REGIONAL STORAGE CAPACITY ESTIMATES: PROSPECTIVITY NOT STATISTICS

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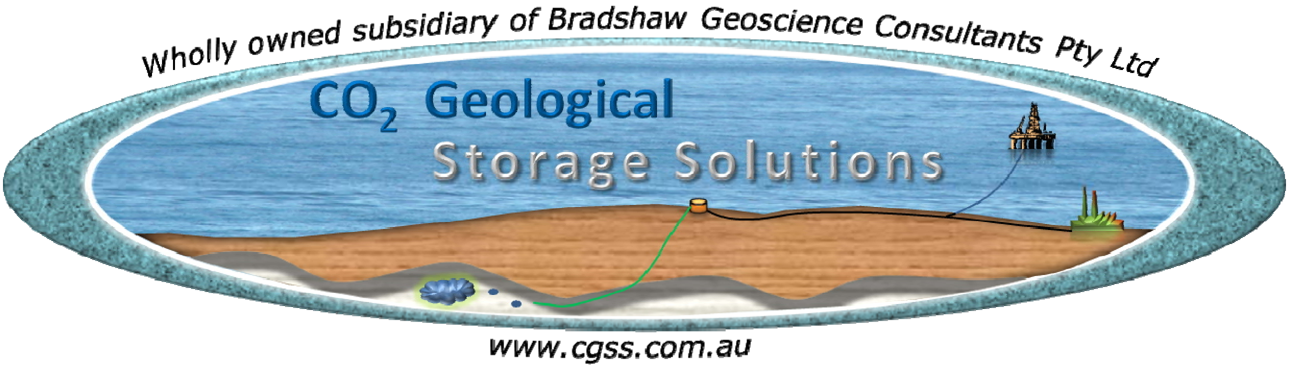
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Abstract

Over the last decade, there has been significant scrutiny and criticism regarding the reliability and efficacy of values put forward as CO_2 geological storage capacity estimates. Initial estimates were unsophisticated, with little or no geological or technical components used in the assessments. Enormous numeric ranges were quoted, and reliance was placed on gross oversimplifications of both complex geological settings, as well as the physical limitations of the geological strata to accept and retain any CO_2 that might be injected and stored. More recent efforts have focused upon the need to determine better standards for making storage capacity estimates and to establish some uniformity in the estimation methods. As more emphasis has been placed on the approaches (formulas and algorithms) that various authors have utilized, less effort is being documented on the actual prospectivity of the rocks i.e. the geology. Unless the rocks at any given site are understood well enough then the level of uncertainty regarding their geological suitability for storage will never be low enough to allow financial investment and consequently geological storage will be unable to prove-up and deliver the outcomes that it promised a decade ago.

The Queensland CO_2 Geological Storage Atlas assessed 36 sedimentary basins across the state of Queensland in Australia and during the assessment a methodology was developed ("CGSS methodology") for regional storage capacity estimations. The CGSS methodology produces conservative regional storage volumetric estimates, that can be relied upon by policy decision makers to be highly likely to be available in a given sedimentary province, and which can be duplicated and revisited by other scientists and engineers, whilst also preserving the assumptions and decision processes. The CGSS methodology contrasts starkly with some existing approaches which deal with prospectivity by applying a Storage Efficiency (SE) factor at a whole of basin scale with limited specific depth, temperature, pressure, geological and geophysical information to guide the estimate or by use of generic assumptions (e.g. for CO_2 density). If such an approach had been adopted in the Queensland Atlas assessment, it would have generated storage capacity values several orders of magnitude higher than the CGSS methodology. Back calculating a Storage Efficiency (SE) factor for the Queensland Atlas assessment, so as to get the same final numerical estimate produced with the CGSS methodology, results in a SE factor of ~ 0.10 – 0.15% of the total basin pore volume. This contrasts with SE factors of ~ 4% commonly applied when using the storage efficiency factor methodologies. Given the high level of technical detail that was used in the Queensland CO_2 Geological Storage Atlas to arrive at a regional storage capacity estimate using the CGSS methodology, and the substantial disparity that a storage efficiency approach generates, it raises the question of how reliable the storage efficiency approach may actually be, especially where site specific or regionally representative geological parameters have not been used as a guide or constraint in an assessment?

1. Introduction

Regional CO_2 geological storage capacity estimates have been recognized for a decade to have been poorly assessed and estimated due to a paucity of data, inconsistent approaches, and inadequate methodology [1]. In the last few years there has been considerable effort to redress this problem and so provide more confidence in the assessments that are being produced [2]. Some recent efforts have focused on development of storage coefficient standards so that estimates can be compared and contrasted between different regions with the aim being to help establish accepted guidelines and practices for determination of the extent of the storage resource that may exist. Whilst this storage efficiency approach clearly has admirable intentions it may actually be misguided, in that it has the potential to be misused by practitioners who do not appreciate, or completely understand, the physico-chemical aspects of geological storage or the substantial variation that does occur in geological formations in the subsurface.

The oil and gas industry has spent decades producing guidelines for resource estimation, principally because of the need to report the size of hydrocarbon accumulations consistently and reliably to finance markets and investors. Geological storage could soon face a similar constraint if value is placed on CO_2 in international market places and as a corresponding value emerges for the access to sedimentary basins, geological storage permits and proven storage volume [3]. Many academic approaches are still being applied to assess storage capacity in sedimentary basins at a regional level which oversimplify, and probably overestimate, the likely pragmatic storage capacity. Providing incorrect estimates, or estimates with inappropriate caveats on the reliability of the work, could produce undesirable outcomes for any future geological storage industry, both technically and financially. Given the substantial time delay that is inherent in indentifying and proving up a geological storage site [4], knowingly applying incorrect assumptions about storage capacity can only lead to increased uncertainty of and disfavour of CCS, with consequent further delay in the uptake of geological storage and CCS. Efforts to establish definitions that will assist the terminology and comparisons between the various mapping efforts for geological storage capacity [5, 6] are to be applauded. At the site level, storage capacity will need to be determined by detailed numerical analysis using geological models and reservoir simulations [5]. However, at regional basin or sub-basin levels building geological models and running reservoir simulations are not realistic in terms of timing and are unlikely to be regularly attempted.

The Queensland CO_2 Geological Storage Atlas [7] assessed 36 sedimentary basins across the state of Queensland in Australia. This work occurred over a twelve month period and during the assessment a methodology was developed ("CGSS methodology") for regional storage capacity estimations. The CGSS methodology produces conservative regional storage volumetric estimates, that can be relied upon by policy decision makers to be highly likely to be available in a given sedimentary province, and which can be duplicated and revisited by other scientists and engineers, whilst also preserving the assumptions and decision processes. The CGSS methodology when applied at a regional level has several key principles that it relies upon, which include; 1) document the geological prospectivity of the area under consideration by examining the overlay of effective seal and reservoir distributions, their quality and characteristics and identify defined storage fairways, 2) calculate CO_2 density curves for each geological province and use these to better estimate in place CO_2 density for at least each 100m depth interval in the subsurface, 3) recognize that the major trapping method for injection volumes at industrial scale will be by **MAS** (**migration assisted storage** – "new term"), and 4) only count in the assessment, the volume of rock that is likely to be permeated by a migrating CO_2 plume.

2. Estimating the regional CO_2 storage capacity - CGSS methodology

The CGSS methodology is applied at the basin scale. It is a four step process with some iterative features; i.e. as the process is followed natural sub-areas which have common parameters within a basin may be recognised. Each of these sub-area(s), or the basin as a whole if no sub-area(s) emerge, has a storage capacity estimated. The basic equation for the volumetric estimation of the CO_2 storage resource in a porous reservoir is:

$mCO_2 = RV * \emptyset * Sg * \delta_{(CO2)}$ ....Equation 1; where

- mCO_2 = mass of CO_2 in kilograms
- RV = total reservoir rock volume in m^3 (adjusted for net/gross, % of viable seal & reservoir, etc).
- $\emptyset$ = average total effective pore space of RV (as a fraction)
- Sg = the gas saturation within the above pore space as a fraction of the total pore space, either as Sg_r for residual gas saturation trapping or $1-Sw_{(irr)}$ for conventional trapping; where Sg_r = residual gas (CO_2) saturation and $Sw_{(irr)}$ = irreducible water saturation (both as a fraction)
- $\delta(CO_2)$ = the density of CO_2 at the pressure and temperature at the given reservoir depth in kg/m^3.

2.1 Step 1 - estimate a CO_2 density versus depth curve for the given area

The density of pure CO_2 (it is assumed that pure CO_2 is stored) can be very accurately calculated provided the pressure and temperature are known [8], so the CO_2 density estimated at any subsurface depth will depend on the accuracy of the corresponding pressure and temperature estimates at that depth. As, within most sedimentary basins, there is vertical hydraulic continuity (at least over geological timescales) and the pressure gradient is normally constrained between fresh and normal-marine-saline water gradients (1.42 to 1.53 psi/m respectively), then with some minimal knowledge of the formation water salinity, and if possible pressure data from water-well flow tests (from either drill stem tests (DST) or production testing), it will normally be possible to obtain a reasonable estimate of a basin's likely regional pressure gradient. Possible overpressured reservoirs and hypersaline conditions can also normally be identified, if not directly accounted for. In onshore basins the height of the hydraulic pressure head needs to be considered; offshore it is generally, but not always sea-level.

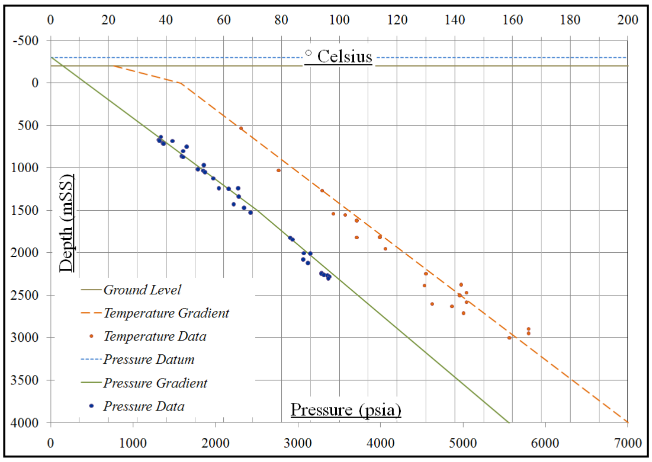


Figure 1: Regional temperature and pressure gradients - interpretation.

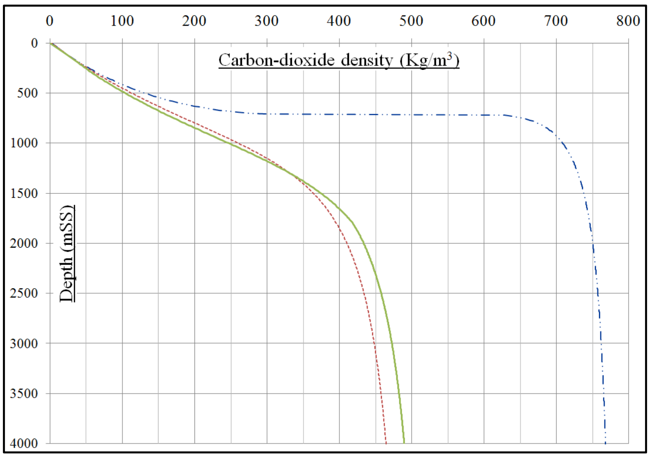


Figure 2: Regional carbon dioxide density curves.

The temperature gradient, in comparison to the pressure gradient, often varies significantly over relatively small distances, so a regional estimated temperature gradient is generally more of a compromise compared with a regional estimated pressure gradient (Figure 1). In addition it can be difficult to get a good temperature profile across the entire vertical geological section. This is because the main source of information is from the petroleum industry where it is common to have only a few control points, normally at the bottom of a well, from which to estimate the temperature profile of the entire sedimentary section. Normally an extrapolated bottom hole temperature (EBHT) can be estimated from maximum temperatures recorded during wireline logging runs; it is generally considered that EBHTs slightly under estimate the actual virgin formation temperature. Occasionally individual wells will have shallower control points due to information gained from intermediate casing runs, perhaps augmented by maximum recorded temperatures from DSTs etc. Some approximation of the average ground surface (or water bottom) temperature is also necessary as this is considered a required control point. Figure 1 shows the regionally estimated temperature and pressure gradients (the green (solid) and orange (dashed) lines) for the Eromanga Basin, interpreted from pressure and temperature control points from wells across the basin. Each of these gradients can have multiple legs interpreted if required. Figure 2 shows three density curves. The red (dotted) curve is for a "hot" 50°C/km and freshwater (low density) basin and the blue (dashed) curve is for a "cold" 20°C/km and saline (high density) basin; both these curves approximate some Australian conditions. The green (solid) curve is calculated directly from the estimated pressure and temperature gradients interpreted in Figure 1 for the Hutton Sandstone of the Eromanga Basin in Queensland, Australia (adjusted to a common datum). Note that in the potential injection zone, from 800mSS to ~2500mSS the density is less than 450kg/m^3.

2.2 Step 2 - estimation of a regional pore volume versus depth curve – regional prospectivity assessment.

This process is a combination of depth structure mapping, net reservoir isopach mapping and porosity estimation for any potential CO_2 storage reservoir unit. A relatively complex example of the Hutton Sandstone from the Eromanga Basin is shown [7]. Figure 3a shows the subsea depth to the top of the Hutton Sandstone and Figure 3b shows a net isopach map. Figure 3c shows the mosaic that results when the depth-structure is cross-multiplied with the isopach (in this case created in ArcView™); ~300 cells have been created, each with a defined depth and thickness range which can be reduced to 92 unique combinations of depth and thickness ranges. In the case of the Hutton Sandstone, porosity is not a simple function of depth, nor is a regional porosity map available, so a moving average approach to the available data was applied and a 'best estimate' of depth versus porosity was created (Figure 4).

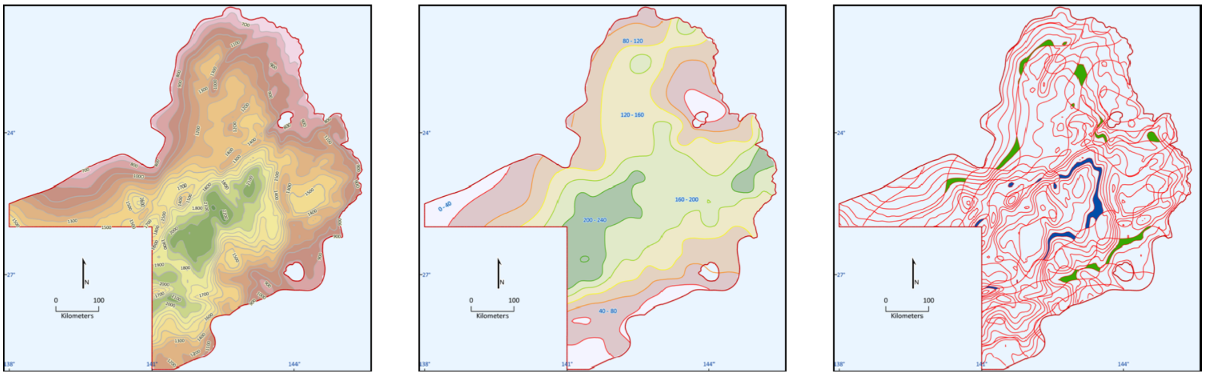


Figure 3: (a) Depth structure; (b) Gross reservoir isopach; (c) Depth-structure/isopach mosaic (Hutton Sandstone – Queensland Atlas [7]).

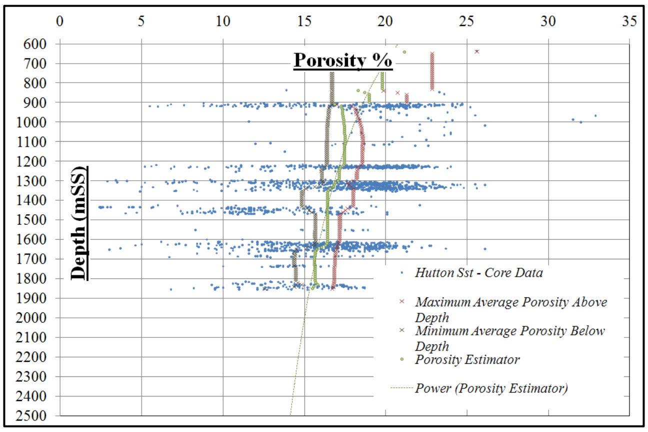


Figure 4: Porosity versus depth estimation - unclustered data.

This can be cross-multiplied with the 92 unique depth-thickness cases to create a seriatim of pore-volume versus depth classes. Additional refinements can be added to better reflect the likely maximum pore volume available for storage. This can include porosity permeability cut-offs, any net to gross factors and minimum depth requirements (so as to remove the pore volume that is above the estimated supercritical CO_2 depth). For the Hutton Sandstone it was known that a significant proportion of samples with porosity greater than the cut-off failed to meet permeability cut-off criteria, and a function was developed to account for this; e.g. 80% of the reservoir that exceeded the porosity cut-off failed to meet the permeability cut-off criteria at a depth >2500mSS. This approach allows sufficient information to calculate a maximum CO_2 storage volume by cross-multiplying the 92 pore-volume-depth cases with the average CO_2 density at the appropriate depth, and summing the results to obtain a total absolute maximum storage potential for this particular reservoir. There are several interpretation pathways that, in a fashion similar to lead and prospect analysis in petroleum exploration, will provide the required pore volume versus depth output. Most if not all of these pathways were used in the assessment of the Queensland Atlas basins [7]. These are the evaluation paths that determine an area's storage prospectivity.

2.3 Step 3 - discounting the maximum regional storage volume estimate – MAS trapping mechanism

The possibility of actually being able to utilise even a small portion of this maximum storage potential in a practical situation is extremely unlikely for a number of reasons, which will be discussed in the context of migration assisted storage trapping (MAS trapping): previously loosely termed hydrodynamic trapping (Bachu et al, 2007), prior to being redefined in the Queensland Atlas [7]. MAS trapping is the only 'immediate' term trapping process that can theoretically store enormous quantities of CO_2 that will likely match or exceed industrial emissions of CO_2. It involves multiple trapping mechanisms that operate simultaneously, with the primary trapping mechanism being discontinuous free-phase trapping of residual gas (RG) in the trail of a migration plume. The contributions of the various secondary trapping mechanisms to the ultimate CO_2 storage potential are not considered here, but note that over time dissolution can be a significant contribution to the total storage (up to 20% is estimated).

The residual gas (RG) trapping mechanism commences to operate (Figure 5) only after injection ceases at the injection well and the pressure gradient driving the water drainage away from the well bore dissipates and formation water moves back, partially displacing the CO_2 (imbibition). Buoyant movement of the CO_2 away from the injection site occurs and a plume of CO_2 forms beneath the seal and commences to migrate up-dip. *"At the leading edge of the CO_2 plume, gas continues to displace water in a drainage process (increasing gas saturation), while at the trailing edge water displaces gas in an imbibition process (increasing water saturations). The presence of an imbibition saturation path leads to snap-off and, subsequently, trapping of the gas phase. A trail of residual, immobile CO_2 is left behind the plume as it migrates upward"* [9]. Eventually this process will completely halt the migration of the plume and the MAS trapping mechanism is mostly complete.

Only a thin layer beneath the seal (Figure 5) will be affected by the migrating plume (i.e. for the MAS mechanism the reservoir storage may not be very 'efficient') and the residual gas saturation (RGS) within the immobilised section of the plume will probably be a very low percentage of the available rock pore volume. In the absence of a reservoir simulation model, a regional volumetric assessment should nevertheless attempt to account for these factors. In the Queensland Atlas [7] these factors have been accounted for under the following assumptions (i) the reservoir is considered homogeneous; (ii) initial injection occurs in a single well over the entire thickness of the reservoir; (iii) formation water is displaced (drainage) radially and uniformly away from the well bore during injection (the pressure-driven phase of a storage project); and (iv) the injected-affected-cylinder of CO_2 that develops around the wellbore only extends out to a radius of 2.5 km (beyond this gravity-driven forces begin to override the pressure-driven forces). CO_2 storage within the injection-affected-cylinder around the well-bore is ideally only a function of reservoir gas saturation where $Sg = 1-Sw_{(irr)}$ ($Sw_{(irr)}$ is the irreducible water saturation of the pore space). When injection ceases, formation water moves, by imbibition (gravity-driven phase), back into the original injection-affected-cylinder and the ultimate storage within it is now a function of Sg_r (the residual gas saturation (RGS). There is therefore now a mass of gas ($1 - Sw_{(irr)} - Sg_r$), which needs to be stored outside of the original injection-affected-cylinder. This mass rises to the top of the reservoir and migrates underneath its seal. The total lateral distance that this mass can migrate away from the injection-affected-cylinder is a function of Sg_r and the thickness of the migrating plume; i.e. increases in either or both of these factors limits the distance the plume will migrate before all the CO_2 is trapped by the RGS process of the MAS trapping mechanism. Simulation models suggest that the migration plumes will rarely be thicker than 25 m in most homogeneous reservoirs, and are often much thinner. In the Queensland Atlas [7] a generic migrating plume thickness of 15 m was assumed, $Sw_{(irr)}$ was set high at 35% (consistent with known Queensland gas field values) and a MAS reservoir efficiency factor calculated for each reservoir. The thicker the reservoir the smaller this number will be; e.g. at 15 m it is 100%, at 50 m it is approximately 30% and at > 150 m it is less than 10%. This MAS reservoir efficiency factor as applied here does no more than poorly mimic an actual situation, but it does serve to identify the significance of this issue and to reduce an unrealistic regional maximum volumetric estimate in a defined manner, commensurate with a regional assessment. A numeric reservoir simulation will significantly improve such an estimate, but it will be impacted by the choice of the thickness of the grid cell size immediately beneath the seal.

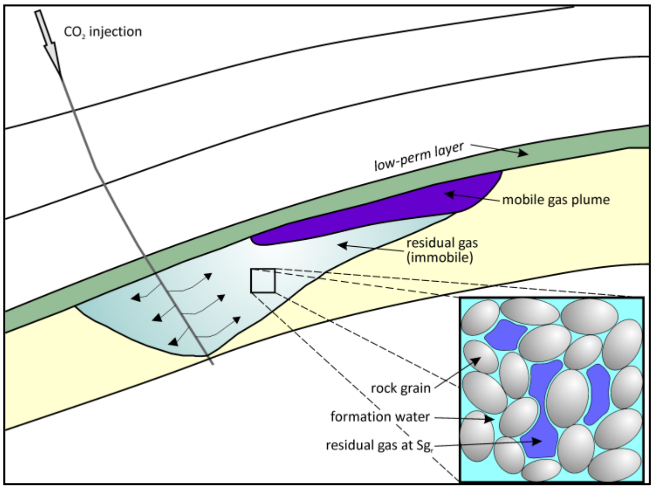


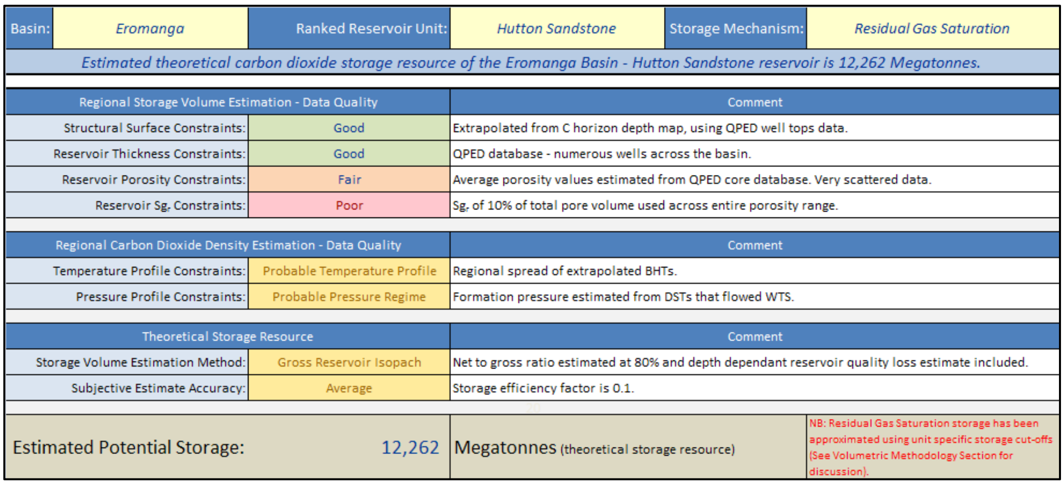
Figure 5: Schematic MAS trapping (modified from Juanes et. al. [9]).

The final discounting that is applied is to estimate the average residual gas saturation, Sg_r in the MAS plume trail. In general Sg_r in sandstone reservoirs increases with decreasing porosity, decreasing sorting, decreasing grain size, increasing cementation and increasing clay content. Sg_r is difficult to estimate without core, and for regional assessments the estimation methods available are limited. Various authors quote ranges of 0.05 to 0.95 for Sg_r. From an empirical method [10], and using the 10% cut-off porosity applied in the Queensland Atlas [7], 0.2 to 0.6 is a likely range for Sg_r. However, it was decided that an average of these estimates could be misleading in the Queensland context and a likely conservative value of $Sg_r = 0.1$ was applied when calculating the final regional estimated CO_2 potential storage volumes.

2.4 Step 4 - Documenting the viability of the volumetric estimate

It is the quality of the data behind the estimated potential storage value that determines the reliability that can be placed on the final volumetric estimate. A summary table that gives a subjective estimate of the accuracy of the final reservoir volumetric estimate, based on both the data quality and the methodology used to calculate the estimate, was used in the Queensland Atlas [7]. The value assigned to the subjective estimate accuracy in Table 1 (from 'Very Good' to 'Poor') is determined from the values assigned to the constraints listed 1) the regional storage volume estimation - data quality, 2) the regional carbon dioxide density estimation-data quality, 3) the storage volume estimation method used.

Table 1: Estimated Storage Potential Summary – example from the Queensland Atlas.



Basin:	*Eromanga*	Ranked Reservoir Unit:	*Hutton Sandstone*	Storage Mechanism:	*Residual Gas Saturation*
Estimated theoretical carbon dioxide storage resource of the Eromanga Basin - Hutton Sandstone reservoir is 12,262 Megatonnes.					
Regional Storage Volume Estimation - Data Quality		Comment			
Structural Surface Constraints:	Good	Extrapolated from C horizon depth map, using QPED well tops data.			
Reservoir Thickness Constraints:	Good	QPED database - numerous wells across the basin.			
Reservoir Porosity Constraints:	Fair	Average porosity values estimated from QPED core database. Very scattered data.			
Reservoir Sg_r Constraints:	Poor	Sg_r of 10% of total pore volume used across entire porosity range.			
Regional Carbon Dioxide Density Estimation - Data Quality		Comment			
Temperature Profile Constraints:	Probable Temperature Profile	Regional spread of extrapolated BHTs.			
Pressure Profile Constraints:	Probable Pressure Regime	Formation pressure estimated from DSTs that flowed WTS.			
Theoretical Storage Resource		Comment			
Storage Volume Estimation Method:	Gross Reservoir Isopach	Net to gross ratio estimated at 80% and depth dependant reservoir quality loss estimate included.			
Subjective Estimate Accuracy:	Average	Storage efficiency factor is 0.1.			
Estimated Potential Storage:	12,262	Megatonnes (theoretical storage resource)		NB: Residual Gas Saturation storage has been approximated using unit specific storage cut-offs (See Volumetric Methodology Section for discussion).	

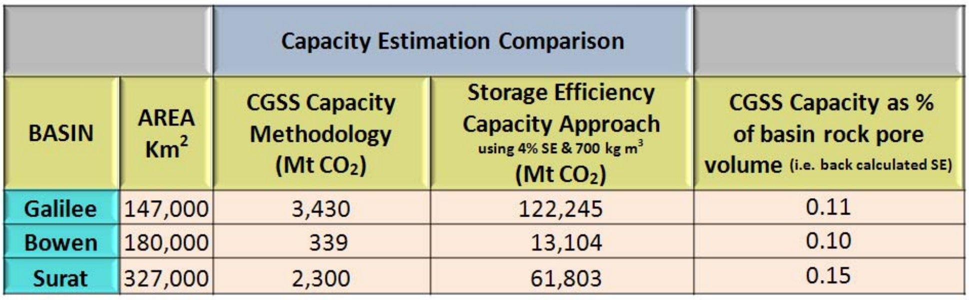
The regional storage volume estimation – data quality heading summarises the main pore volume estimation constraints of: (i) structural surface control, (ii) reservoir thickness, (iii) porosity and (iv) residual gas saturation. Each is subjectively ranked using one of the following categories: very good, good, average, fair and poor. The regional volumetric estimation methodology is directed at every stage of the process towards conservative values; e.g. the temperature gradient is always taken towards the right of the data control points, the pressure gradient is kept as low as the data allows, the pore volume interpretations are focused on defining only those areas where injectivity is likely to be reasonable so as to be included in the total rock volume. The actual reservoir likely to be affected by MAS trapping is estimated and discounted by a conservative estimate of residual gas saturation. The summary assessment gives a comparative understanding of the reliability of the resultant number.

3. How appropriate is the use of Storage Efficiency factors?

The basic formula for calculating the storage capacity for an area is $mCO_2 = RV * Ø * \delta_{(CO2)}$. Some authors and methods advocate use of a Storage Efficiency (SE) factor, by which either the storage capacity, or the gross rock pore volume ($RV * Ø$) calculations, are multiplied by to estimate the effective storage capacity for an area. However, it is questionable how appropriate such an approach actually is and also whether it has been tested to see if it can generate a good reflection of the "real" storage capacity for an area, or is only a "quick look" approach; i.e. it generates only a numerical assessment knowing that this needs to be discounted further to allow for geological uncertainty, lack of data, or lack of time to do a detailed assessment and calculation. The SE factors that have been utilized by authors attempt to account for a multitude of physico-chemical and geological parameters which estimate the percentage of the gross rock pore volume that is invaded by and actually traps and stores the injected CO_2. Most often the final “summed” up discount factor that is used, ranges from 1 to 6%, with 4% being used by many authors for regional assessments. The ranges in the numeric values that would need to be applied for each component that impacts on a SE factor for any generically defined site can be so significant, that the value of such a generalized approach is questionable. Some authors have used a probabilistic approach with Monte Carlo analysis to generate the most likely SE factor. However, there are two risks with this approach; 1) other authors now wish to apply the SE factor to their area / basin / country without acquiring or interpreting any data to define the input parameters for their region, and 2) probabilistic assessment is absolutely no substitute for lack of data or detailed assessment of the geological parameters of a region or site.

At the completion of the 8 work years of technical effort (over a twelve month period) that it took to produce the assessment of 36 sedimentary basins for the Queensland CO_2 Geological Storage Atlas [11] (of which 20 basins were considered to be prospective and assessed in significant detail), CGSS decided to compare the prospectivity assessment approach of the CGSS methodology with what would have resulted from an application of an SE factor. The result of that comparison is shown in Table 2. For the Storage Efficiency approach each of the gross rock pore volumes of the assessed reservoir/seal pairs for the three basins were multiplied by 4% with an assumed generic CO_2 density of 700 kg/m^3. As shown these capacity estimates are orders of magnitude greater than the CGSS Methodology capacity values. If the Storage Efficiency factor for the three basins are back calculated using the CGSS methodology values and allowing for the area of the basin, then a SE of 0.1 to 0.15% is derived; more than an order of magnitude lower than what most authors use in their regional assessments.

Table 2: Capacity estimates for three basins from the Queensland CO_2 Geological Storage Atlas using the CGSS Methodology, comparing application of a simplistic 4% Storage Efficiency factor and a “back-calculated” storage efficiency factor (SE).



		Capacity Estimation Comparison		
BASIN	AREA Km^2	CGSS Capacity Methodology (Mt CO_2)	Storage Efficiency Capacity Approach using 4% SE & 700 kg m^3 (Mt CO_2)	CGSS Capacity as % of basin rock pore volume (i.e. back calculated SE)
Galilee	147,000	3,430	122,245	0.11
Bowen	180,000	339	13,104	0.10
Surat	327,000	2,300	61,803	0.15

The reason for the large discrepancy is that 1) CO_2 density is highly variable in the subsurface (depending on depth, pressure, temperature, salinity) and a single generic value should not be used in an assessment unless a CO_2 density curve has been constructed for an area to use as a guide, and 2) the CGSS methodology relies on specific geological prospectivity data, whereas it is unlikely that generic estimates of ranges in a probability assessment for an area will ever adequately allow for the variability and complexity that a detailed assessment reveals.

In the oil and gas industry, success rates for commercial discoveries ranges from 1 in 3 to 1 in 10, but few authors of geological storage papers consider the likely failure rates of wells to provide high integrity sites over large areas for commercial scale activities for geological storage [4]. When geo-engineering factors such as basin wide pressure build up are also considered, the pragmatic storage capacity will likely be reduced further from the estimates made using SE factors.

4. Conclusions

Assessment of the geological storage capacity of any basin, region, sub-basin, reservoir/seal pair (play), or specific storage site needs to be based on the actual known geological criteria that have significant bearing on the geological aspects of storage capacity, injectivity and geological integrity. This knowledge needs to be used with the insights that geologists can apply to the prospectivity of the area, be that based on regional or local characteristics. Applying generic assumptions for the critical factors of CO_2 density, pressure and temperature, porosity and permeability, injectivity and formation water salinity will lead to gross errors in storage volume estimations by perhaps many times (2 to 3). Not applying a prospectivity approach to an assessment, by using fundamental geological data sets and physico-chemical constraints, could lead to errors of storage capacity assessments by at least an order of magnitude. The CGSS methodology combines geological, physical and chemical constraints, at a basin to site level, to allow the generation of conservative but representative storage volume estimates that both policy makers and financial investors can rely upon in their determinations. 'Rock is King' should be the motto for all site assessments, with a requirement to obtain as much data as is commercially feasible, to both improve the capacity estimates as well as to minimise the uncertainty in predicting the subsurface movement and behaviour of an injected CO_2 plume over both the likely 30 to 50 year period of injection, and into the future once the site has been approved for closure.

5. References

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