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The Energy Technologies Institute's UK CO2 Storage Appraisal Project (UKSAP)

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Abstract

The purpose of the UKSAP project is to provide a realistic, defensible and fully auditable estimate of the capacity of geological formations below the UK's coastal waters to store CO2. Drawing on the expertise of the project participants (10 UK organisations) and accessing existing public domain and commercially available data, the £3.9M project has created a web-enabled database and geographical information system (WDG). This covers all the potential storage volume in the North Sea, the East Irish Sea and the central English Channel. The WDG is designed to assist policy makers and potential participators in projects with high level assessments and planning.

Storage units in the WDG (several hundred) are described in terms of geographical, geological, geophysical and other data relevant to risks in their use, leading to estimates of their storage capacity and economic profile. The ETI will make the WDG accessible to the public after completion of the project in July 2011.

The paper will present the methodology used in creating the estimates and describe high level findings from analysis of the data. The functionality of the WDG will be outlined.

Authourship and Acknowledgements

The UKSAP project was executed by a consortium of ten leading UK Carbon Capture and Storage (CCS) and geological organizations, including representatives of the following: The British Geological Survey[1] (BGS), Durham University[2], Element Energy Limited[3], Geo Pressure Technology Limited[4], Geospatial Research Limited[5], Heriot Watt University[6], Imperial College London[7], RPS Energy Limited[7], Senergy Limited[8] and University of Edinburgh[9].

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Key underpinning work was done by many, including K.Daniels[2], S.Mathias[2], J.Masters[7], R.Orrem[8], G.Riemersma[8], and R.Swarbrick[4].

Introduction

In September 2009 the Energy Technologies Institute commissioned a project to estimate the potential for geological storage of CO2 on the UK continental shelf. The ETI is a limited liability partnership between BP, Caterpillar, EDF, E.ON, Rolls-Royce, Shell and the UK government. Termed the UK Storage Appraisal Project (UKSAP), the £3.9M project set out to develop appropriate methodologies and produce a realistic, defensible and fully auditable estimate for use by policymakers, projects and planning authorities. A web-enabled database and Geographic Information System (WDG) would house all currently available salient data on geological storage units, together with a preliminary estimate of capacity, security of containment assessment and outline economic analysis.

The estimate itself is nearing completion, and will be the subject of more detailed publications later this year. This paper describes the methodology developed for the estimate, some high-level findings from the work and functionality of the database which will be made accessible to the public in the future.

Methodology – Summary

UKSAP started by identifying the saline water bearing reservoir formations (hereafter referred to as saline aquifers) of interest on the UK Continental Shelf (UKCS). These regionally extensive reservoirs were subdivided into individual storage units, which were classified as either fully confined ('closed') pressure cells or 'open' units, based on geological understanding and/ or interpreted formation pressure data. Where identified, structural or stratigraphic traps within these units (termed daughter units) were also characterised and subsequently treated separately for capacity estimation purposes.

Beginning with estimation of the maximum technically accessible pore volume within each unit, the storage resource in terms of mass of CO2 was calculated. Parameters critical to capacity estimation were described by ranges (minimum, most likely, maximum) and Monte Carlo simulation used to yield a probability based result for static capacity.

For depleted hydrocarbon fields, production and injection data were used to estimate the available storage quantity on a 'fluid replacement' basis; net withdrawal of fluids during hydrocarbon production was equated to the equivalent subsurface volume of CO2 that might subsequently be stored.

The project also investigated dynamic behaviour of candidate saline aquifer stores in order to gauge the likely impact on static capacity estimates. Structurally simple, homogeneous flow simulation models were constructed in order to investigate generic effects of various sensitivity parameters (such as depth, thickness, horizontal and vertical permeability, dip etc) on storage in open aquifers, closed systems and structural traps.

General findings from these studies were then considered in terms of their implication for overall UK storage capacity, and as a result two storage 'types' selected for more detailed flow simulation work. These were an open area of the Forties Sandstone Member, and a section of the Bunter Sandstone Formation containing structural closures ('domes'). Detailed geocellular reservoir models were constructed for each, and appropriate grids exported for dynamic modelling. In parallel, geomechanical models were built to ensure that appropriate constraints were applied to bottom-hole injection conditions. Results of the generic and detailed models were then integrated in order to derive methods for 'correcting' static capacity estimates of all identified units for dynamic effects.

Each unit was also assessed for its security of containment, and other aspects which might impact its ability to be successfully operated as a storage site. The level of *confidence* in these assessments, based on data availability and defined criteria, was also recorded. Together with Monte Carlo simulation results, this allows the overall UK storage capacity to be characterised in terms of reliability of assessment.

Finally cost estimates for exploitation of each unit were developed, based on the assessment information contained in the database and assumption of 'single source – single sink' infrastructure. Distinct components of cost are presented separately, such that the impact on transport costs of a hub development for example, may be readily incorporated. Different fill rates and project durations are also considered, covering demonstration to full project scale. The well-counts required by each were estimated from injectivity analysis.

Insufficient information was available to the project to convert these 'resource' level estimates into 'reserve' status at this time. Even so, it is felt that the geographical extent of assessments, representation of data uncertainty, standardized method of calculation, consideration of both long-term containment security and shorter-term operational features, together with economic analyses, make this the most reliable assessment of UK CO2 storage capacity to date.

Storage Unit Mapping from Reservoirs

The reservoir formations of the UK Continental Shelf (UKCS) were identified from the UKOOA lithostratigraphic nomenclature volumes (Knox & Cordey 1992 - 1994). All formations consisting predominantly of sandstone or porous and permeable carbonates were considered to be potential storage reservoirs. The great majority of excluded formations consist of shales, mudstones and other finegrained rocks, or carbonate or evaporite formations that have little permeability.

Limit polygons showing the extent of each reservoir formation were made available to the project in ArcGIS format. A database of geological formation tops (IHS's EDIN GIS database) was used to determine the depth, thickness and strata overlying each reservoir formation. This borehole-derived database was also used to check and edit the limit polygons that define the extent of each reservoir formation.

Detailed top surfaces of various formations interpreted from the PGS 3D seismic megamerge were also available to assist with mapping of reservoir formations.

Subdividing Reservoir Formations into Storage Units

In many cases the location, structure and reservoir properties of individual reservoir formations indicated a need to subdivide them into volumes with common characteristics that could be treated as a single unit of assessment known as a Storage Unit. Storage units form the basis of the resource and capacity assessment within UKSAP. A storage unit is a mappable subsurface body of reservoir rock that is at depths >800 m (TVDSS, true vertical depth subsea) which has similar geological characteristics and which has the potential to retain CO2. The basis for the subdivision of reservoir formations into storage units is described below:

1. Since stores at depths shallower than about 800 m below sea level are likely to contain CO2 in the gaseous rather than dense phase, and in this condition CO2 would be voluminous and highly buoyant, sections shallower than 800m were excluded from the analysis;
2. Those parts of reservoir formations which lie outside the UK Exclusive Economic Zone (EEZ) were excluded from the analysis;

3. Many reservoir formations contain internal permeability barriers that may prevent or severely limit fluid flow and divide them into compartments (Figure1). Reservoir pore fluid pressure data were provided and used by Geopressure Technology (GPT) to define pressure compartments within these reservoir formations.

   Certain other reservoir formations, e.g. the Leman Sandstone Formation, are known to be compartmentalised, but compartmentalisation only becomes apparent when for instance hydrocarbon fields associated with them are produced. In these cases an assumption was made that the entire formation is likely to be divided into compartments of a range of sizes comparable to that of the identified compartments. Where initial estimates suggested the CO2 storage capacity of these individual compartments would be <50Mt, they were excluded from the analysis.

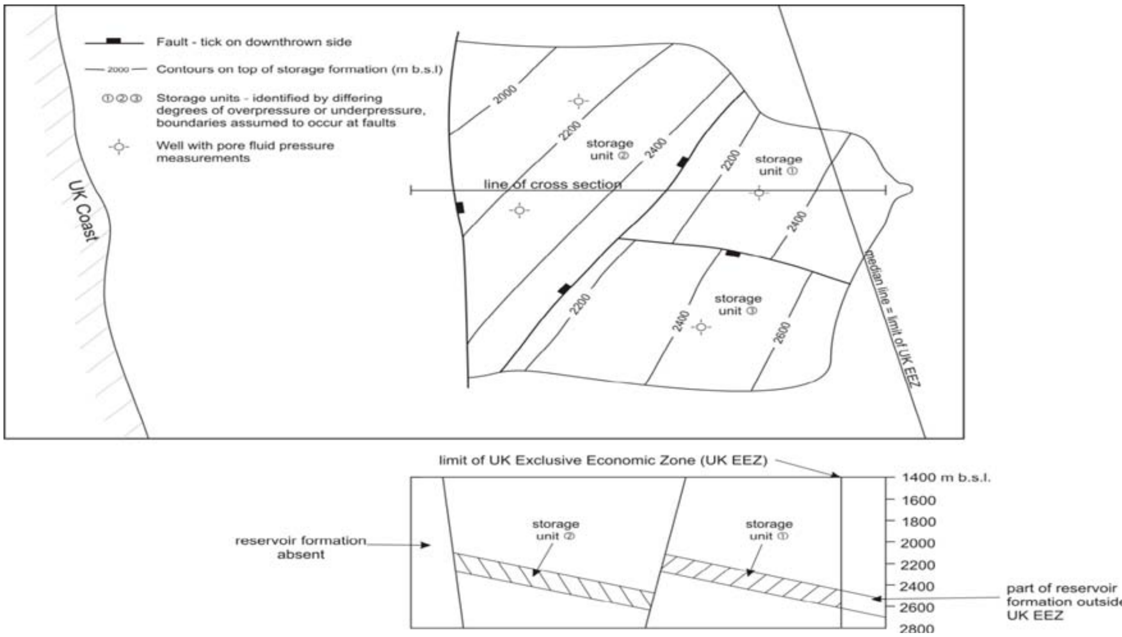


Figure 1: Reservoir formation divided into three storage units, each of which is considered to be a pressure cell.

Reservoir formations that could not be subdivided on the basis of pressure data were either treated as single storage units, or subdivided by other geological means in order to obtain localised storage resource data. The criteria used to decide whether a reservoir formation should be subdivided purely to obtain localised storage resource data were:

a. whether the formation is sufficiently widespread for there to be a benefit in subdividing it into multiple storage units;
b. whether sufficient geological information is available to make the subdivision meaningful.

Reservoir formations in which structural boundaries such as faults are thought likely, but cannot be clearly demonstrated to be boundaries to fluid flow, were subdivided into storage units along their major structural features such as large faults, fault zones, salt walls or dykes. Where no information was available, large formations were subdivided on an arbitrary grid following UK licence block lines.

In reservoir formations which are not thought to contain structural barriers to fluid flow, but where progressive change in the degree of overpressure between the deepest and shallower parts is observed, subdivision into storage units was based on regions of similar overpressure. Examples are the Ekofisk Formation, Forties Sandstone Member, Mey Sandstone Member and the Maureen Formation.

The Cretaceous Chalk – perhaps the largest lithostratigraphic group of reservoir formations on the UKCS – was subdivided on the basis of synclinal features that form 'inverse watersheds' and would likely influence the migration path of injected CO2 (Figure 2).

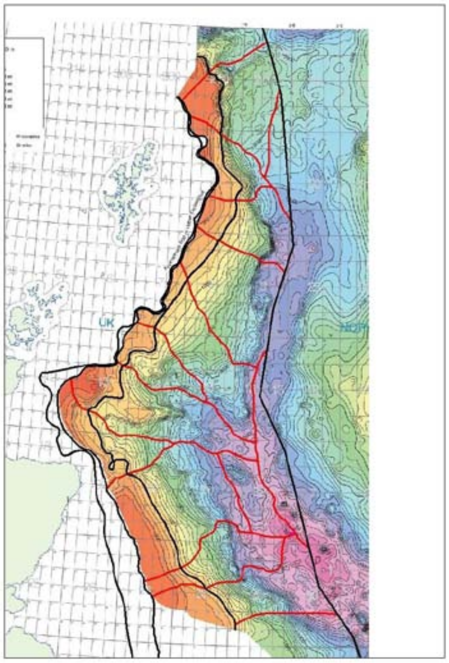


Figure 2: Subdivision of the Cretaceous Chalk, based on the Top Chalk surface (shown courtesy of the Millenium Atlas Co. Ltd.).

4. All 'parent' storage units were then classified as either closed pressure cells (if known or inferred) or open.

Identifying 'daughter units' within Storage Units

Hydrocarbon fields and other identifiable structural or stratigraphic traps, for example the large water-bearing closures identified in the Bunter and Ormskirk Sandstone Formations, have the potential to become more fully saturated with injected (buoyant) CO2 than other parts of a storage unit. Their storage capacity is thus calculated in a different manner to the remainder of the storage unit in which they occur. These structures are described as daughter units in the UKSAP terminology. Figure 3 depicts a 'daughter' within a storage unit.

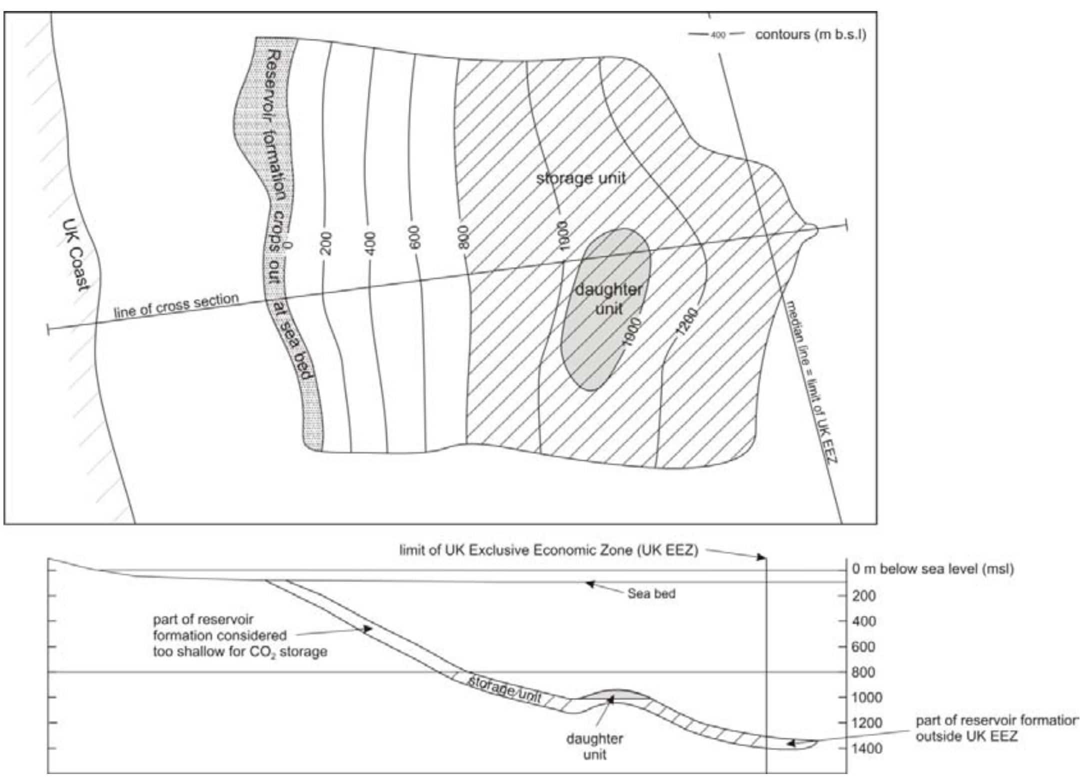


Figure 3: A Simple Storage Unit Containing a Daughter Unit

As at May 2011, a total of nearly 600 storage units have been defined and characterised (approximately 310 saline aquifers, 50 water-bearing closures and 220 hydrocarbon fields).

Summary of the Hierarchy of Reservoir Units in the UKSAP Project

The above describes a 3-level hierarchy consisting, in descending order, of:

- Reservoir formations (regionally extensive geological formations on the UKCS with reservoir properties);
- Storage units (mappable subsurface bodies of reservoir rock on the UKCS at depths >800 mTVDSS with potential to retain CO2, comprising all or part of a reservoir formation);
- Daughter units (hydrocarbon fields and mappable potential traps in the saline water-bearing parts of storage units).

Estimate Classification

A resource can be defined as anything potentially available and useful to mankind. Pore space in a storage unit is a resource that could be used for CO2 storage.

A reserve can be defined as that part of a resource that is available to be exploited economically using currently available technology. It is not considered possible to define any CO2 storage *reserves* within the UKSAP project as the effort required to achieve this level of technical assessment is only likely to be available within a demonstration or commercial storage project. Even so, the goal of the project is to move as far as possible in this direction because it will give policymakers and other stakeholders a more useful idea of the realistic potential for CCS in the UK.

Estimating the Pore Volume of Storage Units

The minimum, maximum and most likely values for the area and average thickness of each storage unit were determined and entered into the project database by the assessor. These were used in combination with a 'shape factor' (between zero and one) to produce an estimate of gross rock volume.

This was then convolved with minimum, maximum and most likely values for average porosity, and areal and vertical net:gross, leading to a probabilistic range of pore volume for each storage unit.

Estimating the Technically-accessible Pore Volume of Storage Units by Static Methods

Carbon dioxide can be retained in a storage unit as follows:

- As a free phase in structural and stratigraphic traps;
- Dissolved in pore fluids present within the reservoir rock;
- As a residual saturation of gas or supercritical phase CO2 trapped by capillary forces;
- As precipitated salts, ultimately originating from dissolution of reactive grains in the rock framework by pore waters acidified by dissolved CO2;
- By adsorption onto the surfaces of organic carbon-rich material within, for example, shales or coals.

However, for a variety of geological and physical reasons only a fraction of the total pore space is generally available to retain CO2, for example because:

- Heterogeneity in the reservoir rock and gravity effects mean that injected CO2 will not contact all the pore space;
- Build-up of reservoir pore fluid pressure may limit the amount of CO2 that can be injected into certain storage units, before limiting pressures (e.g. those that might fracture the cap rock) are reached;
- There is an irreducible water saturation that remains 'locked' within the pore space of reservoir rock that is contacted by water-saturated CO2. This residual pore water may become saturated with dissolved CO2, but it cannot be displaced by it.

Calculation of Technically Accessible Pore Volume within Saline Aquifer Storage Units considered to be Closed Pressure Cells

In areas where regional pressure study maps were available from GPT's regional pressure studies, overpressure values were taken from the appropriate stratigraphic map (GPT/ IHS, 2004 North Sea Central Graben Phase 1 and 2008 North Sea Viking Graben). Alternatively, based on areal and stratigraphic location of the storage unit a single overpressure value was extracted from the IHS pressure database. This was then used to calculate the aquifer pore pressure, lithostatic pressure and fracture pressure at shallowest depth of closure (assumed to be the weakest point, and depth at which the seal would be ruptured if exposed to excessive pressure). Fracture pressure was calculated through algorithms derived from both regional and local Leak Off Test (LoT) data for each of the five principal regions of study.

The limiting pressure for storage was defined as 90% of the minimum of either the assessed fracture pressure or lithostatic pressure. Aquifer Seal Capacity (ASC) was thus calculated as:

ASC = 0.9 x Min(Lithostatic Pressure, Fracture Pressure) – Initial Pore Pressure

The technically accessible pore volume is then calculated based on the isothermal compressibility equation:

S = PV x Ct x ASC

where

PV = pore volume of the Storage Unit
Ct = total compressibility (of fluids plus rock matrix)

Calculation of Technically Accessible Pore Volume within Saline Aquifer Storage Units not considered to be Pressure Cells

Whereas CO2 injection will invariably need to be managed to ensure that near wellbore pressure increase does not threaten hydraulic fracture and potential leakage, the nature of some storage operations will be such that increase in *average* reservoir pressure is not the limiting factor. In such cases, migration of the CO2 plume essentially governs the proportion of the pore volume that can be used.

This efficiency of storage may be influenced by careful design of injection well spacing, trajectory and injection rate, but it is also dependent on reservoir characteristics. In previous studies (IEAGHG, 2009; Goodman et al., in press) it is thought that the likely portion of available pore volume that can actually be filled in such circumstances is of the order of 1% to 6%.

In UKSAP, structurally simple, homogeneous flow simulation models were used to investigate the impact of various sensitivity parameters on CO2 migration (Figure 4). These included horizontal and vertical permeability, porosity, thickness, dip (in the strike and transverse directions), brine salinity and trapped gas saturation. Additional CO2 trapping through mineralisation reactions was not included, since these processes are not generally regarded as representing significant supplementary storage. The ECLIPSE 100™ simulator was used, allowing dissolution of CO2 in brine to be represented.

A high-angle injector with 1 km completion length was located toward the down-dip end of the model, and bottom-hole injection pressure limited to 90% of the assumed fracture gradient (0.8 psi/ ft). Sufficient pore volume was represented up-dip, such that migration distances of many tens of kilometres could be modeled without significant increase in average reservoir pressure. Layer thicknesses were also decreased at the top of the model, to ensure migration was not artificially impeded by large grid-block volumes. Target injection was 4 Mt CO2 per annum for 50 years.

Early runs highlighted the importance of buoyancy effects at moderate permeability and dip angles, with higher dips leading to fast migration along the underside of the caprock. Without pore pressure increasing to a limiting seal-breach condition however, some other criterion was required in order to define when the store was effectively ‘full’. The suggestion of 99% CO2 retention over 1000 years (IPCC Special Report, Sept. 2005) was therefore adopted, in combination with a maximum migration velocity of 10 m per annum (at the leading edge of the plume, at 1000 years). The latter was founded on the draft EU Directive on the Geological Storage of Carbon Dioxide, for ‘long term stability’ of the plume.

Thus the technically accessible pore volume was assessed for a variety of single-well storage scenarios, and ‘upscale’ to dimensions of relevant (non pressure-cell) storage units by a method of symmetrical images.

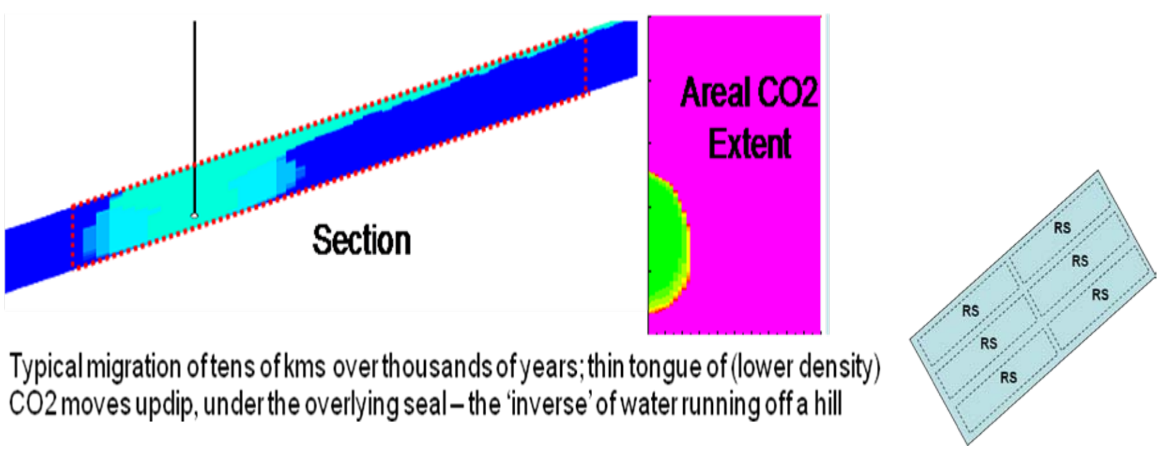


Figure 4: Structurally simple, homogeneous flow simulation model; and full store layout.

Having investigated behaviour of the migrating plume using many variants of the simple model, it was elected to corroborate findings through construction of a detailed model based on seismic and well data available to the project. An area of the Forties Sandstone Member was selected (Figure 5). This was away from hydrocarbon fields and the overlying Cromarty Sandstone Member into which injected CO2 might migrate, and with limited structural closures to buoyantly trap injected CO2. Realistic structure, surface topography and reservoir heterogeneity were incorporated, and the grid artificially tilted to yield models with regional dip varying from 1 – 3 degrees to the south-east.

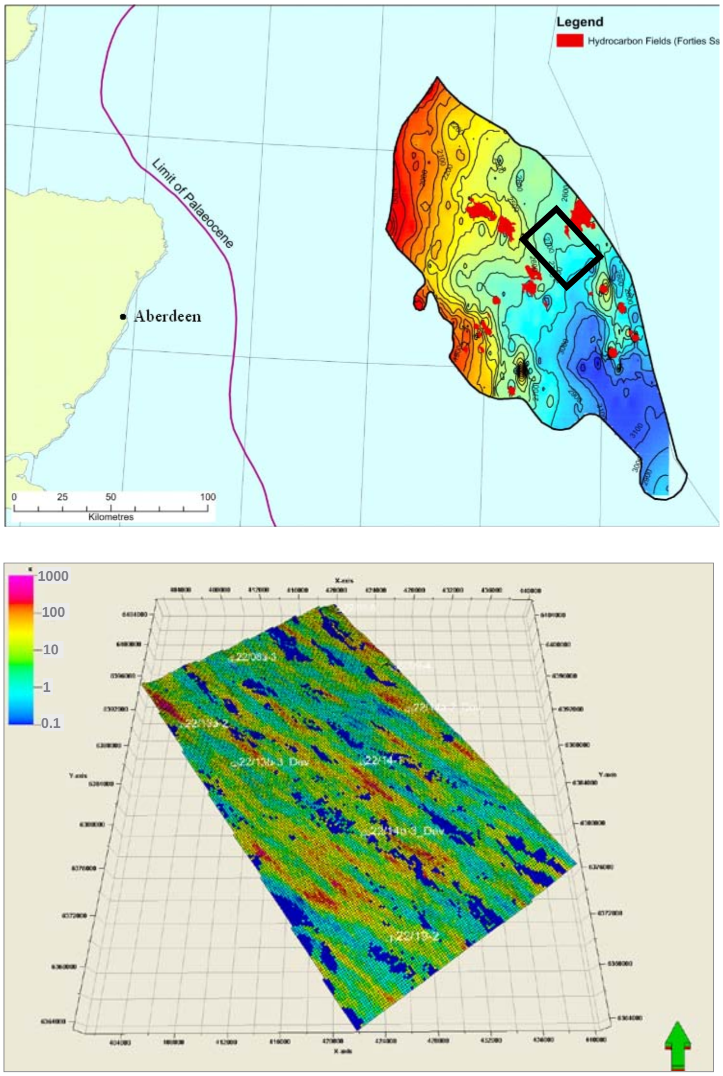


Figure 5: Location of detailed simulation model, Forties Sandstone Member (top), and view of modelled permeability field

Integrating results from the simple and detailed simulation models allowed distributions of 'storage factor' (F) to be defined for three storage 'regimes', with formation permeability and dip identified as the primary controlling variables (Figure 6). At 'low' permeability (Regime 1), storage is compromised by the low injection rates that can be achieved. At 'high' permeability and dip (Regime 3), predicted migration velocity is such that long-term stability of the plume may only be achieved if the amount of injected CO2 is limited. The most effective stores, in terms of technically accessible pore volume, occupy Region 2. Thus:

$$S = PV \times F_{\text{storage regime } i} \; ; 1 \le i \le 3$$

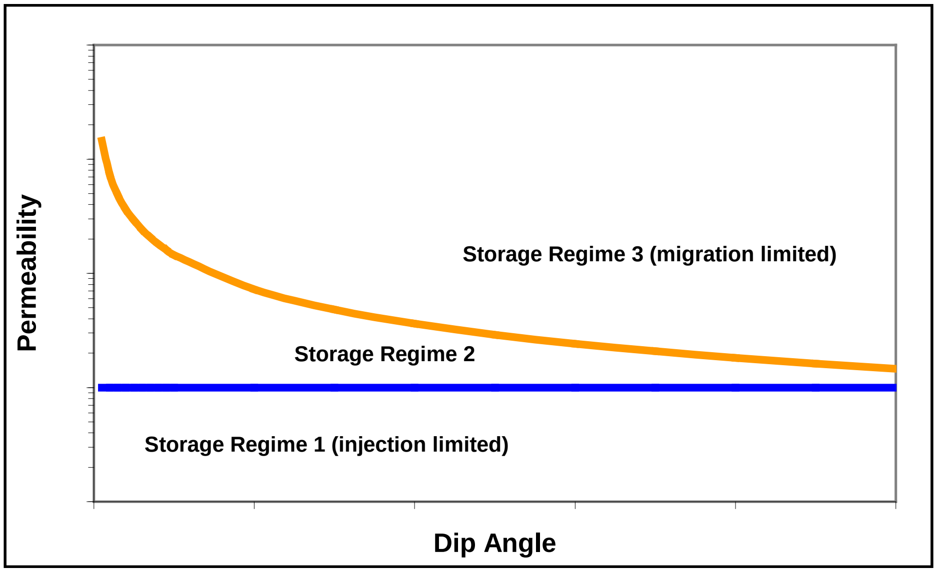


Figure 6: Characterisation of open aquifers from dynamic modelling.

Calculation of Technically Accessible Pore Volume within Saline Aquifer Daughter Units

If mapped in detail the majority of storage units within UKSAP would likely have some degree of identifiable, localised closure at the reservoir – caprock interface, that could buoyantly trap CO2 (similar to the situation seen at Sleipner). Given the geographical extent of study and large number of storage units to be characterised, it has been impossible to consider such closures in most cases. Nonetheless, where individual potential structural traps are known to be large and therefore important in terms of overall UK storage capacity, they have been incorporated. Such 'daughter units' exist in the Triassic Bunter and Ormskirk Sandstone Formations of the Southern North Sea and East Irish Sea respectively.

In assessing the technically accessible pore volume in such cases, two extremes may be considered: the structure itself could be essentially isolated from the associated parent aquifer, for instance through some form of deteriorating reservoir quality; or it could be in complete hydraulic communication and during CO2 injection, brine could be displaced from the structure into the surrounding aquifer. Where the structure is a producing hydrocarbon field, surveillance data will normally be available to help assess where in the spectrum the field in question lies. For water-bearing formations however, such data are rarely available and particularly if the formation is normally pressured there may be little evidence to suggest how the system will behave under dynamic conditions.

As a result, two methods were employed to estimate the technically accessible pore volume of individual water-bearing structures. The total pore volume was first calculated using the minimum of the stratigraphic thickness or structural relief, to capture pore volume from crest to spill-point. Then:

1) Assuming hydraulic isolation of the structure from the associated aquifer, the daughter unit is treated as a 'pressure cell' as previously described;

2) Assuming complete communication with the associated aquifer, the technically accessible pore volume is calculated on a 'fill-to-spill' basis, from the 'moveable' brine saturation and volumetric sweep efficiency:

$$S = PV \times (1 - S_{wirr}) \times \eta$$

where

S_{wirr} is the irreducible water saturation

η is the volumetric sweep efficiency

A range of likely irreducible water saturation was obtained using end-point data from the various relative permeability functions used in the project flow simulation models. A likely range of volumetric sweep efficiency was derived from results of a detailed flow simulation model of the 'Bunter Domes'.

The 'fill-to-spill' estimate is typically an order of magnitude greater than if hydraulic isolation is assumed (when the limiting factor becomes fracture pressure at the crest of the structure). Further simulation study also suggested it was unlikely that in areas where many such structures exist, all could be 'filled-to-spill' without pressure interference significantly reducing the overall accessible pore volume. Based on these results therefore, a third means was introduced to estimate the combined accessible volume in such circumstances:

$$S = PV \times F_{combined\ structures}$$

where $F_{combined\ structures}$ is a function of the number of 'competing' structures present.

Calculation of Technically Accessible Storage Resource from the Technically Accessible Pore Volume

The term technically accessible storage resource (Brennan et al. 2010) is used here to describe the mass of CO2 that could be stored in the technically accessible pore volume defined above.

It is derived by multiplying the technically accessible pore volume by the density of CO_2 at the probable storage temperature and pressure in each storage unit. The maximum, minimum and most likely temperature were taken from corrected well temperature data where available or estimated using a surface temperature of 8 ^oC and range of likely geothermal gradient derived from the Millennium Atlas (Millennium Atlas Co Ltd, 2003). Probable storage conditions were transposed to the centroid depth, by extrapolating pressures and temperature entered for each unit at the shallowest depth. For this purpose a representative brine pressure gradient of 10.066 MPa / km was applied in all cases, and the geothermal gradient for each storage unit assumed to be linear (again passing through 8 ^oC at surface).

The final storage pressure is considered to be the limiting pore fluid pressure determined as described above for pressure cells. For non-pressure cells, it was assumed that pressure increase in the vicinity of injection wells during the operational phase will dissipate 'rapidly' (i.e. within a period very much less than the timeframe considered for safe and secure storage), and thus the final pressure was assumed equal to the initial.

Calculation of Technically Accessible Storage Resource for Hydrocarbon Fields

From its inception, the focus of UKSAP has been on improving confidence in the offshore UK saline aquifer storage resource, the degree of uncertainty associated with previous estimates being significantly higher than for storage in depleted hydrocarbon fields.

A simpler method was therefore invoked for oil and gas fields, whereby the pore volume available for CO_2 storage was equated to the net volume of fluids withdrawn during hydrocarbon exploitation. Relationships for different hydrocarbon types were derived as follows:

Oil Fields

$$\text{CO2 capacity [Mt]} = (Np*Bo + Max[(Gp - Np*Rs, 0.0] * Bg + Wp * Bw - Wi * Bw - Gi * Bg) * \rho_{CO2}$$

Gas Fields

$$\text{CO2 capacity [Mt]} = (Gp * Bg + Wp * Bw - Gi * Bg) * \rho_{CO2}$$

Gas Condensate Fields

$$\text{CO2 capacity [Mt]} = (Gp/SF * Bg + Max[Ncond - (Gp/SF)*CGR*, 0.0] * Bcond + Wp * Bw - Gi * Bg) * \rho_{CO2}$$

where:

Gpsales	=	Cumulative sales gas production [10^6 scm]
Gpfuel	=	Cumulative fuel gas consumption [10^6 scm]
Gp	=	Gpsales + Gpfuel
Gi	=	Cumulative gas injection [10^6 scm]
Np	=	Cumulative oil production [10^6 scm]
Ncond	=	Cumulative condensate production [10^6 scm]
Wp	=	Cumulative water production [10^6 scm]
Wi	=	Cumulative water injection [10^6 scm]
Rs	=	Solution gas-oil ratio [scm/ scm]
CGR	=	Condensate-gas ratio [scm/ scm]
Bo	=	Oil Formation Volume Factor
Bcond	=	Condensate Formation Volume Factor
Bg	=	Gas Formation Volume Factor (=0.000352 z (T + 273) / P)
Bw	=	Water Formation Volume Factor
API	=	API gravity of produced condensate [degrees]
SF	=	Gas Shrinkage Factor
	=	1 / [1 + {(CGR/5.6184) * (API - 5.9)/(API + 131.5) * 0.00309}]

For the purposes of this study, it was assumed that any water influx accompanying hydrocarbon extraction would subsequently be expelled from the field during CO_2 storage.

A simplified flow diagram for calculation blocks is given in Figure 7.

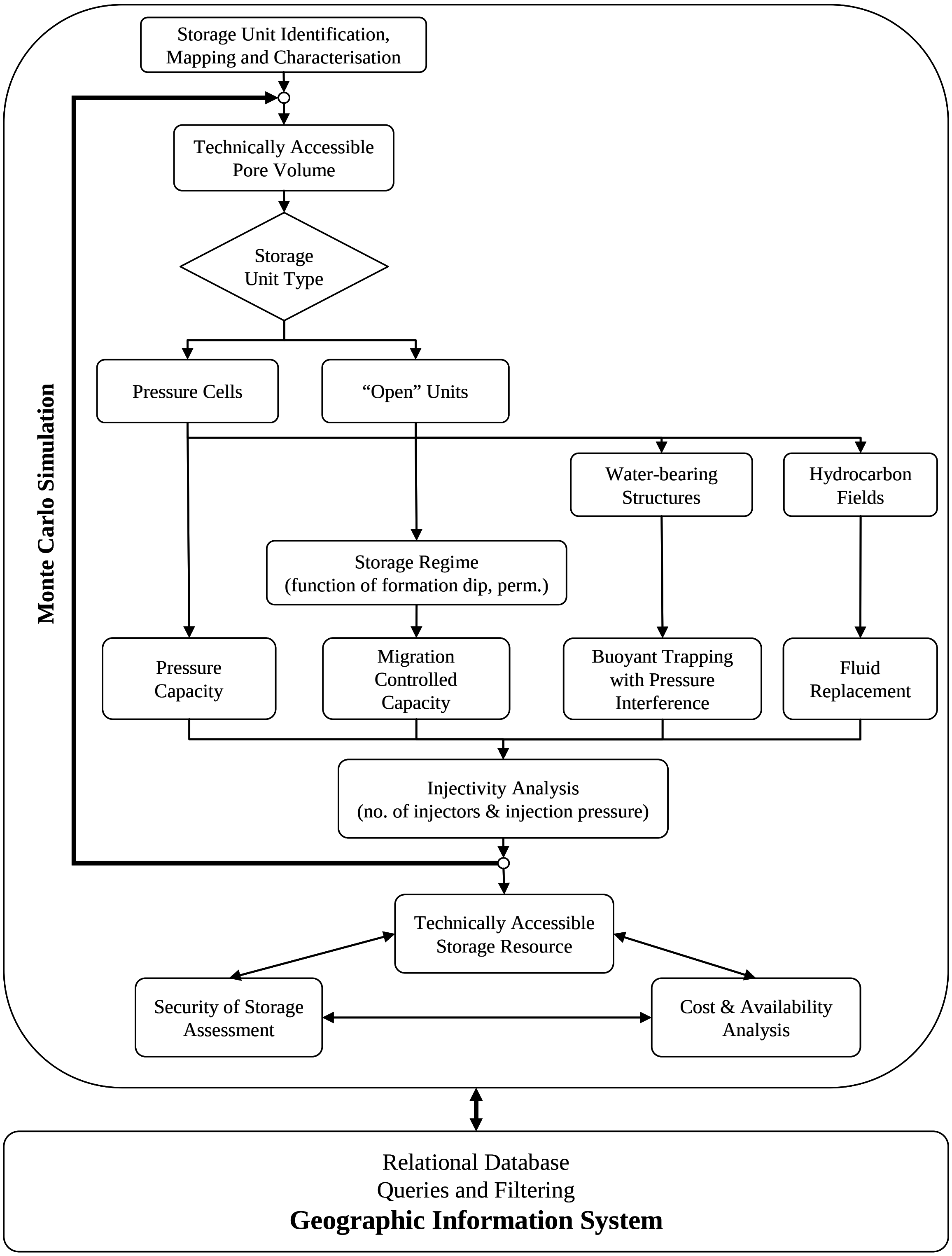


Figure 7: UKSAP Schematic of Workflow, Database and GIS

Security of Storage

In parallel with estimates of the technically accessible storage resource, an assessment of security of storage was completed for each of the saline aquifer storage units, using a Features, Events and Processes approach. The key metric was expressed as the ‘likelihood’ that success of a carbon storage project would be impacted by the identified feature or process, were it to occur. The assessment focused on two potential impairment categories: containment issues (susceptibility to upward or lateral movement of CO2 out of the storage volume), and operational issues (susceptibility to change in achievable storage capacity or injection rate). Twenty-three features or processes were assessed for each unit (Figure 8), in accordance with clear definition of what constituted a low, medium or high likelihood of impaired performance. This template ensured consistent scoring across all assessors and units.

Containment	**Seal**	Frac Pressure	Chemical Reactivity	Lateral Degradation					
	Faults	Density	Throw & Seal	Vertical Extent					
	Lateral Migration	Structural Trend	Depositional Trend	Dip Direction	Dip Magnitude	Rugosity	Hydro-dynamics	Pressure Sinks	National Boundary
	Wells	Density	Vintage						
Operational	**Formation Damage**	Mineralogy	Mechanical Integrity	Salinity					
	Compartment-alisation	Vertical	Lateral	Faults	Diagenesis				

Figure 8: Assessed Impairment Features and Processes

In addition to scoring the elements in terms of likelihood, a ‘confidence’ rating was based on the completeness of data available to make the assessment. Where there were insufficient data to assess an issue, it was assigned ‘unknown’.

The severity of impact of each feature/ process was assessed on a UKCS-wide basis by an expert group formed from the project participants and sponsors. The potential magnitudes of impact on both project cost and storage capacity were considered, yielding generic cost-impact and capacity-impact scales. Thus Boston Squares were generated for each storage unit (Figure 9). A cumulative scoring system (integrating likelihood, severity of impact and confidence data) was also developed in order to allow different units to be compared.

These tools provide the prospective store user or planner with a guide as to what issues and data shortages require urgent attention, in order to improve storage unit characterisation and/ or plan monitoring and mitigation activities. They also allow storage resource estimates to be ranked in terms of reliability, and frequently occurring sources of potential challenge to be identified and collectively addressed.

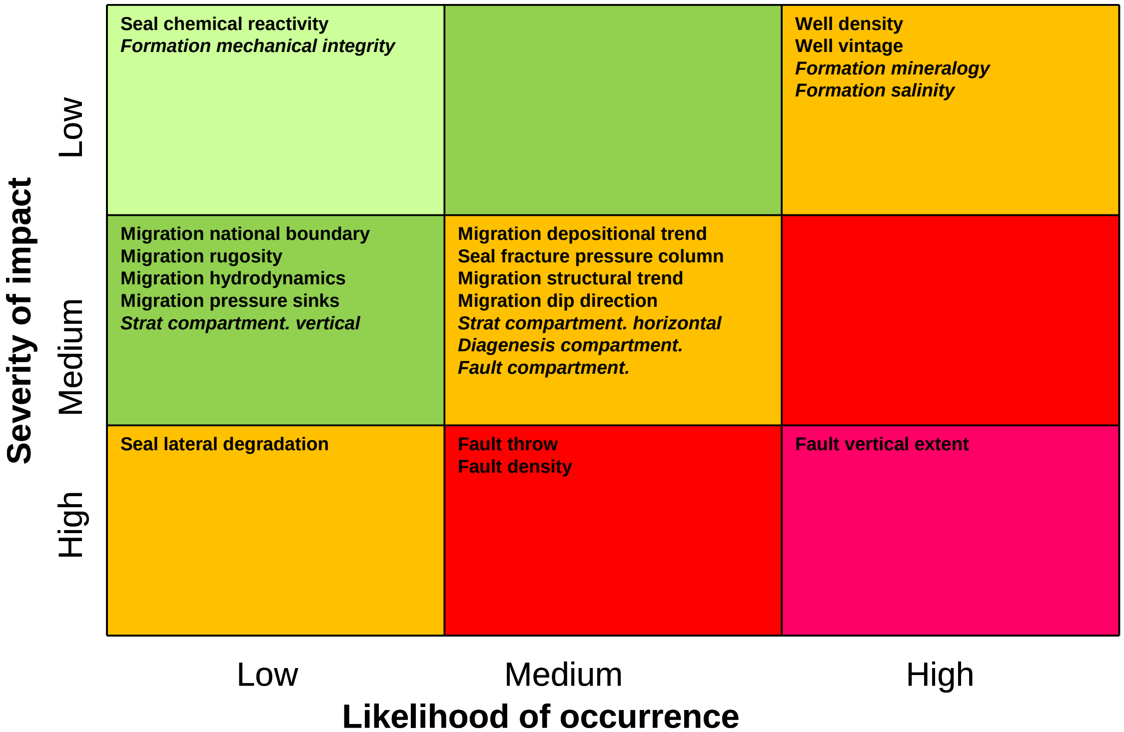


Figure 9: Security of Storage: example assessment

In addition a 'normalisation exercise' was undertaken, whereby a subset of hydrocarbon reservoirs was assessed according to the scoring definitions applied to saline aquifer stores. Hydrocarbon fields are expected to provide secure storage sites for CO2, as they are demonstrated traps for, and allow the production of, substantial volumes of low molecular weight fluids and gases. The majority of features assessed for these reservoirs were indeed ranked as low.

Economic Analysis

The preceding estimates of storage resource and assessments of security of storage underpin the economic analyses provided for each identified unit. A model for the costs of storage is developed that advances the state-of-the art for such basin-wide assessments. Different capital and operational cost components are considered for a variety of injection scenarios, including:

- Site appraisal and development;
- Injection facilities;
- Number of new injection wells required;
- Remediation of existing wells;
- CO2 transport by pipeline.

The marginal transport and storage costs expressed in £/tCO_2 stored will form a key performance indicator for determining the cost-effectiveness of individual projects and for large CCS deployment to be worthwhile from a societal perspective. The marginal project cost is heavily dependent on the precise configuration, utilization, and financing structure adopted. To quantify these various issues, a range of scenarios are examined. Considering two of the most important variables for example, injection rate and duration, scenarios evaluated cover injection rates of 2 – 60 Mt per annum and durations of 10 – 40 years, allowing the economics of projects to be assessed and compared on a unit-by-unit basis.

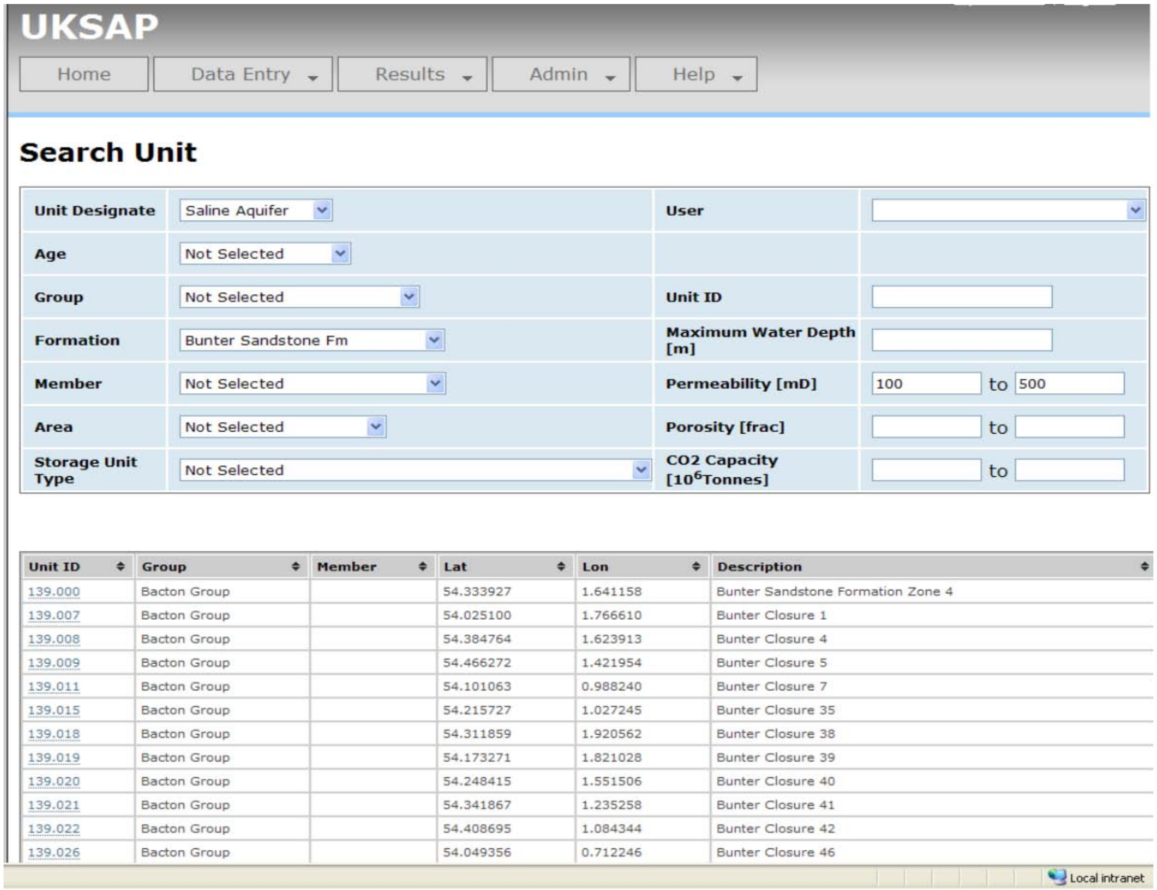
Consideration is also given to the likely timing of storage unit availability, resulting from competition with hydrocarbon production activity.

Thus curves of overall UK storage resource as functions of cost can be developed.

Web-Enabled Database and Geographic Information System

In order to collate, analyse and present the storage unit assessments in UKSAP, a bespoke web-enabled database with associated computational routines, including Monte Carlo simulation, has been built. These are linked to a Geographic Information System (GIS) which uses ESRI's ArcGIS Desktop product.

Nearly 600 storage units are described in the database, and interrogation can begin by 'manually' searching within a list of all available storage units, or selecting various screening criteria to narrow the field of interest (Figure 10). The characterisation and assessment data are then available on a series of 'tabbed' pages. Reference sources for all key parameters and assessors' comments provide an audit trail to the storage resource estimates and assessments of storage security.



Unit ID	Group	Member	Lat	Lon	Description
139.000	Bacton Group		54.333927	1.641158	Bunter Sandstone Formation Zone 4
139.007	Bacton Group		54.025100	1.766610	Bunter Closure 1
139.008	Bacton Group		54.384764	1.623913	Bunter Closure 4
139.009	Bacton Group		54.466272	1.421954	Bunter Closure 5
139.011	Bacton Group		54.101063	0.988240	Bunter Closure 7
139.015	Bacton Group		54.215727	1.027245	Bunter Closure 35
139.018	Bacton Group		54.311859	1.920562	Bunter Closure 38
139.019	Bacton Group		54.173271	1.821028	Bunter Closure 39
139.020	Bacton Group		54.248415	1.551506	Bunter Closure 40
139.021	Bacton Group		54.341867	1.235258	Bunter Closure 41
139.022	Bacton Group		54.408695	1.084344	Bunter Closure 42
139.026	Bacton Group		54.049356	0.712246	Bunter Closure 46

Figure 10: An example menu page in the UKSAP WDG

Alternatively, the search may be accomplished interactively via the GIS, for example by identifying stratigraphic horizons and areas of interest:

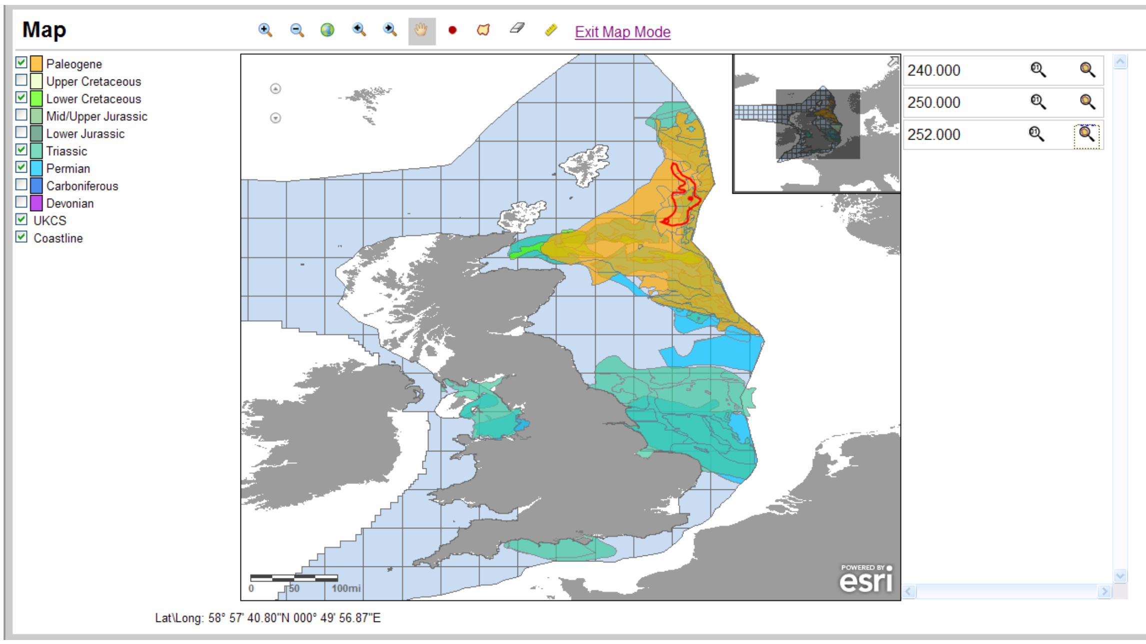


Figure 11: Screen-shot of GIS filtered by stratigraphic horizons, and highlighting one particular storage unit

Once the store or collection of stores of interest has been identified, the linked database may again be accessed to provide individual characterisation and assessment data, along with associated calculated results. The combined storage resource (P_{90}, P_{50}, P_{10}) of all matching units is also provided, by aggregation of component distributions.

High Level Findings

Quantified estimates of UK offshore CO2 storage resource and associated levels of confidence, arising from UKSAP assessments will be the subject of subsequent publication. In the meantime however, qualitative findings may be summarised as follows:

- Storage resource that is potentially technically viable has been identified in all five regions of study (Southern, Central and Northern North Sea, East Irish Sea Basin and Western Channel);
- The spatial distribution of storage units around the UK is such that many are vertically stacked, with deeper stores 'overlain' by shallower ones. This is likely to influence the manner in which the overall storage capacity available is most efficiently exploited;
- The reliability or degree of confidence that may be placed in individual storage unit assessments varies according to the quality and quantity of information available. Through a shared, web-enabled database, guidance was provided to promote a consistent approach from all participant organizations and assessors. Information sources have been recorded and computational methods have been applied uniformly, dependent on the identified storage unit type. Thus the basis upon which each estimate of storage resource has been made may be fully understood, and an audit trail exists to support revision as new or additional data become available;
- It is expected that certain storage units will encounter physical limitations that will dictate the cessation of CO2 injection; this could be for example mechanical strength of the seal, or the spill-point of a structural closure. In others however, it is the *anticipated* migration behaviour of CO2 post-injection that should limit the amount of CO2 stored. Under these circumstances, the criteria that define 'permanent and stable' storage have a direct bearing on assessed capacity;
- For 'open' aquifer stores that rely on residual saturation trapping rather than structural confinement of injected CO2, the combination of formation permeability, dip, and density difference between CO2 and in-situ fluids has a key bearing on the technically accessible pore volume, and hence amount of CO2 that may be securely stored;
- The degree to which the technically accessible storage resource may be practically utilized is influenced by achievable injection rates and the supply of CO2. The former may be tackled by appropriate selection of injection well location, completion and/ or stimulation; the latter may involve CO2 transport over considerable distances to match capture sources with available sinks, requiring careful planning of infrastructure;
- Regarding security of storage in the context of *overall* UK capacity, controls on lateral migration of CO2 in 'open' aquifers were identified as important features, as were the density and vintage of existing well penetrations.

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