Hartley Anderson Limited

Marine Environmental Consultancy

Hypersaline brine discharges likely to arise from carbon dioxide injection into saline aquifer stores

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1 Background

Over the last century anthropogenic sources of greenhouses gases (GHGs) have amplified the natural greenhouse effect and are estimated to have caused approximately 1.09°C of global surface warming above pre-industrial levels (IPCC 2021). Carbon dioxide (CO_2) is the principal GHG of concern as it constitutes the largest component of combustion emissions (BEIS 2021a) and has a potentially long atmospheric residence time (5-200 to ~1,000 years have been reported, see Houghton *et al*. 2001 and Archer 2005).

In response to the Climate Change Committee's (CCC) recommendation for the UK to reach net-zero emissions of greenhouse gases by 2050 (compared to 1990 levels) the UK Government published a Net Zero Strategy in 2019 which sets out a framework and delivery pathway to meet the UK's sixth carbon budget for the period 2033-2037. The Strategy was updated in October 2025 through the Carbon Budget and Growth Delivery Plan.

The Government recognises the role CCUS has in achieving its targets in relation to GHG emissions reductions and reducing the carbon intensity of the energy and industrial sectors. The proximity of emission sources to the geological storage sites provides the right opportunity for these industries to decarbonise through the CCUS cluster approach that the UK had established. The first two clusters, called Track-1, were selected in 2021 (HyNet, East Coast Cluster), and the UK Government has allocated up to £21.7 billion over 25 years to support Track-1. While carbon dioxide storage licences and storage permits are in place for Track-1 projects, further licensing for carbon dioxide storage may be required to support the future capacity required for further decarbonisation. The Clean Power 2030 Action Plan includes an additional 2030 installed capacity for low carbon dispatchable power, which would include CCUS and hydrogen, of 2-7GW. While not forming Government policy, the CCC (2025) Balanced Pathway scenario for net zero by 2050 suggests a potential need for 8GW of low carbon dispatchable power in 2035, rising to 38GW by 2050.

The use of depleted hydrocarbon reservoirs, saline aquifers and halite deposits for storing CO_2, is at an early stage of development and no storage sites in the UK are yet operational. The risk of leakage of stored CO_2 from storage sites is considered to be low. However, for storage in saline aquifers, the pressurisation of the storage formation may result in the need for operational discharges of aquifer water to achieve pressure relief in the store, and result in seepage of aquifer water to seabed via natural rock outcrops. The potential impacts to the marine environment of such seepage or discharge of hypersaline aquifer water need to be understood. In addition, the construction of caverns in rock salt (halite) formations can involve the discharge to sea of significant quantities of high salinity brine.

This briefing summarises the available scientific information and impact assessments made for selected proposed developments.

A Review of Consents (RoC) in relation to UK Special Protection Areas (SPAs) commenced in 2021, with the Habitats Regulations Assessment (HRA) screening identifying 23 projects and 17 related SPAs for which there was a likely significant effect. The draft Appropriate Assessment (AA) was subject to public consultation in 2023 and was subsequently updated following feedback. Of those projects subject to assessment (see Table 1.1 of the RoC AA report), it was concluded that only one project, Race Bank offshore wind farm, would result in adverse effects on site integrity, in relation to the red-throated diver feature of the Greater Wash SPA. This conclusion was based on the potential displacement effects of Race Bank, and a reduction of the available habitat for the species, in the context of red-throated diver feature being in unfavourable condition.

Table 1.1: Proposed CCS projects in UK waters

CCS Project	Location	Type of Storage	Offshore Operator/ Partners	Details
HyNet North West	Liverpool Bay	Depleted natural gas field(s) beneath Liverpool Bay	Eni	Up to 10Mt CO_2 per year by 2030.
East Coast Cluster	Southern North Sea, 145km offshore from Teesside.	Endurance saline aquifer within the Bunter Sandstone *ca*. 80km off the Humber/Yorkshire coast.	BP, Equinor, TotalEnergies	The initial development is for 4Mt/year from 2027 and 100Mt is planned to be stored over 25 years. The ECC has an ambition to store 23Mt CO_2 per year by mid-2030's.
Acorn	Central North Sea	Storage in the Captain sandstone or depleted oil field, *ca*. 100km offshore.	Pale Blue Dot Energy	5-10Mt CO_2 per year by 2030.
Viking	Southern North Sea	Depleted gas field(s)	Harbour Energy	Up to 10Mt CO_2 per year by 2030.

2 The use of Saline Aquifers for CO_2 Storage

The storage of CO_2 in deep underground geological formations subjects CO_2 to temperatures and pressures that exceed the critical point for CO_2, above which it phases into a supercritical fluid which has properties of both a liquid and a gas. Supercritical CO_2 is denser than gaseous CO_2, while still behaving like a liquid, allowing the storage of a greater volume in sequestration. At depths greater than 800m below the seabed the natural temperature and fluid pressures are in excess of the critical point of CO_2 for most places on Earth, such that CO_2 injected at these depths will remain in the supercritical phase.

Porous geological formations are currently considered the most promising CO_2 storage sites. A number of different geological formations have been identified as suitable for CO_2 storage, these include: saline formations, depleted oil and gas reservoirs, unmineable coal seams, basalt formations and organic-rich shales. To provide effective long-term storage the formation must have one or more confining zones with a non-porous caprock, with no leakage pathways.

Saline aquifers are layers of deep sedimentary rocks saturated with saline formation water or brines containing high concentrations of dissolved salts overlain by a caprock layer which is impermeable to water, hydrocarbon liquids and gases, and CO_2. Studies show that saline formations have the largest potential volume for storing CO_2 in the United Kingdom Continental Shelf (UKCS) (BEIS 2022) and globally, with saline aquifers providing an estimated global sequestration capacity of 10,000 Gt of CO_2 (Cao *et al*. 2020).

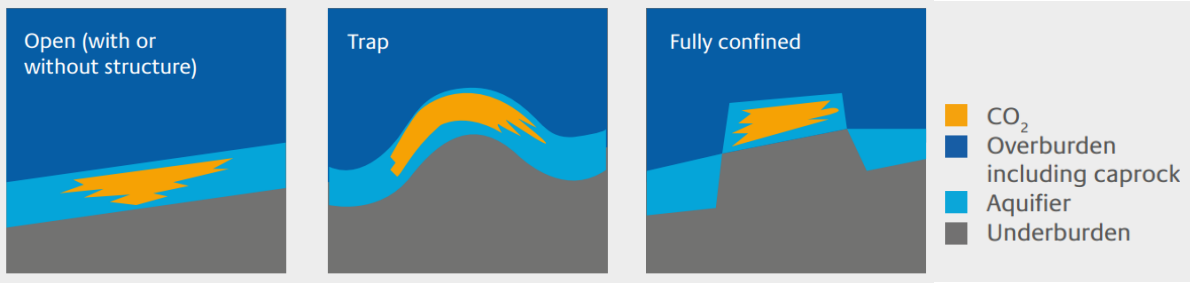
There are four different types of saline aquifer classified as suitable for CO_2 storage, open stores (with or without structure), structural traps and fully confined aquifers (Figure 2.1). The injection of supercritical CO_2 has different effects within each different aquifer structure.

Typically, open aquifers have a large structure and as CO_2 is injected some brine is displaced into the surrounding aquifer. Supercritical CO_2 has a lower density than the aquifer brine and this buoyancy drives the supercritical CO_2 to rise to the roof of the store and migrate up any slope beneath the cap rock (ETI 2018). The CO_2 injection rate will be constrained by the fracture pressure of the overlaying caprock, such that aquifer pressure will rise if the CO_2 injection rate exceeds the rate at which the brine migrates into other areas of the aquifer. If the pressure increases too much it is possible for this to exceed the containment strength of the rock and could lead to fractures in the seal (ETI 2018); to manage store pressures, various projects have proposed the production of aquifer water via wells.

Geological traps in open aquifers effectively confine the buoyant supercritical CO_2 in a geological high point of the reservoir. Due to the open structure of the reservoir the brine is unconfined and some is likely to be displaced to other areas of the aquifer.

Fully confined aquifers are surrounded by impervious rock and provide an effective long-term storage solution for CO_2 where there is high confidence that it will remain within the store and not migrate to other areas of the aquifer which may have faults or other migration pathways. However, as CO_2 is injected into the confined store the pressure increases and as the brine cannot be displaced to adjacent areas, without active pressure relief, the storage capacity would be constrained by the requirement to keep the aquifer pressure below the containment strength of the caprock (ETI 2018).

Figure 2.1: Types of saline aquifer (ETI 2018)



There are five existing commercial-scale CCS projects in saline aquifers, including the Sleipner and Snohvit projects in Norway, Quest project in Canada, Gorgon project in Western Australia and the In Salah project (currently suspended) in Algeria (Table 2.1). The Sleipner CCS project was the world's first industrial offshore CCS project and has captured more than 19Mt CO_2 within the aquifer since injection began in 1996 demonstrating the potential for injected CO_2 to remain securely within the aquifer (Furre *et al.* 2017). Effective site monitoring of both the Snohvit and In Salah projects identified risks associated with increased pressure within the aquifer (Snohvit, Ringrose 2018) and the potential for vertical leakage into the caprock (In Salah, Ringrose *et al.* 2013) which led to interventions to mitigate the risks with a modified injection plan implemented at Snohvit and the suspension of injection at the In Salah project. While injection has not resumed on the In Salah CCS project, investigations on the project have led to many new insights into the rock mechanical response to CO_2 injection, and no leakage has been observed indicating that the CO_2 remains safely contained within the storage complex. These existing CCS projects provide a limited information base for planning future offshore CO_2 storage projects and the effectiveness of a range of monitoring tools (Ringrose 2013).

Table 2.1: Existing CCS projects using saline aquifers as storage facilities (adapted from Cao *et al.* 2020)

CCS Project	Location	Type of Storage	Operator/ Partners	Details
Gorgon	Western Australia	Dupuy Formation, deep saline formation 2.3km deep.	Joint Venture led by Chevron, partners ExxonMobil and Shell.	3.3-4Mt CO_2 per year, injection started in 2019. Expected lifespan of 40 years
Quest	Alberta, Canada	Basal Cambrian Sands saltwater and brine formation 2km deep.	Shell	1Mt CO_2 stored per year since injection started in 2015. Storing over 6Mt CO_2 to date. Projected lifespan for 25 years.
In Salah	Onshore Algeria	Water leg within the carboniferous gas sandstone reservoir in Krechba field, 1.8km deep	Joint Venture BP, Sonatrach and Statoil (now Equinor)	3.8Mt of CO_2 stored since injection commenced in 2004. Injection suspended in 2011 due to concerns of possible vertical leakage into the caprock.
Sleipner CCS	Norway	Utsira sandstone saline aquifer 1km deep.	Equinor	1m tonnes CO_2 injected annually, commenced in 1996. (>19Mt CO_2 stored by end 2020).
Snohvit – 2 x CO_2 injection wells in	Norway	Tubåen formation, sandstone saline aquifer 2.5km deep.	Equinor	Operation commenced in 2007. CO_2 from the Snohvit well stream is captured at the Melkøya plant, returned to the field

CCS Project	Location	Type of Storage	Operator/ Partners	Details
operating field				and reinjected. 700,000 tonnes of CO_2 are captured and stored each year. CO_2 injection wells drilled in 2004 and 2016.

3 Potential for brine discharges occurring deliberately for pressure relief or seepage

Pressurisation of a saline aquifer from CO_2 injection may lead to brine leakage (and potentially of CO_2, see Birkholzer *et al.* 2015 and references therein) from of the aquifer. Potential leakage pathways from an aquifer include an outcrop of the aquifer formation, an undetected permeable fault, activation of benign fault, an existing well bore, and a zone of caprock with enhanced permeability (e.g. interconnected permeable strata within a predominantly impermeable overburden or a gas chimney). Supercritical CO_2 has a lower density than hypersaline brine and would therefore preferentially migrate upwards towards vertical leak pathways. For saline brine to migrate vertically the upward driving force for the brine must overcome density effects (BGS *et al*. 2010). In the event of brine leakage there may be potential for brine to contaminate a shallow freshwater aquifer connected via a legacy wellbore or permeable fault.

Noy *et al*. (2012) conducted a series of reservoir flow model simulations for an area of the Bunter Sandstone formation in the UKCS southern North Sea to investigate effects of large-scale injection of CO_2 into the formation, including effects on pore fluid pressure and the potential to displace formation brines from the reservoir into adjacent formations and ultimately to the seabed surface through outcrops of the reservoir formation. The Bunter Sandstone outcrops near to well 43/28a-3, as confirmed by survey work (geophysical, photographic and physical sampling) undertaken for National Grid in 2012 as part of the Yorkshire and Humber offshore transport and storage project, as the proposed store for the project (Endurance, ~25km to the west) was found to be probably connected to the outcrop. The Bunter Sandstone was estimated to subcrop (i.e. be located beneath a thin veneer of drift) over an area of ~5km^2, with an outcrop at the seabed of ~1.4km^2. Further shallow borehole surveys were undertaken in June 2022 to inform plans for storage at the Endurance for the East Coast Cluster (the diapir/outcrop structure is illustrated in figures 3-21 and 3-22 in the Environmental Statement[1]) (BP 2023). Noy *et al.* (2012) modelled an outcrop area of 7.68km^2 and the results (summarised in Table 3.1) give an indication of the scale of CO_2 injection that could be possible and indicate that increasing the number of injection points (from 1 to 12 injection wells) could maximise storage capacity whilst not exceeding a limiting pore pressure increase (Noy *et al*. 2012). Scenarios 4a and 4b (Table 3.1) indicate that approximately 15-20 $MtCO_2$.yr can be injected into the model for 50 years without exceeding 75% lithostatic pressure within the model, below which the geomechanical stability of the reservoir can be maintained (Noy *et al*. 2012). In scenarios where the reservoir pressure remains below 75%, the peak brine release rate of pore water (i.e. the aquifer water contained in the interstices between the sand grains forming the rock) at the seabed ranges 49-291 kg.s^{-1}, with the total volume of pore water released from the seabed outcrop only sightly less than the final volume of CO_2 injected into the formation (Noy *et al.* 2012). Whether any, or how much brine may be produced from such outcrops will depend on how well the storage site is connected to the wider Bunter aquifer and whether the outcrop is open to flow from the storage site (National Grid & Carbon Sentinel Ltd. 2015).

[1] https://www.gov.uk/government/publications/northern-endurance-partnership-development

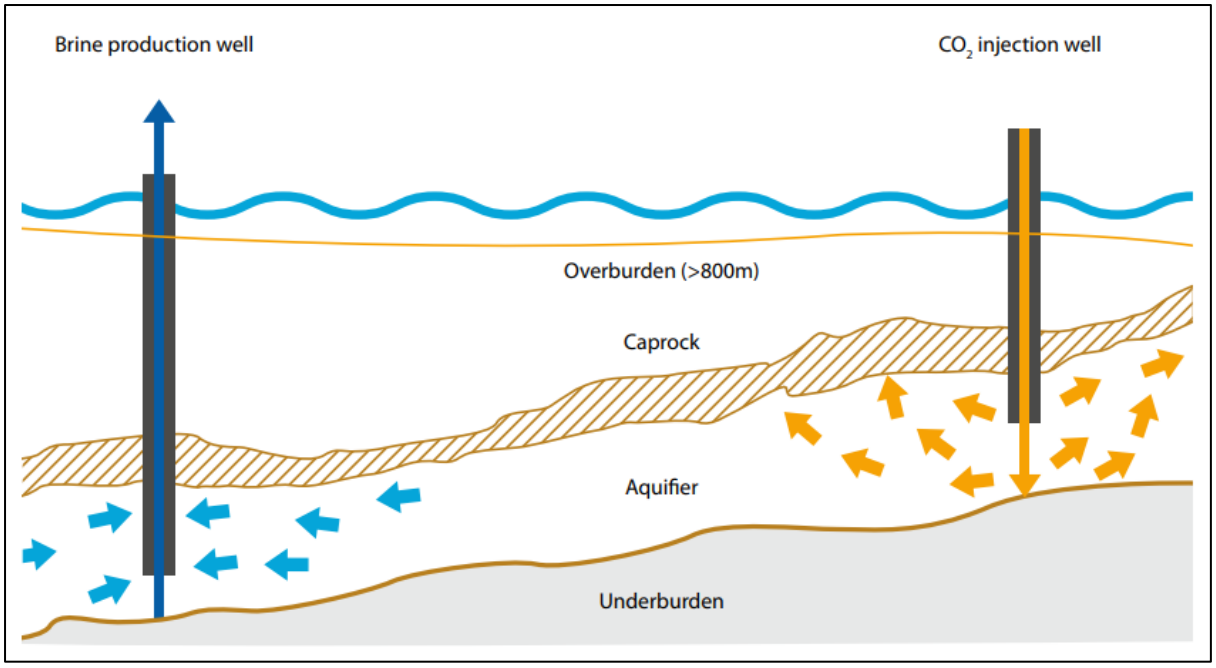
Table 3.1: Modelling potential brine flow from the Bunter Sandstone Formation resulting from large-scale CO_2 injection over a 50 year injection period for a range of reservoir properties (adapted from Noy *et al.* 2012)

	Scenario description	Number of injection wells	Overburden permeability (m^2)	Reservoir permeability (mD)	Total injection rate ($MtCO_2.yr$)	Reservoir pressure exceed 75%	Peak flow rate of brine from outcrop ($kg.s^{-1}$)	Total cumulative flow of brine from outcrop (Mt)	Time for cumulative flow to be reached (yrs)
Base case	-	1	10^{-19}	100	5	No	75	360	>1000
Scenario 1	Raised overburden permeability	1	10^{-17}	100	5	No	35.4	90	300-400
Scenario 2	Reducing reservoir permeability	1	10^{-19}	20	5	Yes	21	277	3000
Scenario 3	Increased number of injection wells	12	10^{-19}	100	12	No	170	840	1500
Scenario 4a	Optimised injection rate of 12 wells, at base reservoir permeability	12	10^{-19}	100	21.9	No	291	833[1]	150[1]
Scenario 4b	Optimised injection rate of 12 wells, at raised reservoir permeability	12	10^{-19}	20	13.7	No	49.2	723	3000

Notes: 1 - This simulation could not be run beyond 150 years in the model, the brine discharged at this time is estimated to be half the long term total.

In order to manage hypersaline aquifer pressure during carbon dioxide storage it may be possible to alleviate the pressure increase by removing some brine from the aquifer via brine production wells (Figure 3.1), potentially increasing the aquifer holding capacity (ETI 2018), although the economic viability of this is unclear. Disposal of the produced brine could be managed in a number of ways such as disposal at the seabed, at the sea surface via a production platform, or it could be reinjected subsurface into other strata (Blackford *et al*. 2021, ETI 2018).

Figure 3.1: Brine production to alleviate aquifer pressure in support of CCS (ETI 2018)



The North Sea has a typical annual salinity range of 34-35.4 PSU (practical salinity units (PSU) are a measure of conductivity or water at a constant pressure and temperature, values approximate to parts per thousand (ppt or ‰) another commonly used measure of salinity), and while the characteristics of brines may vary significantly, hypersaline brines typically exceed salinities of 200 PSU, temperatures of 50°C, are anoxic and have high concentrations of contaminants such as heavy metals (Dewar *et al*. 2022). Discharges of hypersaline brine are likely to result in environmental impacts to the flora and fauna within the vicinity of the discharge location up to distances where sufficient mixing and dispersion have occurred that salinity, and where present, contaminant concentrations, are reduced to within no effect concentration levels.

Dewar *et al*. (2022) modelled the behaviour and potential area of seabed impact of a hypersaline plume under three different release scenarios designed to compare the impact with height of release within the water column (surface, mid-water and seabed releases over a 50m water depth) (Table 3.2). Two further scenarios of smaller discharge rates were designed to approximate an unmanaged seep to the seabed via an outcrop of the aquifer bearing strata, comparing a single point release of 20,000 barrels/day on the seabed with ten diffuse point releases of 2,000 barrels per day each (Table 3.2). Modelling results focussed on the area of seabed impacted by salinity, temperature, oxygen and contaminant levels predicted to exceed toxicological thresholds for impacts to benthos. Impacts higher up within the water column had a maximum horizontal impact over 10's of metres, and given open water currents most motile species would quickly pass through minimising any impact duration.

As may be expected in relatively shallow, well mixed environments, natural mixing processes dominated by tidal flows rapidly disperse hypersaline plumes. In all of the modelling scenarios the predicted temperature change (Table 3.2) and oxygen levels were highly localised and considered too small to present a significant impact (Dewar *et al*. 2022). Impacts associated with increased

salinity and contaminant levels were generally restricted to 10-100m's from a seabed discharge. However, the rapid dilution of the brine as it disperses through the water column from both mid-water and surface release scenarios resulted in a much smaller impact area to the seabed when compared to the seabed releases (Table 3.2, Dewar *et al*. 2022).

Table 3.2: Modelling simulation results assessing the natural dispersion of hypersaline brines from five different discharge scenarios to the marine environment (assumed brine release parameters: 258 PSU at 56°C) (adapted from Dewar *et al.* 2022)

Scenario	Release Rate (barrels / day)	Release mode	Max Salinity Deviation (PSU)	Max Temp. Deviation (°C)	Horizontal distance of impact on seabed from source (m)	
					Salinity	Contaminant
1	40,000	Seabed	13.96	2.95	≤100	≤500
1 (x4)	160,000	Seabed	13.96	2.95	*	*
2	160,000	Surface	1.29	0.29	<20	<50
3	160,000	Mid-depth	2.49	0.54	<20	<125
4	20,000	Seabed single point seep	9.79	2.08	<20	<500
5	10 x 2,000	Seabed multiple point seep	1.85	0.40	ND	<20

*Note: Scenario 1 (x4) included to show overall area of impact to the seabed from four brine production wells spaced at some distance from each (equating to a total discharge to seabed of 160,000 barrels/day). Initial modelling indicated that the four plumes did not interact at the well spacing defined in the model. ND – not detected. * Distance as for Scenario 1, around each of the four wells.*

Qafoku *et al*. (2017) reviewed available literature on the leakage of CO_2 and brine from deep saline storage reservoirs and its potential effects on an overlying freshwater water aquifer. The review investigated effects of CO_2 and brine leakage on the pH, total dissolved solids, contaminants and salinity of the freshwater aquifer, and noted the importance of establishing site specific groundwater quality baseline data against which changes in these characteristics could be measured to monitor for leakages into the aquifer. The review largely focussed on the impacts of dissolved CO_2 within the brine, but some findings are relevant to the leakage of hypersaline brine.

Modelling studies indicated that the width of the leakage pathway was a major factor in determining whether the dense hypersaline brine would be transported through vertical leak pathways with the lower density supercritical CO_2. Narrow pathways were found to increase the co-transport of brine through vertical leak pathways while wide pathways may allow CO_2 mobility without co-transportation of brine (Keating *et al*. 2013, referenced in Qafoku *et al*. 2017).

The solubility of CO_2 within the formation water was found to decrease in highly saline solutions consequently limiting the levels of carbonic acid formation, which may limit the change in aquifer pH and the rate and extent of pH-dependent reactions in aquifers (Horner *et al.* 2015, referenced in Qafoku *et al*. 2017).

While some studies included in the review showed that significant levels of contaminants may be carried upwards from the saline aquifer with the brine and CO_2, site specific properties such as the

minerology (e.g. calcite composition through pH buffering) and sedimentary composition (through adsorption capacity) of the aquifer were important drivers controlling aqueous elemental concentrations and limiting their distribution in the aquifer around the leakage point (references in Qafoku *et al*. 2017, Rossi *et al*. 2022). Modelling the potential fate of organic compounds that may be present in deep saline aquifers (including BTEX, phenols and PAH compounds) and have the potential to contaminate a freshwater aquifer through an unidentified leak path were based on contaminant concentrations typically found in formation water. Modelling of a scenario of continuous brine leakage containing high concentrations of organic contaminants indicated that the spatial distribution of organic contaminants within the receiving aquifer after 200 year leakage was very small due to adsorption and biodegradation mechanisms (references in Qafoku *et al*. 2017).

4 Composition of potential brine discharges from the Endurance saline aquifer as a comparative case study

The Endurance saline aquifer is a domed structure within the Lower Triassic Bunter Sandstone Formation which has been identified as a CO_2 storage site, currently for the East Coast Cluster to capture CO_2 from industries across the Humber and Teesside (Table 1.1). The Endurance storage site is located across UKCS Blocks 42/25, 43/21 and 43/26 of the southern North Sea approximately 70km east of the East Riding coastline of Yorkshire. The central estimate (P50) storage capacity of the Endurance aquifer has been estimated at 450Mt of CO_2 and the first phase of storage is anticipated to have an average injection rate of 4Mt CO_2 per year from 2027, and the wider East Coast Cluster project is anticipated to store up to 23Mt CO_2 year by the mid-2030s[2]. In support of the planning stages of an earlier project which proposed to use the Endurance storage site, borehole samples were collected to characterise the Bunter Sandstone fluids in terms of temperature, salinity, trace elements and other constituents (Hartley Anderson Ltd. 2011, Hartley Anderson Ltd. 2014). Further sampling of the formation water was undertaken in June 2022 at shallow borehole (43/28-NEPBH1), which included reservoir pressure and fluid samples to 291m TVDSS (True Vertical Depth Below Sea Level), the analytical results indicated significant differences between the outcrop and at the store (BP 2023). At the outcrop, salinity increased with depth to 87,050 ppm at 291m, and other minerals and metals analysed for also showed increased concentrations with depth, see Table 4.1.

4.1 Comparison of saline aquifer water with seawater ranges in the North Sea

4.1.1 Temperature and salinity

In the southern North Sea, in the area around the proposed Endurance storage site in the Bunter Sandstone, seawater salinity ranges between 34‰ to 35‰ (Connor *et al*. 2006, based on modelled data), with average sea surface temperatures ranging between 5.3°C in February and 14.0°C in August (Cefas website).

Total Dissolved Solids (TDS) in the Bunter aquifer water sample taken from the separator line during the test flow were 259.680 g kg^{-1} (measured) and 254.014 g kg^{-1} (calculated from the ionic composition) (Expro 2013). This approximates to a salinity some 7.5 times greater than shelf seawater at S_p = 35.

The density and pH of the Bunter aquifer water sample taken from the separator line during the test flow (Expro sample ref: ADS 80553) were 1.1976 kg/l (@20.00 +/- 0.8°C) and 6.14 (@21.1+/-1.2°C) respectively (Expro 2013). Compared to seawater, the Bunter aquifer water is substantially more dense and acidic (density of seawater at surface ~ 1.025 kg/l, mean pH of North Sea 8.03 modelled data (UKMMAS 2010)). The temperature of the Bunter aquifer water was measured in the ranges 10-70°C, with an expected average of around 35°C for the Endurance storage site (Hartley Anderson 2011), which is considerably above the seawater ambient range.

4.1.2 Trace elements and other constituents

The concentrations of some elements in seawater vary over different ocean basins, notably arsenic, copper, iron and manganese; significant horizontal and vertical gradients of trace metal concentrations across oceanic and coastal waters also occur (Bruland *et al*. 1991).

Table 4.1 shows a comparison of concentrations for various components in the Bunter aquifer water with those in ambient global and North Sea seawater. Concentrations in the Bunter aquifer water are elevated above ambient for most trace and other metals. In some cases this may be a function of the

[2] https://www.gov.uk/government/publications/northern-endurance-partnership-development

levels of detection of analysis and values quoted, although many are present at orders of magnitude greater than the ambient seawater concentrations. Results from sampling at the outcrop (see Section 3) related to the Northern Endurance Partnership (BP 2023, results presented as µg g^{-1} dry sediment) indicate that with the exception of lead, metal concentrations are generally below OSPAR Background Assessment Concentration (BAC) levels, where these exist (the comparison was limited to arsenic, chromium, copper, lead, nickel and zinc). Concentrations of metals are generally higher at the outcrop than the storage site.

Table 4.1: Trace and other element concentrations from Bunter Aquifer water compared to ambient seawater values (mg/l)

Element	Bunter Aquifer Water[1]	Bunter Aquifer Water[2]	Mean Ocean Water[3]	OSPAR[4]	North Sea SEA2[5]	North Sea[6]	North Sea[7]	Aquifer c./to North Sea Ambient
Lithium	9.4-10.2	-	0.17	-	-	-	0.1	Higher
Barium	1-2	-	0.03	-	-	0.022-0.08	0.05	Higher
Strontium	128-140	-	8	-	-	-	13	Higher
Magnesium	3137-3962	-	1350	-	-	-	1272	Higher
Potassium	1727-1860	-	380	-	-	-	-	Higher
Iron	<1-3	-	0.01	-	-	0.0018	0.002-0.02	Higher
Copper	1.1-4.8	-	0.003	0.00014-0.00036	0.00023-0.00083	0.00002-0.0005	0.001-0.001	Higher
Zinc	9.6-10.7	-	0.01	0.00017-0.00028	0.00025-0.0014	0.0003-0.0014	0.00055-0.0043	Higher
Manganese	1.9-3.2	-	0.002	-	-	-	0.001-0.01	Higher
Aluminium	<0.7	-	0.01	-	-	-	0.16-0.19	In range
Lead	1.3-1.8	0.002	0.00003	0.00001-0.000017	-	0.00002-0.000081	0.00001-0.00006	Higher
Chromium	0.4-0.9	0.002	0.00005	-	0.00022-0.001	-	-	Higher
Nickel	<0.2-2.2	-	0.002	0.000009-0.000012	-	-	0.0001-0.0005	Higher
Cadmium	0.2	-	0.00011	0.000006-0.000024	0.000004-0.000032	0.000004-0.000023	0.00001-0.00005	Higher
Cobalt	0.10-0.19	-	0.0001	-	-	-	0.0001	Higher
Silver	<0.05	-	0.0001-0.0003	0.0009-0.00105	-	-	-	Possibly higher
Vanadium	0.08-0.10	-	0.0002-0.007	-	-	-	0.0003	Higher

Element	Bunter Aquifer Water[1]	Bunter Aquifer Water[2]	Mean Ocean Water[3]	OSPAR[4]	North Sea SEA2[5]	North Sea[6]	North Sea[7]	Aquifer c./to North Sea Ambient
Arsenic	1.5-2.8	1.3	-	-	-	-	0.003-0.024	Higher
Boron	11-12	-	4.6	-	-	-	-	Higher
Phosphorus	<7	-	<0.001-0.06	-	-	-	-	Possibly higher
Mercury	<0.0002-0.0005[7]	-	0.00003	-	0.00000013-0.000069	0.000001-0.000003	0.000001-0.0001	Higher

Data from: 1. Expro (2013) Ionic composition by volume corrected for MDT dilution; 2 BP (2023) – limited information presented in the ES for the Northern Endurance Partnership in mg/l units. Values are assumed to be from the lowest point in the borehole at 291m TVDSS; 3. Goldberg (1963); 4. Based on background concentrations for SNS from OSPAR (2005). Background concentrations (BCs) are assessment tools intended to represent the concentrations of certain hazardous substances that would be expected in the North-East Atlantic if certain industrial developments had not happened; 5. Cefas (2001); 6. Ekins et al. (2005); 7. Jacobs et al. (1992).
Note 7. Mercury sampling method may result in recording of lower than actual concentrations

4.2 Comparison of saline aquifer water with North Sea formation water

North Sea formation waters vary widely both in total salinity and in their chemical compositions. Warren *et al*. (1994) notes the following:

- Northern North Sea (NNS) – formation waters generally of low salinity and broadly similar chemistry.
- Central North Sea (CNS) - enormous heterogeneity in salinity and chemical composition, can be subdivided into several populations geographically and stratigraphically: highly saline in the Triassic in Central Graben, barium rich in Brae Formation. Geological controls such as salt diapirism and reservoir lithology may be significant factors controlling compositions.
- Southern North Sea (SNS) - highly saline (chloride concentrations of 100,000-300,000mg/l in contrast to ~19,400 mg/l in seawater), but extremely variable chemical compositions which are very different to elsewhere in the North Sea, generally containing high sulphate and iron, (although this may indicate contamination, it is more likely it reflects lithological controls, high salinity from nearby and overlying evaporites, iron from red-bed sandstones).

TDS at 0.2 µm of the Bunter aquifer water sample taken from the separator line during the test flow were 310,993 mg l^{-1} (measured) and 304,207 mg l^{-1} (calculated from the ionic composition) (Expro 2013). In general TDS for the Bunter aquifer water is higher than for produced water, although several SNS fields exhibit a similar TDS (e.g. Esmond, a Bunter Sandstone reservoir, TDS = 303,000 mg l^{-1} and Anglia TDS = 298,766 mg l^{-1}); quite a number of CNS fields have TDS of ~200,000 mg l^{-1}.

Whilst some gas field formation waters in the SNS have similar TDS to the Bunter aquifer water it should be noted that they produced and discharged little water (e.g. Cleeton, Ravenspurn, Thames and Welland), or no water (e.g. Hyde and West Sole) (Hartley Anderson Ltd. 2014).

Some other fields (e.g. Ula in the Norwegian sector of the CNS) do not normally discharge produced water but re-inject it into the reservoir as pressure support, only discharging during periods when

reinjection facilities are unavailable. Produced water volumes discharged on the UKCS associated with oil and gas production decreased between 2010 to 2022, from 202 million m^3 in 2010 to 154 million m^3 in 2022 (NSTA 2022).

Concentrations of trace and other components in Bunter aquifer samples are compared with concentrations in produced water from oil and gas operations in Table 4.2 (from various published sources). Concentrations of magnesium, potassium, copper, chromium, nickel, cadmium and arsenic in the Bunter aquifer samples are higher than the range of concentrations reported for produced water.

Table 4.2: Trace and other element concentrations from Bunter Aquifer water compared to concentrations in North Sea produced waters (mg/l)

Element	Bunter Aquifer Water[1]	Jacobs *et al.* (1992)[2]	Ekins *et al.* (2005)[3]	OGP (2005)	De Vries & Karman (2009)	Neff (2002)	Aquifer c./to Prod. water
Lithium	9.4-10.2	1.4-52.3	-	-	-	-	In range
Barium	1-2	0.06-6.6	0.2-288	-	-	107-228	In range
Strontium	128-140	13.9-393	-	-	-	-	In range
Magnesium	3137-3962	445-994	-	-	-	-	Higher
Potassium	1727-1860	199-1048	-	-	-	-	Higher
Iron	<1-3	1.8-66.9	0.1-15	0.00001-0.032	-	4-11.3	In range
Copper	1.1-4.8	0.01-0.8	0.022-0.082	0.00025-0.0095	0.018-0.047	0.012-0.06	Higher
Zinc	9.6-10.7	0.2-68.9	0.5-13	0.00008-0.085	0.074-5.86	0.010-0.340	In range
Manganese	1.9-3.2	0.27-11.3	0.1-0.5	-	-	-	In range
Aluminium	<0.7	0.6-4.8	-	-	-	-	In range
Lead	1.3-1.8	<0.05-0.84	0.0004-0.0083	0.00015-0.009	0.0018-13.22	0.0004-0.010	In range
Chromium	0.4-0.9	0.07-0.26	-	0.00007-0.078	0.011-0.046	0.005-0.034	Higher
Nickel	<0.2-2.2	0.08-1.22	0.02-0.3	0.00025-0.060	0.017-0.079	0.022-0.176	Higher
Cadmium	0.2	0.01-0.19	0.0005-0.005	0.0003-0.014	<0.0005-0.167	0.0005-0.001	Higher
Cobalt	0.10-0.19	<0.1-0.4	0.3-1	-	-	-	In range
Silver	<0.05	-	-	-	-	-	-
Vanadium	0.08-0.10	0.07-0.1	0.02-0.5	-	-	-	In range
Arsenic	1.5-2.8	0.005	-	0.0005-0.026	0.0005-0.087	0.0009-0.001	Higher

Element	Bunter Aquifer Water[1]	Jacobs *et al.* (1992)[2]	Ekins *et al.* (2005)[3]	OGP (2005)	De Vries & Karman (2009)	Neff (2002)	Aquifer c./to Prod. water
Boron	11-12	1.7-82.6	-	-	-	-	In range
Phosphorus	<7	-	-	-	-	-	-
Mercury	<0.0002-0.0005[3]	<0.001-0.004	<0.0001-0.026	0.00002-0.0089	<0.00006-0.0042	0.00002-0.0027	In range

Data from: 1 Expro (2013) Ionic composition by volume corrected for MDT dilution. 2. Jacobs et al. – Average concentration of metals in produced water discharged in 1989 by Shell in the North Sea (1992). 3. Mercury sampling method may result in recording of lower than actual concentrations.

Some 130 million m^3 of produced water were discharged in 2012 from hydrocarbon production platforms to the Norwegian Continental Shelf, with the highest average daily discharge from a single field of 76,700 m^3 (Bakke *et al*. 2013). Metals found in produced water included arsenic, cadmium, copper, chromium, lead, mercury, nickel and zinc; excluding outlier high concentrations, the levels of all metals except mercury were a factor <100 above Norwegian coastal water background levels (Bakke *et al*. 2013). Monitoring studies around Norwegian fields have only found elevated levels of trace metals in sediments collected close to the installations, attributed to drilling discharges. There are no indications that trace metal concentrations in fish and shellfish sampled close to offshore installations are significantly above natural background values (Bakke *et al*. 2013).

4.3 Comparison of saline aquifer water with salt cavern brine

The Gateway gas storage project (eastern Irish Sea) proposed the solution mining of 20 salt caverns (total gas capacity 1.136 billion cubic metres) over a four year period. The assessment estimated the leaching process at each cavern would involve cycling large amounts of seawater through a well to dissolve the salt with the resultant brine mixture discharged to sea at a maximum rate of 386m^3/hour. The maximum anticipated discharge salinity, which would occur during the cavern commissioning, was estimated to be in the order of 7 times that of seawater (*ca*. 250 PSU), although it was anticipated to be much less than this during most of the leaching process. The maximum temperature of the discharge was estimated to be 8.68°C and would also occur during cavern commissioning.

Modelling studies of dispersion of the brine plume around each of the discharges indicated that the brine effluent would be best discharged through two 0.15m diameter horizontal ports located at right angles to the main current direction at about 10m above the seabed. This configuration would be expected to give at least a 33 times dilution at the point of seabed impact and a maximum salinity rise at the seabed of less than 7 PSU. Further 3D hydrodynamic modelling of the saline discharges showed that the dilution and dispersion of the discharge by the tidal currents would result in a number of separate plumes from each monopod[3]. It was predicted that there would be some merging of the plumes, but only at low salinities (less than about 1 PSU above ambient). The saline plumes were expected to be confined to the bottom 0.5 to 1.0m of the water column. Central concentrations were ca. 7 PSU, consistent with the initial dilution (i.e. no significant build-up was expected, that would reduce the dilution efficiency). The average impact at more than 1 PSU above ambient was expected

[3] The monopods referred to for this project were small structures similar to oil and gas platforms used to house salt cavern leaching equipment, and subsequently used to house the cavern gas wellhead and related equipment.

to be confined to an area within some 100m of each monopod during spring tides and within about 300m of each offshore structure during neap tides.

It was anticipated that the effluent temperature would reduce to about 2°C above ambient or less within 1m of the point of discharge. An insoluble fraction to the discharge was also predicted, mainly comprising fine mudstone particles. Modelling of this fraction found that in all cases the suspended sediment concentration that resulted from the discharge was very low, less than 0.5ppm. This was negligible compared with natural levels of suspended sediment and would not be expected to result in visible discolouration of the water. Very little data is available on the composition of trace minerals in aquifer formation water which may potentially include toxic species. However, the available information suggests a high proportion of sodium chloride and much smaller proportions of calcium, magnesium, sulphate, carbonate and bicarbonate, all of which are present in seawater. Halite deposits, being generally formed by evaporation of seawater over geological timescales, have a composition which is comparable to dissolved salt in sea water (i.e. predominantly sodium chloride). There is little data on the measured composition of brines produced from solution mining of halite caverns on the UKCS.

The Aldbrough Gas Storage Facility is located approximately 12.5km south of Hornsea (eastern England), and comprises nine underground salt caverns. Phase 1 involved the creation of salt caverns in the Zechstein salt deposits under the Holderness coast by drilling wells into the salt strata and dissolving the halites with seawater pumped down the wells (SSE & Statoil 2006).

Salt cavern leaching for this Phase 1 commenced in March 2005 with brines being discharged to sea and was estimated to take some 52 months. Brine discharge modelling was undertaken based on a discharge rate of 2,050m^3/hr with a PSU of 284. The Environment Agency consent conditions for the brine discharge included a regulatory mixing zone 250m from the diffuser within which a salinity of 40 PSU was acceptable. During the first year of monitoring discharge flow rates reached a peak of 1,942m^3/hr with a salinity of 235, averaging at 721m^3/hr with a salinity of 171. Surveys following commencement of discharge indicated that stratification or pooling did not occur. The regulatory mixing zone limit was not approached; maximum ambient salinity monitored was 37 at 250m from the diffuser (SSE & Statoil 2006).

The Whitehills gas storage project similarly proposed to use of salt caverns in the Upper Permian (Zechstein) salt deposits underlying the Holderness coast (E.On 2011). These were to be created by the pumping of seawater down wells drilled into the formation, with the resulting brines discharged to sea. The discharge outfall is approximately 3km from the Aldbrough outfall. The expected salinity of the Whitehills brine discharge was 241 PSU. The Environmental Statement for the development describes disposal of the brine solution to sea via a diffuser located 800m from the shore at a water depth of 7m MLWS (13m MHWS). The diffuser is some 40m long, buried 1.5m under the seabed with a series of riser-heads spaced along it (5.4 m apart) and with a flange at the end to allow access for cleaning. The riser heads terminate 1m above the seabed, each with 4 nozzles through which brine is discharged. The design maximum leaching flow rate is 1,320 m^3 hr-1. Dilution was expected to be 10 fold within ca. 2 m of the riser head discharge points, and modelling of the Whitehills and Aldbrough discharges indicated that the plumes would not overlap (E.On. 2011).

Brine discharge estimates for the Islandmagee gas storage project (Northern Ireland), which similarly proposes to use salt caverns, indicate a maximum discharge of 1,000m^3/hr at concentrations in the order of 8.5 times that of seawater (260 PSU) and a temperature of 10°C above ambient levels (Islandmagee Storage 2019, RPS 2019). Brine dispersion modelling from a three port pipeline diffuser located in 27m of water and subject to strong tidal currents, suggests salinity will no more than 2 PSU above ambient levels within an inner area around the diffuser, and values greater than 40 PSU will only be reached at the discharge point. Dilution increases rapidly away from the point of discharge, and reaches a dilution of >200:1 (36.6 PSU) between 5m and 10m away.

All of the above brine discharges have high salinities, but are a little lower than the Bunter aquifer water.

Table 4.3 compares the trace and other element concentrations in the Whitehill salt cavern brines with the Bunter aquifer water. Concentrations of the various elements in the salt cavern brine appear consistently lower than in the Bunter aquifer water; however, the brine concentrations in E.On (2011), were based on measurements of concentrations in samples extracted from various depths in a core from a borehole into the salt structure and (it is assumed) extrapolated from the expected salinity of the discharge brine.

Table 4.3: Trace and other element concentrations from Bunter Aquifer water compared to concentrations in predicted salt cavern brine (mg/l)

Element	Bunter Aquifer Water[1]	Whitehill Gas Storage[2]	Islandmagee Gas storage[6]	Aquifer cf salt cavern brine
Iron	<1-3	<0.02	-	Higher
Copper	1.1-4.8	0.017-0.0369[3]	<0.002	Higher
Zinc	9.3-10.7	<0.02	<0.004	Higher
Aluminium	<0.7	<0.1[4]	-	Possibly Higher
Lead	1.3-1.8	<0.025	<0.002	Higher
Chromium	0.4-0.9	<0.002	<0.001	Higher
Nickel	<0.2-2.1	<0.005	<0.003	Higher
Cadmium	0.2	<0.002	<0.0004	Higher
Cobalt	0.10-0.19	<0.004	-	Higher
Arsenic	1.9-3.3	<0.005	<0.002	Higher
Boron	11-12	<0.02	<3.8	Higher
Phosphorus	<7	<0.00016	-	Possibly Higher
Mercury[5]	<0.0002-0.0004	<0.00025	< 0.000024	Higher

Data from: 1. Expro (2013) Ionic composition by volume corrected for MDT dilution. 2. E.On (2011). 3. Includes naturally occurring and antifouling contributions. 4. Includes naturally occurring and antifouling contributions. 5. Mercury sampling method may result in recording of lower than actual concentrations. 6: RPS (2019).

5 Naturally occurring brine seeps

Seepage of hypersaline groundwater occur when salt diapirs breach the sediment-water interface or extend to shall sub-bottom depths (<50m) in areas with active SGD (Reilly *et al*. 1996). These high salinity seeps can in extreme cases drive the formation of brine-filled basins or smaller pools on the seafloor, identified in the Mediterranean Sea (e.g. Cita 1991, Herut *et al*. 2022), the Red Sea (e.g. Duarte *et al*. 2020, Purkis *et al*. 2022) and the Gulf of Mexico (e.g. Paull *et al*. 1984), with new discoveries of such features being regularly made. Geochemical profiles through these pools show steep gradients in dissolved oxygen concentrations, redox metabolites, temperature and salinity between the discharging brine and the surrounding seawater (Joye *et al*. 2005). Table 5.1 shows the geochemical composition of brine pools and seeps in the Gulf of Mexico, Red Sea, and Mediterranean, with seawater at each location also shown for comparison.

Table 5.1: Geochemical composition of brine pools from the Gulf of Mexico, Mediterranean and Red Seas in relation to ambient seawater

Site ID	Site Type	Salinity	Cl	Na^+	K^+	Ca^{2+}	Mg^{2+}	SO_4^{2+}	H_2S	Fe^{2+}	NH_4^+
Gulf of Mexico											
Bottom water	Seawater	34	564	462	43	11	11	29	~0	~0	0.1
Site GC233	Brine pool	121	2092	1751	22	36	9.7	<1	0.002	92	11
Orca Basin	Brine pool	258	5000	-	-	32	-	47	0.6	-	0.5
Orca Basin	Brine pool	250	4450	4240	17.2	29	42.4	20	0.025	30	0.5
Mediterranean											
Bottom water	Seawater	35	600	492	11.2	11	56	31	0	-	-
Urania Basin	Brine pool	200	2830	-	-	34	-	85	8.6-11	-	-
Libeccio Basin	Brine pool	321	5333	-	-	21	-	99	1.7	-	3
Tyro Basin	Brine pool	-	5350	-	-	34	-	49	2.1	-	1.2
Red Sea											
Shaban Deep	Brine pool	242	3658	4408	44	20	77	-	-	122	-
Shaban Deep	Brine pool	220	4361	3953	39	19	74	-	-	108	-
Atlantis II	Brine pool	126	2000	-	-	-	-	0	0	0	-
Discovery	Brine pool	252	4000	-	-	-	-	0	0	0	-
Kebrit	Brine pool	252	4000	-	-	-	-	30	0.4	0	-
UK Bunter Sandstone saline aquifer											
Bunter	Saline aquifer	14-310 (>180)	5200	5300	-	23	3	-	-	0.02	-

Source: after Joye et al. (2005).
Notes: Salinity = ‰ (grams of salt per kilogram solution), all other concentrations are measured in mM, except FE^{2+} which is in µM.

The deep Florida Escarpment seeps at 3,270m water depth are hypersaline and sulphidic, which attracts chemosynthetic biological communities, with mussels and tubeworms as key components (Paull *et al*. 1984).

The Gulf of Mexico brine lakes occur in pockmarks overlying buried salt deposits. The salt forms hypersaline brines when it comes into contact with seawater and forms dense 'lakes' as small as 1m across, and up to 20km, on the seabed (Judd & Hovland 2007). Salinities of these lakes are around 121-250‰, compared with 34‰ of the surrounding seawater (Table 1-2; Joye *et al*. 2005), with temperatures of the venting brine elevated by up to 10°C above ambient seawater (Figure 1-2). Nutrient values for brine pool GC233 (Table 1-2), formed from halite dissolution of a salt diapir within 500m of the seafloor, show that brines are an important source of energy rich compounds to surrounding bottom waters.

Some of these 'lakes' have no obvious chemosynthetic activity associated with them other than bacterial action. Others, most notably the Brine Pool (at 640m water depth), have dense mats of methane-using mussels fringing their shores in a 3m wide strip defining the oxic-anoxic interface around the edge of the brine. Although mussels can move short distances, variations in the brine levels in the pools are often too fast for them and some die when the surface rises (MacDonald *et al*. 1990, Van Dover 2000).

6 Review of Dispersion Modelling of Potential Brine Discharges in UK Waters

The Whitehall, Preesall, Gateway and Islandmagee gas storage projects involve creating caverns within halite deposits for gas storage, and modelling was undertaken to predict the dispersion of discharged formation water with salinities of 240-260‰. Halite samples from cores in the stratigraphic interval of the Permian salt sequences in which the Islandmagee gas storage caverns were to be created were analysed for a variety of other elements (As, B, Cd, Cr, Cu, Pb, Hg, Ni & Zn). This was to provide an input to brine discharge dispersion modelling. None of the elements analysed for was found to exceed the relevant Environmental Quality Standard limit in the brine from cavern formation prior to discharge (Appendix B in Islandmagee Storage, 2019). The modelling outputs give an indication of the extent of effects of a highly saline plume (Table 6.1). The results of the modelling studies indicate that a slight increase in ambient salinity may be observed out to 1,500m, while ambient salinities of 36-40‰ may extend up to *ca*. 500m from the discharge location, and salinities exceeding 40‰ will be very localised within 100m of the discharge location. Modelling results for these locations suggest that highly saline formation water will rapidly disperse in near surface waters creating an impact footprint of elevated salinities within *ca*. 500m radius of the discharge location.

Table 6.1: Summary of dispersion modelling predictions of hypersaline brine discharges associated with UK projects

Modelled parameters	Whitehill[1]	Preesall[2]	Gateway[3]	Islandmagee[4]
Location	Yorkshire	Lancashire	Irish Sea	Northern Ireland
Max. flow rate (m^3/hr)	2,050	3,000-3,300	386	1,000
Max. discharge salinity	241	260	250	260
Discharge depth (m)	-	4m	10m above seabed	0.75m above seabed
Extent (m) salinity <1‰ above ambient	1,500	-	-	<100
Extent (m) salinity 36-40‰	500	50-450	100-300	100-200
Extent (m) or area (km^2) salinity >40‰	0.1km^2	50-60m	-	-

Source: [1] E.On (2011), [2] Hyder (2003), [3] Gateway (2007), [4] RPS (2019)

7 Potential Environmental Impacts from Brine Discharges

During the development and expansion of carbon dioxide storage into deep saline formations it may be necessary to reduce pressure within the formation and increase the CO_2 storage capacity by removing brine from the formation, for example, via brine production wells with subsequent discharge to sea or reinjection into other formations. There is also a potential (albeit at a much lower likelihood) for brine leakage direct to the seabed from undetected leak paths in the formation. The potential impacts from discharges or leakages of hypersaline brine to sea associated with carbon dioxide storage activities have not yet been studied, however, discharges of brines from desalination plants and development of salt cavern storage facilities gives an indication of the type of discharge and the potential impacts that can be expected from similar operations offshore.

Modelling, and monitoring of the Aldbrough gas storage project, have indicated potential ecological effects from both saline aquifer and halite solution mining discharges are likely to be associated with osmotic effects of hypersalinity rather than toxicity associated with contaminants within the brine. The ecological effects of brine discharge are expected to be effectively mitigated by dispersion of brine plumes to reduce the salinity effects to sessile organisms within the vicinity. Although there have been no developments of offshore salt caverns in the UK (noting that Aldbrough provides a proxy of offshore discharge effects from an onshore facility), the environmental effects of brine discharges have been well studied in other countries, notably in relation to discharges from desalination plants but also in relation to solution mining. Construction of salt caverns on the coast of the Gulf of Mexico as part of the US Strategic Petroleum Reserve Program in the 1970s was accompanied by a major environmental monitoring study of the discharge from the Bryan Mound (Texas) site, coordinated by Texas A&M University (Randall & Hann 1981). This included extensive measurement of the brine plume and baseline and post disposal evaluation of water and sediment quality, nekton (free swimming fauna), benthos, phytoplankton and zooplankton. Biological, water and sediment quality data indicated no substantial effects of the brine plume, which extended over a maximum recorded area of 7.4km^2 and vertical height above the seabed of 7.6m. A complementary study of the West Hackberry (Louisiana) site found no demonstrable effects on sediments or phytoplankton, and limited long-term effects on zooplankton, benthos and nekton (Giammona & Darnell 1990). Seasonal variability in species abundances was a predominant feature as dramatic population fluctuations occurred in all groups studied.

Differences among stations of relatively small magnitude were observed for many species and biomass estimates. Some of the differences were consistent when specific comparisons were made between control and diffuser area stations. They include: statistically significant differences in population densities of certain numerically dominant macrobenthic species, and significantly lower values for coefficient of condition (weight at length) of certain nekton target species collected in the vicinity of the brine diffuser. None of the observed changes in biotic communities were catastrophic in nature and all other measured parameters were either within expected ranges of or could not be attributed to diffuser activities (DeRouen *et al.* 1983).

A study of the biological effects of brine discharges from two desalination plants in shallow waters of the Mediterranean Sea (*ca*. 2m depth at *ca*. 45m distance from the shore) suggests that while the discharge of brine can impact the sediment biogeochemistry and the distribution and diversity of benthic communities the impact is spatially confined to within tens of metres of the outfall locations (1-30m distance) (Bianchelli *et al*. 2022). The magnitude of the impact will depend on the salinity of the discharge, speed of dilution and the sensitivity of the ecosystem that receives it (Fernández-Torquemada *et al*. 2009). An eight year study of the ecological impacts of brine disposal from the San Pedro del Pinatar desalination plant in south east Spain detected effects on the benthic communities, particularly polychaete assemblages which were associated with high salinity values in the vicinity of the discharge point due to the low hydrodynamic activity. In response to the benthic impacts a diffuser was installed to the end of the discharge pipeline to increase mixing and dilution of the brine with ambient seawater. The benthic community in the vicinity of the brine discharge point

showed relatively rapid indications of recovery (over months rather than years) in response to the increased mixing and reduction in ambient salinity (Del-Pilar-Ruso *et al*. 2015).

Kenigsberg *et al*. (2020) studied the long-term effects on benthic foraminifera of continuous brine discharge from three desalination plants along the Mediterranean Israeli coastline. Changes in the relative abundance of selected species near the discharge locations when compared to the control stations (located several kilometres distance from the discharge) indicated their sensitivity to the brine discharge. The most prominent impact was observed on organic-cemented agglutinated foraminifera species, with a minor local effect also observed on calcareous benthic foraminiferal assemblages (Kenigsberg *et al*. 2020).

Smyth *et al*. (2014) conducted laboratory experiments on the commercially valuable crustaceans, the edible brown crab, *Cancer pagurus*, and the European lobster, *Homarus gammarus*, to determine to what extent exposure to hypersaline conditions (such as a marine discharge of highly saline brine) would initiate a physical avoidance reaction and whether the presence of a shelter would affect the salinity preference of these species. Both species were found to have a significant behavioural response to highly saline brine being able to detect and avoid areas of hypersalinity once their particular threshold salinity was reached (salinity 50 for *C. pagurus* and salinity 45 for *H. gammarus*). The presence of shelters had no effect on this response and both species avoided hypersaline areas, suggesting that if exposed to highly saline brine discharges it is likely that the adults of these species will move to areas of more favourable salinity (Smyth *et al*. 2014).

In addition to the impacts of increased salinity on the receiving marine environment, some studies have suggested that the ecological impacts of the discharge were disproportionate to the relatively minor change in salinity and that changes in local hydrodynamics due to the high volumes of discharge effluent may also be responsible for the ecological impacts observed (Clark *et al*. 2018, Kelaher *et al*. 2022). These studies reported a significant increase in species richness of fish and an increase in the abundance of barnacles around the discharge outlet, while other invertebrates such as polychaetes, bryozoans and sponges were reduced in cover out to 100m from the outfall, which the authors suggest may be in response to the high pressure discharge of water causing water column disturbances which are often otherwise associated with increased food availability (Clark *et al*. 2018, Kelaher *et al*. 2022).

Overall the research into ecological impacts associated with the discharge of hypersaline brine indicates that the influence of brine discharge to the marine environment is spatially localised to within tens to hundreds of metres and may be the result of an increase in temperature, salinity or change to the hydrodynamics of the area.

8 Conclusions

Although not required in the first stage of a carbon dioxide storage project using a saline aquifer, to maximise storage capacity and manage aquifer pressure, discharge of aquifer water may be needed. The behaviour of brine discharges in the water column is a function of the nature and type of discharge, for example whether it is a seep from the seabed through a formation outcrop, or potentially a controlled surface discharge should formation water need to be produced, which would lead to the highly saline and dense fluid sinking through the water column to the seabed. A discharge near the sea surface would result in greater dilution and mixing of the plume compared to a seabed discharge. Studies to date have indicated that salinities exceeding ecological thresholds would be localised and typically range between tens to hundreds of metres from the discharge location (Dewar *et al.* 2022).

Saline aquifer water is typically warmer than ambient seawater in the North Sea, but modelling suggests that elevated temperatures associated with the plumes would be highly localised and unlikely to have significant ecological consequences (Dewar *et al.* 2022).

The discharge of trace elements and other contaminants within hypersaline brine may have the largest ecological impact footprint associated with different brine parameters. However, modelling results suggest that with a worst case seabed release predicted no effect concentrations would be reached within *ca*. 500m from the discharge location (Hartley Anderson Ltd. 2014, Dewar *et al.* 2022). While individual modelling studies and related assessments of the effects of discharges on flora and fauna suggest a spatially limited effect, the potential cumulative effects of multiple projects involving salt cavern construction and saline aquifer discharges have not been studied, and could be relevant to further development of natural gas and carbon dioxide storage projects, particularly in the southern North Sea and Irish Sea.

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