significant impact on its capacity and pressure behaviour. Closed systems are subject to a general (average) pressure increase, as well as near-well pressure increase, that may approach imposed limits and thus limit capacity. Open systems are less susceptible to pressure increase, but injection wells do have a pressure footprint. Where multiple injection sites are used, these footprints may overlap to generate a more widespread pressure increase.

Regional consequences of CO_2 storage – i.e. phenomena within a bounded aquifer, but not necessarily at the injection point – are apparent when comparing the static estimates for closed aquifers and open traps within an assumed "infinite aquifer". If those traps are within a closed aquifer, then capacity potentially cannot be fully exploited without additional measures such as producing formation water. The dynamic simulations show further regional issues that may not be apparent at a site-specific characterization: shallow portions of aquifers are vulnerable to pressure increase, in both open and closed systems, as a consequence of the smaller window between hydrostatic and lithostatic pressure at shallower depths.

The dynamic simulation of CO_2 storage in a closed aquifer with a low permeability caprock shows that treating bounded aquifers as completely closed is a conservative assumption. The displacement of formation water through the overburden – through pore networks or fractures – can mitigate the pressure increase that results from CO_2 injection, to the point where the pressure profile more closely resembles an open system. Simplified solutions for capacity estimation in "semi-closed" aquifers (e.g. Zhou et al., 2008), may be a useful tool in regional capacity estimates. The identification and characterization of regional aquifer boundaries – both laterally and vertically – is critical to the choice of estimation method and the setup of any simulations.

Acknowledgements

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